NEGOTIATING DISCIPLINARY BOUNDARIES

IN

ENGINEERING PROBLEM-SOLVING PRACTICE

Karin Elizabeth Wolff

Full thesis in fulfilment of the requirements for the degree of

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Declaration of originality

I, the undersigned, declare that the work contained in this thesis is my own original work and has not previously been submitted to any other institution for assessment purposes. Furthermore, I have acknowledged all sources used and cited in the list of references.

This research project emerged indirectly as a result of findings in my Master's thesis. A number of papers have been published drawing on aspects of the core theoretical framework introduced in the Master's thesis and situated in the broader empirical site, but from the perspective of curriculum and pedagogy:

Wolff, K. (2011). Integrating multidisciplinary engineering knowledge in a final year technical university diploma programme: an analysis of student praxis. (Unpublished Master's thesis). University of Cape Town.

Wolff, K. (2013). 'Reservoirs' and 'Repertoires': epistemological and discursive complexities in multidisciplinary engineering practice. *Journal of Academic Writing, 3*(1), 84-94.

Wolff, K., & Hoffman, F. (2014). Knowledge and knowers in engineering assessment. *Cristal, 2*(1), 74-95. doi:10.14426/cristal.v2i1.19

Wolff, K., & Luckett, K. (2013). Integrating multidisciplinary engineering knowledge. *Teaching in Higher Education, 18*(1), 78-92.

The research presented here for the Doctoral Degree is located in the field of professional practice and represents an entirely independent study. The thesis is, therefore, presented as a coherent study as per the requirements of the degree. Aspects of the study were presented shortly before submission of the thesis and published in conference proceedings:

Wolff, K. (2015). Insights into conceptual and contextual engineering problem-solving practices in the 21st century: some implications for curriculum redesign. *Proceedings of the 3rd Biennial Conference of the South African Society for Engineering Education* (pp. 189-198). Durban: SASEE.

All previously published theoretical aspects are not repeated verbatim in this thesis, and all empirical findings from the previous study, but with bearing on the current study, are cited appropriately.

Date: August 2015

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Glossary of technical terms[1]

ADC	'Analog-to-digital conversion is an electronic process in which a continuously variable (analog) signal is changed, without altering its essential content, into a multi-level (digital) signal' (www.whatis.techtarget.com).
Blow moulding	'A process for moulding single-piece plastic objects in which a thermoplastic is extruded into a split mould and blown against its sides'.
Brush	'A conductor, often made of carbon or copper or a combination of the two, serving to maintain electric contact between stationary and moving parts of a machine, generator, or other apparatus'.
Bus	'A circuit that connects the CPU (central processing unit) with other devices in a computer'.
Capacitor	'A capacitor is a passive electronic component that stores energy in the form of an electrostatic field' (www.whatis.techtarget.com).
Drive (motor)	'A device that converts any form of energy into mechanical energy, especially an internal-combustion engine or an arrangement of coils and magnets that converts electric current into mechanical power'.
Field Effect Transistor (FET)	'A transistor in which the output current is varied by varying the value of an electric field within a region of the device'.
Graphical User Interface (GUI)	'It is a user interface that includes graphical elements, such as windows, icons and buttons' (www.techterms.com).
Hoppers	'A funnel-shaped chamber or bin in which loose material, such as grain or coal, is stored temporarily, being filled through the top and dispensed through the bottom'.
Human Machine Interface (HMI)	'An HMI is a software application that presents information to an operator or user about the state of a process, and to accept and implement the operator's control instructions. Typically information is displayed in a graphic format (Graphical User Interface or GUI)' (www.subnet.com/resources/dictionary).
Jig	'A plate, box, or open frame for holding work and for guiding a machine tool to the work, used especially for locating and spacing drilled holes; fixture'.
Load cell	'A type of transducer that converts physical force into measurable, quantifiable electric energy' (www.thomasnet.com/articles/instruments-controls/load-cell-basics).
Logic (1)	'A branch of philosophy and mathematics that deals with the formal principles, methods and criteria of validity of inference, reasoning and knowledge'.
Logic (2)	The study of (deductive) 'inferences that depend on concepts that are expressed by the 'logical constants' such as *and, not, or, if…then*' (Britannica Concise Encyclopaedia, 2006).

[1] All technical definitions, unless otherwise indicated, are supplied by Dictionary.com LLC (2015) www.dictionary.reference.com

Logic programming	'The study or implementation of computer programs capable of discovering or checking proofs of formal expressions or segments'. The user writes a database of 'facts' and 'rules', which are collectively known as 'clauses'. 'The user supplies a 'goal' which the system attempts to prove using 'resolution' or 'backward chaining'.
LVDT (linear probe)	'Linear Variable Differential Transformer, a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal' (www.macrosensors.com).
Mechatronics	'The combination of Mechanical engineering, Electronic engineering, Computer engineering, Software engineering, Control engineering, as used in the design and development of new manufacturing techniques'.
Microcontroller	'A small computer on a single integrated circuit containing a processor core, memory, and programmable input/output peripherals'.
Ohm's Law	'The law that for any circuit the electric current is directly proportional to the voltage and is inversely proportional to the resistance'.
Op-Amp	'A high-gain, high-input impedance amplifier, usually an integrated circuit, that can perform mathematical operations when suitably wired'.
PC	Personal computer
P-channel FET	'P-channel mosfets work in the same manner as an N-channel fet, but instead of controlling/controlled by positive voltage, they are controlled by negative voltage signals to the gate. They are off when the voltage to the gate is +V, and on when the voltage is negative, or zero' (www.instructables.com).
Pin	'A pin is a pronged contact as part of a signal interface in a computer or other communications device' (www.whatis.techtarget.com).
Programmable Logic Controller (PLC)	'A device used to automate monitoring and control of industrial plants'.
Printed Circuit Board (PCB)	'An electronic circuit in which certain components and the connections between them are formed by etching a metallic coating or by electrodeposition on one or both sides of a thin insulating board. Also called printed circuit, printed circuit card'.
SAP	Systems Applications and Products in Data Processing (www.guru99.com).
Six Sigma	'A business management strategy that uses statistical methods to identify defects and improve performance'.
Transistor	'An electronic device that can work as an amplifier, transforming weak electrical signals into strong ones. It is normally made from silicon or other semiconductors'.
Zener diode	'A semiconductor diode across which the reverse voltage remains almost constant over a wide range of currents, used especially to regulate voltage'.

Acronyms

AI	Artificial Intelligence
BET	Bachelor of Engineering Technology (new 420-credit, 3-year qualification)
B-Tech	Bachelor of Technology (old 120 – 140-credit, 1-year post-Diploma qualification)
CDIO	Conceive, Design, Implement & Operate
CHE	Council on Higher Education
CHEC	Cape Higher Education Consortium
DMAIC	Define, Measure, Analyse, Implement (Improve), Control (Six Sigma methodology)
ECSA	Engineering Council of South Africa
ESGB	Engineering Standards Generating Body
HE	Higher Education
HEI	Higher Education Institution
HEQSF	Higher Education Qualification Sub-Framework
HSRC	Human Sciences Research Council
HWI	Historically White Institution
ICT	Information Communication Technology
LCT	Legitimation Code Theory
MEFSA	Mechatronics Education Forum of Southern Africa
NQF	National Qualification Framework
R&D	Research and Development
SET	Science, Engineering & Technology
UNESCO	United Nations Educational, Scientific, and Cultural Organisation
UoT	University of Technology
WIL	Work Integrated Learning

Stylistic conventions

- The APA style is used throughout the thesis with the British English convention of single quotation marks. There are, however, also several concepts in this cross-disciplinary study that are indicated using single quotation marks where necessary to indicate specific meanings.
- All theoretically technical terms are initially italicised and defined in the conceptual and methodology chapters. Certain analytical terms are italicised throughout the analysis and discussion chapters to differentiate these meanings from everyday or other meanings.
- Participants are identified through an alphanumeric system (detailed in chapter 5) and participant quotes are presented in numeric format.
- Web references in footnotes and Appendices are hyperlinked for reader convenience.
- The problematic he/she when referring to a generic singular is given as s/he.

Acknowledgements

This thesis is based on research conducted among Mechatronics Diploma graduates from the Cape Peninsula University of Technology, who are employed in multidisciplinary engineering industries in the Western Cape. I would like to acknowledge these practitioners and their industry supervisors for the invaluable contribution they have made to the future of a potentially more responsive form of engineering education in the country.

I am grateful to the founding Head of Program, Mr Francois Hoffman, who set the tone for a dynamic, collaborative and engaged form of mechatronics education that enabled the graduating technicians to find a meaningful place in our local and national industries. I am indebted to Associate Professor Cecilia Jacobs (University of Stellenbosch) for setting me on this course and for not only offering unfailing academic and personal support, but for introducing me to Professor Arie Rip (University of Twente, the Netherlands). Professor Rip, on his annual visits to South Africa, always managed to find time to listen, guide, and advise me on matters of complexity.

My thanks go to my project supervisor, Associate Professor Suellen Shay, and co-supervisor, Associate Professor Karl Maton (University of Sydney) for their illuminating theoretical insights and facilitative supervision. I would also like to acknowledge the invaluable technical engineering support of Dr Simon Winberg (University of Cape Town). A fortuitous airplane journey placed me in the seat beside Professor Johan Muller (University of Cape Town) during my data collection phase, and his probing interest helped me to clarify numerous issues. Professor Chris Winberg (Cape Peninsula University of Technology), too, is to be thanked for including me on much needed research retreats. A particular word of thanks needs to go to valued colleagues and friends: Ms Leigh Sonn for her mathematical and systems insights, Ms Tanya Mohr for her inspiring commitment to transformative education, fellow LCTers in the vibrant LCT forum, especially Dr Sherran Clarence and Ms Nicky Wolmarans.

Words cannot express the gratitude I feel towards my parents for having provided me with loving support and the best educational opportunities from childhood, and instilling in me a spirit of enquiry accompanied by Germanic precision. This work is an attempt to pursue the former with the rigour of the latter. I have attempted to do justice to this. Finally, this work is dedicated to my children, who sacrificed much of their early teenage years watching their mother bowed over a computer. I can only hope their sacrifice is met by an improved South African educational and social landscape.

Thank you to the National Research Foundation for an Innovation Doctoral scholarship, Grant # 95324, which enabled the writing up phase of this thesis.

Abstract

The impetus for this research is the well-documented current inability of Higher Education to facilitate the level of problem solving required in 21st century engineering practice. The research contends that there is insufficient understanding of the nature of and relationship between the significantly different forms of disciplinary knowledge underpinning engineering practice. Situated in the Sociology of Education, and drawing on the social realist concepts of knowledge structures (Bernstein, 2000) and epistemic relations (Maton, 2014), the research maps the topology of engineering problem-solving practice in order to illuminate how novice problem solvers engage in epistemic code shifting in different industrial contexts. The aim in mapping problem-solving practices from an epistemological perspective is to make an empirical contribution to rethinking the theory/practice relationship in multidisciplinary engineering curricula and pedagogy, particularly at the level of technician.

A novel and pragmatic problem-solving model – integrated from a range of disciplines – forms the organising framework for a methodologically pluralist case-study approach. The research design draws on a metaphor from the empirical site (modular automation systems) and sees the analysis of twelve matched cases in three categories. Case-study data consist of questionnaire texts, re-enactment interviews, expert verification interviews, and industry literature. The problem-solving model components (problem solver, problem environment, problem structure and problem-solving process) were analysed using, primarily, the Legitimation Code Theory concept of epistemic relations. This is a Cartesian plane-based instrument describing the nature of and relations between a phenomenon (*what*) and ways of approaching the phenomenon (*how*). Data analyses are presented as graphical relational maps of different practitioner knowledge practices in different contexts across three problem-solving stages: approach, analysis and synthesis.

Key findings demonstrate a symbiotic, structuring relationship between the '*what'* and the '*how'* of the problem in relation to the problem-solving components. Successful problem solving relies on the recognition of these relationships and the realisation of appropriate practice code conventions, as held to be legitimate both epistemologically and contextually. Successful practitioners engage in explicit code-shifting, generally drawing on *a priori* physics and mathematics-based knowledge, while acquiring *a posteriori* context-specific logic-based knowledge. High-achieving practitioners across these disciplinary domains demonstrate iterative code-shifting practices and discursive sensitivity. Recommendations for engineering education include the valuing of disciplinary differences and the acknowledgement of contextual complexity. It is suggested that the nature of engineering mathematics as currently taught and the role of mathematical thinking in enabling successful engineering problem-solving practice be investigated.

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CHAPTER 1: INTRODUCTION

1.1 Background to the problem

> 'Advances in engineering have been central to human progress ever since the invention of the wheel. In the past hundred and fifty years in particular, engineering and technology have transformed the world we live in, contributing to significantly longer life expectancy and enhanced quality of life for large numbers of the world's population' (UNESCO, 2010, p. 3).

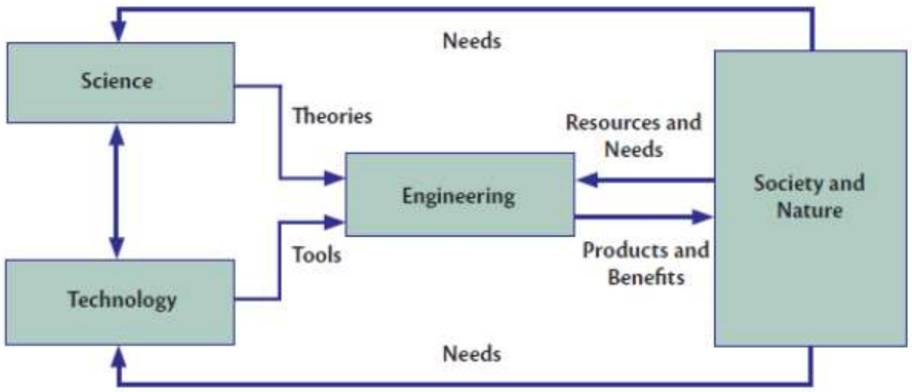


Figure 1-1 Engineering relationship to society & science (UNESCO, 2010, p. 25)

The UNESCO report on engineering is 'the first of its kind to be produced by … any international organisation' (2010, p. 3), and represents an attempt to capture the global status of engineering developments, challenges and education. The report characterises the nature of the field in the 21st century as situated at the interface between science, technology, society and nature (figure 1-1). Each of these facets not only represents different forms of knowledge and practices in their own right, but also reveals increasingly complex and diverse trajectories and interdependencies in the face of globalisation and exponential technological development. This complexity, from a knowledge perspective, has been termed 'Mode 2 knowledge production', which is 'socially distributed, application-oriented' (Nowotny, Scott, & Gibbons, 2003, p. 179) knowledge. It has its 'origins in the synergy and cross-fertilisation in the interstices between established disciplines' (Kraak, 2000, p. 18) and is 'trans-disciplinary … heterogeneous … problem-solving knowledge' (*ibid*., p. 9).

The complex relationship of engineering to society and science, and the characterisation of 21st century knowledge production as 'Mode 2', is reflected in policy-driven engineering curriculum alignment and reform initiatives. Three International Engineering Alliance (IEA) accords[2] (Washington, Sydney and Dublin) designed to facilitate international comparability of engineering qualifications have established the knowledge, attributes and professional

[2] http://www.ieagreements.org/

competency profiles required by three types of engineering professionals: engineer, technologist and technician. The guidelines require competent graduates to demonstrate the application of natural, mathematical and engineering science knowledge and practices; the use of field-specific tools, technologies and methodologies; and a host of attributes such as ethics, life-long learning, social, economic and environmental impact awareness. This holistic, complex and socially-responsible view of today's engineering professional suggests a more demanding curriculum to enable the central 'engineering endeavour': that of 'problem solving' (Sobek, 2004). With virtually identical competency profiles, the differentiation between the three professional types is primarily according to levels of problem-solving complexity:

- Engineers - *complex* problems
- Technologists - *broadly-defined* problems
- Technicians - *well-defined* problems

Tertiary education institutions, worldwide, face the unprecedented pressure of training masses of 'professionals [equipped with the] broad problem-solving skills' (Kraak, 2000, p. 11) necessary to cope with the reality of an increasingly complex field. In addition to the accords-aligned curriculum reform, the labour market demand that engineering graduates be able to contribute productively from the beginning of their careers (Case, 2011) has seen, in some quarters, a shift towards progressive, constructivist pedagogic approaches aimed at developing 'problem-solving' skills through 'guided inquiry, problem-based learning, and project-based learning' (Felder, 2012, p. 11). The UNESCO report (2010) supports such approaches, stating that engineering education 'has a particular need to overcome the Humboldtian notions underlying the 'fundamentals' approach to education' (p. 32). The report suggests that the discipline-based curriculum, 'largely unchanged in 150 years' (p. 126) is responsible for the loss of potential engineering recruits. International literature abounds with statistics on falling engineering enrolment and completion rates (UNESCO, 2010), poor retention rates (Bernold, Spurlin, & Anson, 2007), and 'chronic industry complaints about skill deficiencies in engineering graduates' (Felder, 2012, p. 9). The latter complaint appears to support the notion that engineering education is too theoretical. In the USA, engineering education is regarded by some as in a state of 'quiet crisis' (Jackson, 2007).

In South Africa (the focus of the research) engineering is cited as a particular area 'in which skills are in short supply or decreasing' (CHE, 2009, p. 40). A report by the Human Sciences Research Council (HSRC) describes the current state in South African engineering 'as one of the worst capacity and scarce skills crises in years' (Du Toit & Roodte, 2008, p. 1). Against an overall Higher Education (henceforth HE) participation rate of a mere 16% (figure 1-2), a throughput report commissioned by the Engineering Council of South Africa (ECSA) cites a comparative overall graduation rate[3] in engineering Bachelor's programmes of between 35% and 60% depending on the particular institution (Fisher, 2011). The HSRC further reports a throughput rate[4] (over a 10 year period ending in 2005) as a relatively stable 60% for Bachelor's programmes (engineers) and 40% for Diploma[5] programmes (technicians) (Du Toit & Roodte, 2008, p. 53).

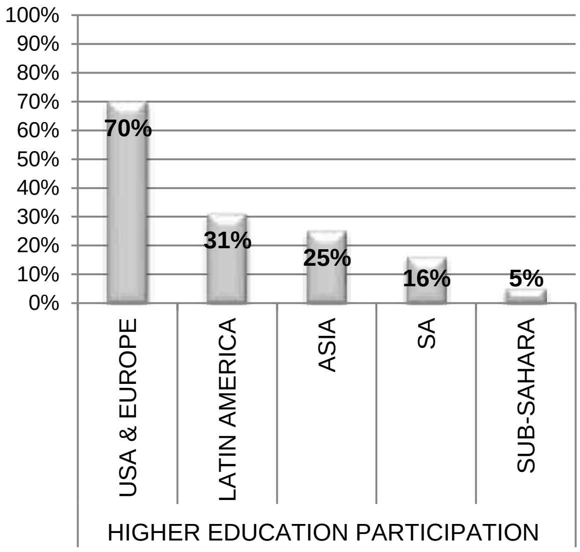


Figure 1-2 Comparative HE participation (Fisher, 2011)

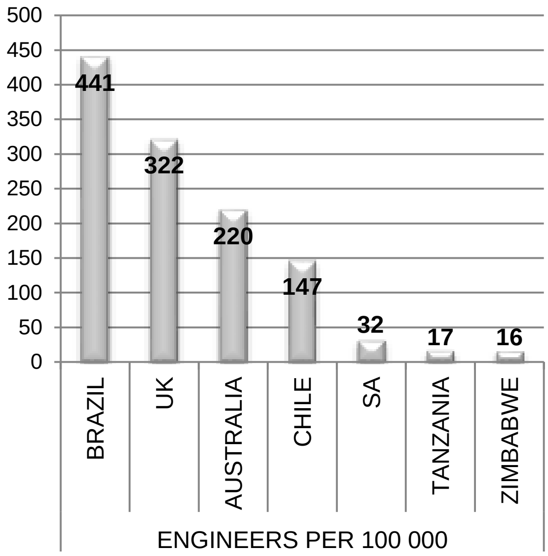


Figure 1-3 Comparative engineering professionals per 100 000 (Fisher, 2011)

This suggests an internationally comparable average non-completion or dropout rate of 50% on South African engineering programmes. Such a rate is unacceptable in a country which is effectively producing only 3.5% of the technicians (Du Toit & Roodte, 2008) required to be a key 'part of the problem-solving solution to sustainable development and poverty reduction' (UNESCO, 2010, p. 32). And yet, on the other hand, over 10 000 qualified Science, Engineering and Technology (SET) technicians were recorded as unemployed in South Africa in 2012 (CHEC, 2013). In the Western Cape alone (the regional site of the research), 31.2% of all 2010 SET graduates were unemployed in 2012 (*ibid.*). Clearly something is amiss.

A comprehensive employer survey on graduate performance (Griesel & Parker, 2009) – of which 56% of the industries surveyed were in SET sectors - revealed the key gap as that 'between employer expectations and higher education outcomes' with respect to *application of knowledge* (p. 1). In the case of engineering technicians in the Western Cape, the most common industry complaints refer to the lack of being 'hands-on' and an inability to 'fault-find'

[3] Percentage of graduates against enrolments in any year.
[4] Calculated as the number of graduates against the number of enrolments 4 (Bachelor's) or 3 (Diploma) years prior to graduation.
[5] There are 6 post-secondary school National Qualifications Framework (NQF) levels, being: Higher Certificate (5), Advanced Certificate (6), Diploma (5 & 6 together), 3-year Bachelor's degree (7), 4-year Professional Bachelor's degree (8), Honour's (8), Master's (9), and Doctorate (10).

(Wolff, 2012). Anecdotal evidence from multiple sources suggests that local industries find graduating technicians ill-equipped to solve 'even the most basic of problems' (Hoffman, 2011). By way of example, a leading international automotive manufacturer with 34 available positions in 2011 could only appoint three local technicians following competency testing (*ibid*.). This assessment of engineering graduate inability to 'apply knowledge' suggests a disjuncture between the view of the academy and that of employers as to what 'apply knowledge' may mean, and calls into question the relationship between 'theory' and 'practice'.

It is the contention in this research that a major factor in engineering education may well be poorly informed conceptualisation of the nature of and relationship between theory and practice with regard to enabling the 'problem solving' necessary for the different engineering qualification levels. The theory/practice relationship is particularly problematic for those qualifications falling between what Muller (2008) differentiates as conceptual and contextual-coherence curriculum structures. The traditional professional Bachelor's qualification in engineering is situated in the former, with strong adherence to the disciplinary (conceptual) fundamentals which are intended to enable 'complex' problem solving. The traditional engineering trades or occupations issued as certificates (such as mechanics, plumbing, electricians) fall in the latter 'contextual' category, with specific 'narrowly-defined' problem-solving contexts in mind (ECSA, 2012). The qualifications for technician and technologist (precisely those practitioners who swell the unemployed SET numbers in the Western Cape) sit uncomfortably between the two. Given the increasingly complex 21st century engineering contexts, as well as the more holistic and demanding engineering qualification prescriptions, how realistic is the 'well-defined' descriptor characterising the level of problem solving required for technicians? Or even 'broadly-defined' for a technologist? What exactly is the nature of the problems engineering technicians/technologists are expected to solve? What are the contexts in which employers are complaining that they cannot 'apply knowledge'?

Social realism offers a range of concepts that can help to interrogate the nature of theory and practice in sociocultural contexts. Engineering curricula undergo what Basil Bernstein terms a 'regionalisation of knowledge' (1996, p. 8). This occurs through a 'recontextualising principle' (*ibid*), which sees the selection and combination of elements of the 'singulars' (pure disciplines such as mathematics and physics) to form a new 'region' (such as engineering). Modern engineering 'sub-regions' (for want of a better term), such as mechanical, electrical or bio-medical engineering, demonstrate selective *re*-recontextualisations of elements of the natural and mathematical sciences, which differ for each of the sub-regions. Engineering for the 21st century has seen multiple recontextualisation stages as designers (a range of stakeholders) attempt to retain the disciplinary fundamentals, keep abreast of rapid technological changes (essentially context-specific), and adequately prepare graduates for the workplace. This has tended towards an increasingly 'segmental' (Maton, 2009) and contextually-coherent (Muller,

2008) curriculum structure for engineering qualifications, particularly at the level of technician. Bernstein argues that for a region to remain viable, ‘we must have an understanding of the recontextualising principles’ (1996, p. 9) and suggests, in the case of an integrated curriculum, that ‘the relational idea’ (1975, p. 93) must be clear. In other words, the coherence of the region needs to be evident in the curriculum structure and, by extension, in the associated pedagogic practice. I suggest that precisely the same principle is present in industrial practice: Practitioners select and ‘recontextualise’ knowledge in application to a problem, and for that application to be successful there must be a ‘relational idea’. Wheelahan (2007) argues that competency-based curricula, with their focus on context-specific and problem-based learning, deny students access to the ‘relational connections’ and ‘collective representations’ about disciplinary ‘causal mechanisms’ (p. 5). The dilemma with the increasing focus on forms of contextual practice is that it assumes that the ‘disciplinary basis of a subject-based curriculum is arbitrary’ and promotes a view of knowledge ‘as undifferentiated – ‘generic’ skills or interchangeable packets of information’ (Maton & Moore, 2010, p. 6). In other words, it assumes that, given the opportunity, students (or practitioners) can ‘construct’ meaning in the same way in the context of all types of knowledge.

Much of the debate around knowledge in education is concerned with typologies for the purpose of designing educational programmes with appropriate forms of knowledge. These forms continue to be persistently binary or simplified characterisations (such as theory/practice), which ‘have become inflexible and incapable of adapting to the increasing pluralism and volatility within the [HE] system’ (Kraak, 2000, p. 17). The pervasive reduction of all theoretical components of a curriculum to the word ‘content’ is evidence of a lack of understanding of the implications of significantly different forms of theory. The knowledge profile for all South African HE engineering qualifications routinely lists *natural, mathematical* and *engineering science* knowledge in one competency outcome, as though they were interchangeable (ECSA, 2012). This simplification and the ‘theory/practice’ differentiation become particularly problematic in the design of a multidisciplinary professional engineering curriculum which may entail the combination of significantly different types of ‘theory’ and ‘practice’. One such region is the emerging field of mechatronics engineering, which represents the formal synthesis of mechanical, electrical and computer engineering, and is evident in an increasing range of practice sites from production automation systems to medical, agricultural, automotive and manufacturing sectors. Mechatronics engineering offers an ideal site for the analysis of the complexity inherent in all 21st century engineering fields affected by the exponential development of computer-based technologies. Secondly, given its multidisciplinary nature, it offers an opportunity to address the evident lack of ‘sophisticated understanding of the forms of knowledge inherent in the disciplines’ (Shay, 2008, p. 596) and their relationship with and impact on each other in the context of multidisciplinary knowledge practice. The core practice of the engineering professional is ‘problem solving’. There is sufficient indication that our current engineering education system is not producing or adequately enabling graduates – particularly at the level of technician - to fulfil this role. The premise in this research is that we will not be able to address engineering education challenges without a better understanding of the nature of knowledge underpinning multidisciplinary engineering problem-solving practice.

1.2 Aim of the research

As early as 1944, Jose Ortega Y Gasset predicted that the skills demanded for the 21st century would be both analysis and synthesis, and that this would require ‘scientific genius… for integration…specializing in the construction of the whole’ (Bordogna, Fromm, & Ernst, 1993, p. 4). He went on to propose that the task of educators would be to cultivate the ‘student’s ability to bridge the boundaries between disciplines and make the connections that produce deeper insights’ (*ibid*.). In the case of multidisciplinary engineering problem solving, this means ‘explicitly negotiating disciplinary boundaries’ (Wheelahan, 2007, p. 5) and enabling access to ‘know-why’, ‘the knowledge condition for exploring alternatives systematically’ (Becher & Parry, 2005, cited in Muller, 2008, p. 18). Engineering ‘problem solving’ is about exploring alternatives and finding solutions. **The aim of this research is to contribute to a better understanding of the negotiation of disciplinary boundaries when different forms of knowledge are integrated in engineering problem-solving practice as observed in industrial settings.**

The research is located within the field of the sociology of education, and draws on the social realist concepts of disciplinary knowledge structures (Bernstein, 1975, 1977, 1990, 1996, 2000) and the Legitimation Code Theory (LCT) concepts of Specialization and Semantics (Maton, 2009, 2013, 2014). The particular focus is on the nature of multidisciplinary engineering knowledge as seen through the lens of engineering problem-solving practice undertaken by novice practitioners in South African industrial environments. The research seeks to understand how technicians/technologists (in a range of congruent mechatronics engineering practice sites) solve engineering problems. Through the development of a ‘language of description’ (Bernstein, 1996) which moves beyond the concept of knowledge typologies, the research entails the mapping of the topology of actual engineering problem-solving processes as reflectively articulated and re-enacted by mechatronics engineering practitioners. The aim is to ascertain whether or not there are observable patterns as the problem solvers in different but comparable contexts draw on different disciplinary knowledge resources. The focus is on the knowledge structures characterising the disciplines of physics, mathematics and logic[6] when they are brought into relationship with each other in solving an engineering systems problem that includes automation technologies[7]. The project extends existing research (Wolff, 2011) into complex engineering practice, in which it was established that the organising principles of the disciplines underpinning multidisciplinary engineering differ significantly from each other. This research project further develops our conceptualisation of the underpinning disciplines as representing different ways of thinking and different kinds of 'code'. The intention of the mapping of problem-solving practice is to illuminate potential 'code shifts' and 'code clashes' (Maton, 2014), so as to inform curriculum and pedagogic design which better prepare students to navigate the crossing of disciplinary boundaries in socio-technical contexts.

1.3 The significance of the research

The increasing demands made on engineering graduates and the inability of HE to adequately prepare students (particularly those on the Diploma programmes) to meet these demands suggest an urgent need for empirical research into the epistemological nature of engineering practice in the 21st century. Current engineering curriculum structures may not adequately reflect the challenges implied in the navigation of and between essentially different organising principles inherent in the engineering disciplines. The multidisciplinary engineering region in question (mechatronics engineering) represents the formal integration of the traditional natural and mathematical sciences with the applied sciences entailed in the production and application of Information Communication Technologies (ICTs). The exponential development and dynamic nature of the latter in relation to the relatively stable engineering 'fundamentals' offers an empirical base through which to better understand the implications for acquisition, application and integration of significantly different forms of disciplinary knowledge. It is hoped that an epistemologically-orientated analysis of engineering problem-solving practice will contribute to a more informed design of curricula and pedagogy better suited to engineering education requirements of the 21st century, particularly at the level of the Diploma. Furthermore, the research makes a methodological contribution in establishing a novel and pragmatic problem-solving framework in which the application of an as yet untried analytical tool serves not only to make knowledge visible, but also to surface the complexity and nuances of the engineering problem-solving space.

[6] The study of (deductive) 'inferences that depend on concepts that are expressed by the 'logical constants' such as *and, not, or, if…then*' (Britannica Concise Encyclopaedia, 2006) and which discipline underpins 'logic programming' - 'The study or implementation of computer programs capable of discovering or checking proofs of formal expressions or segments' (www.dictionary.reference.com).

[7] Significant differences in undergraduate academic achievement patterns between these subjects provided an additional impetus for better understanding of the implications of the different disciplinary organising principles.

1.4 Main research question

What are the patterns of disciplinary boundary negotiation in multidisciplinary engineering problem-solving practice (and what are the implications for the redesign of Diploma curricula and pedagogic practice to facilitate more effective problem solving)?

Sub-Questions:

- Do mechatronics engineering technicians manifest particular patterns in navigating between different forms of knowledge when addressing engineering problems?
- Does an overarching pattern emerge which could be described as potentially archetypal[8]?
- How are the disciplinary forms of knowledge brought into relationship with each other in the problem-solving process?
- What level of understanding is necessary in order to solve that particular problem?
- What is the relationship between the elements in the problem-solving context and their impact on the problem-solving process?

This thesis is primarily concerned with *patterns of disciplinary boundary negotiation in multidisciplinary engineering problem-solving practice.* The implications for curriculum and pedagogy will be suggested in the final discussion chapter.

1.5 Chapter outlines

The nature of the research question requires a fairly broad contextualisation. This first chapter has introduced the problem. Chapter 2 situates the research in the broader contextual framework, drawing on available literature to present aspects of engineering education, engineering knowledge, the engineering profession, and a multidisciplinary review of applicable problem-solving literature. Chapter 3 introduces the social realist theoretical framework, including a range of Bernsteinian concepts and the Legitimation Code Theory (LCT) concepts of Specialization and Semantics. Chapter 4 integrates elements of the contextual and theoretical chapters by presenting a more focused conceptualisation of the empirical research field: mechatronics engineering. These initial chapters lay the groundwork for the integrated research design detailed in Chapter 5. There are three data analysis chapters (6-8), each presenting the detailed analysis of four different case studies in a particular type of engineering practice context. A discussion of the analyses and potential implications for curriculum and pedagogy are consolidated in Chapter 9, in which the research questions are also answered. The final chapter (10) concludes the thesis with suggestions for further research.

[8] Typical of field or context, and potentially suggesting a 'model' or 'ideal'

CHAPTER 2: CONTEXTUAL BACKGROUND AND RELATED LITERATURE

2.1 Introduction

At its most basic, the intention of the research is to understand disciplinary knowledge practices in engineering problem solving so as to enable HE to better equip graduates for industry. In other words, the purpose of the research is to enable better alignment between engineering education and the profession with respect to what it is that engineering graduates – particularly diplomates - are expected to be able to do. In order to address the question of alignment, the research focuses on what it is that they are actually doing when solving problems in real world sites of practice.

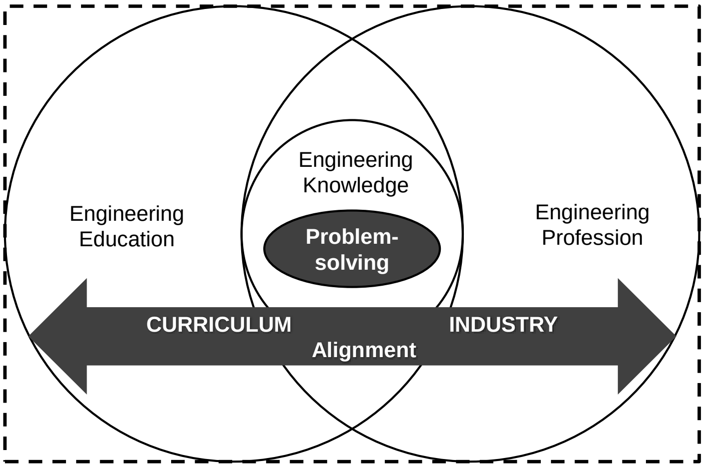


Figure 2-1 Contextual framework

Framed in this way, the research question suggests three key areas that require contextual elaboration with regard to both existing literature and the purpose of the research project:

- Engineering Education
- Engineering Profession
- Engineering Knowledge

Each of these key contextual areas (figure 2-1) will be covered in the following sections, in the order given. The question at the heart of the research, however, revolves around problem-solving practices. Drawing from research across a range of disciplinary fields, the problem-solving and related literature covered in the final section of this chapter will contribute both contextually and methodologically towards a more holistic framework through which to consider examining engineering problem-solving practices.

2.2 Engineering education

2.2.1 History

'The rise to predominance of school culture [or formal academic training] for the social production of professional expertise is a fairly recent phenomenon' (Lundgreen, 1990, pp. 33-

34). Its establishment has served to demarcate access boundaries based on 'educational credentials granting entry into the occupation' (*ibid*.) as opposed to the needs of the profession in practice. The relationship between formal academic education and professional occupations, such as law, for example, appears more coherent, in that a vast body of primarily text-based knowledge needs to be acquired by the mental, verbal and critical faculties, and does not require the use of artefacts beyond those of the texts themselves. In the case of engineering, however, the body of knowledge 'is the product of development of both practice and knowledge over at least four millennia' (Hanrahan, 2014, p. 110). Key to this evolution, initially, were the structures and artefacts to support human survival and progress. As such, the early practical 'professionals' were the master builders and mechanical engineers of antiquity. Until the 19th century, the predominant form of training occurred through apprenticeship to master craftsmen, and the engineering 'knowledge base was not part of the traditional learning offered by the ancient universities to the original professions' (Lundgreen, 1990, p. 34). Engineering had evolved into five branches by the end of the 19th century. Training for civil and mining engineers had become 'academic' and the preserve of the state in continental Europe, while mechanical, electrical and chemical engineering training occurred via apprenticeship in the private sector (*ibid*.). The Anglo-American industrial needs, on the other hand, 'were well served by the existing shop culture of apprenticeship and continuous learning by doing' (*ibid*., p. 46), and these countries initially only saw formal academic engineering training in the field of military engineering.

The philosophy-based enquiry into existence saw increasing attention to 'matter' in the world. The pursuits of alchemists, mathematicians, philosophers and what we would call 'scientists' today led to the discovery of 'laws' applicable to structures and artefacts, and an increasingly complex body of applicable mathematics. By the mid-nineteenth century, with the development of physics and chemistry as formal sciences, 'practical engineering…developed into science-based engineering' (Hanrahan, 2014, p. 111), and different levels of engineering practice saw increasingly differentiated forms of training. 'The rise of large-scale industry and the emergence of science-based industries' led to a demand for 'academically-trained' engineers, who were to become designers, executives and managers (Lundgreen, 1990, p. 35). A number of continental polytechnics (first established in France) had begun to clearly differentiate between lower levels [of training] concentrating 'on workshop instruction and … elementary mathematics, mechanics and drawing' (*ibid*., p. 39), with higher level training 'stressing advanced mathematics and theoretical science' (*ibid*.). These developments followed suit in America in the middle of the 19th century with the establishment of a number of polytechnic institutes.

Professionalisation in the 19th century was accompanied by an increasingly refined and specialised view of the natural sciences (Rip, 2002). The 'British-based iron and steam revolution' saw an exponential increase in information – across continents – and the emergence of a 'rapidly increasing number of design handbooks' written by individual engineering practitioners in different industries (Disco, Rip, & van der Meulen, 1992, p. 468). These developments, together with the concomitant 'gradual intrusion of government into industrial regulation' (*ibid*.) and the rise of professional bodies, were fertile ground for the consolidation of (relatively) standardised engineering training under the umbrella of HE. The emergence in the late 18th century of the polytechnic movement (in France, initially) 'set a typically modern and scientific standard in non-military engineering education which was widely copied throughout continental Europe' (Disco et al., 1992, p. 479). For one thing, the expansion of knowledge frontiers with respect to the natural sciences and technologies meant the generation of increasingly complex 'technical models' and increasing differentiation in the 'division of labour'. A 'technical model… is a symbolic representation of a family of artifacts *(sic)*, such that the latter becomes comprehensible as a system of interrelated and mutually constraining sub-elements' (*ibid*., p. 472). These models are 'deeply anchored in basic sciences', drawing 'heavily on scientific theories about phenomena which are embodied in the artifacts' (*ibid*.). The mandate of the faculty at the new polytechnics was 'to train experts capable of producing "state of the art" designs' (*ibid*., p. 479), which meant the curriculum could not be limited to 'rote solutions to invariant problems' but needed to present 'more general representations' (*ibid*.). And so, not only do we see the emergence of codified, standardised engineering 'textbook' knowledge, but also an increasing number of key stakeholders engaged in the formal engineering education endeavour: academic faculties in the newly emerging HE institutes, government and professional bodies. In the early stages of the 20th century, academic education became the norm for acceptance into professional body membership, and technical colleges 'were asked to seek approval of the professional bodies for their degrees' (Lundgreen, 1990, p. 70). The shift in emphasis to academic research and standards development 'became the distinctive feature of the engineering profession in contrast with the older professions' (Lundgreen, 1990, p. 67).

The discovery of electromagnetism and the ability to control the electron flow in certain substances (such as silicon) led to the invention of the transistor, and irrevocably moved engineering into the computer age in the 20th century. There are few engineering activities today that do not include computers at some, if not all, stages of the conception, design, implementation, and operation (CDIO) processes in an engineering artefact or system. These CDIO (Bankel, et al., 2005) stages have come to represent not only the framework for formal academic education, but also the differentiation of roles in the field, with today's engineers generally seen as being responsible for conception and design, technologists and technicians for implementation, and artisans for operation. Whilst it is easy to see the role of 'science-based' engineering training on the conception and design end of the continuum, and the 'shop-culture' forms of apprenticeship at the operational end, it is the space occupied by technologists and technicians that is proving the most challenging to define with respect to 'what kind of' and 'how much' theory and practice is required to effectively implement and maintain an engineering system in increasingly complex socio-technical contexts. As early as the 1970s, a 'universally recognised problem' was that 'the "fit" between academic engineering and applied science on the one hand and organization-based design problems on the other was leaving much to be desired' (Disco et al., 1992, p. 488).

2.2.2 Engineering education in South Africa

Qualification differentiation and appropriate curriculum design to meet changing socio-economic needs have dominated the South African HE restructuring initiative for a number of years. The question of differentiation between vocational, occupational and professional qualifications is particularly complex, coloured not only by the country's history, but also by national institutional challenges. The driving ethic, however, is anecdotally known as the 'sweeper to doctor' philosophy, suggesting a strong social justice agenda. This is supported by qualification structures and articulation pathways intended to enable all citizens to access and progress through the qualification framework (DHET, 2013). It is against this background that engineering education in South Africa finds itself. Until recently (2013), there have been three main engineering qualifications offered by the now 27 public Higher Education Institutions (HEIs): the 3-year Diploma (technician); a top-up 1-year Advanced Diploma[9] (technologist); and the traditional 4-year professional Bachelor's Degree (engineer).

As part of the recurriculation process in engineering, a fourth qualification type has been introduced, the Bachelor of Engineering Technology (BET), a 3-year qualification that is more theoretical than the current 4-year combination of Diploma and Advanced Diploma. The BET does not include a compulsory internship period, but allows institutions to add 'more content'. The creation of the BET appears to be a response, on the one hand, to the inability of institutions to assure industry internship periods required for Diploma qualification completion, and, on the other hand, to strengthen the mathematics and natural/basic sciences foundation for an increasingly unprepared undergraduate population (CHE, 2013). However, the most recent employer survey cites graduate inability to 'apply knowledge' (Griesel & Parker, 2009) as the key challenge - suggesting the 'gap' lies in 'engineering practice' itself.

The accrediting professional body, ECSA, has in recent years become closely involved with the Department of Higher Education and Training (DHET) in an effort to address urgent skills shortages in the country. The Ministry of Education has set a 30% SET enrolment target in order to meet these needs (CHE, 2009), and a range of stakeholders is engaged in

[9] The Advanced Diploma replaces the currently being phased out Bachelor of Technology (B-Tech).

discussions to ensure what are seen as vital practice-based training opportunities (various work-integrated learning modalities) for undergraduates. The predominant focus of the recurriculation exercise has been the development of qualifications and curricula ‘responsive’ (DHET, 2012) to context, need, policy and capacity. The newly approved Higher Education Qualifications Sub-framework (2013) goes to considerable lengths to establish curriculum and qualification criteria and sketch the envisaged progression pathways. However, there appears to be an urgent need for ‘conceptual refinement’ of professional curricula, which are based on combinations of theoretical and practical knowledge (Shay, 2012, p. 4). It is precisely here that a more theoretically- and research-informed view of the nature of and relationship between knowledge and practice in the professions is necessary.

2.2.3 Engineering education challenges

Despite considerable efforts to improve HE in South Africa, ‘graduation rates remain unacceptably low’ (NPC, 2011, p. 274), with an overall graduation rate for the public HE system between 2004 and 2007 at 16%[10] (CHE, 2009). The statistics for engineering education are varied and unreliable (Du Toit & Roodte, 2008). The most recent available throughput (minimum completion time) statistic for engineering graduation in South Africa is 17% (CHE, 2013). There is an average non-completion/dropout rate on engineering programmes in South Africa of 50% (CHE, 2013; Fisher, 2011). International literature on engineering performance reveals a similar picture. 35% of the roughly 4000 HEIs in Europe produce around a million SET graduates per year (Szentirmai & Radacs, 2012). However, this represents only 60% of the initial intake (Andersson, Chronholm, & Gelin, 2011). Similarly, studies from the USA report only ‘40 to 60% of entering engineering students persist to an engineering degree’ (Bernold, Spurlin, & Anson, 2007, p. 263).

Studies to determine the cause of low retention and high attrition, both locally and internationally, reveal that key factors are content overload, inadequate study skills, misconceptions about the nature of the engineering profession, and the disjuncture between science and engineering (Bernold et al., 2007; Vogt, 2008; Andersson et al., 2011). At a disciplinary level, ‘mathematics is the largest stumbling block causing dropout in freshman year’ (Bernold et al., 2007, p. 264). In one example, only 42% of 1st year engineering students at Wright State University ever complete the Calculus requirements for engineering (Klingbeil et al., 2006). However, there is also high attrition in students who pass mathematics and opt for alternative careers. Locally, the Human Sciences Research Council (HSRC) reports a loss of 25% of engineering professionals to the financial and business sectors (Du Toit & Roodte, 2008). These worrying statistics have led to increasing efforts to determine engineering

[10] The graduation rate is calculated as the percentage of graduations against enrolments in any given year.

success predictors, but with little success. Whilst some studies indicate a positive correlation for school mathematics and science (Zhang, Anderson, Ohland, & Thorndyke, 2004, p. 319), there are others which indicate that ‘grade-point-average… and academic ability are not always predictive of retention’ (Bernold et al., 2007, p. 263).

High engineering dropout rates and ever declining enrolments are not necessarily viewed as a crisis by all stakeholders. In USA studies, there are cases where engineering faculty members believe ‘the dropouts are mainly weak students who are unqualified to become engineers’ (Felder & Brent, 2005, p. 57). Whilst a number of the retention and throughput-focused studies appear to support this deficit approach (Smit, 2012) to the incoming student body, there are also acknowledgements of ‘the widening separation of faculty and curriculum from industry needs and expectations’ (Lang, Cruse, McVey, & McMasters, 1999, p. 43). This finding is echoed locally in employer identification of the same gap with respect to application of knowledge (Griesel & Parker, 2009). Such feedback has seen the widespread redesign of curricula to include problem and project-based engineering education so as to ‘overcome the barriers associated with curricular relevance’ (Bernold et al., 2007, p. 264). Although there are a number of ‘victory narratives’ about a project-based approach to engineering education (usually in better-resourced, smaller programmes, and volunteer participants), there is insufficient research data to draw any meaningful conclusions about its efficacy. Indeed, there is evidence to suggest the contrary (Case, 2011; Froyd & Ohland, 2005; Mills & Treagust, 2003; Wheelahan, 2007). The current status of engineering education – not only in South Africa - suggests the key problem in adequately preparing undergraduates for 21st century industries is an inadequate understanding of the theory/practice relationship, and the disjuncture between the view of the academy and that of the profession.

2.3 The engineering profession

The International Engineering Alliance (2013) proposes a definition of engineering as ‘an activity that seeks to meet identified needs of people and societies by the purposeful application of engineering sciences, technology and techniques to achieve predicted solutions that use available resources efficiently, are economical, that manage risks’ (Hanrahan, 2014, p. 109). This definition is very much aligned to that of the UNESCO (2010) report on engineering, highlighting the complex relationship between society, nature, science and technologies in engineering practice. Given this relationship and the impact of engineering on society, why engineering is regarded as a ‘profession’ and not merely an ‘expert occupation’ is that its structural characteristics include ‘fiduciary responsibility’, ‘collegial formations’ and ‘ongoing … behavioural fidelity to a particular threshold of procedural norms’ (Sciulli, 2005, p. 937). Further professional features are formal academic training, ‘national and international organizations, accreditation and licensing, ethics and codes of professional practice’

(UNESCO, 2010, p. 136). There are over 100 national and international professional engineering bodies representing 15 million engineering professionals worldwide (*ibid*.). The World Federation of Engineering Organisations (WFEO) fulfils the function of enabling international collaboration, policy alignment and involvement in sustainable development initiatives. The primary role of engineering professional bodies is standardisation of practices, accreditation of qualifications, and certification of members.

Three accords govern the nature of engineering professionals: the Washington Accord (Engineers); the Sydney Accord (Technologists); and the Dublin Accord (Technicians). These accords establish the engineering professional profiles; the range of engineering activities and problem solving; as well as the range of knowledge, competencies and 'graduate attributes'. An excerpt from the IEA (2013) Graduate Attributes publication (represented in table 2-1) demonstrates that *the key differentiator is the level of complexity in the engineering activity/problem context*. According to the profiles, engineers work in 'complex', technologists in 'broadly-defined' and technicians in 'well-defined' problem contexts.

Table 2-1 Extract from Graduate Attribute Profiles (IEA, 2013, p. 10)

Differentiating Characteristic	**… for Washington Accord Graduate**	**… for Sydney Accord Graduate**	**… for Dublin Accord Graduate**
Engineering Knowledge:	**WA1:** Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in WK1 to WK4 respectively to the solution of **complex** engineering problems.	**SA1:** Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in SK1 to SK4 respectively to **defined and applied** engineering procedures, processes, systems or methodologies.	**DA1:** Apply knowledge of mathematics, natural science, engineering fundamentals and an engineering specialization as specified in DK1 to DK4 respectively to **wide practical** procedures and practices.
Problem Analysis Complexity of analysis	**WA2:** Identify, formulate, research literature and analyse ***complex*** engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences. (WK1 to WK4)	**SA2:** Identify, formulate, research literature and analyse ***broadly-defined*** engineering problems reaching substantiated conclusions using analytical tools appropriate to the discipline or area of specialisation. (SK1 to SK4)	**DA2:** Identify and analyse ***well-defined*** engineering problems reaching substantiated conclusions using codified methods of analysis specific to their field of activity. (DK1 to DK4)

South Africa, through its professional body, ECSA, is a signatory to these accords, and all engineering qualifications have been designed around these level and competency descriptors. The country, however, compares poorly to both industrialised and emerging economies, producing ten times fewer engineering professionals per capita than the average between Brazil, Russia, India and China. The suggested international ratio of engineers: technologists: technicians is 1:2:4. In South Africa, the most recent analysis cites this ratio as being 1:0.4:1.4. (Du Toit & Roodte, 2008). Effectively speaking, we are only producing 35% of the technicians necessary in comparison to engineers. When placed in relation to the overall engineering practitioner per capita numbers, this means we only produce 3.5% of the technicians required for an emerging economy.

The standardisation of the profession through the various accords, however, does not necessarily enable a view of the profession itself as it is practiced in the field. Nor does it capture the contextual complexities. The impact of globalisation, democratisation and rapid technological development has led to different forms of knowledge production and application. Mode 2 knowledge production (Gibbons, et al., 1994) is 'trans-disciplinary, trans-institutional … heterogeneous … problem-solving knowledge' requiring adaptability and 'broad problem-solving skills to anticipate flaws in production' and an understanding of 'how the environmental context shapes the execution of tasks, and how unexpected factors arise' (Kraak, 2000, p. 11). This definition of the contextual complexities in 21st century knowledge practice poses a serious challenge for 'standardised' engineering education and curricula in an academic context. So, if the role of the engineering practitioner is to 'apply knowledge… to the solution of … problems' in such increasingly complex contexts, let us take a closer look at this knowledge.

2.4 Engineering knowledge

The new engineering qualification standards (2012) established by the Engineering Standards Generating Body (ESGB) list ten 'exit level outcomes', aligned to the profiles and competencies established by the three international accords. The outcomes could be classified as falling into three broad categories: 'knowledge', 'skills' and professional competencies or 'attributes' (Appendix A). The professional competencies are generic in that they encompass communication, ethics, socio-economic awareness, learning, and team-work capabilities appropriate to the particular professional field. Similarly, the 'skills' entail the ability to 'design', 'investigate' and 'use appropriate techniques, resources and engineering tools' following appropriate procedures. The only 'outcome' that explicitly addresses 'knowledge areas' is 'knowledge of mathematics, natural science and engineering science' to 'solve' engineering problems at the three determined levels of complexity (ESGB, 2012).

In contrast to the accords-aligned definition of engineering knowledge, skills and attributes, a recent study on engineering practice from the perspective of academics and researchers claims that 'the knowledge an engineer draws from is continually expanding and evolving because of the work itself' (Sheppard, Colby, Macatangay, & Sullivan, 2007, p. 433). Furthermore, it has the distinctive feature that it is 'not a derivative of science', but has 'an autonomous body of knowledge' (*ibid*.). The authors list seven types of engineering 'knowledge':

1. Theoretical tools
2. Design concepts

3. Criteria & specifications
4. Quantitative data
5. Practical considerations
6. Process-facilitating strategies
7. Contextual knowledge

While these forms of knowledge are valid, this characterisation is even further removed from a disciplinary perspective on 'engineering knowledge'. The accords-aligned 'outcomes' similarly in no way enable an adequate problematising of the nature of disciplinary knowledge underpinning problem-solving practice in the different engineering fields. The common 'fundamentals' – mathematics, physics and 'engineering sciences' – have given rise to a rapidly evolving 'disciplinary map' (figure 2-2), as conceptualised by Hanrahan (2014, p. 113).

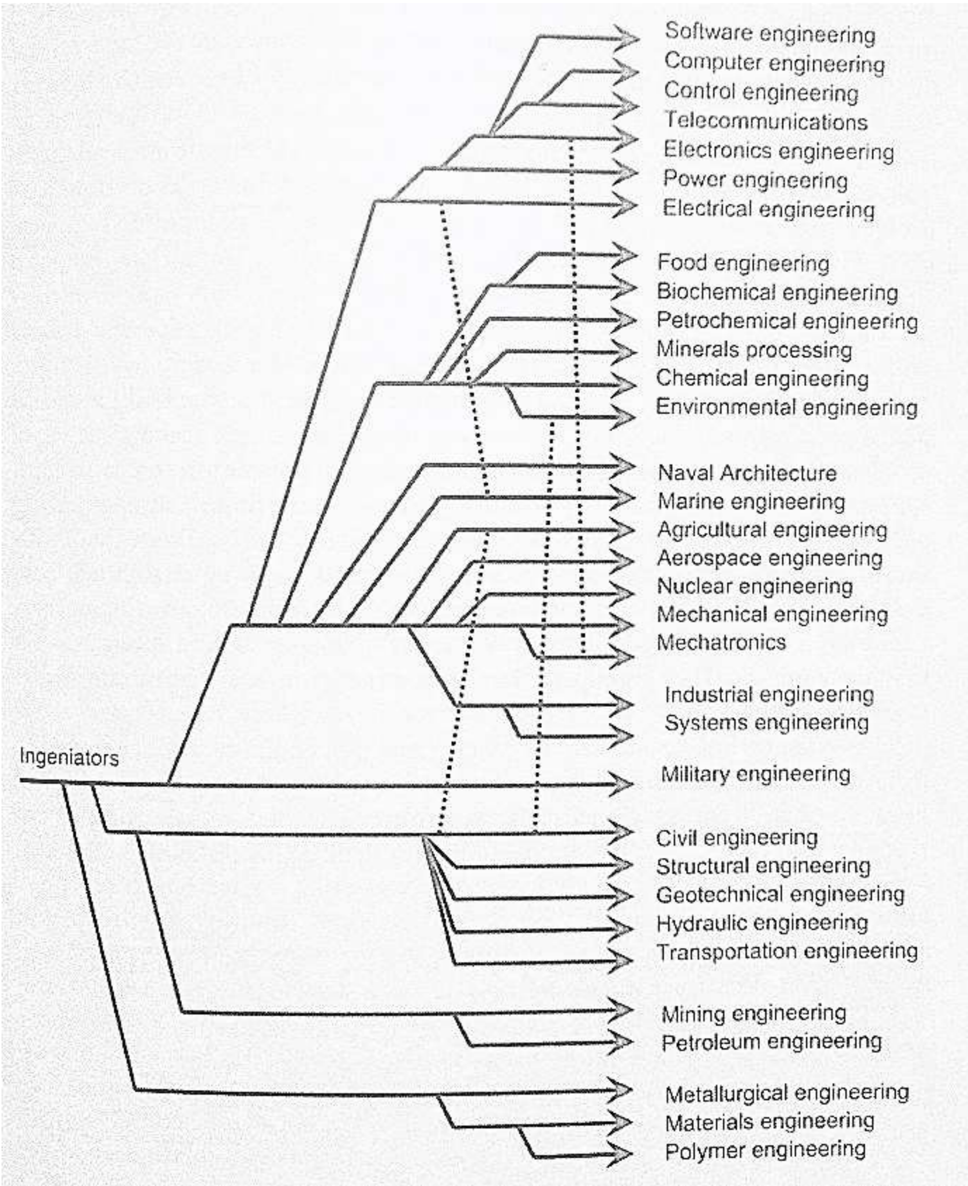


Figure 2-2 Development of engineering disciplines (Hanrahan, 2014, p. 113)

This evolution is what Bernstein refers to as the ‘regionalisation of knowledge’ (2000), and entails the combination of different pure disciplines to form a new ‘region’. In the process of regionalisation, the boundaries between originating disciplines become increasingly weakened, almost to the point of absence. It is the contention in this research that **losing sight of disciplinary ‘organising principles’ does not enable adequate understanding of the different relationships between the same disciplines in different contexts**. Furthermore, it is believed that precisely this blurring of disciplinary boundaries has exacerbated the inability to identify causes of both engineering education and problem-solving practice challenges. The accompanying ‘competency’ discourse and constructivist learning approaches have further eroded opportunities to develop the kind of conceptual grasp required to cope with increasingly complex practices and contexts (Wheelahan, 2007).

The conceptualisation of the role of engineering practitioners remains dogmatically framed by process differentiation (the different CDIO stages) and competencies with regard to the social, professional, technological and scientific. There does not seem to be significant literature presenting any refinement regarding contextual differences, and the relationship between the different ‘core disciplines’ in those different contexts. I would like to suggest that in the majority of engineering fields, engineering practice contexts may be characterised by ‘scale’ with respect to a number of factors:

- Stakeholders
- Product
- Production process
- Economics
- Standards

The larger the scale with respect to product and production processes, the greater the number of potential stakeholders, resources and rules of engagement, and the lower the potential autonomy at the level of the individual. The more complex the rules of engagement, the more likely it is to entail more standardised business communication structures, processes and documentation. These ‘scale’ factors, when set in relation to each other, contribute to the degree of complexity of the engineering activity, and similarly determine degrees of complexity with respect to the types of physical and possibly even intellectual resources used by the practitioner. In other words, there is a theory/practice relationship which may differ in different contexts. Across the continuum, however, is one key objective: to solve a particular problem for people, whether it be the production of a gadget to improve people’s lives or the construction of a bridge to facilitate improved transport access or the refinement of fuel to provide energy. *The question in this research is what does this problem-solving process in different contexts look like from the perspective of knowledge*?

2.5 Problem-solving research

We have established that a commonly accepted view of the role of the engineering practitioner is that of ‘problem solver’, and that the purpose of this research is to achieve a better understanding of real world engineering problem-solving practice. Type the term ‘problem solving’ into any search engine or literature database and two key observations can be made[11]. Firstly, no field is left out of the debate. From psychology to mathematics to engineering and design. The majority of references use the words ‘skill’ and ‘learning’, but a second large category sees terms referring to processes, strategies, approaches and models (figure 2-3).

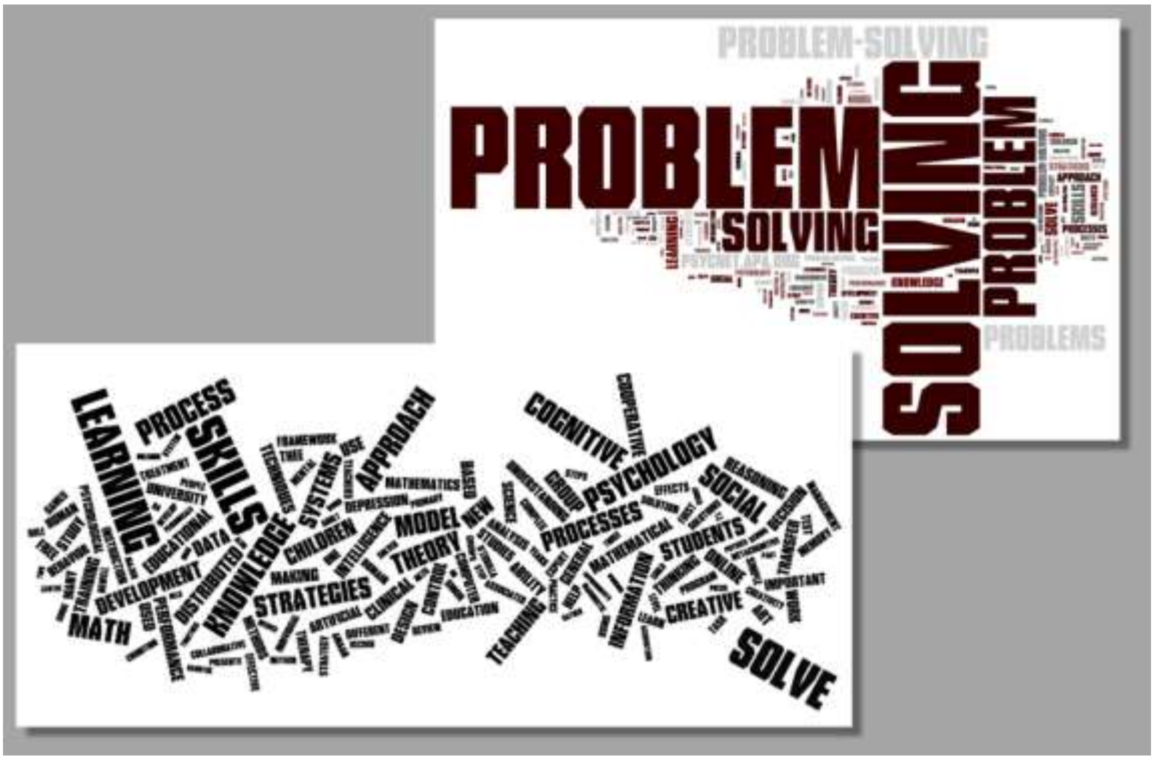


Figure 2-3 A search engine 'Wordle' of 400 entries under 'Problem Solving'

There are literally thousands of ‘methodologies’ on offer. What they all have in common is the suggested or prescriptive ‘how to’ of getting from point A to point B, whether it is the child learning mathematics, the team leader running a project, or an engineer maintaining a production line. Of the most common business methodologies is Deming’s famous ‘Plan-Do-Check-Act’ cycle. This is refined or adapted in numerous context-specific methodologies. Six Sigma[12], for example, a common production process improvement methodology, has two types: improvement – DMAIC (define, measure, analyse, improve, control) and new process/product - DMADV (define, measure, analyse, design, verify). A modification of this is

[11] The ‘Wordle’ was generated using the search terms ‘problem’ ‘solving’ in both Google and Google Scholar. The frequency of individual terms was relatively comparable, so the two sets of text were combined (top graphic), and the search terms (as well as publishers) removed to enable the frequency patterns of the other terms to emerge.
[12] www.isixsigma.com

the 8D method, a common automotive industry problem-solving tool (Chlpeková, Večeřa, & Šurinová, 2014), which includes steps acknowledging problem solving as a team effort.

Whilst many of these 'methodologies' may be prescribed for specific industries/disciplines, they function in the broadest sense as commonly understood or locally adopted strategies to achieve certain ends. However, the key concern in this research - stimulated by seven years' experience in relation to industry practitioners - is that engineering practitioners, from artisan to professional, do not necessarily solve problems 'by the book'. The consistent complaints about graduate inability to solve engineering problems and local evidence of quality and efficiency measures proving ineffective suggest that the problem contexts are more complex than any single methodology is able to address, other than in its broadest sense. So how do we move beyond the 'methodology' and try to understand what this thing called 'problem solving' really means? Methodologically speaking, engineering practitioners 'synthesise' solutions based on an understanding or interpretation following analysis of the nature of and relations between components in a system. The questions for this section of the chapter are 'what is problem solving?', 'what are its components?', and 'what are their features and relationships?'

2.5.1 A definition of problem solving

There are several definitions, depending on the particular field: cognitive sciences, psychology, mathematics, and engineering, to name a few. Common to all the definitions are the concepts of 'goal', 'activities' (to reach the goal) and 'paths'. In the European cognitive science tradition, complex problem solving 'occurs to overcome barriers between a given state and a desired goal state by means of behavioural and/or cognitive, multi-step activities' (Funke & Frensch, 1995, p. 43). In contrast, empirical problem-solving research in the American tradition defined the act as 'any goal-directed sequence of cognitive operations' (*ibid*.). The latter definition being applicable to the simplest of tasks (such as opening a door) renders it inadequate for the purposes of this research project, and I shall use as a starting point the former definition, with its key features of the 'given state' (problem), the 'goal' (solution) and the individual activity process (problem solving) entailed in moving from the one state to the other through 'barriers'. These features constitute the basic 'components' of the problem-solving system. How are they set in relation to each other?

The polymath, Herbert Simon (1916 – 2001), is regarded as one of the founding fathers of fields such as decision making, information processing, complex systems, and artificial intelligence, to name a few. His attempt to develop a human problem-solving theory (Simon, 1978) manifested in a series of computer-simulated studies in problem solving. Early in the empirical studies came the realisation that 'a global theory of problem solving' (Funke & Frensch, 1995, p. 42) was not possible across different knowledge domains, nor generalisable from the laboratory to the real world (*ibid*.). A key contribution made by Simon in the context of the distinction between science as concerned with *analysis* and human purpose as a process of *synthesis* to 'attain goals' was a 'means for relating these two disparate components' (Simon, 1996, p. 3):

Simon differentiated between the *inner* and *outer* environments of a particular artefact or phenomenon (figure 2-4). 'The inner system is an organisation of natural phenomena capable of attaining goals in some range of [outer] environments', which, in turn, 'determine the conditions for goal attainment' (Simon, 1996, p. 11).

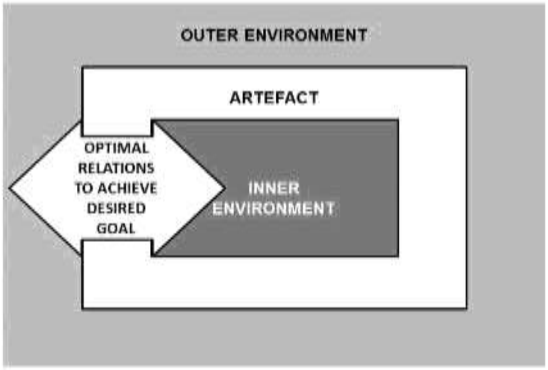


Figure 2-4 Representation of Simon's (1996) Inner & Outer artefact environments

The identification of outer environment 'conditions' for 'goal attainment' is a crucial one, and suggests that the act of problem solving in relation to a particular artefact or phenomenon occurs in a 'problem space' (Lajoie, 1993) which may offer both affordances and constraints (internally and externally), where the 'constraints' allude to the 'barriers' in the earlier definition.

2.5.2 The development & features of a problem-solving model

A range of empirical studies have been conducted which enable a refinement of conceptions regarding the inner[13] and outer environment factors in complex problem solving. Through empirical work in the broad domains of literacies, social sciences, natural sciences and games (Sternberg & Frensch, 1991), distinctive features of the problem-solving process in particular domains begin to emerge. The 'problem solver', essentially 'external' to the problem, demonstrates particular *internal subject factors.* These are given as experience; cognitive variables including knowledge, cognitive style and intelligence; and non-cognitive variables such as self–confidence, motivation and enjoyment (Funke & Frensch, 1995, p. 45). *External factors* emerge as those of the problem structure (complexity and transparency), its context (familiarity) and broader environment (for example, feedback and cooperation) (*ibid*.).

2.5.3 The problem solver

Funke (1995) draws on the internal and external factors to model a 'complex problem solving situation', setting the Problem Solver in relation to the Task and the Environment (represented in figure 2-5).

[13] Note that Simon (1996) was not referring to the 'inner' environment of the Problem Solver, rather to that of the artefact/phenomenon itself – and in which the 'problem' occurs in this research context.

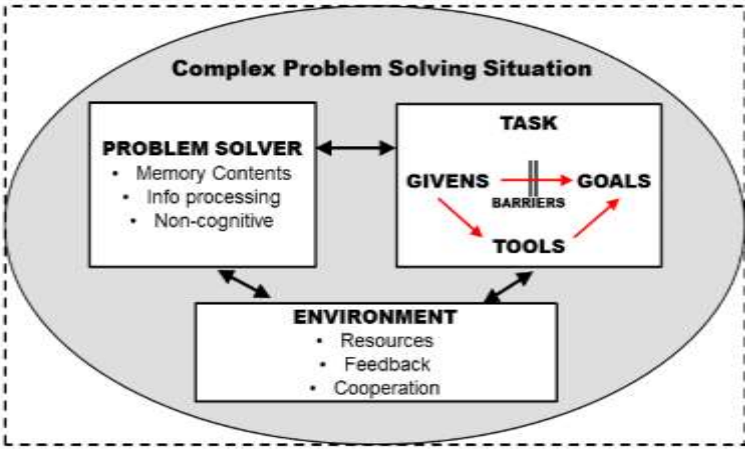


Figure 2-5 Summary of Funke & Frensch's (1995) 'Complex Problem Solving Situation'

The majority of problem-solving studies in the cognitive sciences and psychology focus on the 'problem solver'. A key 'internal factor' is the question of the role experience plays in the problem-solving process. Cognitive psychology differentiates between novice and expert problem solving as the:

> '…scope of knowledge on accumulated information, problem solving schemas, skills, expertise, memory capacity, problem representation ability, abstraction, and categorization abilities, analysis, and synthesis skills, long-term concentration ability, motivation, efficiency, and accuracy' (Wang & Chiew, 2010, p. 83).

With the focus still on the problem solver, the authors summarise common approaches to problem-solving activity as follows:

- 'Direct facts – finding a direct solution path based on known solutions.
- Heuristic – adopting rule of thumb or the most possible solutions.
- Analogy – reducing a new problem to an existing or similar one for which solutions have already been known.
- Hill climbing – making any move that approaches closer to the problem goal step by step.
- Algorithmic deduction – applying a known and well defined solution for a problem.
- Exhaustive search – using a systematic search for all possible solutions.
- Divide-and-conquer – solving a whole problem via decomposing it into a set of sub-problems.
- Analysis and synthesis – reducing a given problem to a known category and then finding particular solutions' (Wang & Chiew, 2010, pp. 82-83).

I would like to suggest that not only are the first seven of these activities encompassed in the last - analysis and synthesis – but that the terms 'analysis' and 'synthesis' require a considerable degree of conceptual refinement if we are to probe the relationship between the problem solver, the problem structure and the contextual environment with respect to the *nature of knowledge* implied in the problem-solving process.

2.5.4 The problem-solving process and cognition

The activities undertaken by the problem solver (those standard stages in the copious available methodologies) draw on different cognitive layers seen as two types of 'life functions': conscious and subconscious (Wang & Chiew, 2010). The authors suggest the 'subconscious' entails tangible experience: sensation, memory, perception and action. The 'conscious' layers have to do with meta-cognitive, meta-inference and higher cognitive functions (Wang & Chiew, 2010, p. 84). This differentiation is significant in that it points to 'how' we know, and I will return to this in the following chapter.

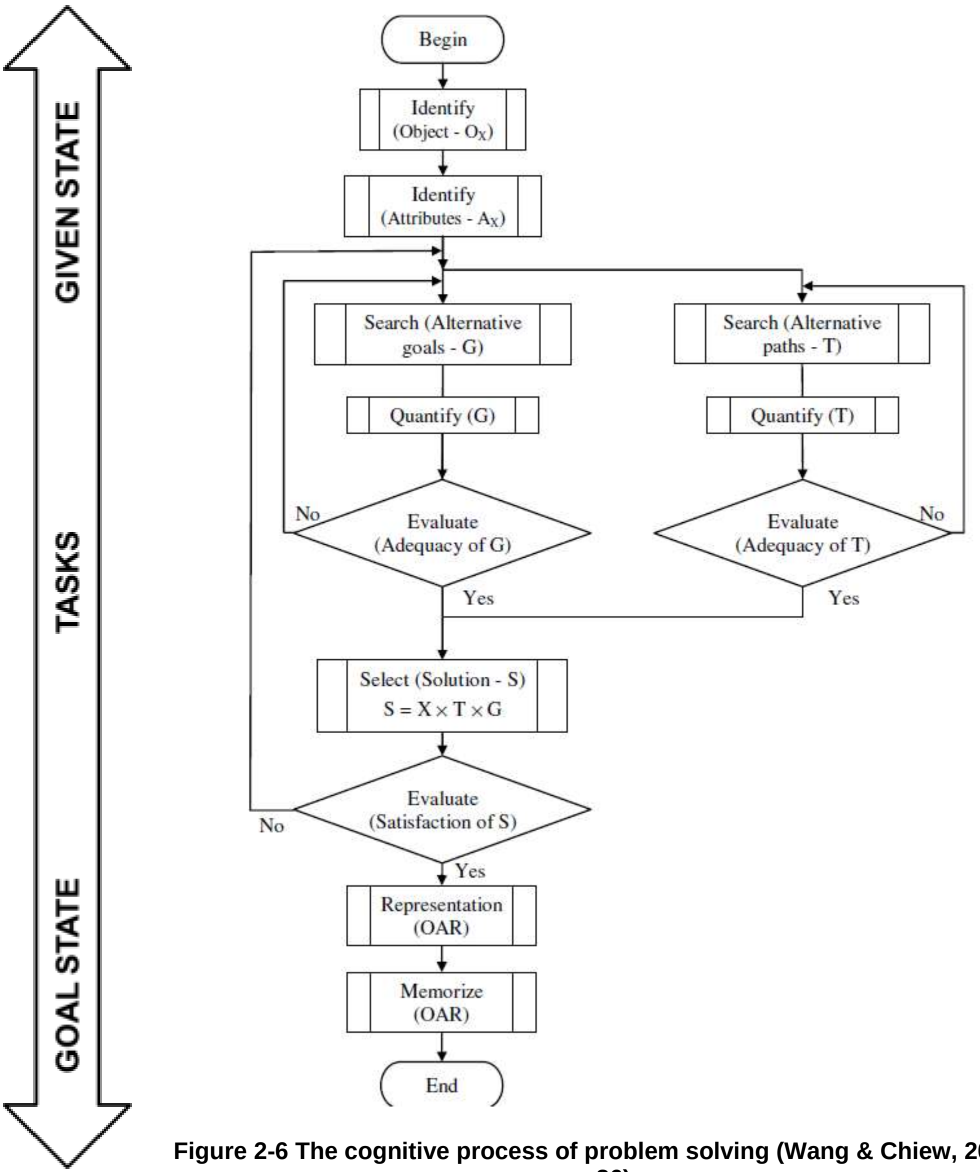


Figure 2-6 The cognitive process of problem solving (Wang & Chiew, 2010, p. 86)

In an attempt to consolidate the various cognitive psychology studies in a coherent, relational problem-solving framework, primarily for the purpose of application to a mathematical model, Wang and Chiew (2010) offer a schematic of the actual problem-solving process (figure 2-6). They attempt to capture the iterative or non-linear aspects by using a process flow model with return cycles. This process is not only reminiscent of the range of process methodologies mentioned, but is also related to a number of pedagogic taxonomies (such as in the work of Vygotsky and Bloom). The value of this process flowchart lies in its relation to cognitive processes as modelled by the authors. They attempt to capture the various stages of the problem-solving process in relation to *which* layer of cognition is implied (figure 2-7).

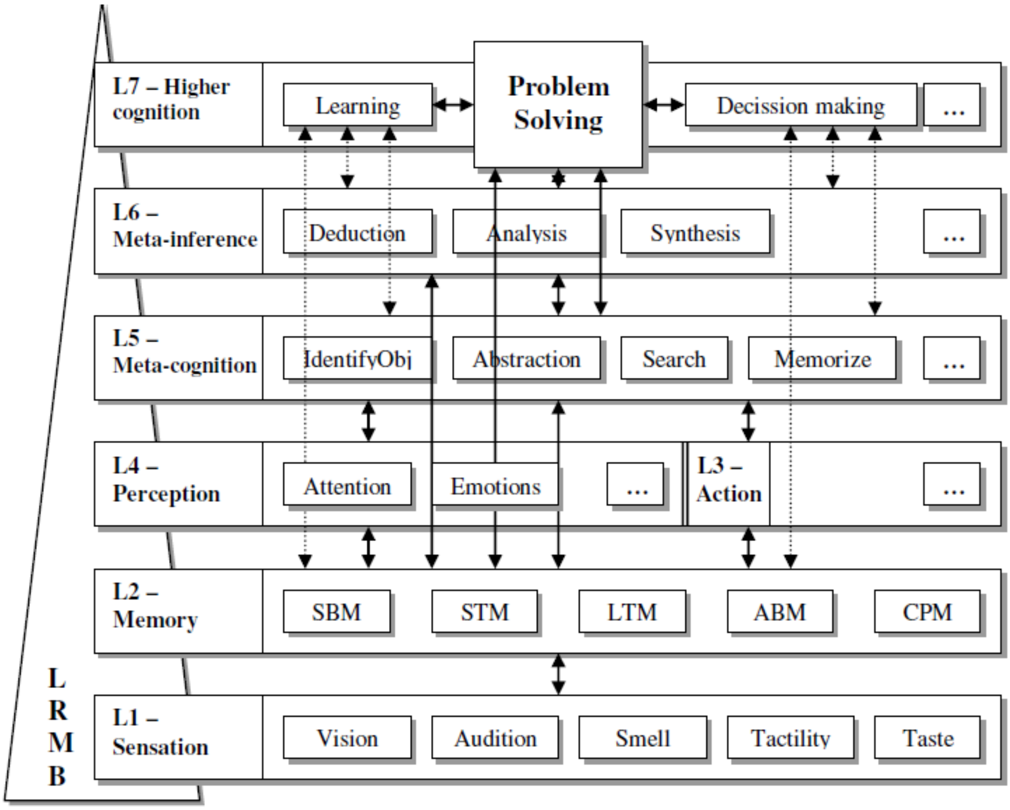


Figure 2-7 Interaction between problem solving and other cognitive processes in LRMB (Wang & Chiew, 2010, p. 90)

The vertical scale refers to the 'layered reference model of the brain' (LRMB), with the lowest level being sensory and the highest being 'higher cognition'. The horizontal scale attempts to capture activity types during the problem-solving process, and which are attributed to a particular cognitive layer. For example, the sensory observations are at a base level, but when focusing on a particular aspect, or 'paying attention', this is attributed to the cognitive layer dealing with 'perception'. The activities of 'analysis' and 'synthesis' are allocated to the second highest cognitive layer – meta-inference. Now, while this suggested model certainly marks a milestone in the development of the cognitive sciences in attempting to capture the problem-solving process, any reference to forms of knowledge seems glaringly absent. Simon (1996) was the first to concede that the problem-solving process differs significantly across knowledge domains. What is clearly established, though, is the problem-solving process as concerning *different* activities through *different* stages in relation to *different* cognitive processes. I would challenge the generalisability of such a model on the basis of the fact that it does not take into account the *different* structures and potential structuring effects of knowledge.

A group of researchers who take us a little closer to the question of 'knowledge' - albeit only for the purpose of 'providing techniques' for computer system specifications that are aligned to 'the human facility of thinking and reasoning' (Gardner, Rush, Crist, Konitzer, & Teegarden, 2011, p. 6) – provide a useful overview of 'cognitive models' which allude to different types of contextual structures associated with cognition in problem solving (figure 2-8).

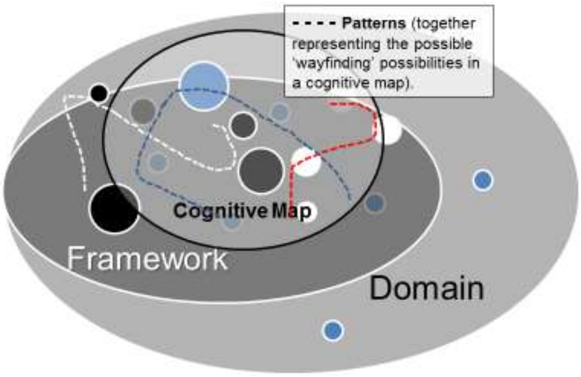


Figure 2-8 Representation of cognitive models (based on Gardner et al., 2011, p. 13 - 14)

Domains are 'explanatory structures' underpinning 'reasoning associated with recurring situations' - 'culturally' determined, and function as 'an organised background'; **Frameworks** are 'domains with additional contextual information'; **Cognitive Maps** are specialised 'frameworks oriented towards wayfinding'; **Patterns** are 'detailed, very context-specific instantiations of frameworks'.

These 'cognitive models' (as an alternative to the Wang & Chiew LRMB model) are highly significant in the field of computer science and programming in 'providing the organising principles that allow individuals to structure and manage' complex objects in complex environments (Gardner et al., 2011, p. 18). The authors remind us that 'just as there is a search for the unified field theory in the hard sciences that would explain and reconcile other theories, there is a search within computer science for the one representation scheme that will mirror all aspects of reality' (*ibid*.). However, they acknowledge that 'we will always require more than one model to obtain a holistic view of an organization or a process or a system' (*ibid*.) by sheer virtue of the different frames of reference.

2.5.5 The problem-solving environment

Given consensus that 'a global theory of problem solving' (Funke & Frensch, 1995, p. 42) is not possible outside of specific domains, it stands to reason that the different domains offer different environmental affordances and constraints. One of the key features of the 'external environment' according to Funke's (1995) summary of the literature is related to people in that environment, with regard to feedback (or delay thereof), ‘expectations, cooperation, peer pressure’ (*ibid*., p. 6). In the field of Artificial Intelligence (AI) problem-solving research, context is ‘virtually always closely related to the specific task at hand, domain, application… and provides constraints on reasoning’ (Brezillon, 1999, p. 44). However, it also acts as ‘adjustable filters’ to ‘provide humans with a much greater control over knowledge’ (*ibid*.). Context is, in fact, the relationship between the problem solver and the other entities (agents or objects) in the problem-solving system. This means that for each relationship the ‘context’ is different. Imagine a team working on the exact same problem. The context for each team member is different, as each team member comes with a different set of ‘internal subject factors’ (Funke & Frensch, 1995) which affect the ‘context’ (the space between the entities).

AI research has revealed four failures of Knowledge-Based Systems (KBSs) with respect to computerised problem solving:

- ‘Exclusion of the user’,
- Incorrect use of human expert knowledge (i.e. ignoring the contextual components),
- Lack of incremental addition of knowledge resources,
- Lack of understanding of ‘user’s problem solving context’ (Brezillon, 1999, p. 51).

One key to partially overcoming such failure lies in ‘making the context explicit’ (*ibid*., p. 53) through tailored explanations (communication) that take contextual interactions into account, but where such ‘explanations’ are often ‘unwritten rules’ that emerge from the development of relationships between stakeholders over time.

In addition to people, relationships between entities, and communication, a fourth feature of the problem-solving ‘contextual structure’ is that of ‘mood’. In a study on creative problem solving, it emerged that the sensation of ‘elation’ positively impacts on performance. (Isen, Daubman, & Nowicki, 1987, p. 1128). The researchers suggest their findings are generalisable to multiple contexts in which problem solving is required. Educational contexts and organisational settings where conditions allow workers ‘to achieve a sense of competence, self–worth, and respect’ may well promote ‘the tendency to combine material in new ways and to see the relatedness between divergent stimuli’ (*ibid*., p. 1130). In other words, organisational conditions affect morale at the level of the individual and group, and this in turn affects the problem-solving context and process.

2.6 Engineering problem-solving research

Engineering undergraduates at all qualification levels are generally exposed to a range of process methodologies, very often limited to computational or procedural processes in particular disciplines or applications. One of the most popular methodologies is the linear ‘conceive-design-implement-operate’ (CDIO) (Crawley, 2001) project methodology. Not only is this the fairly standard 'Design Project' approach in engineering education, but (as previously mentioned) CDIO has come to represent the different practitioner qualification levels. As early as 1966, researchers at MIT attempted to analyse the problem-solving process in engineering design (Allen, 1966). This research is highly significant in that it establishes that 'in studying the engineering design process, we are studying a form of human behavior' which occurs within 'several levels of organizational complexity' (*ibid.,* p. 72), and that no two problem situations are alike or repeatable. This suggests that the analysis of actual problem solving does not equate with the neat methodologies taught and published in various forms. The purpose of the MIT research was to determine the number of technical approaches considered in a range of comparable electrical engineering projects, and the duration of time spent on considering each approach. In other words, the focus of the research is on the decision process and the probability of selecting one solution over another. A key finding is that 'groups producing higher rated solutions generated fewer new approaches during the course of the project' (Allen, 1966, p. 83). This would appear to suggest a greater level of confidence in the original (and smaller) range of approaches considered.

The positive impact of considering fewer approaches is borne out in one of the few studies in engineering problem-solving literature to consider the student process. A study of fourteen mechanical engineering capstone projects at the Bachelor's level reveals that generating new ideas is 'not necessarily a good thing' for students, as 'novice designers simply do not have the repository of knowledge to draw from' (Sobek, 2004, p. 12). In an attempt to empirically validate a general design process model against project outcomes, Sobek presents a statistical analysis of student processes through a sequence of design activities with respect to time taken on each activity, and the impact on project outcomes. As with the MIT study, the paper describes a linear design process moving through a sequence of 'problem identification and definition, ideation, evaluation, and iteration' (*ibid*., p. 2), with each stage being at different levels of abstraction. The methodology here is reminiscent of the LRMB (Wang & Chiew, 2010) mapping of the problem-solving process in relation to the seven defined cognitive layers. The Sobek study findings lead to a recommendation to encourage students to research analogous problems and solutions so as to 'come to a cohesive and deep understanding of the problem' (2004, p. 13) rather than attempting to 'generate ideas' or resort to less productive default trial-and-error strategies. Of interest is the fact that problem definition and engineering analysis at the *conceptual system* level have a more positive impact on project quality than 'engineering analysis at the … detailed levels' (*ibid.,* p. 11). This appears to suggest the value of a broader conceptual grasp of the system as a whole.

The reference (in both the Allen and Sobek studies) to the positive impact of considering fewer approaches in the problem-solving process, however, ignores the question of knowledge. It seems reasonable to suggest that perhaps fewer approaches were necessary as more was known or understood. This is supported by the Sobek (2004) study which recommends better 'problem definition' and more research into known problems. The question of specific disciplinary knowledge or differentiation between knowledge types does not appear in these engineering problem-solving studies. Knowledge seems reduced to a single component in a complex system. It is interesting to note this absence of disciplinary knowledge even from the perspective of engineering researchers and educators in a more recent study on 'engineering practice' (Sheppard, Colby, Macatangay, & Sullivan, 2007). Citing Rubinstein's 'Patterns of Problem Solving' (1984), the authors outline three 'clusters' of [engineering] work activities:

1. Problem or Current State Identification
2. Attribute and Constraint Definition
3. Means-End Development

Although Wang & Chiew's (2010) process model focuses predominantly on the third step and captures an iterative cycle during the 'search – select' phase, Sheppard et al. alert us to the fact that it is 'naïve' to assume the process is linear (2007, p. 432) or that it follows an orthodox 'analytical' path. This is borne out by a number of engineering design studies which have sought to establish the complexity of the space between problem and solution, as well as the significance of appropriate 'problem formulation' (Volkema, 1983; Leonardi, 2011; Paton & Dorst, 2011; Wiltschnig, Christensen & Ball, 2013). The focus of problem solving in these cases, however, is problem solving in a design context. In alignment with the MIT studies on actual engineering practice (albeit in the controlled condition of a classroom), what appears most significant is the need to 'formulate' the problem in the first place, and to break it up into smaller problems. The lack of attention to 'problem formulation' or 'problem identification', to my mind, adds to the glaring absence of the question of disciplinary forms of knowledge in the literature on engineering problem-solving research.

The overwhelming focus in the literature on 'methodologies' (primarily in 'ideal' conditions) suggests two things: On the one hand, there appears to be a clear desire on the part of educators and researchers to better understand 'problem solving' and equip problem solvers appropriately. On the other hand, the methodologies are easy and formulaic, enabling not only an avoidance of the messiness of real world problems, but also the question of 'knowledge'. One example of real world problem 'messiness' is presented in a different study looking at two engineers from two different workplaces solving the same problem with the same devices and access to the same information (Brezillon, 1999, p. 51). They chose methods appropriate to their own contexts, but based on different priorities: 'fidelity and precision versus efficiency' (*ibid*.). The author suggests that 'context appears more as a mechanism for presenting knowledge rather than for modelling knowledge' (*ibid*.).

2.6.1 The nature of engineering problems

What has been further developed, however, is the nature of engineering ‘problems’ in the workplace, which are ‘substantively different from the kinds of problems that engineering students most often solve in the classroom’ (Jonassen, Strobel, & Lee, 2006, p. 139). Based on extensive qualitative workplace analyses arising out of interviews with 106 practicing and experienced engineers, the authors describe a range of engineering problems in terms of twelve themes. These themes collectively (summarised below) highlight the ill-structured, dynamic nature of real world engineering problems, and the predominantly *non-engineering* environmental constraints and requirements which impact on successful problem-solving processes.

1. Workplace problems are ill-structured
2. Ill-structured problems include aggregates of well-structured problems
3. Ill-structure problems have multiple, often conflicting goals
4. Ill-structured problems are solved in many different ways
5. Success is rarely measured by engineering standards
6. Most constraints are non-engineering
7. Problem-solving knowledge is distributed among team members
8. Most problems require extensive collaboration
9. Engineers primarily rely on experiential knowledge
10. Engineering problems often encounter unanticipated problems
11. Engineers use multiple forms of problem representation
12. Engineers recommend more communication skills in engineering curricula

A number of these themes could be categorised according to the features of the problem-solving situation with regard to the people, processes and environment:

- Problem solver (9, 11)
- Problem-solving process and cognition (7, 9, 11, 12)
- Problem environment (6, 8, 10)

However, the first five themes alert us to a key feature in the problem-solving situation: the ‘problem structure’ itself. The components of the ‘problem structure’ speak directly to ‘goal attainment’ (Simon, 1996), paths and constraints. I would like to suggest that merely defining a problem as well-structured or ill-structured is inadequate without considering *what* is being structured. Why are the disciplinary aspects in all these studies noticeably absent?

There are two significant elements with respect to the current research project. On the one hand, the Jonassen et al. study (2006) focused on engineers (mostly professional Bachelor’s) in a range of fields and sites (Civil, Electrical, Mechanical, Product Development, Safety, Quality Control and Management) and with experience ranging from 3 to 41 years. The current research specifically seeks to address the question of how novice technicians/technologists in a single multidisciplinary field solve problems. It would be interesting to note patterns of convergence and divergence with respect to the Jonassen et al. findings in contexts where the practitioners have followed different qualification pathways, but are essentially confronted with similar problem-solving contexts. Secondly, it is now a decade after the Jonassen et al. study, and one which has seen the exponential development of computer-based technologies employed in engineering environments. The current study may enable insights into the implications of increased reliance on diverse technologies in engineering activity.

There is broad consensus that 'real-time'[14] problem solving differs significantly from simulated/curriculum-based problems. In a South African study investigating the knowledge bases in the emerging field of electrical and computer engineering, professionals indicated the undeniable need for undergraduate exposure to such real-time scenarios (Winberg, Engels-Hills, Jacobs, Garraway, & Winberg, 2012). The differentiation between the types of problems and contexts engineering practitioners encounter has implications for the problem-solving categories relevant to the three different professional levels.

2.6.2 Official categorisation of engineering problem solving

In a study on problem formulation in engineering design, Volkema (1983) summarises a number of factors that impede or enable effective problem formulation: problem complexity, the capabilities of the 'planner', and the imprecise boundaries between ill- and well-structured problems (p. 641). The International Engineering Alliance (2013) has established a rubric against which to consider differentiating between types of engineering problems and their levels of complexity (see Appendix B). The 'attributes' of the problem are listed as:

- Range of conflicting requirements
- Depth of analysis required
- Depth of knowledge required
- Familiarity of issues
- Extent of applicable codes
- Extent of stakeholder involvement and level of conflicting requirements
- Consequences
- Interdependence
- Judgement[15]

[14] Real-time processes involve a practitioner's engagement with a control system that receives on-going data and which is responsive to user inputs.
[15] 'Judgement in decision making' is only attributed to technologists and engineers, and is not differentiated.

Each attribute is then defined at three levels of complexity, with the lowest being well-defined problems (technician level) which 'can be resolved using limited theoretical knowledge' and involve few constraints, high standardisation, and a limited range of stakeholder involvement. The third level ('complex' problem solving) is that of the engineer, which requires 'research-based knowledge', entails wide-ranging issues beyond the technical, involves diverse stakeholders with widely varying needs, and lies outside standards and codes of practice. These characterisations suggest engineering problem solving may be classified (fairly neatly) according to scale and scope of autonomy. Firstly, I suggest, given the nature of 21st century professional practice contexts, that a multidisciplinary engineering practitioner at the level of technician seldom operates within the narrow prescriptions of the 'well-defined' problem-solving space. Secondly, the nature of and relationships between the 'problem-solving' attributes identified by the IEA appear uninterrogated in the literature in the context of real world practice. Thirdly, the role played by disciplinary forms of knowledge in the problem-solving equation seems glaring in its absence. It is hoped that the empirical evidence of real world technician problem solving will shed light on these issues.

2.7 Conclusion

In summary, this chapter has presented a contextual background with respect to the evolution of engineering education, the standardisation of the profession, and what are regarded as the knowledge, skills and attributes of an engineering professional. The literature review on problem-solving research in general has provided a number of key features pertaining to the components in the problem-solving system – the components being the 'problem solver' (with his/her internal subject factors), the problem-solving process (activities) relying on different cognitive layers, and the problem 'context' or environment. These features and their relations establish the beginnings of a research design framework in which to consider the broader context for each problem-solving case study. The available research on engineering problem-solving studies echoes the earlier general studies in highlighting not only the significance of 'context', but the relevance of 'real world' contexts. A number of research findings indicate that 'understanding the problem' in the first place is the key to the process. None of these studies, though, engages with the 'contextual' implications of different disciplinary forms of engineering knowledge.

If we are to address the student retention and graduate performance challenges in engineering education, particularly at the level of the technician, and their performance is measured against the ability to solve engineering problems in increasingly complex environments, we need a far better understanding of this process. It is the contention in this research that this understanding is impossible without considering the question of knowledge.

CHAPTER 3: CONCEPTUAL FRAMEWORK

3.1 Introduction to the conceptual framework

It has been established in the preceding chapters that the focus of this research is to understand the nature of engineering problem-solving practice with a view to improving retention and success in engineering studies, as well as alignment between education and workplace needs. The central premise is that the act of problem solving in increasingly complex 21st century socio-technical environments is inadequately conceptualised from the perspective of knowledge. The three international engineering accords stipulate a working/specialised 'understanding of engineering sciences' as the foundation for the different levels of problem solving. The 'sciences' are further differentiated as 'mathematical', 'natural' and 'engineering'. These, then, form the foundational disciplinary knowledge core of the engineering endeavour. If we are to understand engineering problem-solving practice adequately enough to address the current crisis in scarce skills education and employment in South Africa, then we need a more refined and rigorous set of concepts and tools with which to interrogate the nature of and relationships between the different forms of knowledge underpinning engineering problem-solving practice.

Situated in the field of the sociology of education, the research draws primarily on the work of Basil Bernstein (1975, 1977, 1990, 1996, 2000), and subsequent social realist researchers, notably Karl Maton (2009, 2011, 2013, 2014). The key concepts informing this practice-based research are the nature of disciplinary knowledge structures in intellectual fields, and their impact on complex sociocultural practices. Social realism (not a 'school of thought, rather 'a coalition of minds') is dedicated to understanding 'knowledge as an object… real, differentiated and possessing emergent structural qualities' (Maton & Moore, 2010, p. 5). The social realist tradition is located in the space between two dichotomous positions with respect to the question of knowledge. Positivist absolutism sees knowledge as based on empirical, scientific evidence, whereas constructivist relativism sees all knowledge as 'socially constructed'. Social realism provides a means to resolve this 'epistemological dilemma' (*ibid*., p. 5).

This chapter will briefly introduce two relevant historical positions on how it is that we 'know', before detailing the selected social realist concepts. The aim is to provide a conceptual framework for considering the structures of different forms of disciplinary knowledge (with different organising principles) and their potential structuring effects on a number of practitioners in various, but comparable, socio-technical environments as they engage in knowledge practices during problem-solving processes.

3.2 How do we 'know'?

3.2.1 Empiricism versus rationalism

Epistemology is 'the branch of philosophy devoted to studying the nature, sources and limits of knowledge' (Steup, 2015). This research project is essentially concerned with these three aspects during the solving of a problem in a socio-technical context in 21st century multidisciplinary engineering sites of practice. In chapter 2 it was established that the engineering profession is characterised by specific types of knowledge, skills and attributes, and that the different professional levels are dependent on the complexity of problem solving. With respect to the latter, Wang and Chiew (2010) postulated the problem solver's use of conscious and subconscious layers of cognition during the activities of the problem-solving process. The subconscious is that of tangible *experience*, while the conscious is that of meta/higher order *cognition*. This differentiation alerts us to the question of 'how we know', and requires that we briefly consider two earlier schools of thought: empiricism and rationalism.

'The dispute between rationalism and empiricism concerns the extent to which we are dependent upon sense experience in our effort to gain knowledge' (Markie, 2015). The rationalist position holds that we develop concepts 'independently of sense experience'. The continental rationalists (Descartes, Spinoza and Leibniz) postulated three main theses with respect to 'how' we come to know:

- Intuition/deduction: a deduced conclusion based on 'intellectually grasping a proposition' (which is to have an intuitive 'rational insight') (*ibid*.);
- Innate Knowledge: knowledge gained independent of experience, intuition or deduction (e.g. the pain of childbirth by someone who has never seen or experienced childbirth);
- Innate Concept: also removed from experience, but possibly of a higher order (such as the concept of a 'triangle').

Rationalists believe 'reason is superior to experience as a source of knowledge' (Markie, 2015). The British empiricists (Locke, Berkeley and Hume), on the other hand, believed 'sense experience is our only source of ideas'. We might rely on reason to establish 'relations among our ideas', but these are all on the basis of 'sense experience' (*ibid*.).

The importance of this philosophical dispute for the current project cannot be underestimated, as it is linked to conceptions of the theory/practice divide determining qualification differentiation, curriculum structure and problem-solving practice in professional fields. The higher-order qualifications are structured around more theoretical, or conceptual, forms of knowledge. Artisan vocational training is more practical, based on what is formally called 'experiential learning'. The dilemma for professional levels between these two (technician and technologist) is precisely *how much* and *what kind of* theory (mental work) and practice (experiential work) constitutes appropriate forms of education and training. I am not suggesting that the differentiation between qualifications on the basis of the theory/practice ratio is a rationalist/empiricist divide – that would be to conflate kinds of 'learning' with ways of knowing. I *am* suggesting that the progressivist shift towards 'experience-based' learning has assumed that we 'know' (in both mental and manual work) through 'sense experience'. This kind of pedagogy is proving not only controversial, but ineffective in enabling the kind of informed knowledge practices required in increasingly complex professional fields (Case, 2011; Wheelahan, 2007).

3.2.2 Immanuel Kant: Bridging the Divide

Immanuel Kant sought 'to demonstrate that empiricism and rationalism … both necessarily complement each other' (Bellotti, 2006). 'Though all our knowledge begins with experience, it by no means follows that all arises out of experience' (Kant, 1787, p. 31). He maintains that there are forms of knowledge we know without experience, such as Euclidian Geometry or basic mathematics, and that this kind of knowledge is *a priori* – we know it before or without experience[16]. Then there are concepts that we know that arise *out of* experience. These are called *a posteriori* judgements. They are based on empirical evidence. A second set of terms pertaining to defining the nature of knowledge is that of the *analytic* or *synthetic* distinction. Analytic statements are those where 'the predicate of the subject is contained in the subject' (Bellotti, 2006) – for example, 'a triangle has three sides'. They are 'logical truths … regardless of our experience' *(ibid.).* Synthetic statements contain a predicate which says something new about the subject, such as for example, 'the temperature today is 29 degrees Celsius' – you would need to verify this through 'experience' or empirical testing. These four differentiators were in line with empiricist thought. However, the empiricists regarded all *analytic* statements as *a priori* and all *synthetic* statements as *a posteriori*. Where Kant irrevocably changes the field is in suggesting that we can have synthetic knowledge that is both *a priori* and *a posteriori.* In other words, we can have 'informative' knowledge based on pure reason (necessary truth) as well as that based on experience (contingent truth). He uses a range of mathematical concepts (necessary for application in the natural sciences) to demonstrate truths that are not contained in the subject itself (synthetic) and which can be known without experience (*a priori*) (Kemmerling, 2011).

Now, Kant's propositions are by no means taken as a given. They remain debated, and several subsequent philosophers have refuted his distinctions. The point, however, is that Kant

[16] The concept of infinity, for example, is something we 'know' but could never experience.

provides an important aspect of a framework through which to consider the question of knowledge: that knowledge propositions are located in time in relation to experience *and* reason. These are important distinctions for considering knowledge practices in the problem-solving process: How much of *what* is known and *how* is it known in the problem-solving moment? By the same token, how much of *what* is learnt and *how* is it learnt through the process of analysing the cause of a problem and synthesising a solution?[17]

3.2.3 The social realist position

Just as Kant sought to create a framework in which knowledge claims could be founded on both reason and experience, so too does the social realist position hold that 'knowledge is *emergent from but irreducible to* the practices and contexts of its production and recontextualization…' (Maton & Moore, 2010, p. 5). Social realists adopt a 'both/and' position *(ibid*., p. 2) with regard to knowledge as socially constructed (and thus 'empirically experienced') *and* having structural properties developed through consensus 'within relatively autonomous fields of practice' *(ibid*., p. 6). Such consensus in certain knowledge fields leads to the notion of 'laws' or 'axioms' which come to be accepted as logical truths (rational) that do not require experience to 'know', and cannot necessarily be 'constructed' through experience[18]. The question in social realism is how do we understand and make explicit these structural and structuring properties of different forms of knowledge so as to enable 'epistemological access' (Morrow, 2009) in a 'knowledge-blind' (Maton, 2014) educational milieu?

3.3 Social and educational codes

If we can 'know' through reason and/or experience, 'what' is it that we know and how is it that certain things come to be 'known'? A key theorist to shed light on the nature of knowledge was Basil Bernstein (1924 – 2000), who identified the educational arena as not only instrumental in relaying ideological messages, but actively complicit in entrenching existing social power bases. Based on his observations of consistently stratified learning between working- and middle-class children, he developed a theoretically-informed language of description (Sadovnik, 2001) to capture both the perpetuation of social power relations through principles of communication ('codes') and the differential regulation of forms of consciousness (Bernstein, 2000, p. 4). Power relations create, legitimise and reproduce boundaries between categories (whether they be subject areas, objects, or people) and thus establish relations of

[17] The use of *analysis* and *synthesis* with respect to the problem-solving process is not intended in the Kantian sense.
[18] There are two kinds of experience implied here: the 'experience' of setting out to develop/prove an axiom/law, and the 'experience' of first encountering the axiom/law through learning. I believe the empiricists were referring to both forms in claiming 'sense experience' as being the only source of our ideas.

order (*ibid.*, p. 5). Control 'socializes individuals into these relationships' via communication appropriate to categories, and thus regulates the 'relations within given forms of interaction' (*ibid*.). These processes have powerful implications for production and reproduction of knowledge in the field of practice. If forms of consciousness are regulated through the educational experience, then Bernstein's concern with levels of performance based on social class extends to any sociocultural practice based on the acquisition of knowledge.

Bernstein conceptualised the means by which knowledge is regulated and distributed in the 'pedagogic device', which is governed by three sets of rules, each of which is 'associated with a specific field of activity' (Maton & Muller, 2007, p. 19): the field of production (new knowledge); the field of recontextualisation (curriculum); and the field of reproduction (pedagogy). It is through the device that social power and control are manifest in these respective fields. The 'distributive rules mark and distribute who may transmit what to whom and under what conditions' (Bernstein, 2000, p. 31); the *recontextualising rules* regulate the formation of a specific pedagogic discourse, which is in fact a principle for delocating, relocating, and refocusing a discourse (*ibid.*, p. 32). *Evaluative rules* govern the criteria against which acquisition of the transmitted knowledge is measured. In other words, as new knowledge emerges, fields agree (or disagree) on concepts and ways of working with the knowledge; educators select aspects to include in a curriculum; and teachers shape what and how the concepts are taught. All of these processes may demonstrate the effects of a symbiotic relationship between the underlying organising principles of the knowledge itself and its location in fields of practice.

The principle of 'recontextualisation' is at work in all three fields: In the field of production, new knowledge may emerge through combinations of existing knowledge; and in the field of reproduction, the practitioner selects and combines a number of different forms of knowledge in order to enable responsive practice which is not merely a reproduction of acquired knowledge. Effective practice thus implies the recognition and selection of appropriate forms of knowledge and ways in which they interact. This may well be informed by the practitioner's encounter with educational forms of recontextualisation (as evident in the curriculum and subsequent pedagogic practice). Although this research is not concerned with the preceding pedagogic experience, the concepts that constitute the pedagogic device are significant in that one must assume that no matter the nature of the educational background, the practitioner draws on knowledge resources shaped by his/her acquisition and perception of those resources, whether through formal or experiential learning. Of significance to the intended research is the power of the *evaluative rules* informing the practitioner's sense of appropriacy with regard to the solving of a problem. Given the statistics on the failure of graduates to perform as expected, the question of differential access to knowledge as shaped by the pedagogic encounter, as well as the interpretation of *evaluative rules*, cannot be ignored in any study on knowledge practices.

Knowledge practices, therefore, take the shape of 'codes' – invisible structures determining the regulation, circulation and use of forms of knowledge based on rules established in different fields of practice, whether these be educational or social. Our task, as educators within the social realist framework, is to understand how these codes arise, so as to make them explicit for the purpose of 'learning the rules of the game' (and to be able to critique those rules). The task in this research is to make explicit the nature of the knowledge 'codes' underpinning engineering problem-solving practice, so as to understand the relationships between different kinds of 'code' and their potential structuring effects on the practitioner.

3.4 The structural features of knowledge

3.4.1 Discourses

The key Bernsteinian concept in this research is that of the way in which knowledge is structured[19]. 'Different forms of knowledge… [are] realised in … two discourses' (Bernstein, 2000, p. 156). 'Vertical discourse takes the form of a coherent, explicit and systematically principled structure' (*ibid*., p. 157), whereas horizontal discourse is context-specific and context-dependent everyday knowledge which emerges through and is reinforced by social practices. The boundaries between the two discourses are becoming increasingly porous in education. For example, in an effort to enable 'access' to formal knowledge, educators in a progressivist environment may draw on students' everyday experiences in order to introduce particular concepts. So, too, in the professional workplace environment, practitioners will find themselves navigating between the two forms of discourse.

Horizontal discourse is used to refer to everyday knowledge, which is segmentally organised and contradictory across contexts (Bernstein, 1996). Bernstein cites such examples as using the lavatory and tying one's shoelaces. These are not practices which build on each other to achieve an abstract principle (as in the case of vertical discourse), and are acquired through the development of a 'set of strategies' or 'repertoires' which enable one to function in different social or practical contexts. The total sets of 'repertoires' in a particular community are referred to as a 'reservoir'. The less isolated a community, the greater the opportunity for the 'circulation of strategies, of procedures and their *exchange*' (Bernstein, 2000, p. 158) (original emphasis). Globalisation and the ubiquitous Internet have enabled the exponential circulation and exchange of shared sets of strategies, within both horizontal and vertical discourse practices.

[19] Bernstein's characterisation of the different knowledge structures in mechatronics engineering was the theoretical basis of my Master's thesis, sections of which have been published.

3.4.2 Knowledge structures[20]

Bernstein describes two primary knowledge structures within vertical discourse that characterise the way in which knowledge has progressed in the field of production of new knowledge. Hierarchical knowledge structures, represented by the natural and physical sciences, attempt 'to create very general propositions and theories, which integrate knowledge at lower levels' (Bernstein, 2000, p. 161). This results in the 'subsumptive progression' of knowledge over time, where new theories or concepts extend and integrate earlier ones[21] (represented as the outer triangle in figure 3-1). This characterisation is evident in the field of recontextualisation where the formal school curriculum sequences specific concepts to allow for subsumption and integration over time. The principle may also be demonstrated in individual concepts.

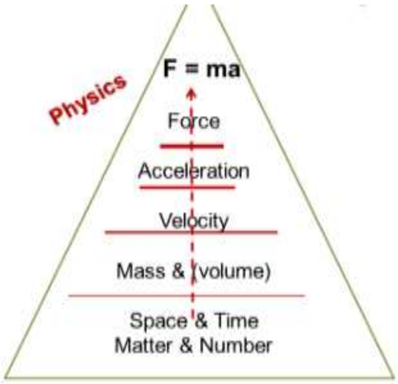


Figure 3-1 Subsumptive nature of hierarchical knowledge structures

The concept of 'force' in physics, for example (figure 3-1), is reduced to an abstract formulation (*F=ma*) which subsumes the concepts of number, matter, mass, time, motion, and acceleration. Force has already integrated the concept of acceleration (a = dv/dt), which is an integration of the relationship between the change in velocity (v) over duration of time (t). Young and Muller describe this principle as a theory-integrating form of 'verticality' (2007, p. 189).

Horizontal knowledge structures, on the other hand, 'consist of a series of specialised languages with specialised modes of interrogation and criteria for the construction and circulation of texts' (Bernstein, 2000, p. 161). This simply means there are different 'languages' of the same type of knowledge, each with its own rules.

[20] The nature of the three types of knowledge structures relevant to mechatronics engineering (the empirical research site) was extensively argued in my Master's thesis and is a fundamental premise upon which the current research is based. The argument is summarised here for the purpose of coherence.

[21] The position taken in this research project does not discount the invaluable contributions of Thomas Kuhn (1962) and Karl Popper (1962) who refute the neat linearity and cumulative nature of scientific progress as suggested by Bernstein's characterisation. Although ostensibly based on patterns observed in the field of production, Bernstein's characterisations, in my opinion, hold firmer in the fields of recontextualisation and reproduction – the focus of this research – where certain bodies of knowledge have come to be known as possessing certain structural and foundational features for which the Bernsteinian descriptions are relevant.

The figure on the right (figure 3-2) illustrates the primary 'languages' of mathematics (algebra, geometry, trigonometry) as a series of 'language' types, each with its own principles, procedures and forms of conceptual linking. These knowledge forms need to be acquired independently, and do not necessarily relate to each other or integrate concepts across the languages.

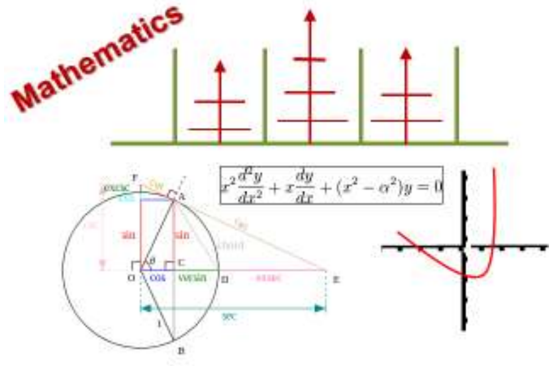


Figure 3-2 'Strong' horizontal knowledge structure

Where the rules for each language of the same type (or family) are 'strong', Bernstein described these horizontal knowledge structures as demonstrating a 'strong grammar'. They 'have an explicit conceptual syntax capable of relatively precise empirical descriptions' (Bernstein, 2000, p. 163). A good example is the theorem of Pythagoras, where the 'conceptual syntax' of $a^2 + b^2 = c^2$ empirically describes and is identified as the relationship between the lengths of the sides of a right-angled triangle. In other words, the conceptual syntax cannot be mistaken for something else. Horizontal knowledge structures with 'weak grammars' are those where the 'capacity of a theory to stably identify empirical correlates' is weaker (Young & Muller, 2007, p. 188). The term 'naturalism', for example, is to be found in several fields and would require clarification with respect to context, hence the notion of a weaker form of 'grammaticality'. The word in itself (and the concept it seeks to express) does not point to anything unambiguously or empirically precise.

These characterisations are important starting points for developing an understanding of the way in which the concepts in different forms of knowledge are organised. The two primary forms, as illustrated, are appealing in their ability to capture the nature of strongly classified 'singulars', such as physics and mathematics[22]. However, the 'regionalisation of knowledge' (Bernstein, 1996, p. 8), evident in such fields as engineering, sees the weakening of boundaries between the disciplinary bases. One example is 'computer engineering', or more specifically, the technologies associated with the communication of information (ICTs), a 'region' which is at the heart of 21st century multidisciplinary engineering practice.

[22] The classification of mathematics as a horizontal knowledge structure is controversial. I believe this stems from conflation of the concept of 'hierarchy' with strength, and 'horizontality' as implying 'weakness'. The position adopted in this research is that a knowledge structure is only classified as hierarchical if in the field of production there is a drive towards 'a grand unifying theory'. This has proven futile in mathematics following the efforts of numerous philosophers/mathematicians, and would deny mathematics its rich and diversely applicable nature. That it has strongly sequenced 'vertical' concept-chains is not in question, but each of the different mathematical 'languages' has a particular kind of 'code'.

The primary disciplines underpinning ICTs are 'logic'[23] and mathematics, both of which Bernstein describes as being horizontally structured with strong grammars (2000). However, the disciplinary 'logic' implied in engineering control systems today has become increasingly complex, and it can be used to illustrate the horizontal knowledge structure with a 'weak grammar'.

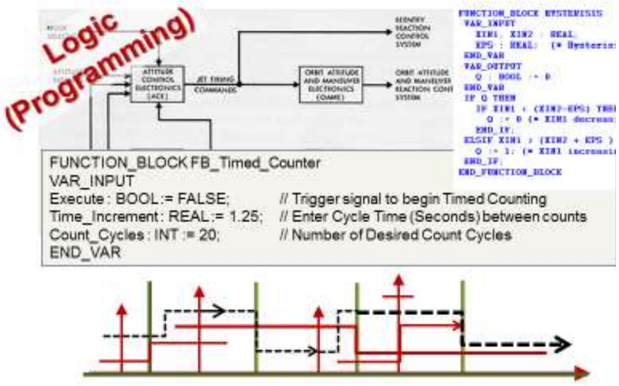


Figure 3-3 'Weakening' horizontal knowledge structure

'Logic programming' languages[24] (illustrated in figure 3-3) can be used in isolation or in conjunction to accomplish the *same objective* (Wolff & Luckett, 2013, p. 82). Multi-paradigm and mixed-modality programming platforms are common, combining syntactical, symbolic and functional features from several sources in response to users' needs (Wright, 1999) and the affordances of the rapidly evolving underlying technologies. Such features - particular to horizontal knowledge structures with 'weak grammars' - highlight the seriality, proliferation and redundancy of programming languages. In other words, progress in the development of these knowledge structures is driven by users, and not by the knowledge itself.

Conceptually, knowledge with a hierarchical structure is dependent on strong sequencing and subsumptive progression. In the case of horizontal knowledge structures, however, 'masses of particulars' (Muller, 2008, p. 15) need to be learnt independently, not necessarily sequentially, and usually in specific contexts. Acquiring knowledge with a horizontal structure and weak 'grammar', such as 'logic programming' (or social science, or 'modern' art, for example) means not only learning each new relevant 'language' as it is created or required, but staying abreast of significant structural and even conceptual changes to the same language as the users drive change in the field of application or social context.

So, the question for this research is *what happens when these three significantly different disciplinary structures* (representing the core disciplines in the region: physics, mathematics and logic) *meet in a problem-solving moment?*

The position the research would like to explore is the question of the shaping of consciousness. On the one hand, Bernstein constructs a powerful argument for the nature of knowledge based on its progression in the field, with the implication that the delocation,

[23] The study of inferences that depend on concepts that are expressed by the 'logical constants' such as *and*, *not*, *or*, *if…then* (www.britannica.com).

[24] Not to be confused with Bernstein's use of 'languages'. The 'declarative' programming paradigm could be regarded as a type of 'language' in the Bernsteinian sense, one of several based on the discipline of 'logic', with its own 'criteria for the construction and circulation of texts' (Bernstein, 2000, p. 161).

relocation, and refocusing of a discourse (2000, p. 32) occurs by way of a deliberate carving out of disciplinary territories, into which students are socialised according to various rules as established by the field. This means that the practice of the practitioner (in this case the problem-solving engineering graduate) may be informed and constrained by prior social, experiential, pedagogic and curricular exposure. These are aspects that need to be acknowledged in this research. However, the question of the inherent causal powers and tendencies that different forms of knowledge possess, and which 'lend themselves more to certain forms of pedagogy, evaluation, identity, change over time' (Maton, 2009, p. 55), and, by extension, practice, warrants investigation if we are to avoid the simplistic and non-agential view that we are merely a product of our environment and socialisation.

3.4.3 The question of boundaries: classification and framing

If the core disciplines are characterised by organising principles which can be clearly differentiated, then these disciplines are regarded as 'bounded'. Bernstein's concept of 'classification' refers to the boundaries between categories, a form of insulation which maintains separation. In a pedagogic context, the classificatory principle is best illustrated through the organisation of knowledge dating back to the medieval universities where the first major division occurred between mental and manual forms. Concerned with only the former, two distinct orders were established. The Trivium consisted of grammar, rhetoric and logic, and was 'very much the regulative discourse … concerned with the construction of inner consciousness' (Bernstein, 2000, p. 8). The Quadrivium classified knowledge into mathematics, geometry, astronomy and music, which in the 19th century developed as 'singulars'. A singular is 'a discourse which has appropriated a space to give itself a unique name' (*ibid*., p. 9). The strong classification of these singulars sees specialisation as a long initiation into the mysteries of a particular 'singular', which guarantees not only subject loyalty but a perception of well-deserved status and, hence, vertical social relations.

Bernstein defines a curriculum comprised of strongly classified singulars as a closed collection-type, which sees the 'organisation, transmission and evaluation of knowledge as bound up with patterns of authority and control' (Bernstein, 1977, p. 81). The 20th century saw the recontextualisation of singulars into regions, such as Medicine, Law, Engineering, and thereby a weakening of classification. Given that the boundaries between disciplines not only reflect but are legitimised by social power relations, the dissolving or blurring of those boundaries has implications for the nature of power in society. When the insulation is threatened or weakened, the category, be it a subject (mathematics) or an agent (engineer), risks losing its specialisation and thus its status. The very nature of social order becomes threatened, no matter how arbitrary that order may be.

Classification creates identities and voices. Each category has a particular voice and in order to access that category (learn mathematics, practice as an engineer) one has to *recognise* its rules. In order to function or participate within a category, one has to *realise* (produce) a legitimate message, in other words, access and use the appropriate form of communication. Bernstein referred to these as recognition and realisation rules (2000). The greater the number of voices recognised and message systems realised, the more elaborated one's orientation to meaning. An orientation to meaning is evident through its codes. 'Code refers to a specific cultural regulation of the realisation of commonly shared competences… It refers to specifically semiotic grammars regulated by specialised distributions of power and principles of control' (Bernstein, 1990, p. 113). In other words, practitioners with an elaborated orientation to meaning recognise and apply (realise) forms of communication appropriate to different contexts, but this recognition and realisation are based on socialisation into the power and control relations evident in society. Fundamental to elaborated orientation to meaning are the underlying external and internal classification and framing values that shape a particular code.

The 'realisation' of messages is governed by framing, which is about *how* who controls *what* across five sites: Selection, Sequence, Pace, Criteria, and Control over the social base which facilitates transmission of knowledge (Bernstein, 2000, p. 12). Strong framing means the transmitter has explicit control over the five sites, whereas weak framing suggests the acquirer has more apparent control. The transmitter can be seen as the educator, the government, or the employer. According to Bernstein, Framing regulates two systems: the Discursive Order which governs the first four sites, and the Social Order which determines conduct, character, manner and posture. He sees the first as taking the form of Instructional Discourse and this as embedded in the second, Regulative Discourse. Essential to Bernsteinian theory is the belief that the Regulative Discourse - the rules of dominant social groups who hold power in society - is in fact the dominant Discourse.

Although these concepts are commonly held to be primarily applicable to the field of education in Bernstein's work, classification and framing have proven invaluable means to make explicit the structures and rules of sociocultural knowledge practices in numerous fields. They may be used to describe the organising principles and relations between people and entities in any context. However, classification and framing are early Bernsteinian concepts, and in order to attempt to investigate the relationship between significantly different forms of knowledge and the negotiation of disciplinary boundaries in engineering problem-solving practice, a conceptually richer 'language of description' is required.

3.5 Legitimation Code Theory (LCT)

Legitimation Code Theory (LCT) forms a core part of a broad social realist 'coalition' of approaches which reveal knowledge as both socially produced and 'real', in the sense of having effects. LCT extends, amongst other ideas, the concepts of Basil Bernstein, and provides a rich (and developing) 'sociological toolkit for the study of practice' (Maton, 2013, p. 5). As such, the LCT framework has been applied to a range of empirical studies[25], using both quantitative and qualitative research methods, for the analysis of macro to micro knowledge practice contexts across the disciplinary map and beyond education. The framework currently comprises five dimensions which offer concepts for the 'analysis of organizing principles underlying practices to enable research to determine difference, variation and similarity, and to explore change over time' (Maton, 2013, p. 10).

This research project employs two key dimensions to analyse the nature of novice engineering knowledge practice over time: Semantics and Specialization. The two dimensions are intended to function as independent and complementary 'languages of description'. On the one hand, Semantics offers a set of concepts through which to interpret the articulated practices of the problem-solving practitioner. Specialization, on the other hand, offers a set of concepts with which to explore 'why' the practitioner does what s/he does. It enables an analysis of the nature of the apparently invisible epistemic relations determining the problem-solving practice. The following sections describe these two dimensions in greater detail, delineating examples of application to this research context.

3.5.1 Semantic codes

'Semantics' conceives 'social fields of practice as semantic structures whose organizing principles' (Maton, 2014, p. 130) are conceptualised as *semantic codes* comprising *semantic gravity* and *semantic density*. *'Semantic gravity* (SG) refers to the degree to which meaning relates to its context, [while] *semantic density* (SD) refers to the degree of condensation of meaning within sociocultural practices' (*ibid*., p. 129). The formula F=ma, as a representation of the physics concept of force, demonstrates a stronger form of semantic density (SD+) than the word 'force' (SD-) which would need provision of a context to clarify the intended meaning. Similarly, the handwritten calculation of a particular structural force has weaker semantic gravity (SG–) than the physical demonstration thereof on a particular object (SG+). These concepts are always relative, and 'enable research to trace the *semantic profiles* of practices in terms of their positions on a scale of relative strengths, and the associated *semantic range* between their highest and lowest strengths' (Maton, 2014, p. 131). *Semantics* is employed in

[25] Education, including biology and history (J. R. Martin & Maton, 2013), ethnographic methods (Hood, 2014), design (Carvalho, Dong & Maton, 2009; Shay & Steyn, 2014), journalism (Kilpert & Shay, 2013), and law (Clarence, 2014).

this research at its most basic level to interpret participant knowledge practices as descriptively and reflectively articulated through various textual and semiotic means (diagrams, demonstrations). This dimension of LCT enables an analysis of references to types of knowledge at different levels of context-dependency (SG) and with different degrees of condensation of meaning (SD).

When set in relation to each other on the *semantic plane* (figure 3-4), four semantic codes are evident:

- '*rhizomatic* codes (SG–, SD+), where the basis of achievement or status comprises relatively context-independent and more complex meanings;
- *prosaic* codes (SG+, SD–), where legitimacy accrues to more context-dependent and simpler meanings;
- *rarefied* codes (SG–, SD–), where meanings of legitimate practices are relatively context-independent but also relatively simple (not related to many other meanings);
- *worldly* codes (SG+, SD+), where legitimacy is related to more context-dependent practices that condense manifold meanings (or related to many other meanings)' (Maton, 2015).

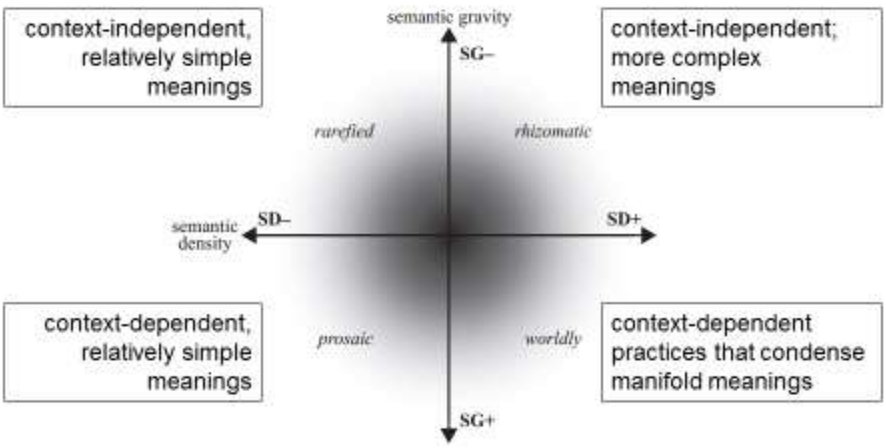


Figure 3-4 The semantic plane - annotated (Maton, 2015)

The semantic codes enable a view of how the practitioner makes meaning in relation to concepts and contexts, and in this research provides an additional lens through which to view their problem-solving practices. The greater challenge, however, and analytical focus of this research is to understand 'why' the practitioner does what s/he does, and the relationship between the generative properties of the significantly different organising principles constituting the core disciplines in a particular field of multidisciplinary engineering in a range of comparable contexts.

3.5.2 Specialization codes

'Specialization codes extends and integrates Bernstein's concepts of 'grammars'' (Maton, 2014, p. 95) and conceives practices as knowledge–knower structures whose organising principles are *specialization codes* comprising *epistemic relations* and *social relations.* Specialization is about what 'counts', what is recognised as legitimate? The epistemic relations concept 'highlights that practices may be specialized by both *what* they relate to and *how* they so relate' (Maton, 2014, p. 175), and the social relations (SR) concept 'highlights that practices may be specialized by… kinds of knowers and ways of knowing' (*ibid.*, p. 184). Epistemic relations (ER) can be applied to the relationship between theory and data, in other words, the relationship between a knowledge claim and an empirical phenomenon. The challenge in this research is the nature of the relations between the theory and data in *three significantly different disciplines* (commonly seen as belonging to a single 'set' of engineering sciences) when they meet in a problem-solving moment. Maton's differentiation within ER between *ontic relations* and *discursive relations* enables a framework through which to examine the research problem with greater conceptual delicacy.

Ontic relations[26] (OR) describe 'how strongly knowledge claims bound and control legitimate objects of study', whereas *discursive relations* (DR) describe 'legitimate procedures for constructing objects of study' (Maton, 2014, pp. 175-176). These two continua are set in relation to each other in such a way as to reveal four *insights* on an epistemic plane (figure 3-5).

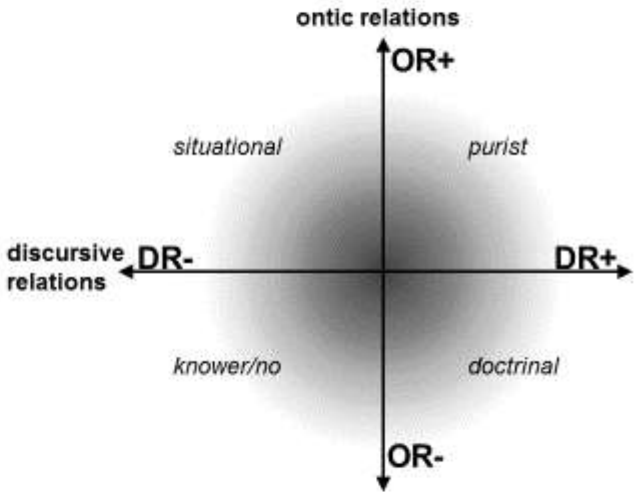


Figure 3-5 The epistemic plane - *insights* (Maton, 2014, p. 177)

By way of elaboration, I will use examples of engineering knowledge practices to illustrate the four *insights*:

Purist insight: This practice modality sees strong adherence to both the phenomenon studied and the approach. If the phenomenon were current flow in an electrical circuit, for example, this is governed by a commonly agreed law (Ohm's Law) and expressed in a particular formula

[26] It is important to differentiate here between 'sense and reference' or 'meaning and naming'. The ontic relations are essentially about the recognition of a concept or phenomenon irrespective of its 'name'. Where this is the case, the ontic relations would be regarded as strong. In contrast, discursive relations may imply naming conventions as well as approaches to a specific phenomenon.

(V=IxR). In other words, there are both strong ontic relations (OR+) as well as discursive relations (DR+).

Doctrinal insight: This is when the practice is governed by allegiance to a particular method irrespective of the phenomenon in question. Examples are the application of mathematical models or the procedural rules governing production processes. The method demonstrates stronger discursive relations (DR+) and weaker ontic relations (OR–).

Situational insight: 'Knowledge practices are… specialized by their problem-situations' (Maton, 2014, p. 176). This means there are choices in how to approach a particular phenomenon, in other words, weaker discursive relations (DR–), but the focus of the potential solution is strongly bound (OR+) by a particular idea.

Knower/no insight: The weakest point of the epistemic relations is either characterised by an 'anything goes' (OR–, DR–) philosophy (no particular *insight*) or the practice is legitimated through the 'attributes of the subject' (*ibid*.). In the latter case, the practice demonstrates a shift away from knowledge and towards a *knower code*.

3.5.3 Focus and basis

ER and SR 'can be used to both describe the *focus* and analyse the *basis* of practices' (Maton, 2014, p. 31). *Focus* is 'what' is being referred to, while *basis* is from what perspective. 'The *strengths* of epistemic relations… refer to the basis of practices' (*ibid.*). An observation to emerge throughout the pilot and ensuing main study is that there are distinctly different focal points during the problem-solving process, revealing different bases of practice or *insight* phases:

- 'how' the practitioners approach the overall problem itself (problem-solver orientation)
- 'how' they determine the cause (analysis)
- 'how' they implement a solution (synthesis)

In addition to the 'orientation' of the problem solver and his/her problem-solving process, the problem environment also suggests a particularly dominant 'basis' for practices in general. So, too, does each problem structure seem to demand a particular *insight* orientation. *Insights*, in other words, demonstrate the *basis* from which a practitioner views a particular situation or activity, or the *basis* of standard operating procedures in an organisation. These are forms of 'code' which could be dictated by the practitioner, the problem or the environment.

3.5.4 Code shifts and code clashes

The LCT framework offers an overarching language of description through which to examine sociocultural practice in which there are different forms of theory and data. Given the evidence that multidisciplinary engineering is comprised of significantly different knowledge structures

(Wolff & Luckett, 2013), and the research focus on engineering problem-solving practice, the LCT tools offer a means to magnify and interpret the problem-solving moment in complex practice. *Semantics* enables the capturing of a dominant problem-solver *semantic code* - how each participant regards and speaks about problems in his/her particular working environment at different levels of context-dependency and condensation of meaning.

Specialization, through the use of the *epistemic plane,* enables a mapping of the continuum-based relationships between *what* the focus of the knowledge claim is and *how* that claim is made. In the problem-solving situation, there are several components:

- The Problem Solver
- The Problem Structure
- The Problem Environment (Context)
- The Problem-solving Process

The language of the *epistemic plane* can be applied to each of these to determine a dominant *insight*. Moving between different *insights* in a single problem-solving moment implies crossing boundaries. The different *insights* represent significantly different ways of thinking. *Insights* are different kinds of 'code'. Consciously solving a problem from a particular *insight* orientation which differs significantly from that suggested by the problem itself or its environment also implies boundary crossing at the very least, but is more likely to manifest as a code clash if explicit code-shifting tactics are not employed.

3.6 Conclusion

The question the research seeks to answer at a conceptual level is 'how do engineering practitioners navigate different sets of knowledge claims, their respective objects of study and the legitimate procedures for constructing these objects of study'? What is the nature and impact of knowledge code clashes and code shifts 'between approaches that appear to share the same bases for legitimation' (Maton, 2013, p. 3). The physics-based and mathematics subjects in an engineering curriculum are commonly lumped together as 'engineering fundamentals'. The inclusion of increasingly technology-based subjects similarly assumes that these share a common epistemological ancestry. Whilst at the site of knowledge production this may be the case (changes in computing capacity, for example, are primarily a result of physics-based research), the application of the technology in the fields of recontextualisation/reproduction requires logic-based thinking and the adaptive, responsive capacity to engage with multiple semiotic systems. Many of these even display a distinct *knower*-orientation[27]. When the problem-solving activity founded on these significantly different

[27] As part of my Master's programme, I conducted an analysis of the evident knower-orientation in control systems practitioner loyalty to particular brands.

knowledge forms is situated within the broader ‘problem-solving situation’, the potential for explicit code shifting and invisible code clashes are legion. It is precisely these shifts and clashes that this research wishes to examine using the social realist concepts as delineated in this chapter. It is hoped that ‘a more sophisticated understanding’ (Shay, 2008) of the navigation of different forms of disciplinary knowledge in engineering problem-solving practice can make a significant contribution to the form of curriculum and pedagogic design necessary to meet 21st century engineering education challenges.

CHAPTER 4: CONCEPTUALISING THE EMPIRICAL RESEARCH CONTEXT

4.1 Introduction

The preceding chapters have presented a broad contextual and specific theoretical framework for considering an epistemologically-orientated examination of problem-solving practices in multidisciplinary engineering. It is now time to consider the empirical research site against the established contextual background, and to do so productively by drawing on the 'language' established in the conceptual framework.

> 'Engineering is … a profession devoted to harnessing and modifying the three fundamental resources that humankind has available for the creation of all technology: energy, materials, and information' (Feisel & Rosa, 2005, p. 121).

Although the above definition is intended to describe all 'engineering', mechatronics engineering (the focus of this research study) represents the explicit combination of materials, energy and electronic information. There are several definitions, more often than not coloured by the context (where a mechatronics programme finds itself situated in a particular institutional structure or industry)[28]. However, the Mechatronics Education Forum of South Africa defines it as 'the concurrent design, manufacture, integration and maintenance of controlled dynamic electro-mechanical systems'[29]. In layman's terms, any device, machine or process with moving parts that is controlled by a computer (no matter how small or basic) is a mechatronic system.

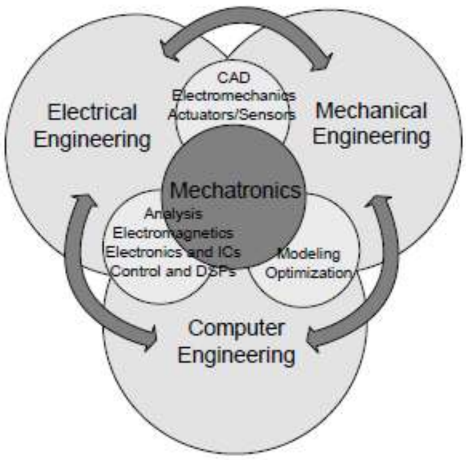


Figure 4-1 Mechatronics engineering fields (Bishop, 2002)

[28] The term 'mechatronics' is a relatively new one in industries, and several sectors see the function fulfilled by their 'mechanical engineers' or 'electronics engineers', as the curricula and technologies may overlap considerably with that of a 'mechatronics' curriculum.

[29] https://sites.google.com/site/mechatronicsforumsa/home-1

Mechatronics curricula (figure 4-1) are broadly designed around three core subject areas: structures, power and control. Epistemologically, ‘structures’ and ‘power’ draw on the mathematics and physics underpinning mechanical and electrical engineering. ‘Control’, in this region, is based on the ‘logic’ and mathematics of computer engineering. Mechatronics represents one of many regions in which the growth of the region itself is not only directly related to but dependent on industry-generated technological developments aimed at more efficient automated production.

There are few institutions currently offering the qualification in South Africa. Three traditional universities offer the qualification as a specialisation from the third year following a professional Bachelor’s base in either Mechanical or Electrical Engineering; one comprehensive university offers a Bachelor’s in Mechatronics; and two Universities of Technology (UoTs) offer the qualification as a Diploma, followed by a fourth B-Tech year[30].

As was established in chapter 2, engineering has undergone rapid regionalisation over the past few decades, and mechatronics engineering is considered merely one of several ‘sub-disciplines’ (Hanrahan, 2014). This regionalisation has implications for how we view the theory/practice relationship, which I believe underpins effective problem-solving practice in complex contexts. This chapter seeks to lay a foundation and present a conceptually-informed contextual language through which to address the questions regarding the negotiation of disciplinary boundaries in problem-solving practices in a rapidly evolving ‘region’. This chapter also partially fulfils a methodological purpose in its use of the social realist concepts to provide the first phase of an organising framework for the analysis of problem-solving practice data. This conceptually-informed ‘organising framework’ is not only necessary as a background for the research design to be detailed in chapter 5, but will also support the nature of methodological choices.

4.2 Mechatronics engineering knowledge

4.2.1 Researcher position

As a researcher in the field of engineering education, I need to declare my position here. My knowledge of mechatronics engineering stems from a five-year period (2008-2012) engaged as professional practice lecturer, curriculum designer and Work-Integrated Learning (WIL) mentor on a new Mechatronics Diploma programme at a University of Technology in South Africa. I am not an engineer. I entered the programme in its second year wearing an Academic Literacies and Humanities ‘hat’. My observation of knowledge integration difficulties in final year Diploma student design projects (supported by academic and industry feedback) sparked

[30] This NQF level 7 1-year qualification is to be replaced by an Advanced Diploma of the same level and duration.

a desire to better understand engineering practice. My simultaneous Master's studies in HE saw an introduction to social realist concepts, which, although intended to apply to sociocultural structures, were useful in my context for understanding the technical structures of an automated system, and the relationships between physical artefacts, the various types of 'power' (force, momentum, electrical) and 'control' (computer-based 'logic' programming). It was through the social realist lens and its accompanying theoretical tools that I began to understand the mechatronics 'region'.

4.2.2 Mechatronics engineering disciplinary roots

In my role as WIL coordinator, I not only placed students in various companies, but also spent time in those environments. An interesting observation was the fact that graduates on the programme were working in every one of the 21st century equivalents of fields originally defined as the 'Mechanical Arts' in medieval times (as illustrated in figure 4-2) (Wolff, 2011). The diversity of the sites of practice, each in their own right requiring context-specific specialisation, suggested implications for the theory/practice relationship in a curriculum intended to provide a broad basis for a single qualification, and yet simultaneously offer the requisite depth with regard to the disciplinary foundation.

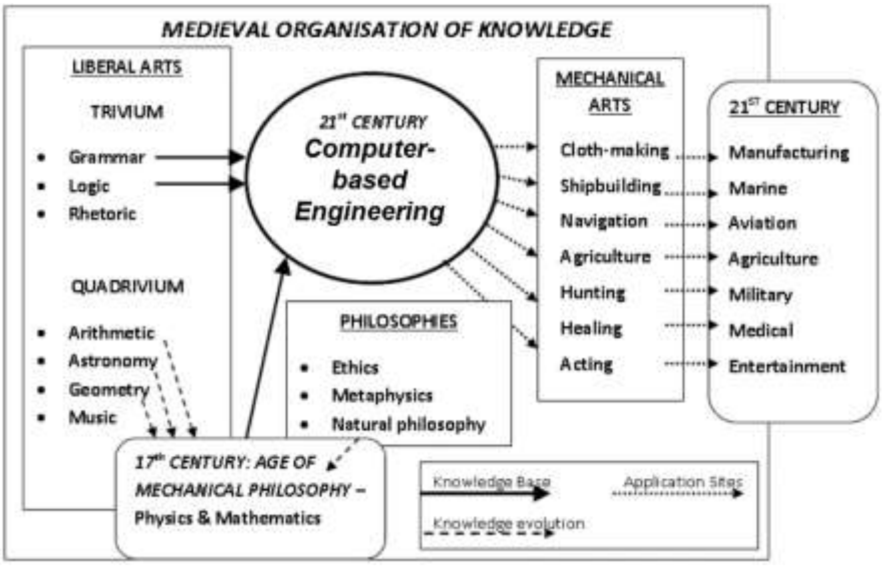


Figure 4-2 21st century computer-based engineering evolution (modified from Wolff, 2011)

A review of the medieval disciplinary map revealed to me that this 21st century 'region' has strong roots in both the Trivium – 'the three arts of language pertaining to the mind' - and the Quadrivium - the four arts pertaining 'to matter' (Joseph, 2002). (As with the rationalist/empiricist distinction, the mind/matter one too points to the theory/practice divide.) The three arts of language are defined as follows:

> ‘Logic is the art of thinking; grammar, the art of inventing symbols and combining them to express thought; and rhetoric, the art of communicating thought from one mind to another, the adaptation of language to circumstance’ (Joseph, 2002, p. 5).

The assumption in modern science-based engineering is that the disciplinary base consists of a core of natural, mathematical and engineering sciences, disciplines which have evolved from the Quadrivium and the physics emerging from the age of Mechanical Philosophy (as illustrated in figure 4-2). Mechatronics engineering, however, is about the ‘control’ of a system with moving parts. This ‘control’ is executed through a computer by way of programming languages (of which there are thousands), and which serve to communicate instructions to and receive feedback from components in an automated system. These instructions are dictated by the programmer and dependent on his/her interpretation of the purpose of the system in relation to what the components can/should do. The form of programming used in mechatronics engineering is known as ‘logic programming’, ‘a declarative, relational style of programming based on first-order logic’ (www.dictionary.reference.com) employing the ‘logical constants’ such as *and*, *not*, *or*, *if…then*’. The ‘grammar’ of each programming language differs significantly, and the ‘logic’ of each system is dependent on programmer choices, the system components and relations, and the type of programming platform. Each system has ‘inputs’ (information entering the system by way of digital or analogue signals) and ‘outputs’ (moving parts that act in a prescribed manner when receiving a signal). Essentially, a programmer adopts a kind of ‘rhetoric’ – ‘the adaptation of language to circumstance’ (Joseph, 2002) - to set up relations between inputs and outputs (figure 4-3) so as to enable a particular system to function as desired. No two programmes are ever identical. And no two programmers can ever construct the same programme (Vandor, 2001).

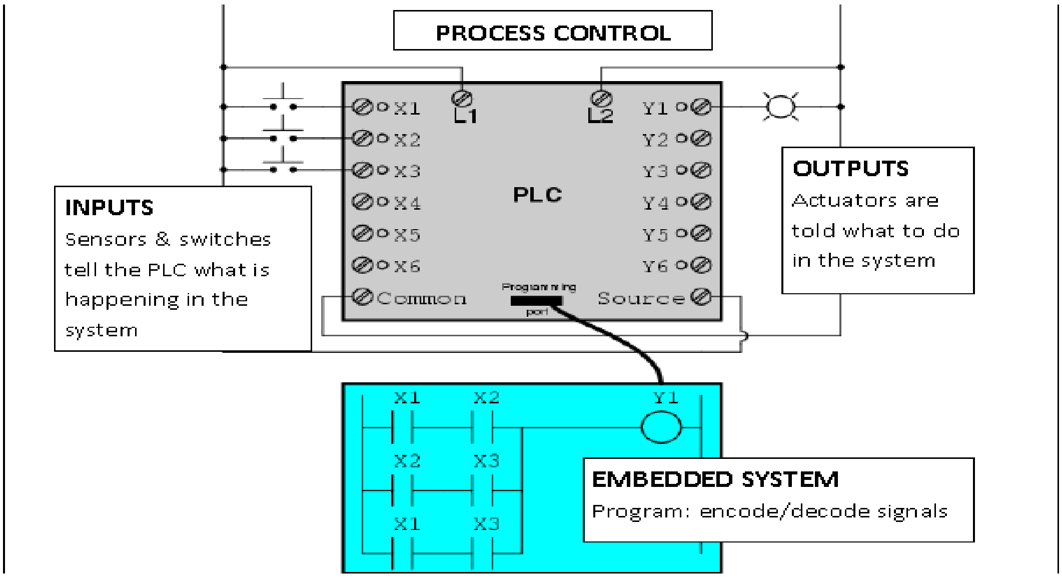


Figure 4-3 Simple overview of PLC layout (adapted from Wright, 1999)

As a language teacher originally, I was struck by the parallels between computer programming and human language features, but that the former is taught in HE as a procedural or applied-science-based discipline. The observation of polarised student performance in the logic-based versus the mathematics and physics-based subjects sparked an even greater interest in understanding the disciplinary differences. There were significant patterns of students achieving distinctions in the one category and failing the other. This later proved to be an indicator of success in certain types of mechatronics industrial contexts[31]. These observations begged the question of whether or not the disciplinary differences have an impact on different practitioners in different environments.

4.2.3 Prior mechatronics knowledge research and observations

Bernstein's theories and LCT provided, in my opinion, a valuable set of tools with which to more closely examine the differences between types of engineering knowledge and their integration in practice, and as such led to my Master's research dissertation: *Integrating multidisciplinary engineering knowledge in a final year technical university diploma programme: an analysis of student praxis* (Wolff, 2011). This research analysed the practices of a particular project group over a 3-month period as they designed and manufactured a computer-controlled, air-powered vehicle. A mapping and coding system was developed to describe the sequence, structure and levels of context-dependency of the different knowledge types on which the students drew. The application of social realist theoretical tools revealed the differences between different forms of knowledge, and led to the suggestion that 'spaces need to be created in our curricula which facilitate the explicit integration of the different forms of knowledge which will enable complex praxis' (Wolff, 2013, p. 92). However, at the heart of 'complex praxis' in engineering lies the issue of problem solving, which the Master's research did not address, and which is thus the focus of the current research project.

A few key observations to emerge from the period of involvement on the programme include:

- Industry confirmation that 'the 'content' of engineering practice other than basic principles is changing far too rapidly for engineering curricula to keep pace with' (Felder, 2012, p. 11).
- Consistent industry observations about the difficulties engineering graduates in general display in fault finding and problem solving.
- The attribution of problem-solving difficulties either to 'not knowing the basics' (theory) or to 'lack of initiative' (practice).

[31] This is intended as an area of further research following completion of the current study.

These observations suggested a need to investigate – with a more rigorous set of tools - how 21st century mechatronics engineering practitioners actually 'solve problems'.

4.2.4 Mechatronics as a region

'Regionalisation', as Bernstein (1996) tells us, leads to a weakening of disciplinary boundaries. 21st century mechatronics engineering curricula tend to manifest a strong allegiance to traditional disciplinary 'fundamentals' as relatively discrete and strongly classified 'singulars' taught in the first phase of the qualification (notably engineering mathematics and physics-based subjects). However, in their simultaneous attempt to address increasingly diverse and specialised labour market needs, mechatronics curricula introduce (in the second part of the qualification) subjects such as 'networking', digital systems, computer-integrated manufacturing and computer-aided design - the disciplinary bases of which are logic, physics and mathematics (Wolff, 2013, p. 87). A review of course content for technician/technologist training in these subject areas reveals a predominantly procedural approach or, at best, a fairly generic 'systems' theoretical framework.

It is my view that these subject areas demonstrate the type of blurring of disciplinary boundaries that occurs after multiple processes of recontextualisation (in the curriculum, pedagogy and contextual practice) as a result of increasing regionalisation in which there is a loss of the 'relational idea' (Bernstein, 1975, p. 93). This may be ascribed to the distance between the relatively stable disciplines of mathematics and physics (in the engineering 'theory' context) and the dynamic evolution in the logic-based engineering specialisations, which manifest in specific applied technologies (practice). Furthermore, it is apparent that the distance between what are regarded as engineering theory and engineering practice is not only widening, but also becoming increasingly complex. This complexity is exacerbated, I suggest, by both the 'discipline-blurring' regionalisation process as well as a lack of understanding of the contextual framework in which problem-solving practice occurs in such regions. In order to examine disciplinary boundary negotiation (the objective of this research), a more conceptually refined view of the regional context will be presented in the following sections.

4.3 Mechatronics engineering practice

Mechatronics engineering practitioners work in and in relation to any environment where there are computers controlling machines. The most common environments would be described as manufacturing, materials processing, packaging, production, and automation plants. The nature of work in these environments ranges from the design, manufacture and modification of the actual devices and automated *systems* themselves to the management and maintenance of the production *processes* undertaken by these systems.

4.3.1 Fully automated production environments

The purpose of automated production is to produce goods as safely, efficiently and cost-effectively as possible, whether food and beverages, components, raw materials processing, packaging materials or vehicles. The level of computer-based control in these environments differs significantly. There are entire automated systems with very little human involvement on the actual factory floor, and where engineering practitioners operate from a room (local or remote) with computers that can view all the systems (common in breweries, for example).

Figure 4-4 A SCADA system (Supervisory Control and Data Acquisition)[32]

The engineers and technicians in such cases do not 'see' the physical systems, rather the graphic, computer-generated representation (figure 4-4) of the system elements and relations. Mechatronics engineering practitioners in such environments specialise in overseeing the automated processes via the computer control centre, and intervening on the floor when the system malfunctions.

4.3.2 Semi-automated production environments

On the other side of the scale of automation, there are industries using dedicated automated machines to fulfil a particular function, but the link between different processes is manual, and carried out by personnel. It is common in such environments to systematically integrate a sub-system or a 'modular unit' to replace the manual process between other automated processes, if the manual process is causing delays or losses in productivity. These are the most common sites of employment for mechatronics engineering practitioners, in three different types of roles. A practitioner may be 1) employed by the specific company to maintain existing systems (which entails monitoring, repair and improvement), *and* to design/source and integrate new 'modular' automation units to improve productivity. Alternatively, 2) practitioners are sourced from companies who act as 'systems integration' specialists. In this case, such practitioners are not based in the particular industry, but act as 'project' practitioners, moving from industry to industry where they develop, build and integrate customised automation solutions for their clients, using the clients' machines. A third alternative in the semi-automated category is the 3) contracting of a company that specialises in building modules and entire sections of a production process. These are called 'machine builders', but effectively speaking they build

[32] Roll wrapper PLC controls http://automatrixinc.com/projects.html

sub-systems which link together in ‘modular units’ and are called ‘machines’. These ‘machines’ can be an entire production line, which is added to a client’s existing production system.

4.3.3 Automation device design and manufacture

A third automation sector focuses on ‘discrete’ devices. Sometimes these are classified as Research and Development (R&D) companies. The automation design and prototyping industry is dedicated to developing new automation solutions, from small controlled devices to larger machines that fulfil a specific discrete function, such as dedicated medical devices, microwave ovens or vending machines. Very often, such development units exist as part of a production industry (as in the automotive, medical or pharmaceutical industries). In South Africa, such in-house automation design and prototyping units in large industries are rare. Where large manufacturing industries are part of multinational corporations, R&D usually occurs at the company headquarters. More common in South Africa are smaller scale prototyping specialists who are contracted per project.

4.3.4 Activities and artefacts

The activities in mechatronics engineering practice range from conception and design of automated systems (or sub-systems) to the manufacture and implementation of new systems, and the maintenance, improvement and operation of existing systems. The activities in the latter are dependent on the level of automation – in highly automated environments, the activities are more likely to be monitoring and improvement via the control system. Where these systems have been designed by international or external systems specialists (very common), maintenance or troubleshooting at the computer programme level is usually conducted remotely, from the company headquarters, or a dedicated service engineer/technician is sent to intervene. The implications, locally, are that practitioners have limited access to the control of the system, and may only be involved at the level of the Human-Machine-Interface (HMI) - a small user touch screen (linked to the controller) with limited control features, where values are set, and processes can be started and stopped.

In lower-level automation, the practitioner is more likely to be involved in the physical (mechanical and electrical) structures and their relation to whatever control system is operating. It is common for small and medium-sized enterprises to develop their level of automation systematically over time, integrating sub-units and systems (of different supplier origins) into their existing systems. This requires innovative and research-informed methods to enable compatibility between different components and sub-systems. Typical artefacts in a practitioner’s day-to-day work are a computer, programmable logic controller (PLC), motors, actuators, sensors, drives and a host of electronic and mechanical components. Forms of information are typically visual, graphic, schematic and relational diagrams representing systems, signals and programming code (see sections 4.5 and 4.6 of this chapter).

4.4 Conceptualising the mechatronics engineering working environment

4.4.1 Extending the inner/outer metaphor

The preceding section presented a descriptive illustration of the nature of mechatronics engineering practice and its environments. These environments and contexts differ significantly, but at the heart of the mechatronics engineering endeavour is the control of an electro-mechanical device or system. Such a device or system is an artefact whose 'inner system is an organisation of natural phenomena capable of attaining goals in some range of [outer] environments [which, in turn,] determine the conditions for goal attainment' (Simon, 1996, p. 11). In terms of goal attainment, there may be a number of potential scenarios. Several artefacts with fundamentally different inner environments can fulfil the same function in the same outer environment. A bird and an aeroplane, for example, can both fly. They are adapted or designed to cope in identical outer environments, but their inner environments differ substantially (*ibid*). A clock, on the other hand, with the same inner mechanism, is capable of functioning in a multitude of outer environments. The environment, however, may dictate the size and outer structure of that clock (wrist watch or Big Ben). Similarly, the outer environment may dictate the conditions for practice.

The purpose of this distinction between inner and outer environments is to highlight the significance of the relationship between natural and artificial phenomena as they meet in a complex, essentially 'artificial' or 'synthetic' system that is concerned with the attainment of functional goals (such as an automation process). The notion of the primacy of the role of 'natural sciences' underpinning engineering activity (the laws of the 'inner environment') has long dominated engineering education. However, it is apparent that there are multiple types of inner/outer constructions, with different parameters, constraints and affordances. I have elected to term these inner/outer constructions '**Knowledge-Practice Environments**' (KPEs).

According to Bourdieu, one of three 'distinctive features of practice… [is that it] is located in space and, more significantly, in time' (Jenkins, 2002, p. 69). To use the earlier examples, 'practice' in the context of the conception, design, implementation (manufacturing) and operation of a single wrist watch *differs substantially* from that of a public clock tower, such as Big Ben, with respect to the spaces in which such activity phases would take place, as well as the use of time. The design of both artefacts could quite feasibly occur in a space as small as a desk. Similarly, the time taken for these activities could be equivalent (depending on the number of stakeholders involved). The actual manufacturing of each artefact requires not only very different types of spaces (given the scale and materials of construction), but also significantly different periods of time. It took 34 years to build Big Ben[33], and modern watchmaker, Donald Corson[34], takes just over six months per handmade watch. In contrast, between 2000 - 4000 Rolexes are produced per day by 5000 employees.[35] In all these examples, the sciences underpinning the 'inner environment' of analogue timekeeping are essentially the same.[36] It is the nature of the outer environments that will differentially determine practices not only with respect to time and space, but also stakeholders and resources.

4.4.2 The Knowledge-Practice Environment (KPE)

Essentially, engineering practice can be seen on a continuum: On the one end we have a lone 'inventor', equipped with his/her own resources designing and manufacturing a gadget, for example, in his/her basement. On the other end of the spectrum we see massive multi-factory manufacturing plants producing goods for public consumption. These two ends of the practice continuum represent the 'inner/outer construction' poles. Ideal engineering problem solving entails establishing an optimal relationship between the inner and outer environments of a particular artefact so as to attain a specified goal that ascribes to the fundamental engineering activity criteria of safety, efficiency, cost-effectiveness and standards. The focus of this research is mechatronics engineering problem solving in different contexts along such a practice continuum, the aim being to understand the navigation of disciplinary boundaries (specifically mathematics, physics and 'logic'). To be able to look at the problem-solving process from a knowledge perspective and which manifests in and around a particular artefact, the literature reveals that there are several components in a 'problem-solving situation' that require consideration:

- The Problem Solver
- The Problem Structure
- The Problem-solving Process
- The Problem Environment

Simon's (1996) inner-outer distinction - in conjunction with the 'problem-solving situation' components detailed in chapter 2 - provides a Knowledge-Practice Environment framework for considering the negotiation of disciplinary boundaries (physics, mathematics and logic) in a particular problem structure (inner environment) which manifests in a particular artefact (problem site) in different outer 'problem environments' inhabited by different problem solvers

[33] http://www.bigbenfacts.co.uk/facts/
[34] http://web.ticino.com/dcorson/watch/
[35] http://www.ebay.com/gds/It-does-not-take-a-year-to-make-a-Rolex-/10000000000017874/g.html
[36] The advent of digital timekeeping, however, implies a very different set of sciences as well as tools.

(figure 4-5). (The KPE schematic provides a methodological starting point for dealing with actual data - to be detailed in chapter 5).

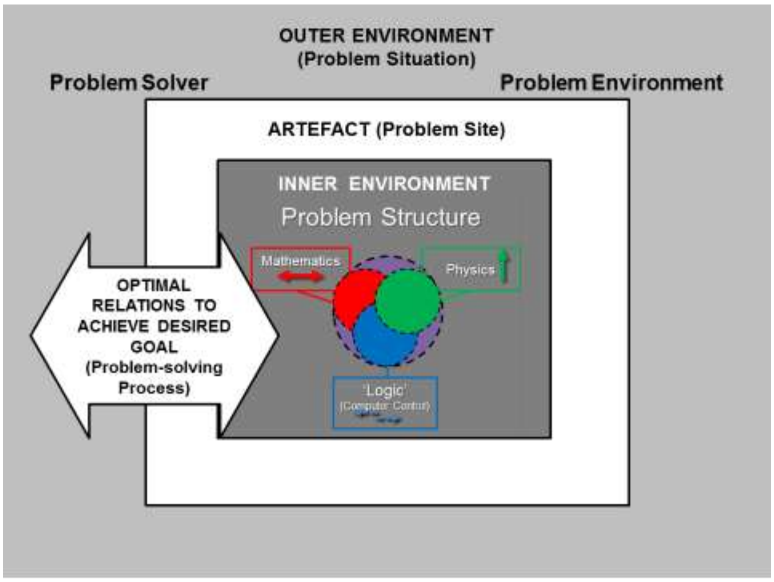


Figure 4-5 The Knowledge-Practice Environment
a modification of Simon's (1996) Inner/Outer environment

4.4.3 Classification and framing of mechatronics KPEs

The implications of the inner/outer components of the problem-solving situation cannot be underestimated. In order to establish a meaningful framework through which to analyse problem-solving processes, the range of outer environments in which such practices occur requires conceptual refinement. Bernstein's concepts of classification and framing - in conjunction with the elaborated Knowledge-Practice Environment framework - provide a 'language' to classify the three significantly different mechatronics engineering environments previously described.

'Classification' in a social realist sense is the *demarcation of boundaries* between entities such that those entities clearly announce their identity – they have distinctive features, names, principles and processes that would not be confused with those of a different entity. When they stand in isolation, clearly separated from other entities, they are said to be strongly classified (C+). Where there are distinct boundaries between specific production processes, for example, with respect to the space allocated to the processes and the role of specific stakeholders, these spaces and stakeholder relations could be termed 'strongly classified': C+. In contrast, where a process or sets of equipment could be/are set up in any space, the boundaries with regard to space allocation would be weakly classified: C–. Similarly, if there are greater stakeholder relations across functional/departmental boundaries (or these do not exist), stakeholder relations could be said to be weakly classified (C–) as opposed to the strong classification of hierarchical organisational structures with dedicated departments. The same principle could be applied to 'time'. Where processes are run at specific times, or in demarcated cycles or shifts, 'time' could be seen as strongly classified (C+). Where there is greater flexibility with regard to the duration of processes and activities (within a broader 'productivity-orientated' time framework, naturally), time is weakly classified (C–). In all these cases, there are KPEs with mixed classification strengths, usually in smaller/medium-sized[37] industries with cyclical/project-based work ($C^{+/-}$).

The following is a simple 'classification' language for a first level differentiation of the different mechatronics engineering KPEs to be explored in this research:

Table 4-1 Classification of KPEs

Classification	**C+**	**C+/-**	**C–**
Space	Clearly allocated areas for specific, dedicated equipment/processes; visible boundaries between these areas	Preferred areas for dedicated processes, but changed to accommodate seasonal or cyclical requirements	Activities can effectively take place in any area
Stakeholder relations	Visible organisational hierarchy; clearly defined roles; departmental structure	Clearly defined roles, but periods of 'integrated' team/ project work	No fixed 'departmental structure'; team/project orientated approach to stakeholder relations
Time	Dedicated continuous process cycles; shift-orientated; staff clock-in/out systems	**Batch manufacturing**: dedicated process cycle (differs between batches) **Project work**: specific timelines & phase deadlines, but flexibility within phases	Broad timelines and deadlines established, but discrete phases at discretion of practitioner/ team; Flexible working hours
Examples	*1)Multinational corporations (automotive; steel; mining; beverage)* *2) Parastatals (Energy & communications)*	*1) Batch manufacturing SMEs* *2) Machine builders* *3) Systems integrators (SMEs)*	*1) R&D prototyping (Micro/Very small)* *2) Specialist device development & maintenance (Micro/Very small)* *3) System's integrators (Micro)*

A second conceptual tool to assist in defining the problem-solving contexts is the concept of 'framing', which is about *how* who controls *what* across five sites: Selection, Sequence, Pace, Criteria, and Control over the social base which facilitates transmission of knowledge (Bernstein, 2000). Taken out of the pedagogic arena, the issues of *pace*, *criteria* and *control* are applicable to most sites of sociocultural practice. Who determines or what drives the 'pace' of an activity? What are the criteria for efficient or effective work? 'Control', in the Bernsteinian sense, is about the Social Order, the underlying 'Regulative Discourse' which determines the rules of conduct in a given environment (Bernstein, 2000). When these are determined by external agents or systems, then such framing would be termed 'strong' (F+). In contrast, when there is a degree of freedom in the pace of work and the criteria for measuring success are

[37] Small and Medium Enterprises (SMEs) are defined differently in different sectors and countries, and based on economic and statistical measures. In manufacturing, micro businesses employ <5 people; very small businesses have <20; small businesses have <50; and medium businesses <200 (Mahembe, 2011).

negotiable, such framing would be termed ‘weak’ (F–). Similarly, where there is a visible ‘social order’ and practitioners are expected to behave in certain ways, then framing over ‘control’ is stronger (F+), as opposed to weaker framing (F–) where individuals have greater autonomy and are encouraged to be creative or ‘think outside the box’.

Essentially, framing over all the sites has to do with degrees of autonomy. As a general rule of thumb, the larger the organisation and its number of stakeholders, resources and processes, the lower the degree of personal autonomy is likely to be. In engineering in general, framing over criteria is relatively stronger than in fields not affecting human safety. All engineering processes and products that may physically affect human beings (whether they be workers or customers) are standards- and specifications-driven. The larger the customer-base, the more stringent the specifications and the more detailed and specific the documentation and reporting processes are likely to be. The more detailed these processes, the more likely there is to be a visible chain of command and formalised stakeholder engagement sessions. These, in turn, imply less autonomy with regard to both ‘social’ and ‘discursive’ order.

Table 4-2 Framing of KPEs

External Framing	**Fe+**	**Fe+/-**	**Fe-**
Pace	Production deadlines driven by international/ national interdependencies	Production deadlines driven by clients (cyclical)	Production deadlines driven by choice
Criteria	International specifications & standards-driven	Client specification- & needs-driven	Internal standards-driven
Control	Visible company/industry methodology & worker training in the methodology	Project-cycle control (usually different project managers & external stakeholders)	Relatively autonomous practitioners
Internal Framing	**F^i+**	**F^i+/-**	**F^i-**
Pace	Production deadlines driven by company/ personal work ethic	Production deadlines driven by work flow	Laissez faire/ creativity-driven
Criteria	Value-driven	Value/innovation-driven	Laissez faire/ innovation-orientated
Control	Tacit company/industry ethic; training by ‘apprenticeship’ or induction	Project-based (changing teams), and internal stakeholder-ethic–driven	Laissez faire/ individualistic

Table 4-2 provides a basic ‘framing’ classification system with respect to pace, criteria and control over the social order. Strong framing, in engineering practice, may generally be seen as referring to externally dictated and visible (or transparent) control measures, determined by international/professional codes and regulations. There are, however, sites of practice where, as in the concept of the ‘hidden curriculum’ in education, the Regulative Discourse is tacit - an expectation of certain ‘ways of being’ – and this framing can be as strong as that of the externally determined protocols. In order to differentiate between framing types and strengths where relevant, F^e is used to refer to externally-dictated framing (as in specification/rule-bound), and F^i refers to framing over practices determined by an 'internal' code (for example, a particular company ethos). The internal code may well match that dictated by external stakeholders or regulatory bodies, but it may also reflect an entirely different set of values or priorities.

The different classification and framing strengths have implications for 'goal attainment'. In other words, the KPE configuration determines conditions with regard to stakeholder relations, reporting lines and procedures, levels of autonomy, forms of written and verbal discourse, and access to the tools and resources required to engage in effective practice. The usual delineation of practice environments is according to type and size of business. The Small and Medium Enterprise (SME) definition in South Africa categorises businesses according to economic and statistical features (Mahembe, 2011). It will be noted that the classification and framing (external) models presented suggest a 'scale' continuum which is comparable to the SME and large company definitions. The strongly classified (C+) and externally framed (F^e+) category would generally be applicable to large industries (with a staff complement of >200), in which the nature of work is fairly stable and consistent. The mixed category (C+/- and F^e+/-) typically represents SME businesses where the nature of work is cyclical, project-based or dynamic. The weakly classified (C–) and externally framed (F^e–) industries tend to be very small (<20) or micro (<5) businesses, where there may be a greater degree of innovation, development and flexibility[38].

The internal framing (F^i) scale, however, suggests conditions for practice or 'goal attainment' that are less visible. These are often tacit influences that reveal a certain 'basis' (Maton, 2014) for practice. They may be at odds with the visible basis, or the espoused company ethos. I will return to the issue of internal framing in chapter 5. The classification and framing (external) frameworks, in conjunction with the earlier sector descriptions, now allow for a more conceptually refined characterisation of mechatronics engineering KPEs in which problem solving takes place.

4.5 Classification of mechatronics systems

Any controlled electro-mechanical artefact, no matter how complex, is generally regarded as a 'mechatronic system'. There are three types of systems categories roughly aligned to the earlier descriptions of automation levels and device/machine types: Contained, Modular and Distributed. Figure 4-6 presents a summary of key features, which will be elaborated in the following sections.

[38] These are broad generalisations based on an analysis of the predominant features of over 70 mechatronics-related industries in South Africa. It is quite feasible to find a micro business manufacturing standard components in a strongly classified (C+) and strongly externally framed (F^e+) environment.

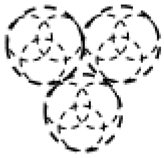
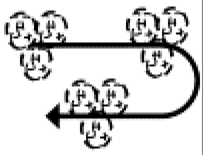
System	Representation	Examples	Industries	Typical C/F
Contained		• Microwave oven • Automated medical device • Vending machine • Access control system	• Tech R&D • Prototyping • Component suppliers	S: C-,Fe- M: $C^{+/-}$,$F^{e+/-}$ L: C^{+},F^{e+}
Modular *(sets of contained-type systems)*		• Production machine • Production sub-system	• Machine Builders • Machine Suppliers • Systems Integrators • Panel Builders	S: $C^{+/-}$,$F^{e+/-}$ M: $C^{+/-}$,$F^{e+/-}$ L: C^{+},F^{e+}
Distributed *(sets of modular systems)*		• Production line • Manufacturing plant • Factory	• Manufacturing • Packaging • Food & beverage processing	S: C^{+},F^{e+} M: C^{+},F^{e+} L: C^{+},F^{e+}

Figure 4-6 Mechatronics systems categories

The features of the different mechatronic systems categories are drawn from my personal exposure to over 70 industrial sites, and have been verified by a mechatronics engineering expert (Hoffman, 2011). These are not defined as categories in any formal texts on mechatronics systems 'types'. Most texts on mechatronic systems focus on discrete 'disciplinary regions' (such as the oft-cited 'mechanical', 'electrical', and 'control' distinctions), individual systems components or process types, or systems architecture from a mathematical, logic and modelling/simulation perspective. There is a fair amount of literature on closed/open or static/dynamic systems, but, to the best of my knowledge, there is no formal characterisation that defines the different systems types in relation to Knowledge-Practice Environments (KPEs).

The broad principle behind the categorisation is the concept of a unit of the physics-mathematics-logic relations (illustrated as the single Venn diagram in figure 4-6) which constitutes a 'contained system'. The next level is a set of such units which constitute a 'modular system'. The third level is represented as a set of 'modular systems' that constitute a 'distributed system'. This representation in itself enables a view of the distance between the base unit disciplinary relations in the context of increasingly complex constellations of units and sets.

4.5.1 Contained Systems

The term 'contained' here refers to the discrete devices or single-function stand-alone machines described in section 4.3.3. These are the most recognisable mechatronics devices to the general public, including automated tellers, vending machines and microwave ovens (figure 4-7).

Figure 4-7 Contained Systems examples[39]

The focus of Contained Systems work is usually around the combination of electronics-type components set in relation to other electro-mechanical components so that energy is managed appropriately, and that signals are sent/received – usually via a microcontroller – which will enable a discrete, contained outer system to function. Mechatronics practitioners can be involved across all stages of the conception, design, manufacturing, maintenance and operation of such devices. The conception, design and prototyping, however, would usually be undertaken in a specific 'new product development' environment. This may be a separate R&D prototyping company, or a dedicated R&D department of a larger organisation. Where such devices are produced in larger quantities, then this would occur in a standard manufacturing environment (which may consist of elements of the following two categories, namely Modular and Distributed Systems). The operation of such devices is usually the public or specific personnel (such as doctors or nurses in the case of medical devices). Where the focus is the maintenance of such devices, this is usually undertaken by technicians who are employed by the device supplier. Typical distinguishing features of the Contained Systems KPE in the R&D prototyping sector are captured in table 4-3. The nature of 'prototyping' developmental work is such that it is better facilitated in more flexible environments, such as small design studios or spaces where independence and informal cross-pollination is encouraged. Development in such environments is strongly supported by access to the *reservoir* of available local and international expertise on the Internet. These environments

[39] Image credits: All images labelled for non-commercial reuse.
https://www.flickr.com/photos/timtimes/7943826816
http://benefitof.net/6-major-benefits-of-atm-banking/
https://en.wikipedia.org/wiki/Pharmacy_automation#/media/File:Kirby_Lester_KL60_fully-automated_dispensing_system.jpg
https://en.wikipedia.org/wiki/Vending_machine#/media/File:Snack_machine_3538.JPG
https://commons.wikimedia.org/wiki/File:Microwave_oven_(interior).jpg
http://www.medicalexpo.com/prod/alere/product-67555-600929.html
https://en.wikipedia.org/wiki/Roomba#/media/File:Roomba_original.jpg
https://en.wikipedia.org/wiki/Lego_Mindstorms_EV3#/media/File:Lego_Mindstorms_EV3_brick.jpg

tend to be less strongly classified (C–), and allow for weaker external framing on procedures (F^{e-}). External framing over criteria would tend to be strong with regard to component specific standards, but weaker in relation to a new product for which there may not necessarily yet be a specific standard. There would, however, be standards applicable to the purpose of the device and the environment in which it is to operate.

Table 4-3 Classification & framing: Contained Systems

Knowledge area focus			Primarily 'electronics' orientated (with a more acute degree of mathematics and physics) and the specific programming language of the controller, usually a microcontroller
Business size category			Micro – Very small (<20) (Unless part of larger company in-house development)
Classification	Space	C–	Smaller spaces, 'hubs' or offices; very often open-plan and team work stations
	Stakeholder relations	C–	More lateral, individual to small teams; often informal, verbal and frequent communication between team members
	Time	C–	Small-project orientated work cycles; new/changing project briefs; broad deliverable deadlines established, but flexible activity duration
Framing (external)	Pace	$F^{e+/-}$	Dependent on interdependencies
	Criteria	$F^{e+/-}$	Dependent on type of product (medical, chemical, automotive = F^{e+})
	Control	$F^{e+/-}$	Dependent on type of product and nature of company

4.5.2 Modular systems: Machine builders

The focus of practice in a Modular Systems context is twofold. On the one hand, there is the conception, design, manufacture and installation of production machines which fulfil a specific process activity, such as a labelling machine. The purpose of these machines is to be used in semi- or fully-automated environments.

Figure 4-8 Modular Systems examples[40]

Such machines (figure 4-8) could consist of a single integrated unit or several modular units in relation to each other. Several sub-systems or modules may be linked together in a

[40] Image credits: All images labelled for non-commercial reuse.
www.festo-didactic.com
http://www.engr.wisc.edu/isye/isye-research-manufacturing-and-production-systems.html

particular machine to fulfil a sequence of processes (in bottling, for example, a machine can consist of different modules to pick up, fill, cap and move the bottles along a conveyor). A different sub-system or set of modular units would be responsible for collection, washing and breakage control of the bottles. Machine builders are responsible for the production of such units and modular sub-systems, for an ever-changing client base.

Modular Systems may have one or more control devices, usually a programmable logic controller, and these are connected via an electronic data network. The design, manufacture and installation of such Modular Systems usually occur in different sites. Machine builders generally have a particular machine-type specialisation, and the areas in which the construction of such a machine takes place can vary considerably. Generally, there are large open factory spaces with components and manufacturing machinery arranged around the periphery of a particular machine-building area. This suggests a relatively strong classification of the space in which the 'building' occurs (C+). However, the machines are usually custom built, and each machine may have different dimensions or additional modules, requiring greater flexibility in spatial allocation. Machine production is cyclical, with clear beginning and end stages. Thus one sees changes in the way space is utilised and allocated across a project cycle, and between different machine-building projects (C–). Similarly, different stakeholders are involved at different stages of the machine-building process, and the strength of classification can depend on the nature of the client as well as the organisational structure of the machine-building company. The larger the client organisation and the machine-building company, the more likely the classification of stakeholder roles and forms of communication are to be strong (C+). It is, however, most common to find very small (<20) machine building firms with greater flexibility in spatial use, stakeholder relations and time frames (C–).

Table 4-4 Classification & framing: Modular Systems - Machine Building

Knowledge area focus			Electro-mechanical, PLC programming, client-specific systems and process requirements
Business size category			Very small - Small (<50)
Classification	Space	$C^{+/-}$	Medium to large central 'machine building' spaces; designated team/management offices;
	Stakeholder relations	$C^{+/-}$	Differentiated teams (Design, Manufacturing, Sales, Maintenance); daily/weekly informal and formal verbal briefing; project management documentation
	Time	$C^{+/-}$	Medium-project orientated work cycles; new/changing project briefs; specific phase and deliverable deadlines established, but flexible activity duration during phases
Framing (external)	Pace	$F^{e+/-}$	Dependent on interdependencies
	Criteria	$F^{e+/-}$	Dependent on type of product (medical, chemical, automotive = F^{e+})
	Control	$F^{e+/-}$	Dependent on type of product and nature of company

As in the case of Contained Systems, external framing would tend to be strong with regard to component specific standards, but weaker in relation to a custom-built machine for which there may not necessarily yet be a specific standard[41]. However, there would be purpose- and environment-specific standards. A major factor in machine building is the custom-design process to suit a particular client's needs and specifications. This entails flexibility with regard to design, rapid familiarisation with unfamiliar production environments, and good relationships with external component/part suppliers.

4.5.3 Modular Systems: Systems Integrators

The second Modular Systems category pertains to the work of systems integrators. Here the focus is on integrating the different system modules through a controller (controllers) into an existing system (production line), which may consist of various processes running at various levels of automation. At a simpler level, a systems integrator connects various electro-mechanical and data devices through a controller so as to automate a process or sets of processes via a computer program. Systems integrators are like consultants. They do not work in a specific type of production environment. They can work from home (or anywhere) to set up the control system, but would mainly work at the client's automation site during the physical integration of different modular units (which may either already exist or may have been commissioned from machine builders). Classification of space and stakeholder relations is thus fairly weak from the perspective of the systems integrator, who needs to function across spaces and across personnel (C–). As in the case of machine builders, systems integrators need to be flexible with regard to the design of a solution for a particular client, rapidly familiarise themselves with unfamiliar production environments, and establish good relationships with personnel at the automation site.

Table 4-5 Classification & framing: Modular Systems - Systems Integration

Knowledge area focus			Electro-mechanical, PLC programming, context-specific systems and process requirements
Business size category			Micro - Very small (<20)
Classification	Space	C–	Dependent on environment in which systems are to be integrated; SI can be based at home or in small offices;
	Stakeholder relations	$C^{+/-}$	External/consultant Systems Integrator liaises with the client team (usually differentiated); daily/weekly informal and formal verbal status updates; project management documentation
	Time	$C^{+/-}$	Medium-project orientated work cycles; new/changing project briefs; specific phase and deliverable deadlines established, but flexible activity duration during phases
Framing (external)	Pace	$F^{e+/-}$	Dependent on interdependencies
	Criteria	$F^{e+/-}$	Dependent on type of product (medical, chemical, automotive = F^{e+})
	Control	$F^{e+/-}$	Dependent on type of product and nature of company

[41] The first Automation Standards body was constituted in 2006, following 'a feasibility study, market study, and legal assessment …[which] indicated that a standards conformity program was needed to provide a useful link between automation standards and the products, services, processes and systems that use them' (https://www.isa.org/).

4.5.4 Distributed Systems

In Distributed Systems, the focus is entirely on the production of goods in semi- to fully-automated environments, such as plants and factories which consist of multiple machines and sub-systems (figure 4-9). These may have independent or integrated control 'hubs' which, together, complete a number of processes to produce goods.

Figure 4-9 Distributed Systems examples[42]

Table 4-6 Classification & framing: Distributed Systems

Knowledge area focus			Manufacturing processes (electro-mechanical and user-orientated control); Improvement methodologies (Six Sigma, Lean Manufacturing, World Class Manufacturing)
Business size category			Medium - Large (>100)
Classification	Space	C^+	Large 'plants'; designated management and support staff offices; boardrooms; formal reception areas
	Stakeholder relations	C^+	Clear organisational hierarchy; formal recorded daily, weekly and monthly reports from all staff levels (operators to senior management)
	Time	C^+	On-going continuous, batch or mass production; often 24/7 and shift work
Framing (external)	Pace	$F^{e+/-}$	Dependent on interdependencies, but tends towards F^{e+}
	Criteria	$F^{e+/-}$	Dependent on type of product (medical, chemical, automotive = F^{e+})
	Control	$F^{e+/-}$	Dependent on type of product and nature of company, but tends towards F^{e+}

Overall 'process control' is the key objective, with the end goal being to produce goods safely, efficiently, cost-effectively, and to specification. Mechatronics practitioners in these environments are largely concerned with the maintenance and improvement of existing systems and processes. Continuous Improvement Processes (CIP) is a relatively standard methodology. In such environments, the classification of space, stakeholder relations and time is almost always stronger than in the previous systems contexts (C+). These environments tend to be more formal, and require more stringent documentation and communication processes. As such, external framing would be strong (F^{e+}).

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[42] Image credits: All images labelled for non-commercial reuse.
https://en.wikipedia.org/wiki/Industrial_control_system#/media/File:NIST_Industrial_Control_Security_Testbed.jpg
https://upload.wikimedia.org/wikipedia/commons/0/06/Graaff_Fruit-Ceres_packing.jpg
www.automatrixinc.com
http://www.siemens.com/

4.5.5 Implications of KPE and systems differences

Mechatronics engineering practitioners find themselves working in all these KPEs, in roles ranging from design to manufacturing, maintenance or simple operation. Although the previously detailed systems have focused specifically on manufacturing environments and automation devices, there are significant numbers of mechatronics engineering practitioners working in a broader range of 'control' environments, from those which may be classified as 'electronics engineering' to 'systems engineering'. These include the marine, aviation, military, medical and energy sectors.

The contextual KPE differences, described by Simon (1996) as the 'outer environment' of a particular artefact with a set of 'inner environment' features, I suggest, may have a significant effect on problem-solving practices. At the heart of each of the mechatronics systems types lies a particular confluence of mathematical, physical and engineering science knowledge (the 'inner' aspect of Simon's model). The relationship between these forms of knowledge are made more complex by different levels of disciplinary stability. The structural and behavioural aspects of the different systems artefacts may be relatively stably described in traditional engineering disciplinary terms as needing to function according to well established laws of physics (motion, gravity, energy-conservation, thermodynamics, electrostatic, and so on) and mathematical relations. However, their interdependence in order to facilitate an automated process is established via a 'control system', which is a relational and instructional 'language' not bound merely by the laws of the natural and mathematical sciences.

4.6 'Logic' control systems

I have already suggested that the languages of 'control' in this region draw on the earlier mentioned features of the Trivium: grammar, logic and rhetoric, and that this form of knowledge differs significantly from the organising principles underpinning mathematics and physics (Wolff & Luckett, 2013). The 'control logic' of emerging technologies is a dynamic, fluid and highly context-dependent form of knowledge, which is in contrast to the stable physics and mathematics forms of knowledge accepted as legitimate in the region. In as much as we have established the complexity of the 'outer environment' and suggested this has implications for practice, 'control logic' is a dynamic *inner* environment form of knowledge which may have similar implications for problem-solving practice. For this reason, a brief overview is necessary of the nature of control systems in mechatronics engineering KPEs. The intention is to demonstrate the different forms of meaning-making encountered by practitioners in the field, and to be cognisant of the potential impact of engagement with different forms of representation as dictated by different problem-solving contexts.

4.6.1 Control systems

The *design* of control systems is governed by: the physics laws (mainly voltage regulation) of wired (electrical) and wireless (electromagnetic) signals; the mathematical algorithms behind the frequency and patterns of on/off signals (voltage regulation); and the layers of different kinds of logic determining where the on/off signals (messages) are sent and how they are interpreted. Understanding these design principles scientifically ***does not necessarily*** contribute to the end-user's application of the system (the mechatronics engineering practitioner), as the logic of the communication possibilities of any given component or sub-system is largely dependent on decisions made by the original design team. These 'decisions' manifest as communication protocols (rules). Some protocols have a 'governing body', and a large user support network in online environments. With the exponential development in computing efficiency (largely driven by physics-based discoveries), components and sub-systems are continually evolving to include, for example, additional functionality. This can mean changes to structure and function, and usually means that specifications for such component/sub-system-use are revised. End-users thus need to keep up to date with the latest required protocol/control system documentation, available as user manuals. But often, the associated documentation for particular devices or components is ambiguous, out of date, sometimes contradictory, or may even be difficult to understand (Briand, 2003).

The control system sector is highly competitive given the rapid development of automation technologies. A phenomenon in developing countries is the local development of context-specific automation solutions (Manufacturing the future, 2012). The licenced software that accompanies the high-end and costly automation technologies (mainly of USA and German origin) may be prohibitive to the small manufacturer. As such, the past decade in South Africa has seen a shift to investigating cheaper alternatives and developing local solutions. A number of HE engineering faculties are actively engaged in research and development in conjunction with industrial, and even international, partners.

4.6.2 Programmable Logic Controllers

The primary form of systems control used by mechatronics practitioners is called a PLC (a Programmable Logic Controller). They look like little boxes (figure 4-10 left) with dozens of 'slots' (electrical terminals) into which various components (like sensors, actuators and other control items) are connected by various wires. These 'boxes' are about the size of a lunch box. Several may be connected to each other in a 'rack' (figure 4-10 middle) for more complex tasks. They are mounted on panels inside wardrobe-sized cabinets (figure 4-10 right), and can control a single machine or an entire factory. There are many PLC makes, and all generally can be used to control *any* process.

		
Single PLC	*PLC module rack*	*Control panel with multiple PLC modules*

Figure 4-10 Programmable Logic Controllers (PLCs)[43]

Inside the PLC there is an 'embedded system'[44] – electronic circuitry and microcontrollers which function like a computer (but which the programmers do not see). An external computer is connected to a PLC (initially) to send instructions to each of the terminals (inputs and outputs). The programmer 'connects' each input component (like sensors) and output component (for example a switch or a motor) in the programming environment. This is all 'virtual'. S/he specifies *what* is connected to *what*, what actions need to occur, the duration and sequence of actions, and process stages. (It is very much like writing a movie script, without the real actors being cast yet). The programming can all be done initially without actually wiring the physical input and output components to the PLC, or without being anywhere near the automation site. The program is created in a simulated environment, and the program elements look nothing like the real physical artefacts. When the programmer is satisfied that the instructions and processes are as desired, the program is stored on the PLC and the external computer is disconnected. The programmer or a systems integrator will then connect the actual PLC (which now has its program on board) to the physical system that is being automated by way of wires from the components to the input/output 'slots' on the PLC 'box'. If there are problems in the connected system, the PLC may be reconnected to the external computer so as to find the problem, or change settings.

PLC manufacturers are keen to build brand loyalty, and it has become a very competitive field. Most well-known manufacturers sell PLCs with proprietary software. This means the PLC has very specific programming software which is licenced. Users are generally reliant on these manufacturers for after-sales service, software troubleshooting and upgrades. There are

[43] www.siemens.com/; www.festo-didactic.com

[44] Mechatronics practitioners – particularly in Contained Systems environments – also work with small-scale controllers (microcontrollers), which are in fact 'embedded systems'. The major difference between working with PLCs and embedded systems is scale and forms of integration. While PLCs are stand-alone devices intended for larger scale industrial applications and can handle industrial environments, embedded systems are integrated into an electronic circuit, are more sensitive to environmental conditions, and on their own are generally suitable for smaller applications.

dedicated online or 'registered customer' user-fora which carry all the manuals, datasheets and help files. Many of these PLCs and the licenced software are very expensive, and prohibitive to the smaller manufacturer who wishes to automate a process. Practitioners working with PLCs are very dependent on access to information resources, the majority of which are available on the Internet. The working environment thus needs to guarantee reliable Internet access. There are several sectors in which Internet access is prohibited or restricted, as internal processes may be affected by hackers or viruses. Cybersecurity is a major issue where companies are concerned about protecting their Intellectual Property. The implications for practice are that practitioners may be limited to the officially supplied user/data documentation, which is not necessarily always up to date as changes to new technologies are fairly rapid.

Then we have manufacturers who have an 'open' PLC ethic: Buy the PLC and the software is free, or open, or the PLC can make use of existing compatible open source software. In this case, the user is reliant on other forms of software troubleshooting support (most commonly, an open user forum). The implications for the open PLC practitioner are that s/he is reliant on the *reservoir* of expertise, accessible via the Internet, and that there are no dedicated software experts. A major challenge is compatibility between different components and programming environments. One of the most frequent problems to occur is a manufacturer claiming compatibility with certain software or hardware, but this being applicable to a specific version or a specific feature. Very often, such details are in the fine print of the supplied documentation, which can run up to hundreds of pages.

4.6.3 PLC programming languages

Given rapid and dynamic changes in the broader ICT field, the International Electrotechnical Commission (IEC) established a standard for PLC programming languages in 1993. There are five types of PLC programming languages (figure 4-11), several of which may be used in conjunction in one environment. Most PLCs are able to support a number of the languages. The choice of language(s) depends on the hardware itself, the nature of the process that is to be controlled, 'ease of maintenance by the final user' (Thayer, 2009) and the context (such as universality, affordability of the hardware, and programmer comfort). PLC programming languages are graphic, alphanumeric symbolic systems. The programming language is the *invisible* layer behind the functioning of a physical, automated system. The examples are merely intended to give the reader a sense of what such programming environments and languages look like. They differ significantly from structurally representative mechanical engineering drawings, as well as from the relationally representative electrical engineering schematic diagrams.

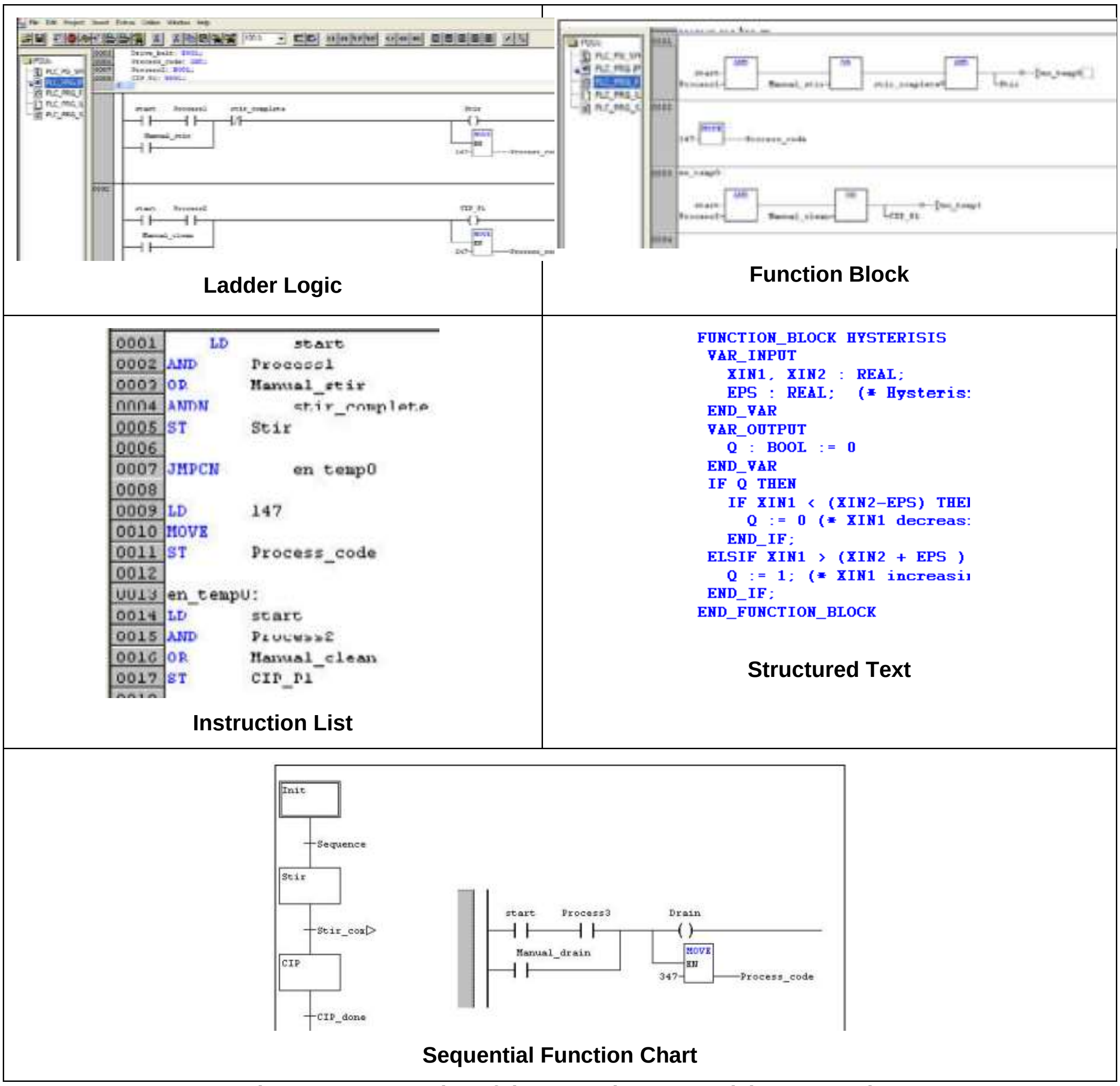


Figure 4-11 Examples of the 5 PLC languages (Thayer, 2009)

The intention with the preceding summary of features is to demonstrate that the different mechatronics ‘regional’ disciplines function at different levels in relation to reality. Mechanical engineering artefacts are visible structures, and the form of representation illustrates this (figure 4-12). Electrical engineering is a process of powering a system at a relational level. Computer engineering is the layer of invisible control behind the visible system. ‘Shifting between these fundamentally different representations requires conceptual grasp of the form of representation appropriate to a specific context’ (Wolff, 2013, p. 91).

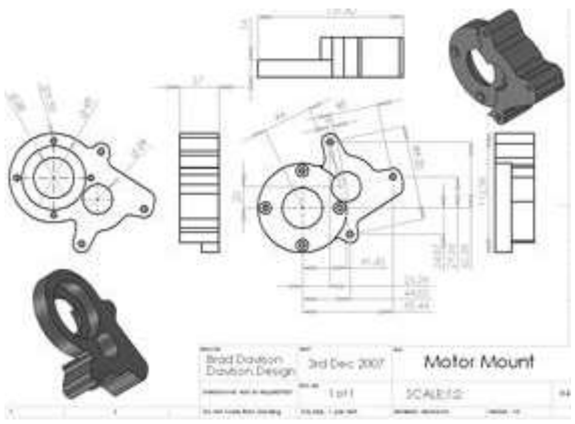
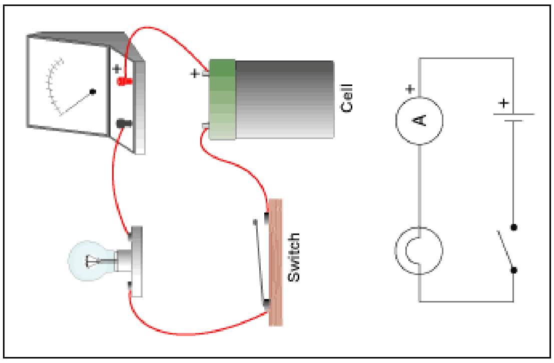
	• Mechanical engineering A mechanical engineering drawing structurally and dimensionally represents a physical artefact. In other words, there is a direct relationship between the object and its representation. The lines represent structural boundaries.
	• Electrical engineering An electrical diagram uses standardised symbols to represent objects and illustrates the connections between these objects and the flow of electrical current. The lines are actual physical wires. One only has to learn what the various symbols represent to be able to map the diagram onto the physical system.

Figure 4-12 Mechanical and electrical diagrams[45]

4.7 Conclusion

In summary, this chapter has presented a conceptualised contextual framework for considering problem-solving practices in a range of industrial sites. Practitioner forms of engagement occur in three types of Knowledge-Practice Environments (KPEs): Contained, Modular and Distributed Systems. These three systems are characterised by both scale and purpose. Using the Bernsteinian concepts of classification and framing, a language was developed to characterise the nature of space, stakeholder engagement, time, pace, criteria and control (in the sense of social order) in the three KPEs. These differences highlight the potential affordances and constraints that may impact on knowledge practices in the different environments. The chapter concluded with a description of the forms of computer control in the research region, so as to highlight not only the different forms of disciplinary knowledge and their semiotic representations, but also the levels at which the different disciplines function in relation to physical reality.

[45] Motor mount drawing: www.davisondesign.co.nz; Simple circuit: www.curriculum.edu.nz

CHAPTER 5: RESEARCH METHODOLOGY

5.1 Introduction to the methodological approach

The empirical focus of this research is multidisciplinary engineering problem-solving practice, as demonstrated by novice practitioners in the field of mechatronics engineering in South African industrial sites. The purpose of the research is to understand the nature of and relationship between different engineering disciplines in a number of comparable problem-solving processes undertaken by different practitioners. The research wishes to illuminate patterns of disciplinary boundary negotiation during problem solving in the context of different Knowledge-Practice Environments (KPEs). It is believed that such an analysis could inform improved design of engineering curricula and pedagogic practice so as to align with the needs of the profession, particularly for qualifications at the level of Diploma.

The research is essentially located in an intersection between two disciplinary 'regions': engineering and sociology. This location has had a profound effect on the methodological choices. To a large extent, the research process has both mimicked the practices of the research focal region (solve the problem 'strategically') as well as been cast in the light of the research question itself (figure 5-1):

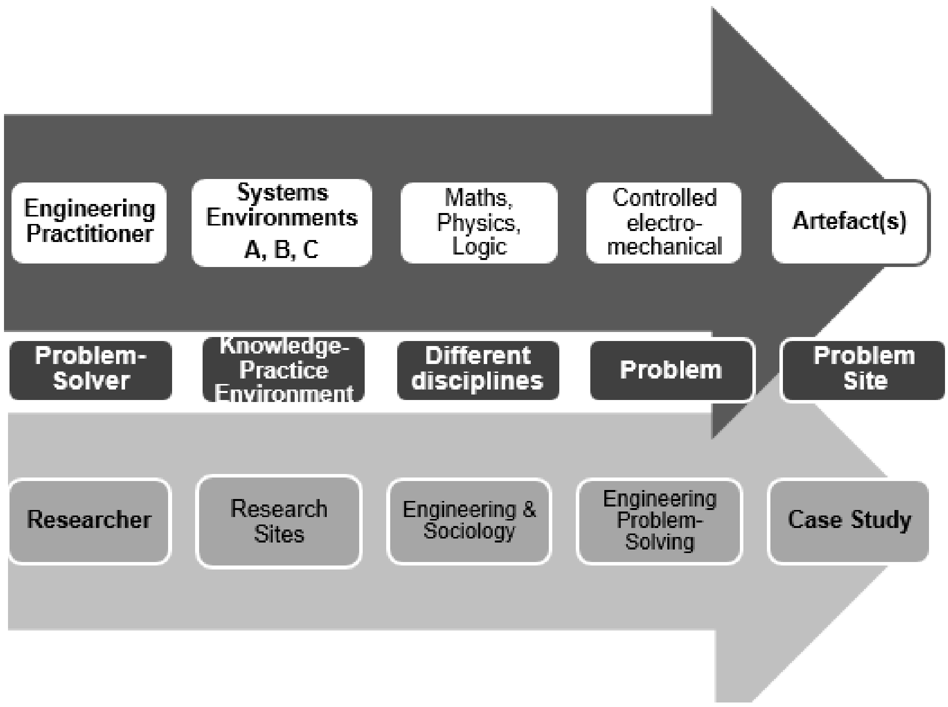


Figure 5-1 Research question & research process parallels

In trying to understand how engineering problem solvers in particular environments move between different disciplines as they attempt to find an optimal solution to a problem that manifests in a particular artefact, I - as researcher – become a problem solver in particular environments, moving between different 'disciplines' (engineering and sociological concepts) in attempting to understand (find an explanation) a problem (participants' problem-solving processes) that manifests in a particular artefact (case study). My location and perspective in relation to the research focus suggests its own forms of disciplinary boundary negotiation. This has a number of methodological implications. The intention in this chapter is to present a methodologically-detailed framework situated within an overall research design, and to describe and motivate choices, methods, tools and strategies for addressing the central research question.

5.2 Coherent methodological pluralism

In attempting to establish a coherent 'epistemologically and methodologically congruent standard' (Caelli, Ray, & Mill, 2003, p. 9) through which to engage in the research process required for this particular project, a number of important factors need to be clarified: 'researcher position', 'congruence between methodology and method, a clear articulation of the researcher's approach to rigor, and an explanation of his or her analytic lens' (*ibid*.). I shall briefly elaborate on the first three of these factors in two sub-sections before introducing the research design framework and the range of analytical lenses.

5.2.1 Researcher position in relation to methodology

My position as an initial outsider to the field of research was established in section 4.2.1. The not-entirely circumstantial simultaneous exposure to Bernsteinian theoretical tools led to an iterative inductive-deductive research approach over the subsequent years and on various research projects dedicated to understanding the nature of knowledge in multidisciplinary engineering knowledge practice. Inductively, I sought patterns in knowledge-practice data, and attempted to conceptualise these within a framework that could explain such patterns. I alternated with a deductive approach – based on significant quantitative performance data – testing the hypothesis that the empirically verifiable organising principles of different engineering disciplines required significantly different ways of thinking. The inductive-deductive relationship in itself epitomises the straddling of approaches to research in the social sciences.

My own tertiary education 'disciplinary socialization' (Caelli, Ray, & Mill, 2003, p. 5) occurred within the context of the Humanities - initially English Literature and the Performing Arts, and subsequently Education – all fields which value constructivist, interpretativist, rich ethnographic and/or phenomenographic approaches in qualitative research. However, my formal employment in an engineering education environment and initial engagement with research participants in industrial sites demanded a significant shift not only in communication strategies, but also in the selection of analytical tools which could more usefully be translated back into the field of enquiry for the purpose of engineering staff development. In other words, I needed to find ways to research engineering practice that did not alienate practitioners or engineering educators. The reality of the field of research is that it has distinctive discursive practices (Wolff, 2013). The engineering practitioners and educators with whom I have worked over the years understand pictures, formulae and datasheets. Bernstein's initial conceptualisations, which evolved into the now highly productive field of LCT, offered the ideal tools of translation – sets of practical, visually-accessible, schematic conceptualisations of practice. And it was through the use of these tools (and theories) on numerous research and educational projects that I began to understand the engineering disciplines and related practices.

5.2.2 Overall methodological approach

The pragmatic shift to engineering ways of meaning-making stretches to an engineering take on the overall methodological approach: How do I solve my problem safely, efficiently, effectively and according to specifications? This 'engineering-speak' translates comfortably into sociological approaches to methodology. To rephrase the question: How do I answer the research question ethically, strategically, empirically- and theoretically-soundly, and with validity? As in the case of the engineer, the problem needs to be solved 'pragmatically'[46] – an approach which 'enables researchers to be flexible in their investigative techniques' (Onwuegbuzie & Leech, 2005, p. 383). The Knowledge-Practice Environment (KPE) framework developed in chapters 2 and 4 suggests not only multiple layers, but also elements which individually need to be approached from necessarily different perspectives. Methodological pluralism in this research project is, therefore, unavoidable. As in the case of the engineering endeavour, however, the methods in each of the research question components cannot afford to be gratuitous, given the complexity suggested by the research question 'system'. I believe a strategic synthesis of different approaches can best address the question of how practitioners negotiate disciplinary boundaries in engineering problem-solving practice.

My theoretical position is unambiguously that of a social realist: I entered this research project with observations of and questions about the uninterrogated and seemingly symbiotic (or even 'causal') relationship between forms of knowledge in practice by different practitioners in different mechatronics engineering contexts. Though the starting point may appear fairly deductive - that 'knowledge is emergent from but irreducible to' (Maton & Moore, 2010, p. 5) its contexts of practice and has analytically verifiable structural and structuring properties - the research process has employed a number of methodological approaches that could be seen

[46] The research acknowledges the multiple definitions of Pragmatism as a philosophy, but intends the use of the word in the context of 'practically relevant' (www.pragmatism.org).

to have inductively aided the development of a layered and rigorous methodology. Since no two problem-solving cases are the same, the primary choice of method is that of the case-study – an approach which emphasizes 'the rich, real-world context in which the phenomena occur' (Eisenhardt & Graebner, 2007, p. 25). The logics of the two approaches suggest they are 'mirrors of one another, with inductive theory building from cases producing new theory from data and deductive theory testing completing the cycle by using data to test theory' (*ibid*.). This research does not seek to produce 'new theory'. Rather, it utilises existing theoretical lenses, and develops the possibilities of theoretical tool application (in a manner as yet untried) to examine the phenomenon of engineering problem solving from the perspective of disciplinary boundary crossing. With the 'case-study' approach being 'incapable of providing tested generalizations' (Allen, 1966, p. 73), this research adopts a 'matched-case' approach - a 'research strategy employed by experimental psychologists in the study of human problem-solving behaviour' (*ibid.).* Case studies are initially grouped into three categories so as to elicit comparable or differentiated patterns of problem solving. In order to meaningfully come to any conclusions that may speak to engineering problem-solving practices beyond a particular case, or even sets of comparable cases, a number of 'mixed-methods' strategies have been employed to gather, compare and analyse data.

There are 'five broad purposes of mixed methodological studies' described by Greene, Caracelli and Graham (1989) in (Onwuegbuzie & Leech, 2005, p. 384). The five purposes, listed (and clarified) below, have contributed to the overall research design to be presented in the following sections of this chapter:

- **Triangulation**: the purpose of triangulation is to seek 'convergence and corroboration' (*ibid*.) via different methods. In this study, the element of triangulation manifests as that *within* each case study by drawing on different forms of data gathered in different ways around the same question, as well as *between* different case studies in 'matched case' sets.
- **Complementarity**: this is the process of enhancing, illustrating and clarifying 'results from one method with the results from the other method' (*ibid*.). Essentially, this strategy was employed by using both the methods of surveying and semi-structured interviews.
- **Development**: the use of the results of method A to inform method B. In this research, the results of a pilot survey led to the development of the interview strategy; furthermore, the results of the first pilot study interviews informed a refined data collection process.
- **Initiation**: 'discovering paradoxes and contradictions that lead to a re-framing of the research question' (*ibid*.). The observation of the impact of the different problem-

solving contexts explored during the pilot study led to a re-shaping of aspects of the central research question with respect to analytical lenses.

- **Expansion**: the need 'to expand the breadth and range of inquiry by using different methods' (*ibid.*). This is essentially the methodologically pluralist endeavour, which seeks to illustrate the problem to be answered in the richest possible manner.

The objective of including the full range of mixed methods purposes listed above has been to enable the most rigorous possible research process, which offers 'the best opportunities for answering important research questions' (Johnson & Onwuegbuzie, 2004, p. 16). This implies a range of 'tools, techniques, or procedures used to gather the evidence' (Onwuegbuzie & Leech, 2005, p. 6). The following research design will detail the sources and methods of data collection in the various research sites, and elaborate on the specific analytic lenses brought to bear in engaging with the data (Onwuegbuzie & Leech, 2005). Limitations of the study will be detailed in relation to research sites, participants, data selection and analysis methods. The chapter will conclude with a section on measures to ensure validity of the study, and the possible challenges.

5.3 Research design

The research design employs a metaphor drawn from the empirical site – that of an integrated modular system. As detailed in chapter 4, a modular system is one consisting of several sub-systems (combinations of components), which - when integrated effectively – fulfil a specific production purpose. The 'production purpose' in this research is to produce 'patterns of problem solving' that illuminate disciplinary boundary crossing, code shifting and code clashing when different practitioners draw on the three core disciplines (mathematics, physics and logic) to solve problems in different KPEs. My role as researcher is that of a 'systems integrator'.

5.3.1 An integrated modular research system

The base metaphorical 'component' of the research design 'modular system' is *the case study*. Each case study represents a Problem Situation in which a Problem Solver in a particular Problem Environment undertakes a Problem-solving Process in relation to a Problem Site (an artefact) so as to achieve a desired goal. Together (figure 5-2), these components represent the case-study Knowledge-Practice Environment (KPE), at the heart of which is the actual Problem Structure characterised by a relationship between mathematics, physics and logic.

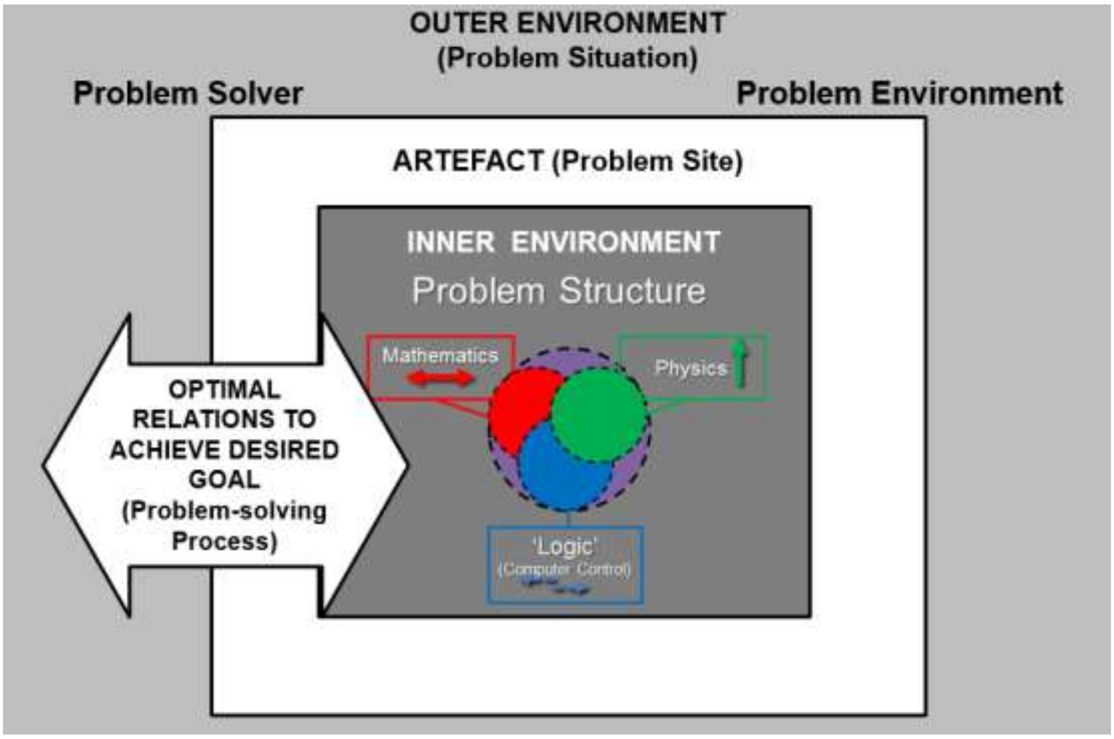


Figure 5-2 Case-study KPE features: Research design 'component'

A 'modular system' cannot function at the 'component level'. So, a single case study will not answer the research question. Different components make up a sub-system, which fulfils a specific function in the modular system as a whole. A useful analogy, again, is a modular 'bottling system', where one sub-system washes the bottles, another fills them with liquid, and a third sub-system caps the bottles. Together, however, they produce a beverage. In this research, the sub-system is the different mechatronics engineering KPE categories that were identified in chapter 4: A – Contained Systems; B – Modular Systems; and C – Distributed Systems. Each category, by virtue of the KPE similarities for participants in such a category, offers the opportunity to 'produce' problem-solving patterns that may legitimately be compared to each other, and could potentially 'produce' a sub-system pattern. Four case studies have been selected in each of these categories (imagine that each sub-system has four components). Three of each set of four category case studies are drawn from exactly the same KPE in A and C (in other words, three practitioners working at the same company, but on three different problems). A fourth case study from the same KPE category, but a different company of a different scale, has been selected as a comparison. In KPE category B, two machine builders and two systems integrators have been selected, each from a different company or organisation.

Together, the twelve selected case studies constitute the research 'modular system' (figure 5-3).

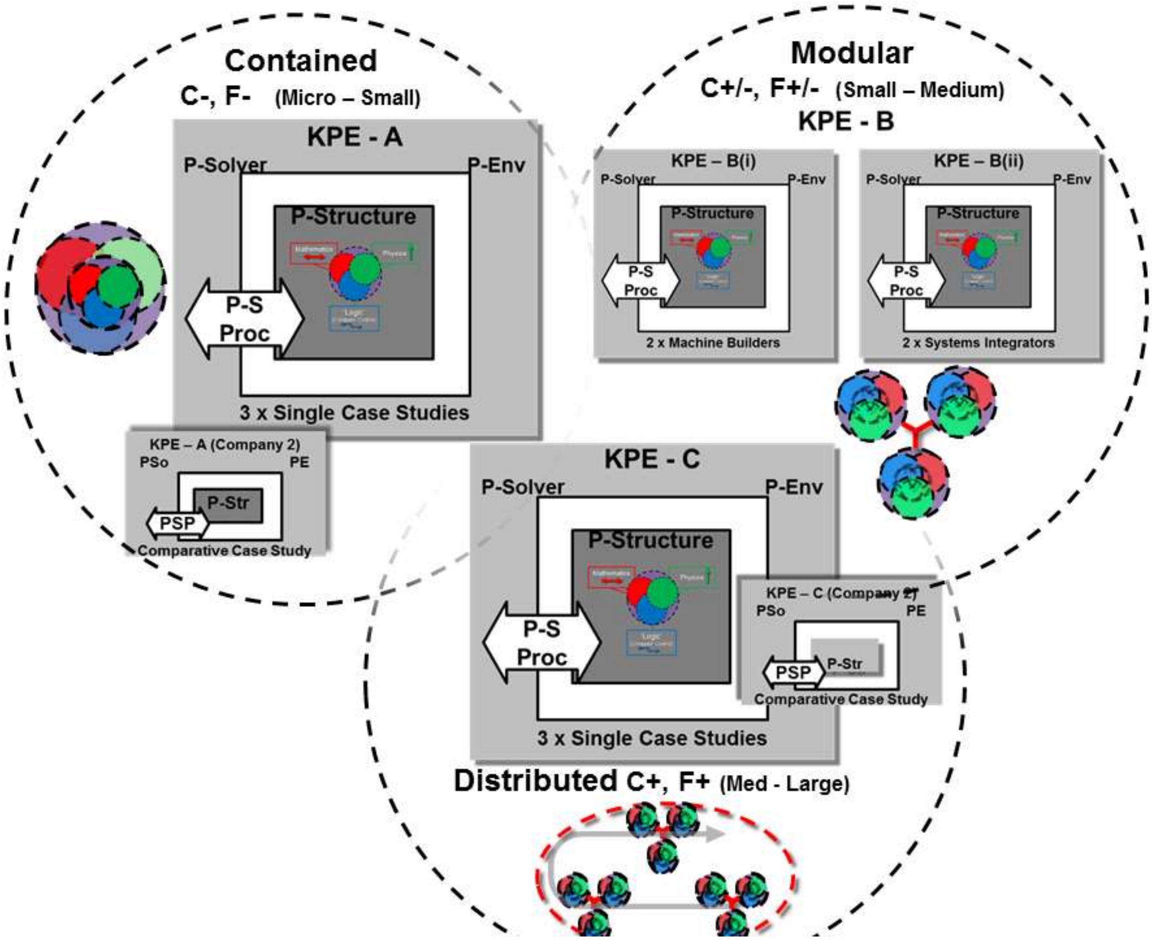


Figure 5-3 Research design: Integrated modular system

As the 'systems integrator', I am required to set these sub-systems in relation to each other such that they 'produce' meaningful problem-solving patterns. In order to do so, I need to understand each component (case study) in its own context, then compare and contrast the different components in each sub-system (case-study set/KPE category), and finally regard the integrated modular system as a whole (compare all case-study sets) in order to effectively answer the research question. The understanding of the system will require different tools and analytical lenses at different stages.

5.3.2 Research sites and participants[47]

Fifty mechatronics technicians/technologists employed in the Western Cape volunteered over the period of 2012 – 2014 to participate in the research project. All the participants – barring one[48] - hail from the same institution, the only University of Technology in the region, and only one of two institutions in the country to offer a Diploma in Mechatronics Engineering. Although

[47] All participants and their sites of practice have been anonymised in accordance with the research ethics agreement.

[48] One participant (case study A2) from a local university – working in the same KPE context as two of the 50 volunteers – offered to participate. His case study is included as an interesting potential comparison given his different curricular and institutional background.

this may appear to present a limitation to the study – a single graduate institution source – it also offers a fixed variable in that all the participants (barring A2) experienced the same curriculum[49]. Given the focus on technician/technologist problem-solving practices so as to better understand appropriate curriculum and pedagogic design for labour-market orientated 21st century engineering education, the limited choice of only two national institutions effectively means 50% of the available sources are included in the study. The second limitation is that all participants are regarded as 'novices' with working experience of up to five years in industry. As with the limited number of institutional cohort sources, the limitation in level of experience is determined by the novelty of such programmes in the country. 'Mechatronics' as a sub-discipline or engineering 'region' is relatively new – so there are few officially qualified mechatronics technicians/technologists in the country. The first qualifying cohort of the institution in question entered industry in 2009. What there are, however, are large numbers of mechanical or electrical engineering technicians/technologists working in automation in precisely the same environments and roles, but with entirely different curricular and experiential backgrounds. The variables implied in the case of these practitioners led to the decision to exclude them from the study. However, it was the industry feedback on newer graduate inabilities *in general* (in relation to the automation sector) that added impetus to the need to understand the practices of this particularly complex engineering region by focusing on participants explicitly trained for it. The selected industrial sites include the following:

- Prototyping/R&D (micro-control-based Contained Systems)
- Systems integrators (PLC-based Modular Systems)
- Machine building (PLC-based Modular Systems)
- Manufacturing (PLC-based Distributed Systems)

Of the original 50 volunteers, 27 finally participated in the first phase of the project by completing a survey-orientated questionnaire. The following factors are common to these participants:

- Currently employed as a mechatronics technician/technologist at one of the identified research sites;
- Working under the guidance of/having access to identified expert practitioners;
- Previous experience as volunteer participant on qualitative research projects on the undergraduate Mechatronics Diploma.

[49] The curriculum in question – during the research participants' education – was widely regarded as a relatively successful hybrid curriculum (traditional + project-based) with more than double the institutional and national throughput (percentage of students completing in minimum time). The focus of this research is NOT from a 'deficit' perspective. These practitioners have been selected precisely because they potentially offer the most equipped basis from which to explore the problem-solving practices required at the level of technician.

The participant hailing from the local university is officially an 'engineer', but employed in the same 'technician/technologist' capacity as his colleagues who were interviewed, and working under the guidance of the same expert practitioner at the company in question. Of the 28 first phase participants (including A2), 18 were interviewed at 11 different companies representing the three KPE categories. 12 case studies were finally selected for analysis, followed by phase three expert verification interviews at eight of the 11 different sites of practice.

5.4 Data collection methods

Data collection took place over a 16-month period between February 2014 and April 2015, in three specific phases, with each phase being preceded by a pilot study.

- Phase one: Problem-solving questionnaire
- Phase two: Semi-structured interview
- Phase three: Expert verification

The following section details the three phases and a number of select analysis features relevant to the data collection process. The subsequent sections will focus more specifically on the range of analytical tools.

5.4.1 Phase one

A first draft of a questionnaire was issued to the original group of volunteering participants via a website link to an online questionnaire. The volunteers were recruited from the part-time B-Tech classes at three different sessions between November 2012 and February 2014. The original questionnaire (and research proposal submission) assumed all participants would be those from the post-graduate programme of the institution in question, and that the 'problem-solving' focus would be in relation to their industry-based projects. However, it emerged that 'problems' for the project report were constrained by the required 'academic' technical discourse and perspective. Secondly, given the data collection period duration, some participants had already completed the B-Tech by the time they engaged with the questionnaire. A second draft of the questionnaire (Appendix C) omitted any reference to the B-Tech elements and simply focused on eliciting descriptions of real problems encountered in this region on a day-to-day basis. Participants were also given the option to submit their responses via email in electronic portable document format (PDF). The questions were divided into two groups:

- Personal and company contextual questions
- Problem-solving contextual questions

The latter asked for the following:

- Identify and briefly describe a recent problem you encountered and solved in your current work.
- What did you do to solve the problem?
- Why did you solve the problem in the manner described? (What were you thinking at each stage? What did you know? What did you not know?)

The responses were recorded on an automated spreadsheet (the 'back-end' of the online questionnaire) and the electronic submissions were integrated into the spreadsheet. Based on these responses, types of problems were matched, and some were disregarded as they did not fulfil the 'controlled electro-mechanical' problem specification for the research. A total of 28 questionnaires were finally received (including A2).

5.4.2 Phase two

The second phase entailed follow-up semi-structured interviews with a selection of participants. A pilot interview phase highlighted the significance of the different contexts, and led to the development of the KPE methodological framing – grouping the participants according to types of KPE. A second finding based on the pilot study interviews was the relevance of my degree of familiarity with the problem features. In some cases I could draw on my own knowledge of physics and mathematics at a basic level, but found the 'logic' and specific technology aspects challenging. Following the first three pilot interviews (not included in the final case studies), I decided to conduct my own basic research into the problems as described in the questionnaire submissions so as to spend less time on the participant having to explain basics to me without getting to the heart of the problem they were trying to detail. Thirdly, a pilot interviewee found it easier to set up all the relevant artefacts so as to re-enact his problem-solving process. This was to represent a significant turning point in my approach to data collection. I subsequently selected cases based on the practitioner's ability to re-enact the problem-solving situation in relation to the actual artefacts and environment. These re-enactments were to become the primary protocol for phase two. It is worth mentioning here that all the sites of practice are known to me, and access was granted (on condition of company anonymity) to all production sites[50].

The Sobek study (2004) made extensive use of retrospective and depositional methods, process observation and participant journals in the attempt to analyse engineering student problem-solving processes on design projects (chapter 2). Although these are useful methods, the retrospective articulation may represent a re-ordering of actual activities for the purpose of narrative logic. The re-enactment protocol, firstly, provided a better environment for the

[50] Where the site of the problem was an external client (B1, B2) or the participant had resigned (C4), interviews were conducted at an alternative location, but with additional visual and textual information.

participant to take me through the problem in a sequence that more closely represented the original situation, as the actual artefacts are generally set in relation to each other in a specific order so as to fulfil a specific function (which in itself has a sequence). Secondly, working with the actual artefacts enabled me as researcher to probe more deeply and the participant to respond more focally. In all cases, the participants were able to move between the artefacts and pen-and-paper when seeking to explain a particular disciplinary phenomenon. The video and audio recordings of phase two interviews were transcribed (verbatim) into discrete, thematic statements onto an electronic spreadsheet for analysis (see Appendix E for a sample analysis system). This technique firstly captures a 'running narrative' (Leonardi, 2011, p. 352) of the problem-solving context and specific processes, and then provides a 'script' which enables the coding not only of 'specific aspects of the problem solving approach' (Atman & Bursic, 1998, p. 130), but also the specifically sought disciplinary references. A similar approach was used in an engineering design team study on problem-solution co-evolution (Wiltschnig, Christensen & Ball, 2013). As a development of the 'think-aloud' protocol, these verbal protocol analysis approaches have become increasingly common in a range of qualitative studies, including LCT.

5.4.3 Phase three

The third data collection phase consisted of expert verification interviews. Eight industry experts[51], representing the three KPE categories, were interviewed during the early part of 2015. The purpose of the interviews was to verify company/organisational contextual information to inform the classification and framing attributed to the KPEs, and to probe the relevant participants' problem-solving processes. The latter was conducted by way of a verbal reminder of the particular focal problem (of which each supervisor was aware at the time), and a schematic simplification of the analysis of the problem-solving process (to be detailed in section 5.5.3). A third section of the interview questions focused on the problem solver's attributes and abilities in relation to those valued by the company. The expert interviews were not electronically recorded, but conducted as a more informal discussion during which notes were made[52]. These discussion notes were used in support of the subsequent data analysis.

A key development during phase three was the discovery that the 'expert' supervisors could only verify the general electro-mechanical disciplinary aspects of the problem-solving decisions taken by the participants. They could not corroborate the 'logic'-based problem-solving strategies involving particular technologies unless they had had prior experience with those specific technologies, which none had had. The experts could generally only offer

[51] Two each from KPE A and C, and each case-study supervisor in KPE B.

[52] My relationship with the industry experts has always been one of collaborating on improving engineering education, and the interviews were framed by this ethic.

generic opinions as to the manner in which a particular problem was solved. The criterion was always 'optimal functioning' of the system as per specification. In other words, the system must work safely, reliably, efficiently and cost-effectively. And if it does, then the problem was solved effectively.

5.5 Data analysis methods

As each case study represents the basic 'component' in the research design sub-system (KPE category), the following sections describe the relevant approaches and analytical tools with respect to the case-study data elements (as developed in chapter 2):

- Problem Environment
- Problem Solver
- Problem-solving Process
- Problem Structure

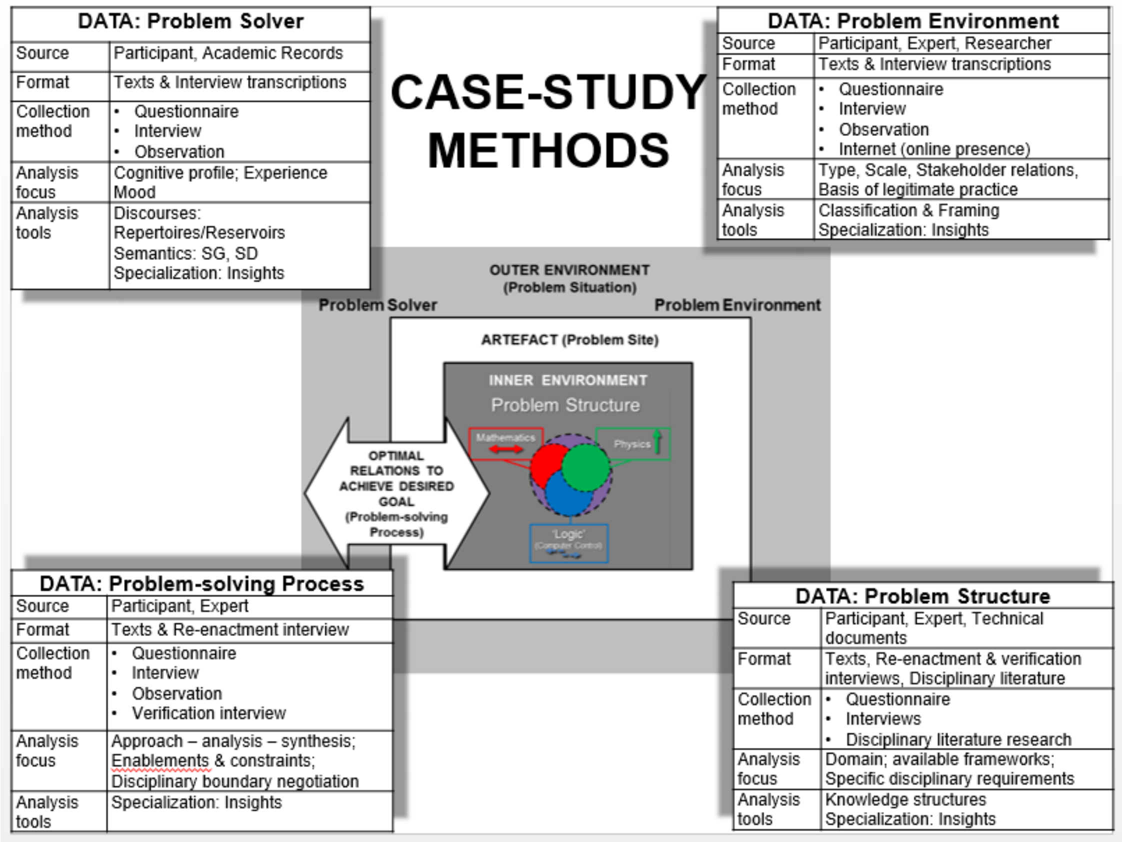


Figure 5-4 Overview of case-study methods

5.5.1 Problem Environment

Eight companies/organisations were finally selected to represent the three types of KPEs as described in chapter 4. Data to define the particular environment were drawn from the employed participants, their supervisors, prior researcher engagement (company visits in earlier WIL coordinator capacity), as well as a study of their online presence (company website). These data are therefore in the form of questionnaire and interview texts, observation, and Internet research.

The focus of analysis was to determine the scale and type of business, as well as stakeholder relations, in order to 'paint' a background picture which could inform the participant's problem-solving process. This analysis – using the Bernsteinian tools of classification and framing - was already detailed in chapter 4. A second analytical stage is employed in the subsequent case-study chapters to illuminate the 'basis of legitimate practices' (Maton, 2014) in each respective environment.

As described in chapter 3, Specialization codes conceive practices as knowledge-knower structures. Within the 'knowledge' practices (epistemic relations), 'practices may be specialized by both *what* they relate to and *how* they so relate' (Maton, 2014, p. 175). The different industrial sites focus on different aspects of automation (and the underpinning knowledge) in different ways. The environments themselves sometimes explicitly indicate a certain 'way', which can be read as what the company values and how it operates. This is either visible on the premises (posters on walls and documents pinned to operations boards) and websites, through company references to particular methodologies, or it emerges through engagement with the company stakeholders.

Examples of '*insight* orientations' evident on a range of sample automation company websites are as follows (figure 5-5):

Situational insight: eg. Customised solutions As a premier turnkey automation solutions provider, **Intec Automation, Inc.** engineers and builds custom equipment that adds quantifiable value to your operations… www.intecautomation.com	*Purist insight: Allegiance to science and appropriate methods* **ISI** was formed in 1991 with the mission to provide innovative products for Thermal Analysis... The DTA Thermal Analyzer measures the temperature difference between a sample and an inert reference as a function of time or temperature. This method is similar to DSC but does not quantify energy measurements.... www.instrumentation-specialists.com
Knower/no insight: People-orientated/ unclear basis of legitimacy Be great people. Make great companies. At Automation Anywhere, we believe that people who have time to create, think, and discover … build great companies. www.automationanywhere.com/company	*Doctrinal insight: Allegiance to method* Crown Equipment Corporation is … dedicated to lean manufacturing and Total Quality Management. Continuous improvement has been intrinsic to the company's philosophy since… The newest component … is Six Sigma. www.reliableplant.com

Figure 5-5 Sample company *insight* orientations

In each case study, an analysis of the websites, premises, and the participant and expert interview texts revealed a dominant *insight* orientation. These are detailed in the opening section of each category of the case-study analyses in the ensuing chapters.

5.5.2 Problem Solver

Twelve participant case studies were selected out of the original 50 volunteers, 28 questionnaire submissions, and 18 interviews. Data were drawn from participant profile information, questionnaires, interview text transcriptions, and video-recorded observations. The focus of analysis for each problem solver was to determine the following:

- Cognitive profile
- Experience
- Mood

It is important to note that the explicit focus of this research is less the participant's 'state of knowledge' (Turns, Atman, Adams, & Barker, 2005, p. 28) than the actual disciplinary knowledge itself as underpinning (and potentially having a causal effect on) human action. However, the problem-solving process may be informed by the relationship between a particular problem solver and the problem in context. To ensure interpretative validity, and in acknowledgement of the fact that this research falls within the sphere of socio-cultural practices, the fullest possible picture of all variables is sought. As such, a profile is established and presented for each of the case-study participants (table 5-1).

Table 5-1 Participant profile details

Profile category	Profile item	Description
Personal details	Participant	Identified by category code and case number
	Age	At the time of the interview
	Gender	M= Male; F= Female
	Race	B= Black; C=Coloured; W=White
	Language (Mother-tongue)	E= English; A= Afrikaans; F= French; Sp = Spanish
Academic	Mathematics	Combined Diploma Mathematics modules
	Physics-based	Combined Mechanical & Electrical theory-based subjects
	Logic-based	Combined Programming & Networking subjects
	Technology	Practical technology-based subjects (e.g. Computer-Aided Manufacturing)
	Qualification completed	NDip (3 years); B-Tech (4 years)
Employment	Duration of employment	Length of time employed as of in-service training to interview date
	Work experience prior to/ during studies	Any formal or part-time work experience prior to/ during studies Y=Yes; N=No
Other	Specific personal or contextual factors that may be significant	Any additional factors that may inform the analysis

Each case-study participant is identified using an alphanumeric system aligned to the research design (KPE Category A, B or C; Participant 1, 2, 3 or 4). The purpose of this system is to deliberately remind the reader that the focus is not on particular 'problem solvers', rather patterns that emerge that can speak to the question of knowledge underpinning practice in different but comparable contexts.

An academic performance profile was determined based on the participant academic record for the focal disciplines. Subject results were grouped and averaged according to their disciplinary basis (mathematics; physics – electrical and mechanical; logic – programming; practice – technology-based practical subjects). The rationale for including an 'academic profile' picture is that the participant's preferred way of working or approach to a particular knowledge area may well be reflected in their academic history.

A second, qualitative analytical tool was used to support the painting of a practitioner profile: The participant interview statements were analysed using the concepts of semantic gravity and semantic density in order to determine each participant's dominant semantic code. Several studies have effectively used the dimension of Semantics to analyse types of knowledge in relation to their degree of semantic gravity - ranging from the context-bound (actual object/function) to the abstract (principles or disciplinary representation, such as formulae) – and/or degrees of semantic density (from the everyday 'naming' of objects/processes that would be accessible to the layperson to terms or statements that require multiple stages of 'unpacking'). One recent study in particular on chemistry education (Blackie, 2014) uses the concepts together to allocate the general semantic code of a particular feature of chemistry (from the formula to variations in the description of processes).

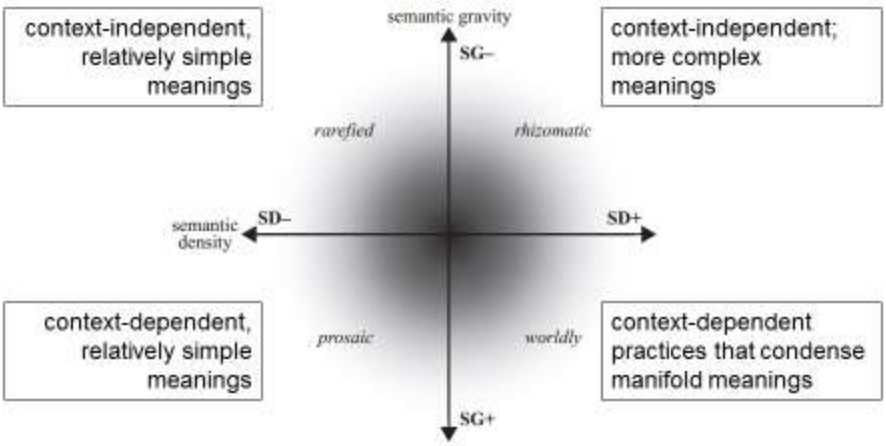


Figure 5-6 The semantic plane (Maton, 2015) – updated and annotated

A simplified system has been employed in this research to capture the dominant semantic code of each practitioner from a 'soft focus' perspective (K. Maton, personal communication, June 23, 2015). All questionnaire and interview transcriptions directly related to the problem-solving description were broken into discrete statements. Each statement was assigned a -1 or +1 value in both the SG and SD categories according to whether it was context independent

(SG -1) or dependent (SG+1), and entailed complex (SD+1) or simple (SD-1) meanings[53]. A spreadsheet function was used to add the total value of each of the four semantic codes (*rarefied:* SG–, SD–; *rhizomatic:* SG–, SD+; *worldly:* SG+, SD+; and *prosaic:* SG+, SD–). These totals were calculated as percentages so as to be able to compare relative references across cases, and were used to generate a radar chart plotted onto the semantic plane.

An example of the use of this method is as follows (figure 5-7):

Transcription	SG	SD	Code	Analysis
This is the circuit diagram of this board, which is our latest sliding gate controller	1	1	Worldly	Context-dependent; complex meaning
and in the last revision I added a small circuit called the 'battery disconnect circuit'	1	1	Worldly	Context-dep; complex meaning
On the previous cards, if you have a battery connected to the card and then the power goes out then the battery is supposed to take over and run the gate	-1	1	Rhizomatic	General principle; complex meaning
It can only disable the 'switching off' process. It can't enable the switching on process, that is all analogue	-1	1	Rhizomatic	General principle; complex meaning
And it can't switch it off - it can only delay the switching off. Which is all we want…	-1	-1	Rarefied	General principle; simple meaning
Here, once the current draw is removed it'll cool down and then come back	1	-1	Prosaic	Context-dependent; simple meaning

Case study example (% of references)	Rhi	Wor	Pro	Rar
	14	44	32	10

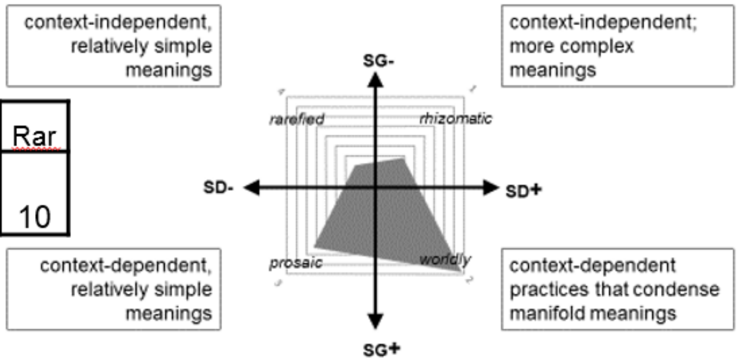


Figure 5-7 Semantic code method

The intention of the 'cognitive profiling' and dominant semantic code in each case study is to be able to inform the analysis of the problem-solving trajectory. Should, for example, a participant have performed poorly in the mathematics and physics-based subjects, it might be reasonable to expect the participant to articulate drawing on such disciplinary knowledge in a manner different to someone with 'visible access' to the disciplinary resources, and vice versa. Secondly, the profiles were intended to inform (if necessary) the differences between the practitioners' practices in each of the problems in a particular category (KPE) in relation to each other and against their own backgrounds. This triangulation is intended to enable a comparison of different case studies in the same KPE. Furthermore, the profiling is intended

[53] Semantic density values have been assigned as complex when a term or concept within a discrete statement requires knowledge beyond that of high school. Each statement is treated as though heard for the first time. In other words, there is no assumption of 'cumulative' (Maton, 2014) knowledge building across the interview.

to contribute to the analysis of the epistemic journey the participant undertakes when solving the actual problem, and which is analysed using the *epistemic plane* (to be elaborated in section 5.5.4 – Problem Structure).

A second focus of the problem-solver analysis is that of the role of 'experience'. In addition to quantitative data on the number of years in practice, and the number of different practice sites, the Bernsteinian concepts of 'reservoirs and repertoires' are employed. The nature of each KPE provides a framework against which to consider the potentially available *reservoir* of knowledge – from stakeholder relations to documentation access. The less isolated and larger a community is, the greater the opportunity for the 'circulation of strategies, of procedures and their *exchange*' (Bernstein, 2000, p. 158). References to drawing on the knowledge of colleagues, prior experience, formal documentation, and user fora on the Internet provide insights into the participant *repertoires* – 'sets of strategies' through which to function in different social or practical contexts (Bernstein, 2000) – as well as the nature of the supporting *reservoir*.

A third problem-solver feature to be considered stems from the collective nature of the prior features: mood. The particular KPE, its stakeholder and structural features, as well as participant confidence with respect to knowledge (cognitive profile) and practice (experience) manifests as a particular participant 'mood' – a significant aspect in the problem-solving process (Isen, Daubman, & Nowicki, 1987). As part of the company contextual background, the questionnaire also asked for general contextual challenges experienced by the participants. Essentially, 'mood' could be related to the degree of autonomy available to or sought by a practitioner in the context of framing over selection, sequence, pace, criteria and social control: what they select to solve their problem, in what order, at what pace, against whose/what criteria, and underpinned by what form of Regulative Discourse. Rather than an elaborate analysis of each of these in each case study, the concept of epistemic relations proves a useful overarching tool, revealing the *insight* orientations of the KPE features, as well as the specific trajectory over a particular problem. When these *insight* orientations reveal code-shifting or code-clashing challenges, participants have either indicated a degree of discomfort in the environment or this has been my observation as researcher. It is precisely these challenges that are the focus of the research.

Using the preceding analytical tools to establish the precise nature of the particular KPE, and the cognitive, experiential and mood 'profile' of the problem solver enables a more informed analysis of the case-study problem-solving process.

5.5.3 Problem-solving Process

The problem-solving process entails navigation of a particular problem site which manifests in a set of artefacts (one of either the Contained, Modular or Distributed Systems types). The artefact(s) becomes the mediating terrain for goal attainment – finding a solution to the problem. Each case study commences with a brief description of the actual problem as summarised from the participant questionnaire and interview texts. This establishes the nature of the particular artefacts in question (many of which are introduced in chapter 4). The focus of analysis, however, is three key stages in relation to the artefact(s):

- Approach to the problem
- Analysis of its cause
- Synthesis of a solution

Each of these stages is analysed using the *epistemic plane* (figure 5-8) to determine the dominant *insight* at each stage. The allocation of a particular *insight* is supported through textual references, observation, and industry expert verification.

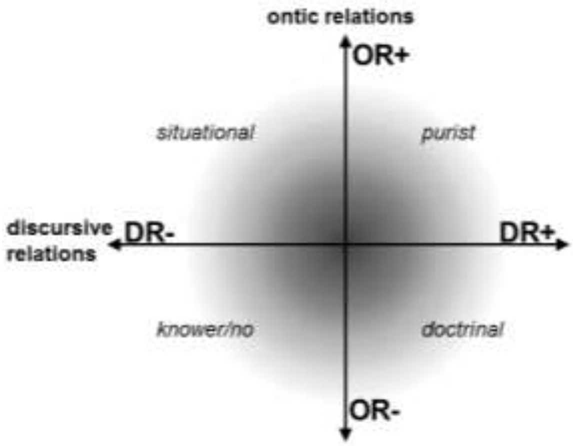


Figure 5-8 The epistemic plane (Maton, 2014)

The following 'language of description' (Bernstein, 1996) captures the broad *insight* category with respect to each key problem-solving stage:

Table 5-2 Problem-solving language of description

Problem-solving stage	Basis of practice			
	Purist (OR+DR+)	*Doctrinal* (OR–DR+)	*Situational* (OR+DR–)	*No/Knower* (OR–DR–)
Approach (Focus: The problem)	'Scientific' or 'Principled; appropriate to 'epistemic' nature and procedures	Systematic procedural 'method' irrespective of 'epistemic' nature of problem	Approach determined by particular situation; evidence of alternative approaches tried or possible	No clear approach (ER-SR-); or clearly knower-orientated demonstrating strong social relations (SR+)
Analysis (Focus: The cause)	Epistemically appropriate knowledge claims and procedures	Methodologically-driven analysis, irrespective of 'epistemic' nature of problem	Analysis shifts between different problem aspects dependent on context; evidence of alternative analytical methods	No clear analytical framework (ER-, SR-); or knower-orientated analysis demonstrating strong social relations (SR+)
Synthesis (Focus: The solution)	The solution implemented is epistemic in nature	The solution is methodological in nature	The solution is designed around this particular situation (it would not be the same for the same problem at a different site or time)	The solution is not based on a clear framework (ER-, SR-); or knower-orientated solution demonstrating strong social relations (SR+)

The analysis of the case-study problem-solving process is mapped as a trajectory over the problem as a whole onto a graphic representation of the *epistemic plane.* This mapping visually tracks technical, disciplinary and contextual participant references across the key activity stages and illuminates the *basis* of their statements. The problem-solving map is situated in relation to the dominant *insight* orientation of the KPE features in order to analyse relational patterns that emerge in context (see figure 5-10 in section 5.5.5 - Sample application of analytical tools). As a general rule, the focal areas in engineering problems are already captured by the *insight* quadrants on the *epistemic plane*: the situation (with a number of possibilities), the scientific/technical principles, the equipment or business processes, and the people. The problem-solving map thus essentially captures what the *focus* of the practitioner is and simultaneously the *basis* of practice at that problem-solving moment or stage. Where these occur in the same quadrant, there is what we may call *insight alignment* or coherence: in other words, a legitimate recognition and realisation of applicable codes of practice in relation to particular phenomena. However, despite a particular *focus* demanding a certain *basis*, a practitioner may not recognise or be comfortable with the 'rules' of a particular *insight* and this may manifest as a code clash from the perspective of the participant. Similarly, the problem structure or environment may dictate a certain *basis* of problem-solving action which may or may not be held as legitimate by the practitioner or the broader field. These essentially suggest code-clashing moments and may be gleaned from participant texts and behaviour.

Where there are such indications of particularly challenging moments during the problem-solving process, the trajectory maps and dominant orientations enable an examination of possible code-shifting and code-clashing causes - informed by the nature of the problem structure (5.5.4). These moments are indicated as 'no entry' symbols on the axes or specific quadrants on the graphic problem-solving trajectory maps. In order to refine the examination of these code-clashing challenges, the analysis draws on the full range of Bernsteinian and LCT concepts as delineated in chapter 3:

- The three knowledge structural types (hierarchical, strong and weak horizontal)
- Semantics (semantic gravity and semantic density)
- Specialization (epistemic relations and social relations)
- Epistemic relations (ontic relations and discursive relations)

Each of these provides a means to examine differences between and within knowledge claims. In order to obtain expert verification of the problem-solving process, the *epistemic plane* was simplified so as to be meaningful for non-sociological practitioners. The ontic relations axis is translated as the strength of the phenomenon - 'what' the focus of the knowledge claim is, and the discursive relations axis is translated as 'how one talks about or represents the claim'[54]. (The 5P model[55] schematic and description is presented in Appendix D).

5.5.4 Problem Structure

The fourth feature of the case-study data analysis process is that of the problem structure itself. Mechatronics engineering, as detailed in chapters 1, 3 and 4, consists of forms of knowledge drawn from three core disciplinary regions: mechanical, electrical and computer engineering. Each of these represents particular knowledge 'domains' within which there are types of knowledge based on laws, processes and artefacts[56]. These domains and a range of their constituent knowledge elements have been set in relation to each other so as to be able to locate the precise disciplinary problem focus of each case study (figure 5-9).

The computer engineering domain has been separated into two domains – hardware and software – as these represent different layers of knowledge: physical and virtual respectively. Each of the now four domains entails significantly different knowledge structures (as detailed in chapter 3). The dominant knowledge structures are indicated diagonally across the four major domains. These knowledge domains entail specific 'frameworks' on which a practitioner can draw. In this research context, the closer the problem lies to a hierarchical (physics-based) domain, the more specific the framework. In Bernsteinian classification and framing terms, this implies strongly classified (C+) and framed (F+) principles and related formulae. By way of example, Ohm's Law implies a set framework (reduced to V=IR) not to be confused with Newton's Laws of Motion (one aspect of which is F=ma). Each of these symbols and concepts represents one specific thing. In contrast, the closer the problem lies to the weak horizontal knowledge structures (logic-based), the greater the number of available frameworks, hence the more weakly classified (C–) and framed (F–) the principles and procedures within the domain as a whole. By way of example, the term 'function' in different programming languages has different names, and by the same token, the same 'term' can have different meanings in different programming languages (Interview B4).

[54] For the sake of the expert-verification interviews the concept of 'no' *insight* orientation was not included on the 5P model. However, the difference between 'knower' and 'no' *insight* was deduced by differentiating between 'focus' and 'basis'. If the 'focus' during the problem-solving process is on 'people' and the 'basis' demonstrates strong social relations (SR+), then the dominant *insight* is a *knower insight*. If, however, the 'basis' is in fact from an epistemic relations (ER+) perspective, with – for example - a *doctrinal insight* – expecting 'people' in the system to operate along pre-determined procedural lines with strong discursive relations (DR+), then the basis reveals 'no' *insight* orientation with an ostensible 'focus' on knowers in the system.
[55] Although the model may at face value not capture the precise nuances of the Epistemic Plane, it uses language and concepts that are understood in the relevant practice sites.
[56] The domain content has been drawn from an analysis of a range of mechatronics engineering curricula in conjunction with knowledge type references across the participant interview transcriptions.

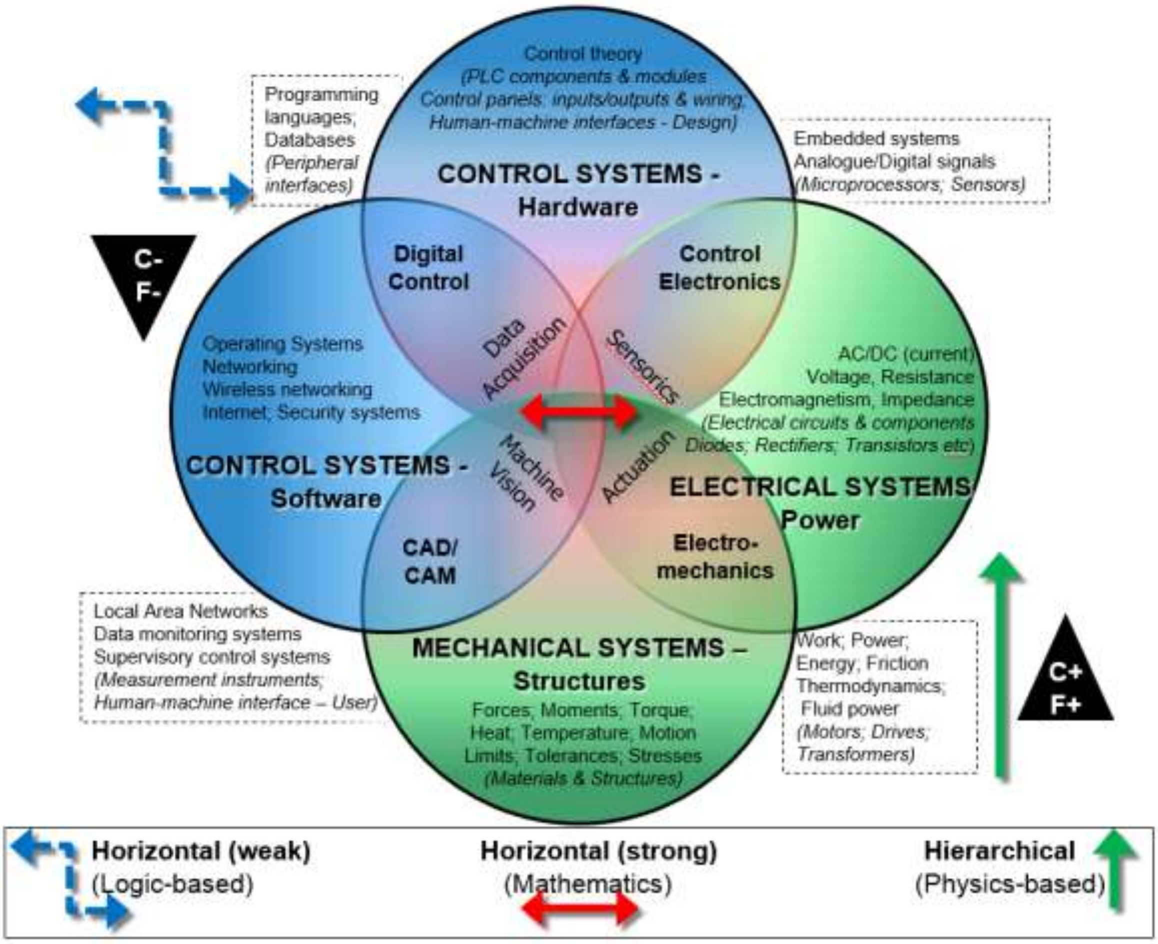


Figure 5-9 Mechatronics problem-solving knowledge domains

Of the original submissions, only those case studies were selected which explicitly involved the three core disciplines by way of the problem being located in a controlled electro-mechanical system. I have elected to consistently use a particular set of colours (mathematics - red; physics - green; 'logic' - blue) to indicate both the existence of and focus on the underpinning disciplines within an outer (purple) 'contextual' circle. This colour-system is used in conjunction with the problem-solving trajectory mapping to indicate the underlying disciplinary basis of the problem-solving statements. The use of colour here enables a more efficient identification of disciplinary boundary crossing within and across the different *insights* as represented by the *epistemic plane*. The disciplinary nature of each problem is gleaned from the participant texts, researcher observation and industry expertise. Of key interest is the participant's identification of the underlying disciplinary basis of the cause of and solution to the problem, and the way in which the participant articulates this analysis and synthesis. The Bernsteinian concepts of knowledge structures, as well as the LCT semantics tools are used to characterise the disciplinary nature of the focal problem. Aspects of the problem that emerge as challenging are closely examined to be able to determine the cause of the challenge: KPE constraints, problem-solver *insight* orientation or constrained access to required disciplinary knowledge.

5.5.5 Disciplinary boundary-negotiation analysis

The key focus for this research is the interpretation of the problem-solving trajectory as mapped onto the *epistemic plane* (figure 5-10 right), with the use of additional explanatory tools, in order to reflect the disciplinary boundary-negotiation patterns that emerge in each of the case studies. Examples of dominant *insight* orientations are presented per KPE feature on the left. The basis of these orientations is motivated in each case-study analysis in the ensuing chapters.

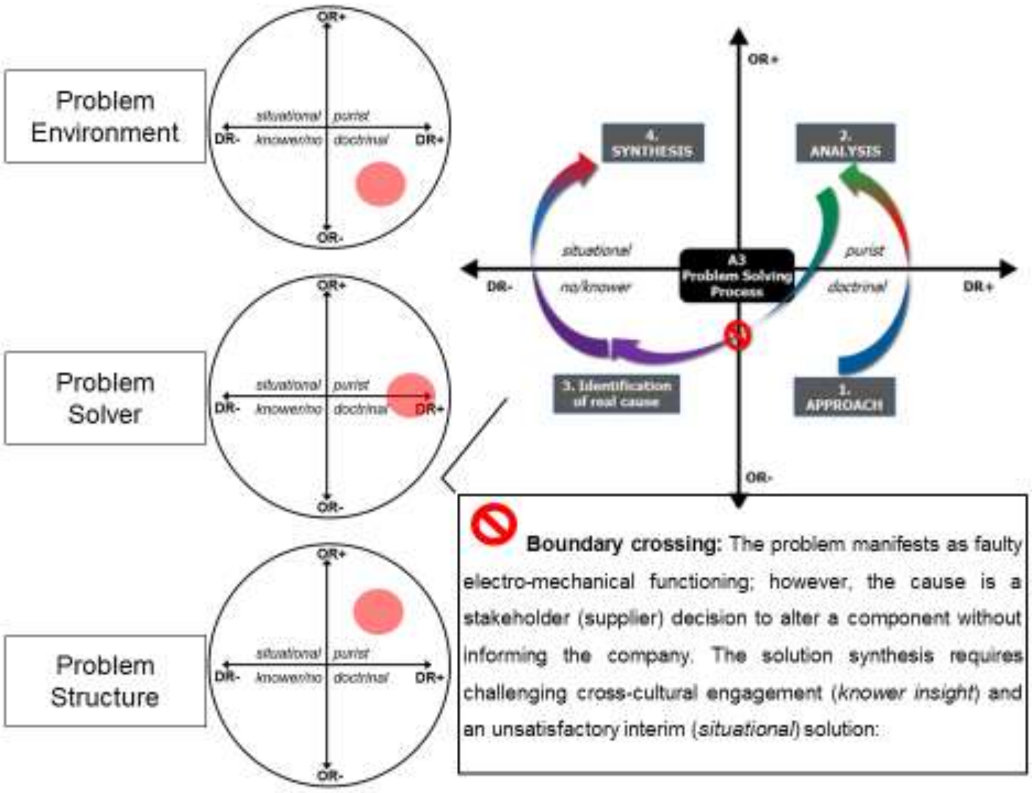


Figure 5-10 Sample application of analytical tools

Of interest is the perceived relationship on the part of the practitioner between the different forms of knowledge, the objects to which they refer and the procedures underpinning the actual practice. For example, whilst it may commonly be assumed that the *doctrinal insight* characterises the approach to mathematics fundamentals, one may find a practitioner using a *situational* perspective in simply tweaking or adjusting values on a control panel (trial-and-error approach) without a real understanding of the mathematics necessary to solve the problem. It may be that in such cases the assumed mathematical understanding is not necessary. A second example is the engagement with people in the problem-solving process. Where a practitioner shifts focus to the *knower* quadrant (lower left) based on strong social relations (SR+) – acknowledging 'kinds of knowers and ways of knowing' (Maton, 2014, p. 184) that are legitimate in the KPE, the *basis* is regarded as demonstrating a *knower insight*. However, if the focus on knowers reveals an expectation that their practices operate according to the procedures associated with the inanimate elements in the system (for example, standardised processes with strong discursive relations DR+), then that moment in the problem-solving process demonstrates simultaneously weak epistemic relations (ER-) and weak social relations (SR-). This reveals a *'no' insight* orientation.

A final analytical element added to each case study is the classification of the problem according to the criteria established by the IEA Graduate Attributes and Professional Competencies (2013) framework. Each of the eight differentiated problem attributes is assigned a value according to the three levels:

- 1 = well-defined (technician)
- 2 = broadly defined (technologist)
- 3 = complex (engineer).

Based on the data provided to support the detailed analysis of each of the case study components in the relevant chapters, values have been assigned to each attribute so as to determine an overall complexity rating for each case study[57]. (See Appendix B for total values).

Table 5-3 Problem complexity rating system (IEA, 2013)

	Attribute	**Well-defined Problems (Technician)** **Value = 1 per attribute** *Engineering problems having some or all of the following characteristics:*	**Broadly-defined Problems (Technologist)** **Value = 2 per attribute** *Coherent and detailed knowledge with the following characteristics:*	**Complex Problems (Engineer)** **Value = 3 per attribute** *Indepth knowledge with the following characteristics:*
1	**Range of conflicting requirements**	Several issues, but few exerting conflicting constraints	A variety of factors which may impose conflicting constraints	Wide-ranging or conflicting technical, engineering and other issues
2	**Depth of analysis required**	Can be solved in standardised ways	Can be solved by application of well-proven analysis techniques	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models
3	**Depth of knowledge required**	Can be resolved using limited theoretical knowledge but normally requires extensive practical knowledge	Requires a detailed knowledge of principles, applied procedures and methodologies, often within a multidisciplinary engineering environment	Requires research-based knowledge which allows a fundamentals-based, first principles analytical approach
4	**Familiarity of issues**	Frequently encountered and familiar	Belong to families of familiar problems which are solved in well-accepted ways	Involve infrequently encountered issues
5	**Extent of applicable codes**	Encompassed by standards and/or codes of practice	May be partially outside standards or codes of practice	Outside standards and codes of practice for professional engineering
6	**Extent of stakeholder involvement**	Limited range of stakeholders with differing needs	Several groups of stakeholders with differing/occasionally conflicting needs	Involve diverse groups of stakeholders with widely varying needs
7	**Consequences**	Locally important and not far-reaching	Important locally, but may extend more widely	Have significant consequences in a range of contexts
8	**Interdependence**	Discrete components of engineering systems	Are parts of, or systems within complex engineering problems	Are high level problems including many component parts or sub-problems
	TOTAL - LEVEL OF COMPLEXITY			

[57] The complexity ratings have been verified with an independent, certified mechatronics engineer, and are merely intended to support the qualitative data.

It is hoped that understanding how these practitioners approach complex problem-solving moments, navigate between different forms of knowledge, with different *insights*, and subsequently effectively solve (or do not solve) problems can make a significant contribution to improved curriculum and pedagogic design. The analysis of the problem-solving processes, as methodologically detailed in this chapter, seeks to illuminate the research sub-questions:

- Do mechatronics engineering technicians manifest particular patterns in navigating between different forms of knowledge when addressing engineering problems?
- Does an overarching pattern emerge which could be described as potentially archetypal?
- How are the disciplinary forms of knowledge brought into relationship with each other in the problem-solving process?
- What level of understanding is necessary in order to solve that particular problem?
- What is the relationship between the elements in the problem-solving context and their impact on the problem-solving process?

5.6 Validity

The research design takes cognisance of the complex and inter-dependent relationship between five key components: the question, the purpose, the methods employed, the theoretical framing and the criteria (Maxwell & Loomis, 2003). Methodologically and conceptually, this research initiative straddles different paradigms. On the one hand, the translation of human behaviour to graphic visual statements by way of assigning values and measuring differences may suggest a 'positivist', quantitative approach. However, this translation of human behaviour is essentially interpretivist, and herein lies a key validity issue. I am required to present an account not entirely dependent 'on features of the account itself, but [which] in some way relate to those things that the account claims to be about' (Maxwell, 1992, p. 283), in my interpretation (using a particular theoretical lens and set of tools) of participant reflection on and re-enactment of their own problem-solving actions. A range of tools is used to capture these processes, which have implications for interpretive validity. Concept maps, verbal protocols and ethnographic details are all approaches to 'inferring a person's state of knowledge' (Turns, Atman, Adams, & Barker, 2005, p. 28). However, the explicit focus of this research is less the participant's 'state of knowledge' (*ibid*.) than the actual disciplinary knowledge itself as underpinning (and potentially having a causal effect on) human action. There are a number of variables that may impact on the intention to focus on the knowledge itself, namely: individual cognitive processes, personal experience, and articulation resources. In acknowledgement of these factors, the principle of 'triangulation' has been applied in the use of industry expertise as well as engineering faculty academic support[58] in enabling an informed analysis of the nature of the epistemic relations at micro problem-solving moments. The intention of the analyses is to offer insights into the nature of professional disciplinary knowledge practices in multidisciplinary engineering contexts.

A second validity consideration is the researcher presence at the research sites. It is important to establish that the different forms of data collected (questionnaires, interview texts, re-enactment observations and expert interviews) enable significant comparison and triangulation. Secondly, the participating industries have long supported initiatives to contribute to an informed understanding of problem-solving practice that can lead to improvements in the South African engineering education system, particularly for the engineering Diploma. Care was taken to establish a site-appropriate research protocol that took the nature of industry processes in particular contexts into account. This is with respect in particular to matters of safety and productivity.

Approval was obtained from the University of Cape Town via the functioning of the Education Faculty's Higher Degrees Committee as a sub-committee of the University's Ethics Committee. As each participant is employed at a particular industrial site where the research was conducted, formal permission and consent forms were processed for the graduate and industry participants. Participants were informed of the nature of the research and requirements at an informal meeting during November 2012, and subsequently at two different meetings until February 2014. As a matter of courtesy, the Dean of the Engineering Faculty of the graduates' institution was informed of the project and not only endorsed the research project, but assured continued support for initiatives he describes as invaluable in contributing to curricular decisions. Confidentiality has been maintained as far as possible. The names of the participants are not disclosed in the research transcription. The focus of this research is problem-solving patterns from a range of participants and NOT individual problem-solving processes. Hence, no conclusions will be drawn that may allude to individual performance.

[58] It is to be noted that I have had the disciplinary support of Dr Simon Winberg (UCT Electrical Engineering), Mr Francois Hoffman (CPUT Mechatronics), Dr Mark Jacobs (CPUT Engineering), and Ms Leigh Sonn (CPUT Mechanical Engineering).

CHAPTER 6: CASE STUDIES – CATEGORY A – CONTAINED SYSTEMS

6.1 Introduction

Contained Systems, as described in chapter 4.5.1, refer to discrete devices or stand-alone machines that fulfil a specific function. Typically, they are designed in research and development units which are either sub-sections of the actual manufacturing environment, or the design and prototyping occurs at research institutes or prototyping companies. As the term 'contained' implies, these units – although always cognisant of the end-user – are relatively isolated from other similar systems, and their development often occurs in similar isolation with small teams and flexible framing over working conditions. The two companies selected for comparison in this category offer two distinct perspectives. The first company (figure 6-1) is a small access control company which both develops and manufactures security access systems. Two of the selected practitioners work in the R&D unit and a third works in maintenance, although all three work in relation to the same system. The second company (figure 6-2) is a local branch of an international medical equipment firm, whose primary objective is to maintain and repair intelligent medical devices located around Africa, but which are developed in Europe. The case-study site operational layouts are illustrated as follows:

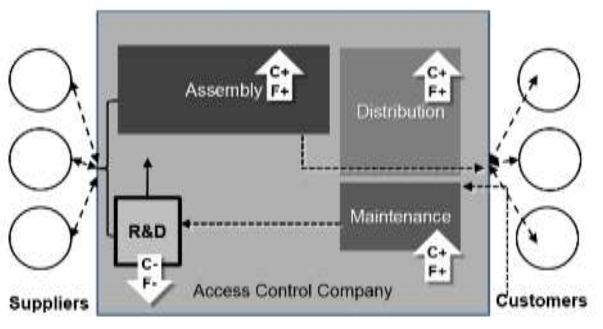


Figure 6-1 KPE A Company 1 Layout & classification

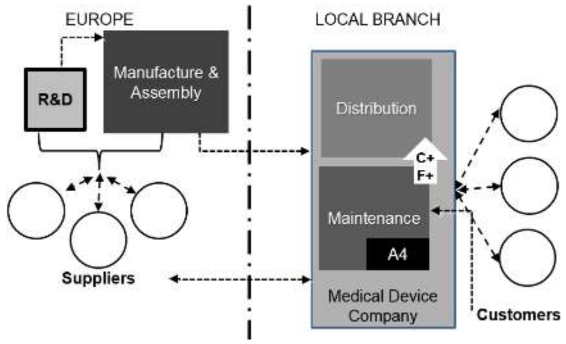


Figure 6-2 KPE A Company 2 Layout & classification

Each case study focuses on a different area of the mechatronics knowledge domain map. For ease of reference, the four case studies are located on the simplified schematic in figure 6-3. This chapter presents an analysis of the four 'contained system' case studies as methodologically detailed in chapter 5. Following the individual analysis of all features of the KPE, a discussion section summarises the key features that emerge from a comparison across the case studies.

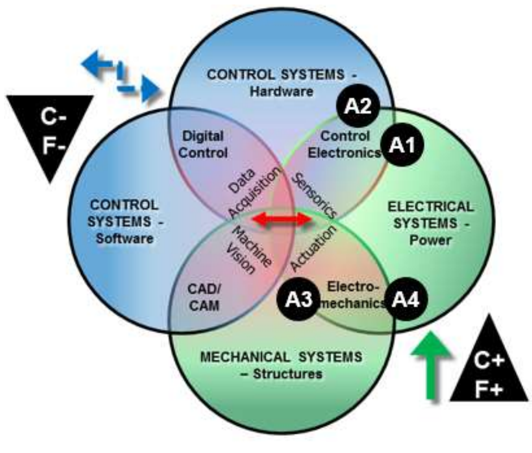


Figure 6-3 KPE A Case-study domains

6.1.1 KPE A: Company 1 description

The first case-study site for KPE A is an 'access control' company in the Western Cape, which specialises in the development and modification of 'access control systems' for gated communities and businesses. In layman's terms, their work is around controlled, motorised devices that open and close gates and doors based on electronic triggering mechanisms and wireless communication systems. By way of example, imagine you are visiting a gated community and when you arrive at the gate, you enter a code on a pin-pad at the entrance to inform the resident that you have arrived. S/he is alerted to your arrival by way of what looks like a 'telephone system', and enables your entry by pressing a switch. This switch remotely triggers an actuator which causes the gate motor (many metres away) to start up. The motor drives a mechanical system that allows the gate to roll back on its track. A sensor or timer triggers the reverse process to close the gate. The control system (like a micro-computer), which resides in the actual motor casing, controls locally connected sensors and actuators, as well as remote communication through a range of wireless technologies.

The company in question designs, develops, assembles, distributes and maintains such systems. The manufacturing of the core product (the motor itself) is outsourced to a manufacturer in Asia according to company specifications, but assembled, packaged, distributed and serviced locally. This particular company offers a unique opportunity to investigate different levels of engagement in the R&D process as well as manufacturing and maintenance, as all the activities occur at a single site. The small company employs under 50 staff, with artisans in the assembly and distribution plants, mobile technicians working with customers, local technicians/technologists working in maintenance, and a small team of technicians/technologists/engineers working in the more recently established R&D section.

6.1.2 Classification & framing of company

The company website boasts its 'passion for our products' along with numerous visuals of the demographically diverse staff complement all engaged in relevant activities which demonstrate the actual working processes[59]. With the majority of employees working in assembly and distribution, in dedicated areas and according to standardised operating procedures and documentation, these aspects of the company manifest strong classification of space, time and stakeholder-relations (C+). In addition, there is strong external and internal framing over pace, criteria and social order (F+). The priority here is efficiency, cost-effectiveness and competitiveness. All the manufacturing processes demonstrate hierarchical personnel structures with well-documented daily briefings and updates.

[59] This is an interesting recent development, as - at the time of the interviews - the website was more technical and practical. There were no visuals of staff.

In contrast, the very small, six-member R&D team works in a separate building sharing small design offices in groups. Desk spaces are littered with computers, electronics, tools and diagrams, and there is a communal ‘brainstorming hub’. The nature of work could (and does) take place anywhere, and the team (which ranges from technicians to engineers) has lateral staff relations, with a senior technician as supervising/mentoring engineer. Although there are broad project delivery targets, the flow and pace of activity is dictated by a spirit of technological innovation within the bounds of feasibility. This area of work is both weakly classified and framed (C–, F–).

Table 6-1 KPE A Company 1 - Classification & framing

Knowledge area focus		Primarily ‘electronics’ orientated (with a more acute degree of mathematics and physics) and the specific programming languages of the microcontroller and communication system			
Business size category		R&D section - Very small (<20) Other (Assembly, distribution & maintenance) – Small (<50)			
Classification & Framing		**R&D**		**Other**	
Classification	Space	C–	Smaller shared design offices and brainstorming hub	C^+	Dedicated areas
	Stakeholder relations	C–	More lateral, small teams; informal, verbal and frequent communication between team members	C^+	Hierarchical personnel structures
	Time	C–	Small-project orientated work cycles; new/changing project briefs; broad deliverable deadlines established, but flexible activity duration	C^+	Standardised cycles & shifts
Framing (external)	Pace	F^{e-}	Dependent on interdependencies; but practitioner-driven	F^{e+}	Customer-needs and company-target driven
	Criteria	F^{e-}	According to standard component/ usage specifications, but innovation-driven	F^{e+}	According to standard product & service-delivery specifications; customer-orientated
	Control	F^{e-}	Owner encourages autonomy and innovation	F^{e+}	Procedures-governed

The three practitioners selected at this company work in relation to the central product – a micro-controlled motor at the heart of the access control system (figure 6-4). Two of the participants (A1 & A2) are physically situated in the R&D unit, while the third participant (A3) is responsible for maintenance problems and thus works in relation to customers, mobile technicians, the maintenance and R&D units.

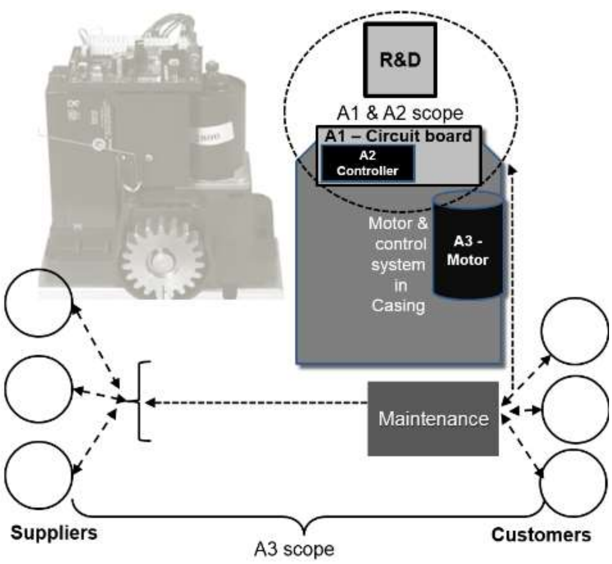


Figure 6-4 KPE A Collective case-study schematic

6.2 Case study A1: Problem in context

A new automated access control system is being developed by the company. This system is attached to a motor which regulates a gate for entry and exit purposes. The new system is using a more powerful microcontroller so as to include more specialised functions. A1's role is to add a 'battery disconnect circuit' (amongst other things) to the new system. The reason for this is that if the motor gets disconnected from the main power supply (as a result of load-shedding[60] or someone forgets to switch it back on), the on-board battery is used to power the motor as well as the circuit board and control system. Even if the main power supply is switched on again, the circuit board still continues to draw power from the battery and the battery can run down. 'You don't want the board to discharge the battery to the extreme' (A1-36). To overcome this, A1 has designed a small circuit which 'reads' the voltage over the battery, and when it drops below 18V, the circuit 'disconnects' the battery so that it can be recharged (if the system is connected to the mains). The procedure for such modifications is standard: It gets built on a prototype and then onto the actual printed circuit board (PCB).

A1 built a prototype circuit using what is called a 'Zener diode' to read the voltage levels and trigger the disconnection and reconnection of the battery.

> *'This was working in a prototype version, then I put it on this board [the new PCB], then I* ***encountered the problem****… that on the demo board there wasn't as much capacitance on rail but on my PCB there was a 2000uF and when power was applied, the large amount of current required blew the transistor.' (A1-47)*

'Capacitors' store energy. When connected to power, the current would surge into the circuit, through the transistor in question, and charge the capacitors. This surge is too much for the transistor in question to handle repeatedly, so it 'blows'. A1 needed to regulate the incoming energy better. So he solved the problem by adding a different component - a P-channel Field Effect Transistor (FET). This is used to amplify or switch an electronic signal, and can control the voltage in a circuit. The focus of the problem-solving analysis is the process A1 underwent after moving from the prototype to the actual PCB, causing the transistor to 'blow', determining the reason and then implementing the FET solution.

6.2.1 Problem environment

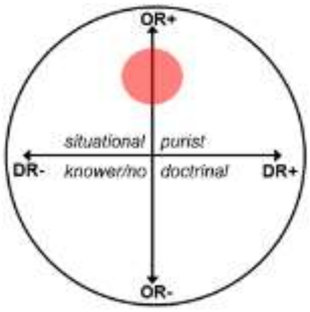
It has already been established that A1 works in the company's R&D unit. Although physically isolated from the company's assembly, distribution and maintenance functions, the purpose of this unit is to create responsive solutions to customer needs, the national context (increased premises security) and technological developments.

[60] The process of interrupting the national electricity supply in phases around the country. This is a common occurrence at the time of the research in South Africa (2014 – 2015).

6.2.1.1 Classification and framing

Classification and framing in A1's environment are weak (C–, F–). He (a technician) shares a design office with two other practitioners (a mechatronics technologist focusing on the mechanical design of the motor system, and a mechatronics engineer focusing on the micro-control system). Their different qualification levels make no difference here, and their supervisor - a technician with over a decade's experience - is highly regarded by all three. The practitioners communicate with each other freely (bouncing ideas or asking for technical input), and move to different practical areas as need dictates. Other than broad delivery targets, their work pace is largely driven by their own abilities and access to the necessary resources.

6.2.1.2 Dominant KPE Insight



The dominant *insight* orientation in this part of the business is *situational/purist*[61]: These access control systems are custom-made designs – in other words, responding to a particular customer 'situation', but also based on the appropriate laws of physics underpinning electronics. There are different possible solutions to a specific technical need, and this is determined by available resources, cost, feasibility and practitioner ability.

6.2.2 Problem solver

6.2.2.1 General profile: cognitive, experience and mood

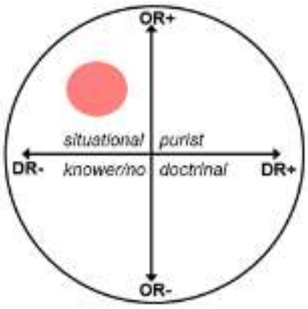
Participant A1 is a friendly, inquisitive and communicative individual. He was selected for the 'think tank' because the owner had seen him present his final year Diploma project and was impressed by the young man's passion. His cognitive profile, based on academic performance, reveals a slightly higher than average student (in context) with grades ranging from 65% for mathematics to 72% for the logic-based subjects. He had had no formal or relevant work experience prior to enrolling for the Diploma (which he completed in minimum time), but had spent a childhood 'taking things apart' and 'fiddling with computers'. At the time of the interview, aged 24, he had been with the company for a year and a half, and although he enjoys his work, he mentioned that he intended to return to university to complete a Bachelor's in Engineering[62]. I suspect that this decision is based on his wish to improve the physics and mathematics knowledge necessary in R&D work.

[61] All '*insight*' and semantic code descriptors in the data analysis chapters are italicised as they are technical terms.
[62] A local university offers a good Engineering transfer programme for students with a Diploma in a cognate field, whereby they may enter the third year of the Bachelor's Degree.

Table 6-2 A1 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
A1	24	M	W	E	65	68	72	71	Dip 3yrs	1.5yrs	N	ADHD

6.2.2.2 *Analytical profile: discourses, semantics and insights*



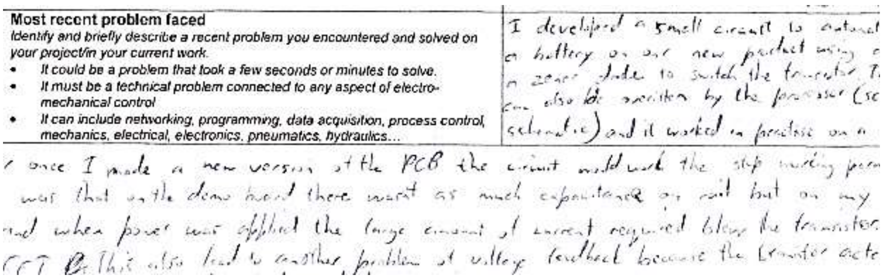


Figure 6-5 A1 Sample text

A1's *situational insight* orientation is apparent from the outset, as well as throughout the problem-solving description. He did not complete a problem-solving questionnaire online or electronically, but (upon prompting) printed the questionnaire and scribbled (almost illegibly) in the various text block areas and around the margins (figure 6-5). During the re-enactment interview itself, he constantly refers to the diagram and PCB, but has to find what he wants to discuss by working out what is what, and what the currently flow is. (There are components that dictate current flow direction and amplification). There is not necessarily a logic to an overall explanation of the problem in context. He picks up different pieces as the interview progresses, responding to the 'situation' that there is a researcher trying to understand the problem. He claims he knew 'nothing' before starting to work at the company:

> *'I basically came here knowing nothing, except what I learnt from my in-service training company - which I basically taught myself… when I started here [name] was manager - he was a mentor - and he taught me a lot.' (A1-97)*

He taught himself by using existing designs, trying to understand them, and building his own small circuits, all the while using the available *reservoir* in his environment and on the Internet:

> *'I tend to refer to a lot of older designs - I have a whole bunch - and if I need to reference something I go there, but if it's something new I would do a quick google search.' (A1-107)*

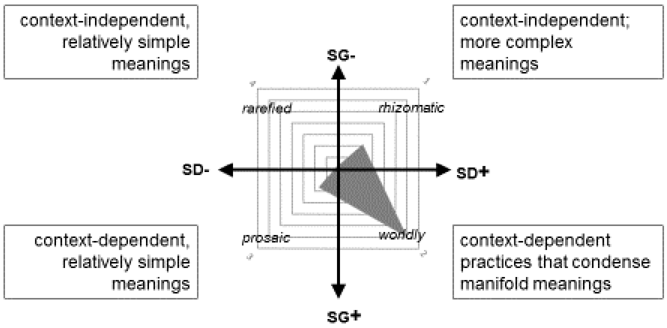


Figure 6-6 A1 Semantic code

An analysis of the core problem-solving process using the semantic plane (figure 6-6) reveals a predominance of semantically dense terms (SD+), and context-specific references (this circuit board) (SG+).

6.2.3 Problem-solving process

The problem-solving process is captured on the epistemic plane (figure 6-7) as a movement across the three key stages: approach, analysis and synthesis. The predominant forms of knowledge referred to at these stages are colour-coded as follows: Context – purple; Logic – blue; Physics – green; Mathematics – red. The following sections provide a detailed analysis.

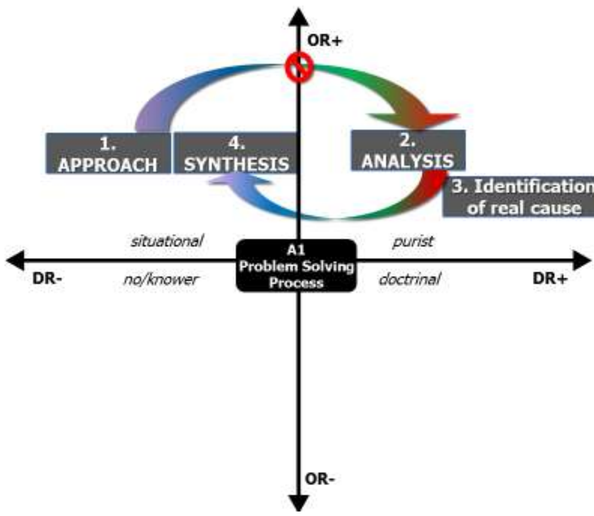


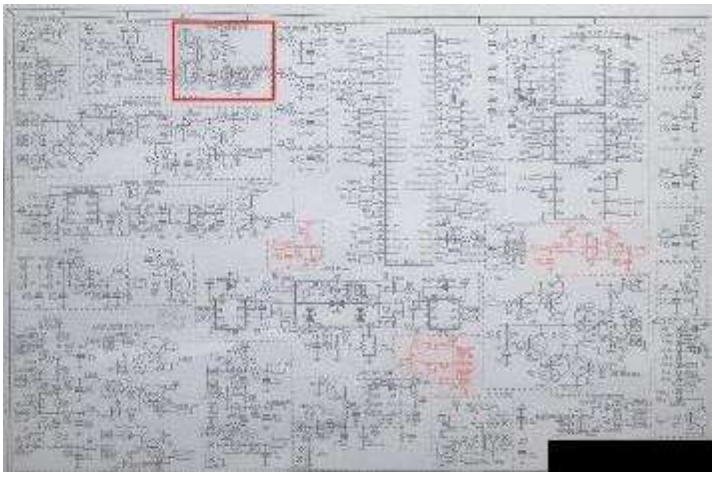
Figure 6-7 A1 Problem-solving process

6.2.3.1 Approach

As this is a new custom design, there is not an 'off-the-shelf' or ready-made system. The broader problem itself (that of enabling the battery to disconnect) is predominantly determined by the arrangement of components in relation to each other with respect to the flow of current and the impact of these components on the overall energy relationships in the PCB circuitry. The choice of where to position certain components and in what relationships to the others is determined by what the system needs to 'do' in this particular situation, but is also ultimately the PCB designer's decision based on additional constraints or affordances (such as laws of physics and spatial allowances). In other words, there is both a circuit 'logic' as well as a level of contextual decision-making. When the Zener diode circuit is transferred from the prototype (without the capacitors) onto the actual PCB (with capacitors), the relationships between the components with respect to energy behaviour change.

When A1 approaches the problem, it is from the perspective of 'this particular situation'. In other words, here is a new product and it needs to do a number of additional and different things from the one previously produced, and there could be a number of ways to do this: the first solution attempted being the Zener diode circuit, and the second (following the impact on the transistor) being the P-channel FET. This suggests an initial *situational insight* with strong ontic relations (OR+), and methodological pluralism or weak discursive relations (DR–). At a literal level, the 'language' and terms used to identify and describe the problem in context tightly 'bound' the referents, but the approach may vary according to the relationships between the referents and what needs to be accomplished.

6.2.3.2 Analysis



A1's problem Circuit Diagram (A4 sheet size; and not a 'structural representation' of the PCB)

Sample PCB (Size relative to A4 Circuit Diagram left)

Figure 6-8 A1 Artefacts

The analysis focused on an explanation of the impact of the Zener diode on the final PCB (after it worked on the prototype). The PCB is represented by an elaborate circuit diagram (figure 6-8 left) which does NOT structurally represent where the actual components are on the physical board. Throughout the analysis, A1 moves back and forth between the circuit diagram and the actual PCB (figure 6-8 right) explaining the current flow and how the individual sub-circuits work. There is not necessarily a logical or procedurally efficient sequence to his explanation. He moves from one circuit to another and then to a different component, but at each stage explaining the various power values (mathematics). He articulates the various aspects of Ohm's Law (physics) continuously, several times also correcting himself. He mentions that he does not calculate that much, and has at times been 'totally out', but that he did do so for the 'Zener diode' and FET circuit. He demonstrates these calculations and notes in the 'little black notebook' his mentor suggested he use.

His analysis of the problem is mostly centred on the question of power relations (physics and mathematics) between components in the various sub-circuits and overall PCB circuit, in other words, maintaining strong ontic relations (OR+). However, discursively he moves between two types of 'procedures' for making claims about the particular object of study. On the one hand, there are several examples of the straightforward application of mathematics and physics underpinning Ohm's Law from a *purist* perspective with strong discursive relations (DR+):

> *'So that transistor needs to be able to handle 800mA, so if you take 800 divided by 40 [writes out calculation on diagram], you get the base current that you need, which is [thinks a second] 20. So you need 20mA…' (A1-53)*

On the other hand, he comfortably moves into first person, weakening the discursive relations (DR–), when he explains the relationship of the 'battery disconnect circuit' to the microcontroller:

> *'As soon as that voltage goes below that threshold of that Zener diode it would send a signal to the micro … so it says "oh X%$#, I must quickly save the position that I'm in before the power goes down so that when the power goes back up I know what position I was in".'(A1-40)*

This personification seems natural to his *situational* orientation and demonstrates the shift between levels of semantic gravity (SG) and semantic density (SD) in that he is explaining the principle behind how the microcontroller would work in this situation in relatively simple terms. His analysis of the problem demonstrates a constant shifting between DR+ and DR–.

6.2.3.3 Synthesis

A1's first solution to the overall problem (integrating a battery disconnect circuit) was the use of a Zener diode. He selected this based on consulting existing circuit diagrams he had previously worked on. However, when the 'blown transistor' problem cropped up on the real PCB, he used Google to solve the problem. He had used FETs before and thought they might work, but 'wasn't sure I could just drop them in'. He literally typed 'Replacing a PNP transistor with a P-channel FET' into the search engine and deduced from the component explanations on a particular website what he should do. He had examined the PCB and determined that the difference between this situation and the prototype was the existence of the capacitors, and the current flowing through the affected transistor towards the capacitors (real cause of the problem). By using a P-channel FET, he could regulate the voltage better when the current was flowing. In other words, he 'synthesised' a solution for this particular problem in this context by implementing one of a number of solutions, NOT based on strong 'legitimate procedures' for a strongly bounded knowledge claim (the control of voltage). The solution had to fit into the logic of the PCB as a whole. He drew from his own experiential knowledge, in addition to existing circuit diagrams and an Internet source.

6.2.4 Problem structure

The problem would be classified as falling within the domain of 'electronics', with a specific theoretical focus on Ohm's Law: 'There are certain formulas in Physics that are so powerful and so pervasive that they reach the state of popular knowledge'[63]. Ohm's Law is simply the relationship between current, resistance and voltage. Although most commonly expressed as V=IxR, there are several quick-reference versions of the various derivable formulae (figure 6-9).

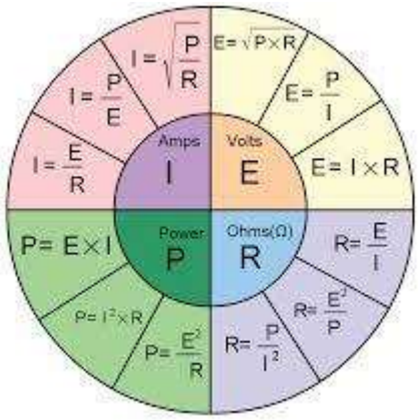


Figure 6-9 Ohm's Law (commons.wikimedia.com)

Initially, working with electrical circuits requires students and practitioners to constantly apply the formulae and actually physically calculate the values. With experience, practitioners develop a sense of how much or within what range certain values will be. In order to apply the law, however, a practitioner is required to firstly understand the logic of a circuit. This is underpinned by two forms of knowledge: practical components and applicable physics. They have to know what a component does in a circuit, how it is connected to the others, and what the current flow behaviour is. Once this is known, mathematics is used to alter or interpret existing behaviour. A1 describes the logic of the circuit and his understanding of the problem as follows:

> *'What was happening was this power supply goes to V3 & V2 [top left circuit], from there [V3] to there [V2] to there [straight down] and through that diode to V5 [pointing out route on diagram]. But because there was no diode here [Zener circuit] it would just flow up through here [transistor] straight into V1… So then I saw quite a bit of current being drawn from the power supply, - I didn't know where it was going - so it was actually charging the battery directly - it was like you plugged the battery straight into the supply.' (A1-86)*

His analysis demonstrates the movement from a weak horizontal knowledge structure (logic), to a hierarchical knowledge structure (physics) and back to a strong horizontal knowledge structure (mathematics). Although the 'logic' referred to in this case is not 'programming logic', it operates with precisely the same rules: If *x* is set in relation to y in ABC manner, then … The choices, however, are limited by the laws of physics inherent in each of the components (the voltage range, for example). This means that although the PCB designer may choose to situate different components in relation to each other (DR–), the behaviour of the system is always dictated by a strongly bounded knowledge claim (OR+) – that of Ohm's Law. And

[63] http://www.physicsclassroom.com/class/circuits/Lesson-3/Ohm-s-Law

Ohm's Law demonstrates a fixed set of discursive relations (DR+). The problem structure is thus a movement between weak (DR–) and strong (DR+) discursive relations in relation to a fixed ontological referent (power relations in a circuit as defined by Ohm's Law). However, this is not the first time A1 has encountered problems regarding voltage calculation. In a different context, a previous supervisor commented that 'there was also an overvoltage that caused the ICs to blow'. This suggests A1 does not have a firm enough foundation in hierarchical nor strong horizontal knowledge structures, both of which require strong discursive relations (DR+).

6.2.5 Boundary navigation

The overall problem in its context is rated at a total value of 13, which places it in the 'broadly-defined' (technologist) category. The nature of the 'problem in context' is precisely that of this research: the implications of the broader/wider context. When A1 moves his prototype design to the actual circuit board environment, he has not considered all the other components on the board, how they are connected and how the energy flow through all the components might affect individual components. Although one might be tempted to declare that the problem could have been solved with a firmer understanding of the combined physics and mathematics principles (in other words, through a *purist insight*), the reality is that the circuit design as a whole (figure 6-8) is significantly complex, and it is probably humanly impossible to predict the entire system's behaviour on the strength of physics and mathematics as represented in a complex visual schematic alone. Developing or decoding such a complex electronics diagram relies heavily on prior examples, an adequate grasp of the appropriate principles and procedures, and the tools with which to experiment through trial-and-error. The boundary-crossing pattern in this case is that between forms of knowledge with weaker discursive relations (DR–) and those with stronger DR+ (the logic of the circuit design and the rules of Ohm's Law respectively). Shifting between these is not necessarily a code clash, rather simply more challenging for A1, who is more comfortable in a *situational* context (OR+, DR–), preferring to use a trial-and-error methodology, admitting to not calculating much and actually often being wrong. A1's 'experimental temperament' (A1 supervisor) echoes his *situational* orientation and suggests he is more responsive to knowledge structures with weaker forms of 'grammaticality' and weaker discursive relations.

6.3 Case study A2: Problem in context

A2 is working in conjunction with A1 (and others) on a new automated access control system being developed by the company. The company has decided to use a more powerful controller so as to include more specialised functions. A2's role is to set up the new microcontroller, replicate the original functions of the old microcontroller and then program the controller, so as to achieve a more efficient automated access control system. A2 set up the controller environment on his computer by using a small prototype PCB that A1 built with the new 16-bit controller. The set-up entailed following a standard procedure (initiated by a set-up wizard):

> *'If you are starting a new project… it takes you through a whole wizard, choose what device… choose what programming tools… then choose compiler. So like a normal setting up…' (A2-32)*

Following this, the various controller 'hardware modules' (responsible for different operations in the system, such as receivers and transmitters) are then split up and configured. This means setting up the relations between different hardware and software components in the programming environment. In layman's terms, this is like telling *what* to connect to *what*, and what to do when it receives a digital signal. Although several of the configuration processes were similar to the 8-bit controller, a number of adjustments were required.

A problem arose with the Analogue-to-Digital Converter (ADC). This is a feature of the microprocessor that takes an analogue signal (a continuous wave representing temperature, sound, light, pressure or an electrical signal) and converts it to a digital signal ('an electrical signal … represented by a computer …[as] a series of bits that are either in the state 1 (on) or 0 (off)'.[64] To test whether or not, and how, the ADC worked, A2 connected a thermal sensor to one of the microchip inputs and attempted to get a temperature reading on the computer. He had no luck for an entire day. When he finally consulted the errata sheet ('as a last resort') that came with the microprocessor, he discovered the ADC only worked in a certain mode (10-bit) and not in the mode he was 'running' (12-bit). (This is similar to the problem many PC–users face today, where they purchase a newer PC which is 64-bit, but may be connected to a printer which requires a 32-bit mode – one then has to install a special 'driver' to enable the printer to be operated through the PC)[65]. Based on the errata sheet information, he then altered the running mode to 10-bit and was able to read the temperature.

[64] http://www.chegg.com/homework-help/definitions/digital-signal-4

[65] 'The number of bits in a processor refers to the size of the data types that it handles and the size of its registry. A 64-bit processor is capable of storing 264 computational values, including memory addresses, which means it's able to access over four billion times as much physical memory than a 32-bit processor!' (http://www.digitaltrends.com/computing/32-bit-64-bit-operating-systems/#ixzz3Bu1yzqAk)

6.3.1 Problem environment

The problem environment in this case is virtually identical to that of A1. A2 works in the same design office in the company's R&D unit. Here, classification and framing are weak (C–, F–), given the innovative thrust of the 'think-tank', the use of space as required and the lateral team-orientated staff relations. The dominant *insight* orientation is *situational/purist*, focusing on custom-made and innovative security solutions based on sound physics principles. Both A1 and A2 are mentored and supervised by the same person. The only significant difference is that A2's role is that of programmer, and that most of his work is conducted on his computer.

6.3.2 Problem solver

6.3.2.1 General profile: cognitive, experience and mood

Unlike all the other participants, A2 does not hail from the same educational programme. He is in fact a mechatronics engineering graduate from a local university. He offered to participate in the research project when I conducted interviews at the site. Since they were all working on the same project in different capacities, I believed this might be a useful comparison.

Table 6-3 A2 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
A2	24	M	W	E	70	70	70	75	BEng 4yrs	0.5	Y	Studied at a local Historically White Institution (HWI)

A2 comes across as a professional and slightly reserved young man. He has now been with the company for 6 months. Also 24 years of age, his academic record reveals a low 70s average across all areas, and he completed the Bachelor's in Engineering in minimum time (4 years). Unlike A1, he gained work experience during his studies in an engineering environment. However, A2 did not feel technically equipped to deal with the complexities of the different technologies:

> *'I get frustrated when this language can't do what another language could do, because I always used that feature and then I have to find a way around that.' (A2-20)*

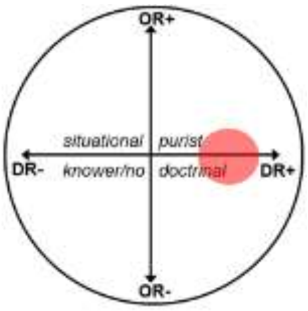
He gets on well with the team and finds that he is learning a great deal from his supervisor, who confirms that he is 'keen and learning'.

6.3.2.2 Analytical profile: discourses, semantics and insights

The problem-solving questionnaire is particularly revealing (figure 6-10). In contrast to the scrawled A1 contribution, A2 completed the questionnaire electronically (without prompting) in basically detailed, numbered sequence with appropriate explanatory sections in parentheses. He elected to use red text in order to differentiate clearly between the questionnaire content and his submission.

> 1: I searched the Datasheet and application note looking for everything that relates to the internal temperature measurement unit (using CTRL-F and appropriate search phrases). I noted anything I found on a piece of paper. I then implemented this to no avail.
>
> 2. I googled the problem mostly looking at forums and seeing if anyone had experience a similar problem.
>
> 3. I compared my code to that of some examples in the forums and found no major differences. I did notice that they had been using it in 10bit mode but I did not see how this could make a difference at the time.
>
> 4. I consulted the errata sheet as a last resort (I am not used to using microcontrollers with an errata sheet, this is normally updated or noted in the datasheet on their website). Here I found the problem clearly described.
>
> 5. Made a mental note to look at the errata in step 1.

Figure 6-10 A2 Sample text



His textual contribution and interview suggest a *purist/doctrinal insight* orientation. The re-enactment interview did not require much prompting and suggested he was constantly aware of 'principles and standard procedures'. The programming procedures followed were sequentially presented, with explanatory, analytically-orientated detail where necessary and appropriate discursive conventions.

He draws comfortably on the resources available in the broader *reservoir* (Internet, colleagues, user data documentation). The analysis of his interview using the semantic plane (figure 6-11) reveals a majority of *worldly* references (SG+, SD+) as is to be expected in such regions. There are, however, a relatively equal number of references to general, simple meanings both dependent and independent of context (which are mostly for my edification or for conceptual explanation).

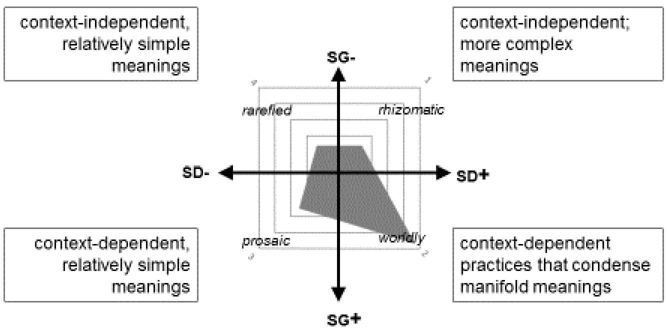


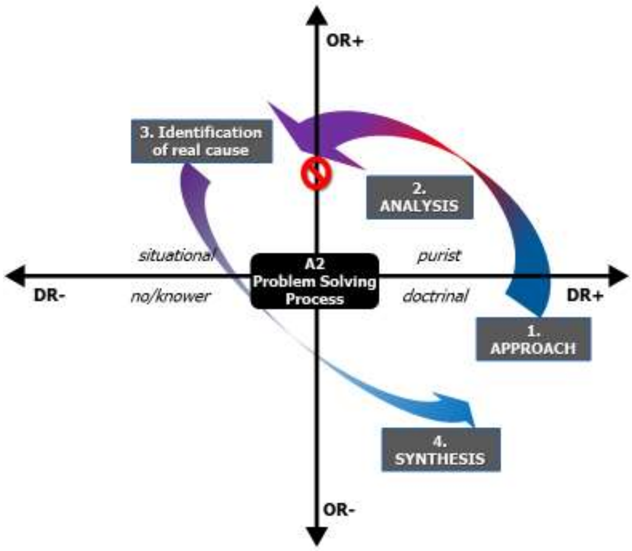
Figure 6-11 A2 Semantic code

6.3.3 Problem-solving process

6.3.3.1 Approach

A2's approach to the general problem of getting the microcontroller set up is entirely procedural. There is a standard methodology: install the software, connect the hardware, and 'configure' the system step-by-step, usually following the programming 'tree-structure'. His explanation of the fairly generic sequence (OR–) suggests strong discursive relations (DR+) or a *doctrinal insight.*

Figure 6-12 A2 Problem-solving process (right)



Although this is the first time he has ever worked with a 16-bit chip (which can handle 256 times more data than an 8-bit and has far greater mathematical precision), he sets off comfortably based on a standard approach he has used with other forms of control, which suggests weak ontic relations (OR–). What further supports this is the fact that the 'language' and 'terms' in this case could apply to any computing environment:

> *'Normal file management stuff, like normal applications up there… This [upper vertical tree section] is a project area. It comes up first, and then each project folder contains all these different files…' (A2-23) (Figure 6-13)*

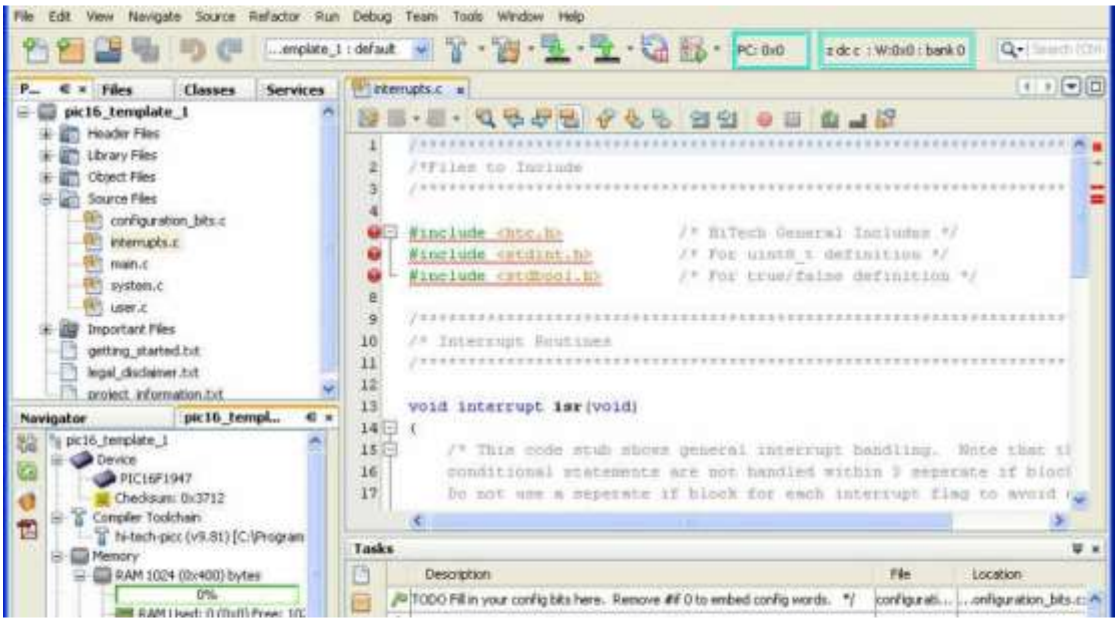


Figure 6-13 A2 Problem site - the control environment

6.3.3.2 Analysis

When the actual problem occurs, that of the ADC not reading temperature, he appears to anticipate a *purist* basis to the problem:

> *'I thought I had set something up wrong - because it's quite complicated. … I thought somewhere in the configuration - the sort of 6 configuration – uhm integers - each 16-bit - there is such a combination of things I could have had wrong.' (A2-16)*

Configuration with respect to '16-bit integers' here is a reference to the logic of the system with respect to the mathematical coding of 'integers' as binary digits ('0's and '1's). This is what enables information to be sent as 'on'/'off' signals. In other words, there are strong ontic relations (OR+) as he starts his analysis of the problem, coupled with specific procedures for talking about the referent (DR+). However, he then tries multiple approaches (DR–), drawing on formal textual knowledge formats, as well as the Internet:

> *'I searched the datasheet and application notes looking for everything that relates to the internal temperature measurement unit. I read through quite a number of forums and nobody had the problem… I compared my code to that of some examples in the forums and found no major differences. I did notice that they had been using it in 10-bit mode but I did not see how this could make a difference at the time.' (A2-37)*

This shift towards attempting several approaches to solving the problem demonstrates a move from *doctrinal* temporarily through *purist* and on to *situational insight* (figure 6-12). At no stage is there an issue with regard to the physics of the actual temperature sensor. He understands precisely how this works and that he should be able to get a signal. However, his explanation of 'bits' and 'integers' suggests he initially thought the problem was *purist* in nature. The issue is actually the 'logic' of how the platform has been set up to receive or send information – and this is based on a vendor decision. Even though this set-up may have been based on mathematical decisions originally– how many bits are required to process different sets of information – for the programmer in this context, it is simply a matter of knowing which settings or parameters to use. No prior theoretical knowledge could have enabled better insight.

6.3.3.3 Synthesis

A2 notes on his questionnaire that 'as a last resort' he finally read the errata sheet (which their collective mentor has always insisted is the first step in using new hardware or software). There, 'I found the problem clearly described – it just doesn't work in 12-bit mode. It only works in 10-bit mode' (A2-7). In other words, this particular controller under these particular circumstances (using the ADC feature to read temperature) only works in a particular mode. So, he altered the mode and could finally read the temperature. The solution was thus a procedural one (*doctrinal*) based on this specific component's settings (*situational*) – which he would have known about had he read the errata sheet.[66]

6.3.4 Problem structure

The problem is located in the electronics domain, which lies in the convergence of physics and logic, in other words, between hierarchical and weak horizontal knowledge structures. This is possibly the most difficult shift to navigate as it is essentially the shift between strong (DR+) and weak (DR–) discursive relations as well as a shift between strong 'verticality' (subsumptive principles) and weak verticality (expansive possibilities). The cause of the problem is quite simply a decision made by the vendor to allocate a particular parameter for certain operations – a *situational* problem structure with *doctrinal* requirements[67]. He could only have known this through experience of this particular set of circumstances and equipment.

6.3.5 Boundary navigation

The ease with which A2 describes the *doctrinal* processes, as well as the signs of an attempt to understand the problem theoretically, suggest A2 is more comfortable when he has existing and known frameworks on which to draw (DR+). His declared surprise that the problem was to be solved simply through reading the vendor documentation, and that this information appears to be theoretically arbitrary, suggests an assumption that his known theoretical and procedural frameworks – possibly inculcated as a result of a more theoretical Bachelor's education - should have been sufficient. His dislike of encountering the limitations of his own knowledge is apparent. The code clash here is that between a *purist/doctrinal* problem solver (DR+) and the demands of a *situational* context (OR+, DR–). Despite the equivalence in academic performance across the knowledge types, his procedurally efficient engagement in the research interview suggests a possibly stronger 'structuring effect' of hierarchical and strong horizontal knowledge structures. As in his colleague's case, the overall problem in its context is rated at a total value of 13, which falls within the 'broadly-defined' (technologist) category.

[66] As part of my research, I downloaded the datasheet for the microprocessor A2 is using, and skimmed through, looking for Analogue-Digital-Converter information. At the top of page 3, under Analog features, it clearly says: '10-Bit, up to 13-Channel Analog-to-Digital Converter'. However, this is page 3 of 268!

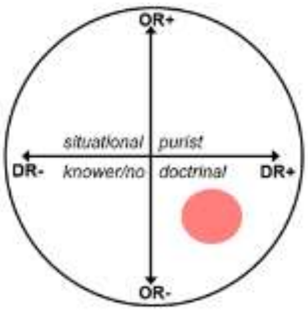
[67] Unlike case studies A3, B3, B4 and C1 – where vendors/suppliers changed specifications or documented them inaccurately, and this implies necessary navigation of the *knower* quadrant – in A2's case, the vendor decision was part of the original specification.

6.4 Case study A3: Problem in context

A3 is responsible for the maintenance of existing client access control systems. His scope of work thus involves customers, suppliers, the roving company technicians, and the R&D unit. After months of operation in the field, the company's specialised access control motors are reported as opening and closing the various gates at irregular speeds. The problem does not appear to be the 'control' - in other words, when the users 'press the button' or 'activate' the gates, they work. They just open and close with varying, as opposed to consistent speed. The technician in the field determines that there is no interference on the gate track, and logs a report. At first these reports just trickle in, and are not considered serious. When, however, it becomes apparent that all the motors as of a particular point in time after six months of operation in the field are acting up, A3 is assigned to the investigation.

The investigation reveals that the size of the brushes[68] in the motor are not according to the company specifications. The problem, it turns out, is caused by an Asian manufacturer's decision to cut costs by shaving a mere millimetre off the millions of brushes they produce. These brushes are supplied to the motor manufacturers who, in turn, sell hundreds of thousands of motors around the world - A3's company being one of several customers whose motors are custom-made. As an interim measure, the company recalls all the faulty motors and replaces the existing brushes (at considerable cost) with those of a different type of motor, but which fit the brush-holders better. There have been 'fiery debates and endless convoluted communication' (A3-180). The problem (at the time of the interview) had still not been satisfactorily resolved. Sending hundreds of motors back to the supplier is not an option, but this particular line had to be stopped - a decision for which A3 was responsible.

6.4.1 Problem environment



It has already been established that A3 works in the company's maintenance unit. Classification and framing here are strong (C+, F+), with dedicated spaces, roles and well-documented protocols. The purpose of this part of the company is to deliver, install and maintain products efficiently and cost-effectively. A3, unlike his colleagues A1 and A2, is constantly on the move – from the repair centre to R&D to customer sites (if necessary). The dominant *insight* in this part of the business is entirely *doctrinal*.

[68] A 'brush' is a component attached to a spring and made of copper wires (or carbon) and which is used 'to convey current between the stationary and moving parts of an electric generator' (dictionary.reference.com).

6.4.2 Problem solver

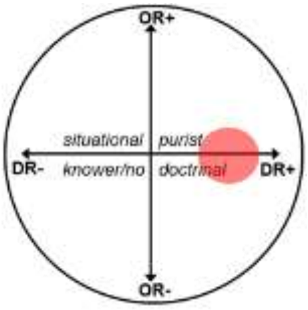
6.4.2.1 General profile: cognitive, experience and mood

A3 is very efficient, having volunteered participation and submitted his questionnaire in record time and with precision-orientated detail. Initially an undergraduate for a year at the same local university that A2 attended, A3 subsequently moved to the UoT. His cognitive profile, based on academic performance, reveals distinctions for all key subjects barring the physics-based ones. Although not unhappy in the environment, A3 yearns to do the kind of developmental R&D work of his colleagues. However, his academic accomplishments and disposition have resulted in a more managerial position – liaising with local staff, suppliers and customers – while simultaneously having to solve problems (both epistemic and social in nature) against tight deadlines. His previous part-time work experience has stood him in good stead in his current capacity.

Table 6-4 A3 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
A3	26	M	C	E	75	70	75	75	B-Tech	3	Y	Started 1st year at HWI

6.4.2.2 Analytical profile: discourses, semantics and insights



A3's *purist/doctrinal insight* orientation is apparent from both the problem-solving questionnaire (6-14) and interview. He is consistently methodical and analytical.

2. Setup experiments/testing
2.1. Non-invasive
2.1.1. Get samples (faulty and good working samples)
2.1.2. Setup control and experiment (control: the product in good working order; experiment: the product with the strange behaviour)
2.1.3. Run testing (samples)
2.1.4. Monitor and measure differences non-invasive (Temperature, current draw, voltages, speed etc.)
2.1.5. Document processes and results
2.1.6. Eliminate factors (eliminate the non-invasive factors as the test proceeds narrowing down on the factor(s) "problem area" influencing the motor to behave strangely)
2.1.7. Run test number 2 (samples)
2.1.8. Document process and results
2.2. Invasive
2.2.1. Disassemble motor samples
2.2.2. Compare parts (measurements: dimensions, continuity, resistance etc.)
2.2.3. Test and measure parts
2.2.4. Re-assemble
2.2.5. Run tests

Figure 6-14 A3 Sample text

He draws on a range of appropriate discourses – moving comfortably between technical detail and more *prosaic* explanations both with regard to context and for my benefit as researcher. Unlike A1 and A2, the available *reservoir* is limited to documentation peculiar to the company's systems – both technical and managerial, so A3 does not generally use the Internet for any specific work purposes. However, when using unfamiliar equipment or components 'I go and Google the part' (A3-144). He is also, however, able to draw on the *repertoires* of colleagues working in his area. The semantic code analysis (figure 6-15) demonstrates a predominance of *worldly* references, along with a greater number than his colleagues of references across the plane. The increased number of *prosaic* references are attributed to more contextual, simply stated information regarding the difficulties encountered with their international supplier in their attempt to solve the problem.

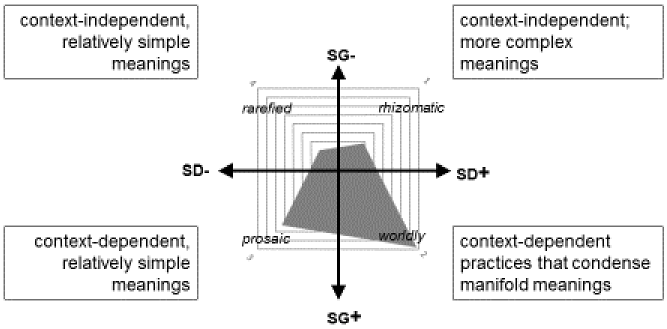


Figure 6-15 A3 Semantic code

6.4.3 Problem-solving process

6.4.3.1 Approach

From the outset, and in both the questionnaire and interview, A3 demonstrates a systematic and methodologically structured approach to the investigation which he lists as four major phases:

1. *The gathering and analysis of all relevant information leading to a number of feasible hypotheses*
2. *Non-invasive experimentation and testing - which involves comparing known working motors to the defective motors - so as to eliminate factors*
3. *Invasive testing - which requires disassembly and a step-by-step root-cause-analysis of the mechanisms of the motor itself*
4. *Modification/Conclusion based on the invasive testing phase*

These phases are further broken down into 28 distinct steps in his questionnaire text, with numbering up to the third level. Although it is a methodology that could be regarded as fairly generic, A3 utilises a fair amount of specific technical and scientific detail in the questionnaire text. Step 2.1.4, for example, is 'monitor and measure differences (non-invasive), such as temperature, current draw, voltages, speed etc.' He indicates in the text that 'it was found that the motor brushes and brush holders varied in size (incorrect size) and this was causing the strange behaviour.' The approach in this case demonstrates strong discursive relations (DR+), and would be his approach to any fault reported on equipment (OR–) – hence displaying distinct *doctrinal insight*.

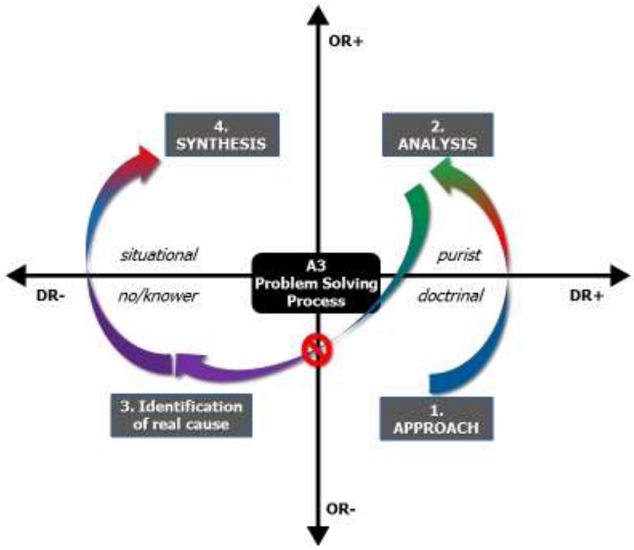


Figure 6-16 A3 Problem-solving process

6.4.3.2 Analysis

A3 describes the problem analysis (figure 6-16) in a rigorous, scientifically analytical and 'principled' manner, beginning with sensory observations. At every step of the explanation, he draws the schematic representation of the motor components, and explains the mechanical and electrical aspects with relevant mathematics and physics principles (figure 6-17).

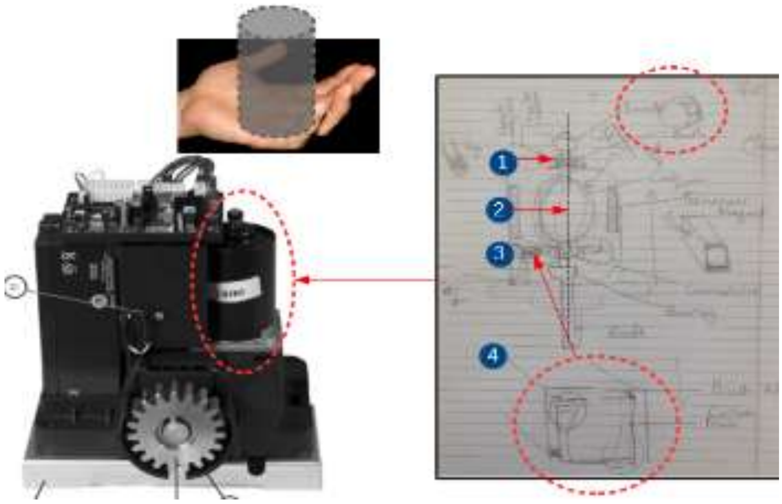


Figure 6-17 A3 Artefacts

When running the motor, he observed heat around the bush area (1). The 'bush' surrounds the motor shaft (2) and sometimes, if an inferior industrial adhesive is used, this can seep into the shaft and cause excessive friction (hence, heat). This is ruled out, and the shaft is next investigated. If the bearing is not held in place, 'then when it turns in one direction, the motor pulls up, so the whole shaft pulls up' (A3-79). This too is eliminated. The third concern was the 'brushes' (3): Upon inspection, it is discovered that the edges of the brushes (4) are irregularly worn. In other words, they are moving up and down inside the brush-holders and over time, since they are slightly too small, they are wearing down in an uneven manner.

> *'I wanted to try and understand why it's doing this? You know the normal set up of this motor … the wires go in, up through the coil and from the coil down into the armature and then the brushes… touch the commutator and then it magnetises the coil. …The 2 permanent magnets opposing it… generate a magnetic field onto the commutator.' (A3-36)*

He continues explaining the various tests conducted, maintaining strong ontic relations (OR+) and discursive relations (DR+). When he checked the dimensions of the brushes and brush-holders, having observed the irregularly worn brush edges, he discovered them to be incorrect. The gap was 'much larger than in other motors' (A3-99). (Note, the 'gap' is around 1mm.) The real cause of the problem was the supplier's decision to purchase brushes from a different supplier, who had elected to cut costs by trimming 1mm off the specified dimensions. The complete analysis demonstrates both legitimate procedures in reference to tightly bounded objects, hence a *purist insight* (OR+, DR+).

6.4.3.3 Synthesis

Solving the problem was an entirely different matter, and required a considerable shift in perspective. From the outset, a number of additional 'design and manufacturing' problems were emerging, and A3 engaged in months of communication with their Asian suppliers. Once he had discovered the incorrectly sized brushes:

> *'I then contacted them and they did tests while I was compiling my report (on our testing), and they claimed their tests showed everything was working fine…Their engineer said it can't be the brushes because the brushes don't influence speed. They sent us lots of beautiful graphs which made no sense at all!' (A3-166)*

He explains that it has been really difficult to communicate with their Asian suppliers, and it would appear that the engineering practitioners on either side view the 'science' differently. A key illuminating moment during the interview was when asked if the problem was caused by human error, A3 insisted 'No, it was a deliberate design change ignoring our specifications'. Despite this statement, the real cause of the problem lay in a decision taken by people. This fact, and the subsequent 'argumentative' engagement with those people, indicates a distinct *knower* phase in the problem-solving process. The interim solution to replace the existing brushes with a local alternative (at great expense to the company) demonstrates the synthesis of a solution based on *situational insight*.

6.4.4 Problem structure

The problem at a theoretical level would be classified as falling within the domain of 'electro-mechanics', with a specific theoretical focus on electromagnetism, motion, friction and materials. These are all underpinned by the physics of forces and energy - classic hierarchical knowledge structures – together with mathematics. A3's systematic explanation of the invasive investigation follows both a visually 'vertical' route through the motor as well as a hierarchically layered analysis starting from the excess heat as a symptom through the motion that generated the heat to the friction (and irregular wearing) of the brushes. Situated within standardised company protocols (*doctrinal* logic), the approach and analysis indicate strong discursive relations (DR+) and, where appropriate, strong ontic relations (OR+).

The dilemma upon discovery of the incorrect brush size, however, forces a movement towards weaker discursive relations (DR–) that are entirely contextually determined:

> *'Well, [laughs] the [Asian nationality] - it's hard to communicate, be it the language or the fact that they kick out so much that they are more concerned about quantity and not quality.' (A3-173)*

The problem in the broader context is harder to solve than the purely physical or theoretical problem in the 'contained system' itself. The journey into the *knower/no insight* quadrant has no accompanying protocol, and is in fact ineffective, requiring an interim *situational* solution.

6.4.5 Boundary navigation

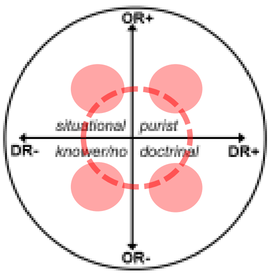
A3 navigates the knowledge forms with strong discursive relations (DR+) very well (and is clearly theoretically strong), but encounters a definite code clash when the discursive relations weaken (DR–). He is surprised that the suppliers even question the physics-based findings. An indication that the movement into the *knower/no* quadrant represents a distinct code clash for this practitioner lies in his insistence that 'no, this was a design change' when questioned about 'human error'. In other words, the focus on stakeholders or people in the problem situation is not accompanied by a recognisable shift to strong social relations (SR+), where 'kinds of knowers and ways of knowing' (Maton, 2014) are taken into account. This is ironic given the amount of literature and anecdotal evidence on East-West cultural challenges in economic exchange practices, particularly in engineering businesses. The fact of the company's recent shift to an ostensibly *knower*-orientated position (the profiling of all staff on their website) suggests an attempt to solve what are clearly social relations related operational inefficiencies. Further evidence of A3's preference for stronger discursive relations lies in the fact that the *situational* solution (OR+, DR–) was also not ideal, and he reports that 'we insisted they change it back - in our report were the new dimensions' (A3-168). This problem complexity rating (18) pushes it into the lower end of the 'complex' domain as a result of the stakeholder range and consequences criteria.

6.5 Case study A4: Problem in context

The comparative case study for the Contained Systems category is situated at a medical device distribution and maintenance company in the Western Cape. A4 works as the primary technician at this small (<20) branch of an international firm. He is responsible for liaising with all medical centres (hospitals, clinics and practices) across Africa where their devices are used, and for repairing those devices. In the event of a serious software problem (the programming of a specific unit), the devices are shipped to the European head office. The problem in question is the electro-mechanical malfunctioning of a device which doctors and clinics use to conduct infectious disease testing. The malfunctioning of devices is reported via standard procedures to the closest centre (in Africa, it is the company in question). The technician (A4) determines whether he can assist telephonically or whether the device needs to be couriered to the service centre itself. In this case, a particular device was returned to the company by a national clinician. The mechanism opening and closing the device had jammed as a result of a swollen battery. This, in turn, was caused by the device not being charged correctly. The analysis was conducted following a standardised and extensive device receipt, decontamination, external investigation and disassembly protocol.

6.5.1 Problem environment

The small local branch consists of a distribution room, training venue, and separate offices for HR, sales and training personnel. The technician, A4, has an entire wing to himself which consists of separate, sequenced office spaces arranged according to the maintenance process: receipt of faulty equipment, decontamination, non-invasive testing, invasive testing and repair, and a return 'station'. This office arrangement was established by the technician himself in conjunction with the local branch manager. The environment is thus strongly classified (C+) and processes are strongly framed (F+). However, the practitioner was accorded the freedom to establish a more rigorous system.



(Problem environment & problem solver)

A key feature of the company is their consciousness of their brand and the associated values. Their website and premises announce their allegiance to sound scientific, professional and moral principles. The large, colourful, scientifically-detailed device illustrations and inspiring 'protocol' posters succeed in contextualising both the science and the protocols from a human (*knower*) perspective through the use of several 'real' case studies of successful medical care as a result of using their devices. The *insight* orientation of the company as a whole, and the branch itself, suggests a holistic one.

6.5.2 Problem solver

6.5.2.1 General profile: cognitive, experience and mood

Probably one of the (many) highlights of my experience as a researcher on this project was my interview with A4. I arrived to be warmly welcomed into the company's training venue/ boardroom. A4 had placed refreshments and high-quality company stationery in the training venue (for my use). He then politely asked whether or not I minded, but he had drawn up an agenda for us, with specific amounts of time allocated to the various activities. The process started with introductions to each of the small company's one-person departments and was followed by a 'problem-solving process' tour of his wing. I was struck by his charming confidence and professionalism, and it was clear he is well-regarded by his colleagues. A high achiever across all theoretical subject areas, the 26-year-old French-speaking participant had not only worked throughout his studies, but had also (it emerged during the interview) engaged in numerous additional online learning courses. My first impression was that if ever there was an ideal 'match' between a problem solver and his/her environment, this was it.

Table 6-5 A4 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
A4	26	M	B	Fr	89	75	89	58	B-Tech 4yrs	1yr	Y	International, from central Africa

6.5.2.2 Analytical profile: discourses, semantics and insights

6. The device was switched on to verify whether the door will open properly or not. The door did not open properly and a beeping was coming out of the device. The beeping indicates that an axis is not initializing and since the door did not open properly, the first assumption before opening the device is the y-axis that is not initializing.
7. The device was disassembled. Once disassembled, sequence 6 was repeated to find where the problem was coming from. From visual inspection, it was definite that it was the motor of the y-axis that did not operate properly.
8. Through sequence 6, it was also identified that the power did not last for more than 15 minutes.
9. The battery was replaced.
10. The optic which is responsible of taking images when the XXX count test occurs was realigned and the focus was adjusted.
11. The device was validated according to international standard (ISO-XXXXX) and returned to client.

The problem-solving thinking will be explained per sequence.

1. When the customer contacts me, the primary target is to take away his pain. By establishing a relation of trust, this allows me to take away his pain for the first minutes of the conversation and allows me to establish a proper communication for data acquisition. Study has proven that a stressed customer will deliver inaccurate data thus leading me to spend more time asking questions and spending more

Figure 6-18 A4 Sample text

Speaking hardly any English when he first arrived as a student in 2010, I was struck by his phenomenal adoption of industry-specific discourses. His entire demeanour speaks of having absorbed the company 'way of being'. He had responded immediately to the questionnaire request and had submitted a detailed, sequential breakdown of his problem context, stakeholders and problem-solving process (a sample is presented in figure 6-18).

The semantic code analysis (figure 6-19) reveals a predominant *prosaic* code (SG+, SD-) attributable to his experience with customers. He ensures that he does not alienate the participant through the use of dense technical terms, and adopts this approach with me as researcher, without being at all patronising. His supervisor confirms that this general approach is due to A4 being surrounded by non-technical personnel. A4 shifts naturally between the technically-specific details and simple contextual explanations.

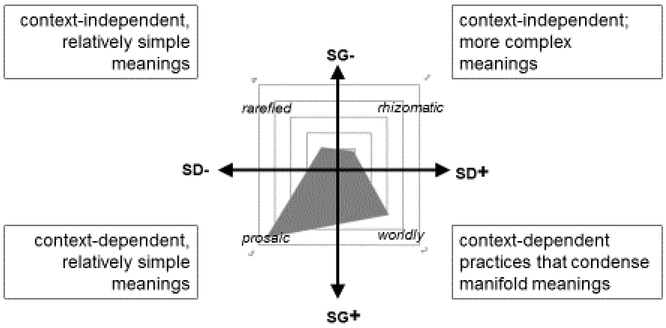


Figure 6-19 A4 Semantic code

6.5.3 Problem-solving process

6.5.3.1 Approach

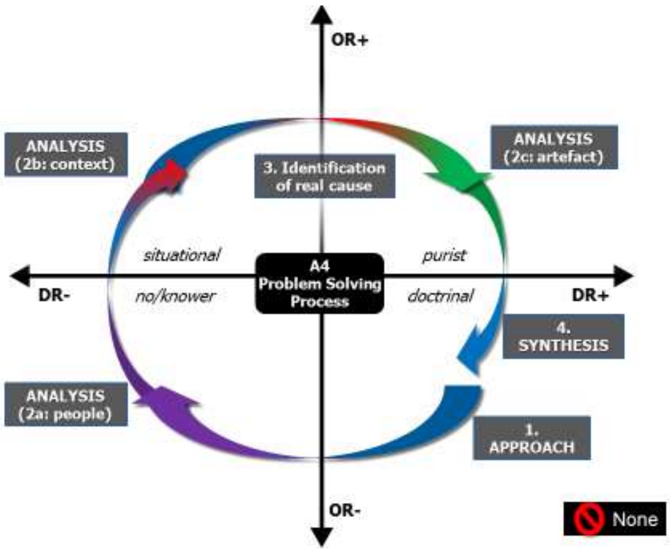


Figure 6-20 A4 Problem-solving process

A4's approach to any process - whether completing the questionnaire, preparing for our interview or working with customers – suggests a holistic cycle (figure 6-20) underpinned by appropriate protocols. In all cases, he first takes the people into account (as with his welcoming of me as researcher) and the 'situational' context before considering the focus of the conversation or problem.

In both the questionnaire and interview, A4 confirms that establishing a relationship of trust with the customer is vital:

> *'When the customer contacts me, the primary target is to take away his pain. By establishing a relation of trust, this allows me … for the first minutes of the conversation …to establish a proper communication for data acquisition. Study has proven that a stressed customer will deliver inaccurate data.' (A4-110)*

This 'data acquisition' means ascertaining the exact context. Context is important. For example, if the customer is in the Free State, then A4 knows a common problem is that 'the area is very sandy, so the first thing is… to check that the gears are clean' (A3-60). Understanding the stakeholder and context enables a more informed focus on the epistemic nature of the problem, and subsequently the appropriate protocols. The basis of his approach as a whole shifts around the epistemic plane as the focus of his analysis shifts, and similarly the strength of the discursive relations shifts. I am tempted to regard A4 as a *purist* in the broadest sense in that his approach to any aspect of the problem acknowledges that there are 'principles' and associated 'procedures' whether they be disciplinary or social in nature.

6.5.3.2 Analysis

The analysis at an epistemic level, once he has established the nature of the stakeholder and situation, proceeds with methodical and analytical depth, demonstrating strong ontic relations (OR+) and discursive relations (DR+). He follows a routine 'structure – power – control' process, beginning with examining the physical artefact to determine if there is structural damage. Then he moves on to power:

> *'For example, I know it's a power problem when the instrument can't switch on - then I know, based on the circuit, that I have to start there. The problem could be the transformer… or one of the modules could not be allowing the device to charge.' (A4-49)*

The device in question when assessed externally revealed a 'structural' problem caused by a 'power' problem: The door could not close properly. He re-enacts the problem in the allocated venue:

> *'The first assumption before opening the device is the y-axis is not initialising… By disassembling the device, I … was able to visualise and see where the problem was coming from… I opened the location of the battery and saw that [it] was swollen…. [this] had caused a strain on the displacement of the y-axis thus causing one of the motors to fail.' (A4-103)*

6.5.3.3 Synthesis

The synthesis of a solution in this case was quite straightforward: 'The battery was replaced' and a recommendation made to ensure the customer followed an improved battery recharging process. The solution is accompanied by a *doctrinal* device validation process according to international standards (ISO), and returned to the client according to FDA (Food & Drug Administration) and WHO (World Health Organisation) procedures.

> *'If a device is faulty, everything gets logged onto the WHO and they can track any faulty device and know whether it is the technician who destroyed the device, or if it wasn't repaired properly.' (A4-33)*

6.5.4 Problem structure

The problem structure - if taken in the holistic context – moves from the weak horizontal knowledge structures associated with socio-cultural contexts (different customers and their situations) to the hierarchical knowledge structure of physics underpinning electro-mechanical functioning in relation to mathematical concepts underpinning motion along different axes. The technical problem is governed by strong ontic relations (OR+) and associated discursive relations (DR+), in other words *purist* in nature. The knowledge frameworks within this domain on which A4 is able to draw include force, motion, electromagnetism and mathematics. However, in this case, analytical depth is not necessary as the problem announces itself visually and structurally, and he is not required to repair the battery. During the interview process, however, A4 demonstrates a sufficient range of sample problems (including logic-based problems) he has encountered and successfully solved to date (corroborated by his supervisor). This indicates a solid conceptual grasp of the fundamentals of the associated disciplinary bases.

6.5.5 Boundary navigation

What was evident – and unanticipated – in this case was the apparent lack of challenging code shifting or any visible sign of a code clash. His supervisor stated that A4 solves all problems 'very well… partly because of the kind of person he is. He is both analytical and intuitive'. A4 navigated the various aspects of his professional environment with ease, shifting seamlessly between strong and weak ontic relations and discursive relations. A common feature of the international graduates of the programme in question has been a particular difficulty in adapting to the technical/practical requirements of working environments. This was not evident in A4's case. What is most notable in the case is that when the problem-solving process shifts into the *knower/no insight* (OR–, DR–) quadrant, the shift is towards strong social relations (SR+), valuing the customer as a particular kind of *knower* with legitimate ways of knowing.

The level of problem-solving complexity (16) is at the upper end of the second, technologist, band.

6.6 Category A: Comparisons and discussion

As a brief reminder, the focus of this research is to ascertain problem-solving patterns in comparable mechatronics engineering contexts, and how different forms of disciplinary knowledge (which represent different kinds of 'code') are navigated. The aim is to identify code-shifting challenges and possible code clashes. The four preceding case studies in the Contained Systems category entail forms of disciplinary knowledge more closely situated within the physics-based domains of 'control electronics' and 'electro-mechanics'. Despite the commonality of both knowledge domains and systems category, each case study offered a distinctly different problem-solving trajectory as represented on the relevant case-study epistemic planes. Why are the problem-solving trajectories so different? I will examine these differences according to the KPE features.

6.6.1 Problem environment differences

A key feature common to all four is the availability in their environments of mentors, support and access to the local *reservoir* of expertise. A significant difference, however, is in the classification and framing. A1 and A2 are situated within a weakly classified and framed environment that affords them greater autonomy (C–, F–). In contrast, A3 and A4 are operating under more regulated, strongly classified and framed working conditions (C+, F+), as well as being required to engage with a larger number of stakeholders. This difference manifested as a fuller problem-solving cycle in the A3 and A4 cases. As was established in chapter 4, the greater the number of stakeholders and processes, the more likely there is to be strong classification and framing of the environment. This implies the availability of codified *doctrinal* protocols (OR–, DR+) that may dictate the necessity to move beyond the epistemic heart (OR+, DR+) of the problem from a disciplinary perspective. In other words, it is not the classification and framing of the environment that dictates a broader problem-solving process. Rather, it is the scale of the problem that dictates the classification and framing of the environment.

6.6.2 Problem-solver differences

An entirely unanticipated finding was the relationship between the case-study cognitive profiles and the problem-solving processes. The first observation is that the higher the academic performance, the fuller the problem-solving process description and cycle. A second observation, and in fact an absolute anomaly, is the corresponding performance in both mathematics *and* logic in three of the four case studies in this KPE category (figure 6-21). Furthermore, A3 and A4 are representative of a mere 2.9% of a 290-mechatronics student cohort analysis who achieved distinctions for *both* mathematics and logic. One of the driving forces behind the research is a desire to understand the dichotomous or bi-nodal academic performance pattern that emerges between these two knowledge structures in this region.

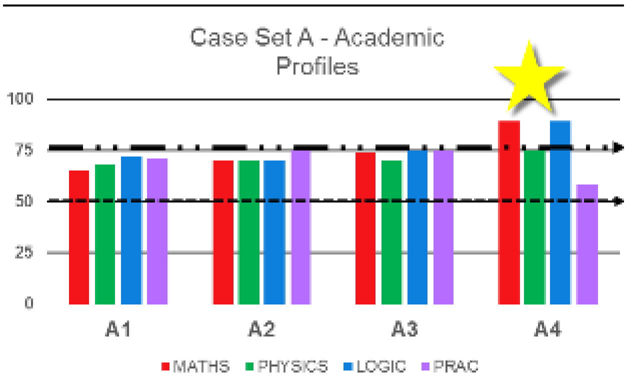


Figure 6-21 KPE A Academic profile comparison

By far the most common pattern is the 52% of students who barely pass mathematics (many after repeating) and yet achieve high distinctions for the logic-based subjects. The positive feedback from industry on the success of this latter category of graduates seemed to demand an investigation into how these technicians work with knowledge, given the common assumptions about mathematics as an engineering 'fundamental'. I had been sceptical about this assumption, but my data - following the first KPE category analyses - were beginning to say something about the value of mathematics with respect to the possible 'structuring' effects of knowledge. At a literal level, A4, in particular, produced a well-structured, responsive and insightful 'problem-solving process' research experience.

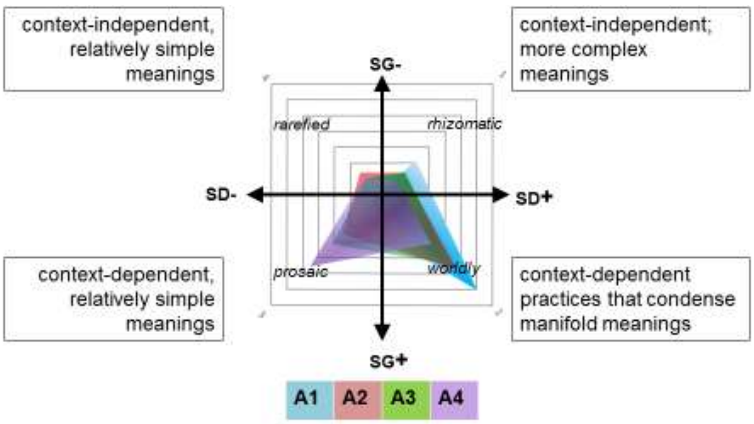


Figure 6-22 KPE A Semantic code comparisons

The semantic code comparison reveals a high number of *worldly* (SG+, SD+) references as is to be expected in technical professions. However, placed in relation to each other (figure 6-22), what emerges is a greater number of *prosaic* references from the case studies with higher mathematics *and* logic marks (A3 and A4). In other words, the ability to move comfortably between a strong horizontal knowledge structure (mathematics) and a weak horizontal knowledge structure (logic-based) appears to be reflected in the ability to navigate comfortably between complex and simple meanings.

6.6.3 Problem-solving process comparisons

It is here that the most striking impact of the relationship between academic performance and problem-solving description becomes evident. Across the four case studies, the higher the mathematics *and* logic marks, the more analytically detailed the problem-solving descriptions. In both A3 and A4 cases, the participants presented methodical, appropriately technically detailed problem-solving descriptions. They share the *insight* orientations of their environments, and both proceed from a *doctrinal* position, with clearly well-established procedural protocols in place. Where they differ is that A4 proceeds in clockwise fashion around the epistemic plane, first analysing the stakeholders and context – which requires weak discursive relations (DR–) - before moving into the heart of the problem from a *purist* perspective. A3, in contrast, proceeds to the science underpinning the problem (OR+, DR+) without having considered the broader context of the stakeholders implied in the problem. This necessitates an uncomfortable detour into weaker discursive relations (DR–) terrain when he is required to deal with the real cause of the problem – international supplier decisions. A4 is the only case study in this category where there is no evident code clash. The remaining three all present code-shifting challenges or actual code clashes along the discursive relations axis (between DR+ and DR–). This is significant in that I would like to suggest it equates with the difference between the strong and weak horizontal knowledge structures as represented by mathematics and logic. The evident discursive relations (DR) axis code clash is supported by the quantitative findings regarding dichotomous academic student performance in these two subject areas.

6.6.4 Problem structure comparisons

There is no comparison between any of the KPE A case-study problem structures except for the fact that they all occur in the context of a controlled electro-mechanical contained system. Where the focus of the problem is underpinned by a particular physics element, in all cases prior knowledge of the requisite disciplinary fundamentals was not only necessary to solve the problem, but was available *a priori*. Where this was not readily available (A1), the problem was more difficult to solve. In contrast, where the focus of the problem was a particular logic-based technology, this knowledge could only be gleaned through engagement and experience – whether that of the practitioner or the available *reservoir*. However, given that only A2 (and A1 to a lesser extent) was challenged with a logic-based problem, I shall refrain from elaborating on this in this chapter. The problem complexity ratings for A1, A2 and A4 fall within the ‘technologist’ or ‘broadly-defined’ band, whereas A3 lies in the ‘complex’ band.

6.6.5 Closing word on KPE A case studies

Briefly[69], this chapter has presented an analysis of four Contained Systems case studies occurring in two small KPE contexts, namely an access control company and a medical device company. A comparison across the KPE features reveals that such environments are generally more weakly classified and framed, entail more support, and allow for greater practitioner autonomy. This appears to enable the practitioners to begin the problem-solving process from their natural *insight* orientation. Where practitioners engage with external stakeholders, there are usually *doctrinal* procedures governing processes. There appears to be a relationship between higher academic performance in both mathematics *and* logic, and the articulative capacity to detail the problem-solving process using a broader range of references. The problem structures are generally located closer to the physics-based knowledge areas, requiring access to *a priori* physics principles. The most common code-shifting challenge occurs on the discursive relations axis between ways of approaching the phenomena that are legitimately accepted as ‘fixed’ (DR+) and multiple possible approaches (DR–). There is no emerging pattern applicable to this KPE category.

[69] Chapter 9 will consolidate and discuss the data analysis chapters.

CHAPTER 7: CASE STUDIES – CATEGORY B – MODULAR SYSTEMS

7.1 Introduction

As detailed in chapter 4 (sections 4.5 and 4.6), Modular Systems consist of a number of sub-systems which together fulfil a specific process activity. Such a set of sub-systems is commonly referred to as a 'machine' and one or more can make up a production line in manufacturing environments. There are two kinds of mechatronics engineering practitioners who work with Modular Systems: machine builders – who conceive, design, manufacture, install and often maintain such machines for an external client – and systems integrators – who design, implement and also maintain ways to connect existing manufacturing systems through the use of additional sub-systems and a central control system. The practitioners in the former category work in teams and usually have a dedicated machine-building site, but their work also entails travelling to and working at the site of installation. The latter category sees practitioners – often working individually - moving from client to client in manufacturing and production environments that range from small to large companies, where anything from automotive parts to beverages to chemicals is produced. The design and programming of the integrated system, however, can take place anywhere.

The key challenge in systems integration is linking different electro-mechanical processes to each other by way of a control system, which has two features: the visible layer (hardware) and the invisible layer (software). The sub-systems and components may all have different origins and different possibilities for integration. The central control system needs to send and receive signals and data from all the sub-systems, which may have their own forms of internal control. However, compatibility is a major issue. Imagine a United Nations meeting with all the major and minor global languages represented. In order for everybody to understand all speakers, there are interpretation and translation processes occurring simultaneously. Not only can these be literal translations, but the interpreter needs to be sensitive to the unique ways in which certain concepts are understood in certain cultures. This is the nature of the systems integrator's challenge: enabling all the physical (hardware) elements in the system to communicate (via software) as required so that the electro-mechanical processes can take place efficiently and automatically.

The four case studies selected for this category represent both machine builders and systems integrators (figure 7-1). However, two further distinctions have been introduced: commercial versus R&D. For the purpose of this research, two machine builders and two systems integrators have been selected, one of each in both the commercial and R&D categories. Effectively speaking, however, they all see themselves as systems integrators.

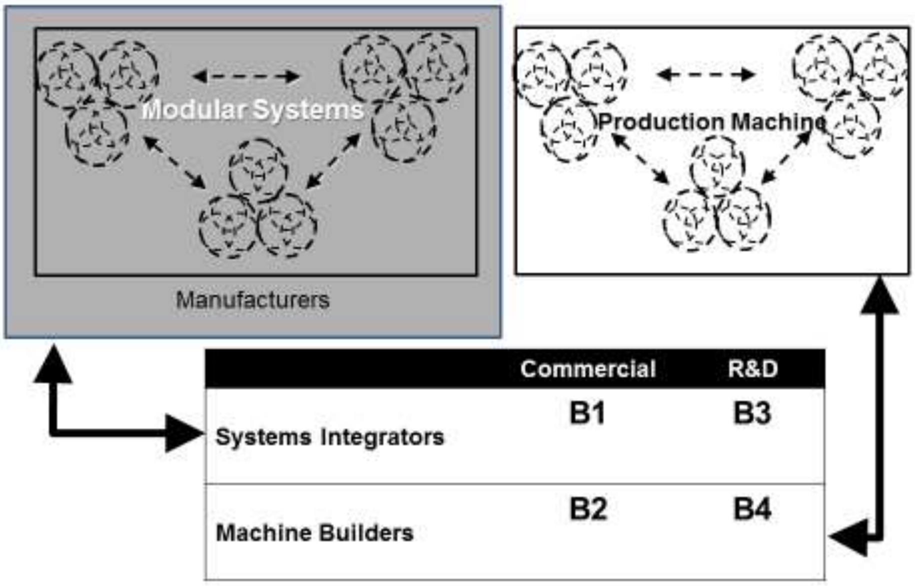


Figure 7-1 KPE B Case-study allocation

7.1.1 KPE B: Commercial and R&D environment descriptions

Each practitioner in this category works for a different commercial company or R&D institute. All their work is regarded as project-based, and thus cyclical. The client environments for which machines are being built or in which systems are being integrated are all strongly classified and framed (C+, F+) manufacturing environments with production deadlines, such as those in the KPE C Distributed Systems category (chapter 8).

Table 7-1 KPE B All case-study companies - Classification & framing

Classification & Framing		Commercial		R&D	
Knowledge area focus		Electro-mechanical, PLC programming, context-specific systems and process requirements			
Business size category		Small - Large		Micro - Very small (<20)	
Classification	Space	C^{+}	External traditional manufacturing sites, with strongly classified areas of operation	C–	Smaller shared design offices and brainstorming hub
	Stakeholder relations	$C^{+/-}$	External consulting Systems Integrator liaises with the client team (usually differentiated); daily/weekly informal and formal verbal status updates; technical documentation	C–	More lateral, small teams; informal, verbal and frequent communication between team members; research-type documentation/reports
	Time	$C^{+/-}$	Medium-project orientated work cycles; new/changing project briefs; specific phase and deliverable deadlines established, but flexible activity duration during phases	C–	Small-project orientated work cycles; changing briefs based on research development; broad deliverable deadlines, but flexible activity duration
Framing (external)	Pace	F^{e+}	Client-driven	F^{e-}	Practitioner-driven
	Criteria	$F^{e+/-}$	Dependent on type of product (medical, chemical, automotive = F^{e+})	F^{e-}	According to standard component/ usage specifications, but innovation-driven
	Control	$F^{e+/-}$	Dependent on type of product and nature of company	F^{e-}	Autonomy and innovation orientated

However, the environments in which the research and development of the machines/systems is being conducted (table 7-1) are similar to the Contained Systems category (chapter 6) in that the work is innovation-orientated and sees a greater deal of flexibility. The scale of these machines or systems, however, is such that classification of space may be stronger than in KPE A. Stakeholder relations in the R&D category are more lateral, and framing over pace, criteria and control is relatively weak (F–). In other words, there are two Knowledge-Practice Environments implied in category B. On the one hand, each practitioner works for a specific consulting company or institute which regards certain *insight* orientations as the legitimate basis for their nature of work. However, each client represents a different *insight* orientation. The practitioner is required to navigate between the values as manifest in operations in two different KPEs. This chapter presents an analysis of the four Modular Systems case studies (figure 7-2), beginning with those in the commercial sector and followed by two in the R&D sector. The knowledge domains entailed in this category (figure 7-3) are predominantly logic-based. Following the individual analysis of each, a discussion section summarises key features that emerge from a comparison across the case studies.

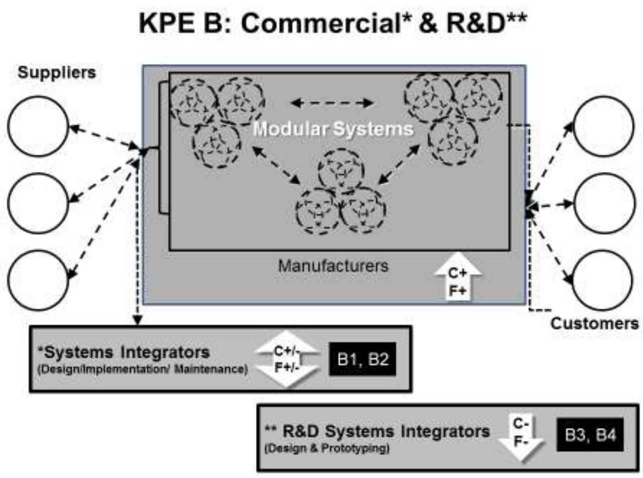


Figure 7-2 KPE B Layout & classification

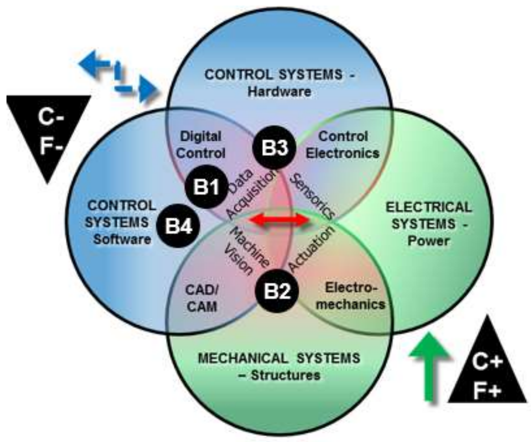


Figure 7-3 KPE B Case-study domains

7.2 Case study B1: Problem in context

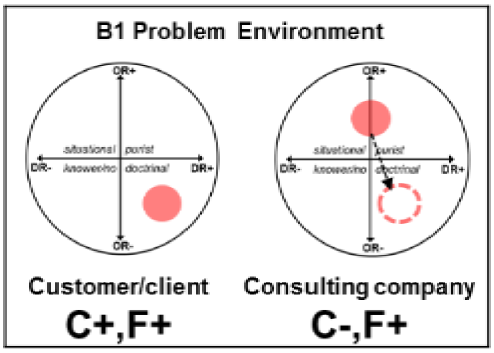
At the time of the interview, B1 worked as a systems integrator for a large (6000+) multi-facetted communications company. The South African-based company had recently (2013) bought several smaller local, regional, national and continental IT-based independents and consolidated its business under one umbrella. B1 had been employed at one such small branch of a national systems integration company. His role in the local systems integration unit of the new company remained unchanged: the needs-analysis, design and implementation of communication interfaces between existing processes for food and beverage processing clients. Such work is largely computer-based, requiring the reprogramming of existing systems to include new features.

The problem in question is situated at a large food processing plant and required the automation of information between the packaging and distribution departments. Practically-speaking, packaged food products leave the packaging department on pallets on a conveyor system. These pallets carry barcoded identification to indicate type, quantity and quality checks. Previously, each pallet would be scanned manually – much in the same way a supermarket cashier scans purchases. In order to improve efficiency and centralise all product data, this manual scanning process is redesigned to be automated using a 'fixed line scanner' mounted on the conveyor system. The information from the barcode scan is sent via a specific kind of cable to a local personal computer (PC), and from there to the central data management system (SAP) where all product and distribution information is stored. B1 has integrated the automated scanning system using the original PC, but the pallets are being rejected as the SAP system is not receiving the full barcode:

> *'The bug that I identified is the PC app is splitting up the barcodes that are being sent which means that SAP returns with a message to say invalid barcode.'* (B1-7)

Why the PC application is splitting the barcodes could be due to several reasons: the application itself, the cable 'port', or the SAP programme. Instead of wasting time doing a root-cause analysis, B1 removes the PC, its barcode application and the cable from the problem, and integrates a small module with which he has had significant prior experience, and which scans the barcode and sends the information directly to the SAP system.

7.2.1 Problem environment



As established in 7.1.1, the client's food production environment is strongly classified and framed (C+,F+) and the driving principle is meeting production targets as efficiently as possible. B1 is expected to solve the problem in the most effective, sustainable way with the shortest loss of productivity. B1 works in multiple spaces, and has greater flexibility in terms of stakeholders and time.

The dominant *insight* orientation of the client environment is *doctrinal*: standardised and regulated food processing, packaging and distribution systems that are required to function responsively and competitively in the supply chain between raw materials and consumer distribution outlets. The dominant *insight* orientation of the local consulting company would originally have been a *situational/purist* orientation: custom-designed integration solutions based on feasibility and sound scientific principles. However, the newly formed massive communications company – by sheer virtue of its size and recent stock-exchange listing – has seen a concomitant strengthening of framing over pace, criteria and control. At this early stage, I predict an increase in documentation and reporting standardisation, which implies a shift to weaker ontic relations and stronger discursive relations (OR–, DR+). However, B1 hails from an OR+, DR–/+ environment – custom-made, technically sound solutions for clients – and at the time of the interview, this was still the problem-solving ethic.

7.2.2 Problem solver

7.2.2.1 General profile: cognitive, experience and mood

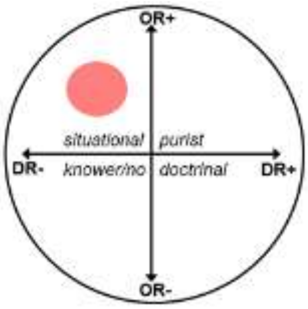
B1's cognitive profile, based on academic performance, is the norm for the majority of successful graduates on the originating programme. A low pass in mathematics and the physics-based subjects, and an adequate 70% for the logic-based subjects. A self-declared 'non-academic' practitioner, his forte lies in engaging practically with the latest technologies, specifically communication systems.

B1 had more than a year's technical work experience prior to his studies and had attended a technical school. He continued to work throughout his studies, and was quickly appointed for his in-service training period by a very small systems integration company which also acted as sole agent for a particular range of imported technologies. He received frequent specialised training in several hardware and software solutions during his time at the first company. Unhappy with the working conditions, however, he joined the second company (research site). Shortly after the interview, B1 left the second company and joined a third, smaller custom-orientated systems integration company. At the time of writing (2015), B1 has worked at three different companies in five years. He has the broadest range of experience of all the participants, and is highly regarded as an effective problem solver. However, he is most effective with more autonomy, and I suspect the shift from the second company was not only for financial reasons, but also in response to the increase in regulation and accompanying managerialism.

Table 7-2 B1 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
B1	27	M	W	A	54	52	70	78	B-Tech 4yrs	4yrs	Y	Technical high school and prior work experience; has worked for 3 different companies over past 5 years.

7.2.2.2 Analytical profile: discourses, semantics and insights



I have a client at [redacted] that needed to be able to Stop pallets from going to the warehouse if it has not been scanned in by the fixed line scanners. I have installed and commission the solution\design that I gave him. With my solution I have identified a bug in there plant that is actually in all of their plants currently. What is happening is the barcode that is scanned is being sent to a pc via RS232. On the PC there is a custom app written by someone that looks at all the RS232 ports and waits for the barcode. If it receives a barcode is initiates a SAP transaction to create a transfer order so that the pallet can be transferred to the warehouse.
The bug that I identified is the PC app is splitting up the barcodes that is being sent which means that SAP return with a message to say invalid barcode.

Figure 7-4 B1 Sample text

B1's *situational insight* orientation is clear from his claim that most of his work is 'trial-and-error'. The questionnaire response (a section of which is in figure 7-4) is brief and includes a computer-generated sketch (figure 7-5). There is no indication of an attempt at discipline-based analysis. Unable to visit the client site, the problem-solving explanation is supported by photographs and diagrams.

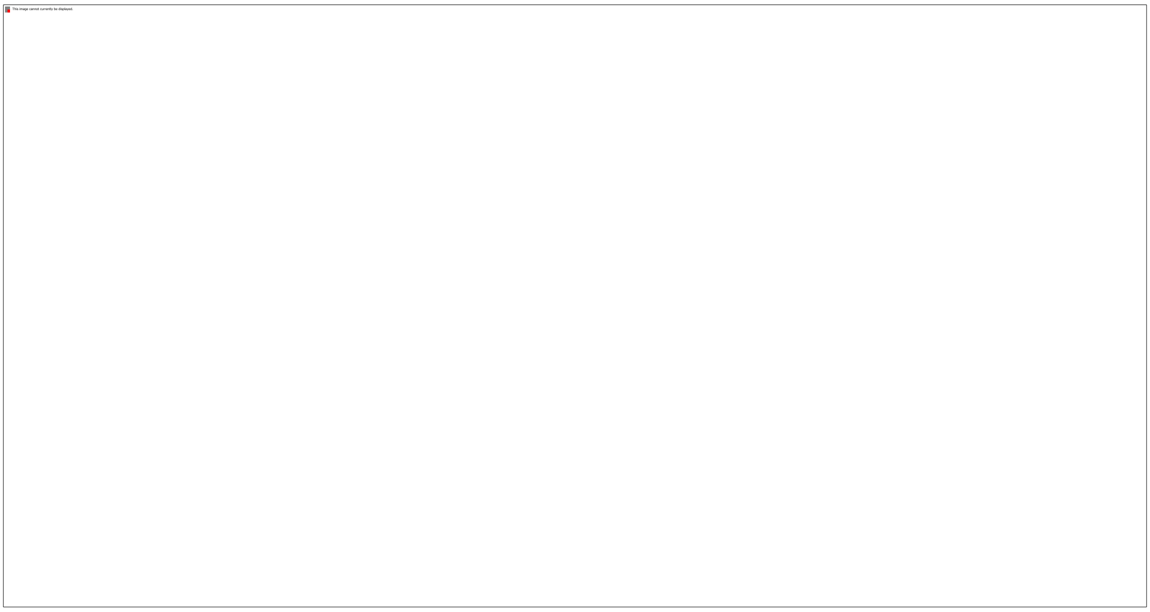


Figure 7-5 B1 Artefacts

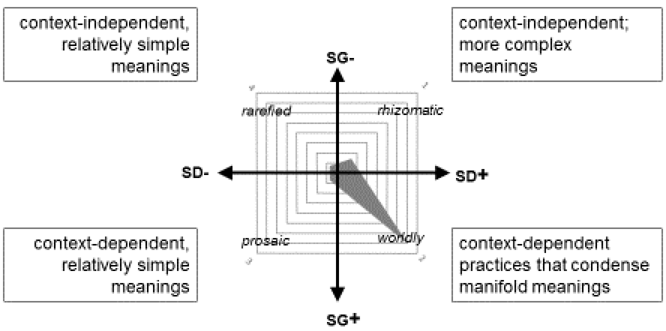


Figure 7-6 B1 Semantic code

The entire explanation is relatively procedural and technically specific. An analysis of his textual and interview contributions (figure 7-6) reveals the least elaborate problem-solving details of all the case studies, and predominantly *worldly* references.

7.2.3 Problem-solving process

7.2.3.1 Approach

B1's approach is always *situational*. Each client represents a new situation with unique attributes. This client requires automated scanning of the barcoded product pallets, and the information to be integrated into their central product information system. The first step is to examine the premises and existing system information. Based on this, B1 integrates the new barcode scanning system, but the SAP system returns a message saying 'barcode invalid'.

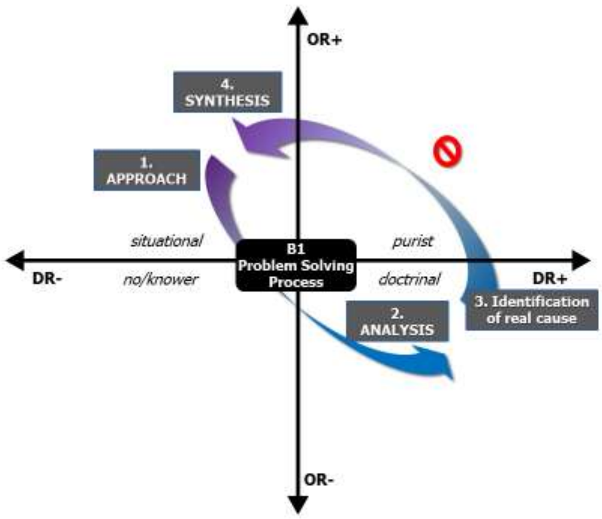


Figure 7-7 B1 Problem-solving process

7.2.3.2 Analysis

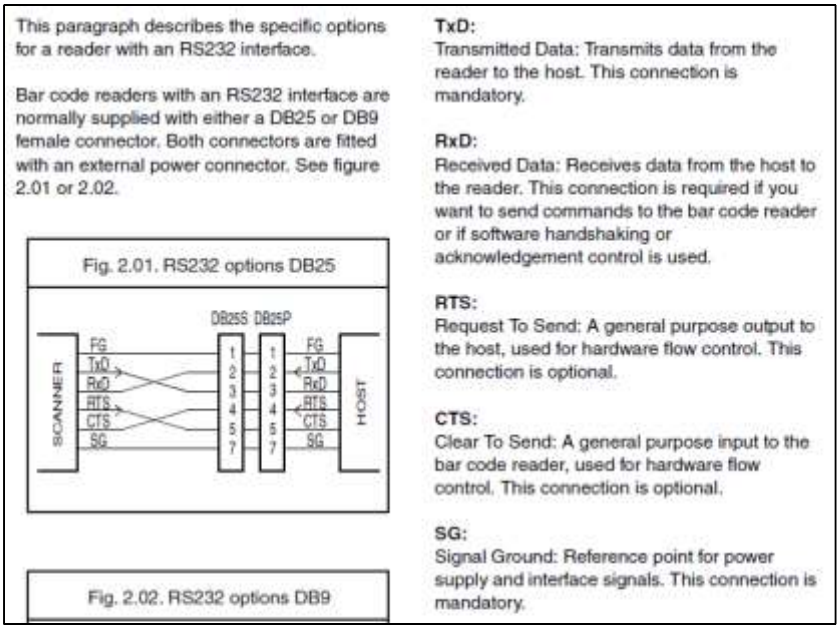
The analysis proceeds with a *doctrinal* (OR–, DR+) description of how the system is set up to work, and could also be applicable to any such system using the same components:

> *'The barcode that is scanned is being sent to a PC via RS232. On the PC there is a custom app* ***written by someone*** *that looks at all the RS232 ports and waits for the barcode. If it receives a barcode, it initiates a SAP transaction to create a transfer order so that the pallet can be transferred to the warehouse.' (B1-4)*

He did identify that the 'barcode invalid' messages were as a result of the barcode arriving 'split up' at the SAP end. He does not engage with the issue that this was 'written by someone', and, at the time of the interview, he had still not identified why the barcodes were split up:

> *'I am currently investigating where the bug in the system is. It could be in the RS232 port hub or the custom app or even in the SAP transaction.' (B1-8)*

B1's entire problem is logic-based. It is a matter of understanding *what* is connected to *what*, and *what* is 'speaking to' *what* in *what* language and with *what* rules. These rules are not standardised, and are dependent on suppliers of the specific components. The sample explanation from a barcode reader manual (figure 7-8) demonstrates the nature of knowledge implied. The sample illustrates the connections between each 'pin' (connection point) on a specific kind of connector cable and that of the specific scanner. Each pin has a specific function, such as receiving data or sending data or sending requests. Such connectors have their own brand-based logic and naming systems.


This paragraph describes the specific options for a reader with an RS232 interface.

Bar code readers with an RS232 interface are normally supplied with either a DB25 or DB9 female connector. Both connectors are fitted with an external power connector. See figure 2.01 or 2.02.

Fig. 2.01. RS232 options DB25

Fig. 2.02. RS232 options DB9

TxD:
Transmitted Data: Transmits data from the reader to the host. This connection is mandatory.

RxD:
Received Data: Receives data from the host to the reader. This connection is required if you want to send commands to the bar code reader or if software handshaking or acknowledgement control is used.

RTS:
Request To Send: A general purpose output to the host, used for hardware flow control. This connection is optional.

CTS:
Clear To Send: A general purpose input to the bar code reader, used for hardware flow control. This connection is optional.

SG:
Signal Ground: Reference point for power supply and interface signals. This connection is mandatory.

Figure 7-8 B1 Barcode reader manual

It is important to differentiate here between the *situational* (OR+, DR–) nature of the possibility of using several types of connectors to fulfil the same function and the *doctrinal* (OR–, DR+) processes underpinning each type. Once the selection is made, each type of connector or component has standard procedural rules pertaining to itself, irrespective of the particular application and not necessarily governed by strongly bounded ontic relations. In other words, the component-specific rules (DR+) are not related to a specific principle that would hold across all such components, other than the fact that there needs to be a connection system that enables the components to function in relation to each other.

7.2.3.3 Synthesis

B1 knows that the cause of the problem is a procedural one: Somewhere in the communication system between the scanner and the SAP system, there is a line of code or a function that is splitting the barcode. However, it would take too long to retrace all the code pertaining to the different pin signals and the PC application. The simplest solution is a *situational* one: Remove as many unknowns as possible (the PC and the cable) and integrate a known sub-system with which he has prior experience (from his first company). There is no attempt to engage in a disciplinary analysis of each of the elements that may have given rise to the problem, as this would be a waste of time which would cost the company in productivity. The local consulting company supervisor was not *au fait* with the specific problem, but confirmed that not only had B1 satisfied the client's requirements, but he had also identified additional areas of improvement.

7.2.4 Problem structure

The problem structure is relatively simple, as detailed in the analysis section: the logic-based decoding of an existing connection and communication network as represented in figure 7-5. The system is physically connected through hardware, and these components are understood and visible. At a primary level, each link in the communication system is dependent on either electrical or electromagnetic signals (physics) being sent and received, according to mathematical patterns. This would usually be a starting point if there were any indication of messages not being communicated. This is not the case here. The problem lies at the code level – the invisible 'logic' layer. Practitioners in this position would be heavily reliant on the existing programme and schematic documentation. Even better, however, would be access to the person who wrote the code. B1 mentions that 'someone' wrote the custom application, but he does not know who the person is. Very often, the rush to meet production deadlines sees practitioners paying less attention to the documentation phase – particularly if they are not selling the product (machine). In other words, they rely on the collective or specific local *reservoir* to maintain or improve the system. This short-sightedness is exacerbated by the lack of standards for such documentation (DR–). The attempt over the past two decades – in the face of globalisation and the proliferation of such systems – to establish standards, such as IEC61131[70] marks a deliberate need to strengthen the procedures (DR+). However, the sheer scope and volume of available technologies, platforms and programming languages emerging as a result of rapid user-orientated development suggests the effort at standardisation may prove complex in the longer term. This is why practitioners often prefer to start from scratch and use what they know, moving from the *situational* requirements to familiar *doctrinal* procedures (OR+, DR– to OR–, DR+) if this is possible. The problem structure in this case is dominated by different categories of weak horizontal knowledge structures – the 'logic' behind the forms of communication in each component (PC application, connector cable, and the SAP system).

7.2.5 Boundary navigation

B1 establishes what is to be the most common feature of this category – the diagonal movement from the *situational* possibilities (OR+, DR–) to the *doctrinal* procedures behind a particular possibility (OR–, DR+). A second feature of this category is the seeming inaccessibility of disciplinary explanations of the causes of the problems. In electro-mechanical systems, the laws of physics are often visible or empirical: motion, heat, friction, and so on. In the domain of logic-based programming, although there may be general rules

[70] 'The International Standard IEC 61131 applies to programmable controllers (PLC) and their associated peripherals such as programming and debugging tools (PADTs), Human-machine interfaces (HMIs), etc. which have as their intended use the control and command of machines and industrial processes' (www.plcopen.org).

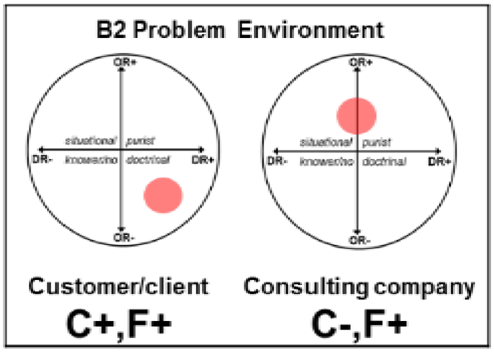
(as suggested by the development of standards), the reality is that 'standard industrial communication protocols are not necessarily as standard as we may think they are' (Interview B4). 'Interaction with a new technology marks an occasion in which much ambiguity and uncertainty exists' (Leonardi, 2011, p. 349). This in itself places the complexity rating – which in this case is 15 (technologist) – above that of the technician level where 'standard, codified' approaches are characteristic. B1's boundary navigation is essentially that along the discursive relations axis: the open-ended, multiple possibilities (DR–) and the specific *doctrinal* rules (DR+) pertaining to each selected component. The latter are further exacerbated by the particular discourse (culturally-framed), terminology (*knower*-orientated[71]), and standards (industry-regulated) informing the design team's discourse use. One might argue that a more disciplinary deconstruction of the problem (*purist insight*) could have led to the identification of the code problem, and while this would be appropriate and is indeed the practice in an R&D environment, commercial enterprises do not necessarily have the luxury of time for such analysis in the absence of component/system-specific expertise (Baird, Moore & Jagodzinski, 2000). B1's solution was appropriate and effective in this context.

[71] The choice of terms is influenced by *knowers* in the field of production. A smaller communication systems manufacturer may elect to align with the 'big players' and deliberately use terms suggestive of those players, with the intention of piggy-backing on the implied status.

7.3 Case study B2: Problem in context

B2 works for a local machine-building company which specialises in large industrial scale production lines. Their premises are the size of an airplane hangar, and the multi-system ‘machines’ they build can measure up to 40m in length. Recently, the company has also become an agent for a European-based machine building company. B2 - whose official title at the company is ‘electrical engineer’[72] - is now the maintenance technologist for existing and future clients who have purchased the European machines, which are mainly used in pharmaceutical product production. His role is thus similar to A4 (medical device technician), except that the scale of the machines means B2 travels to the operation sites around the country for maintenance purposes. The problem he elected to describe was ‘intermittent faults on the servo motors driving the sealing bars’ on a high-speed automated diaper production line. A servo motor is ‘a device that enables and controls motion and its direction with a high degree of accuracy’ (B2-4). It is connected to a control system and has a built-in feedback device that regulates the motion of a machine part. The clients had already been advised to replace the motor, the drive itself and the cable, but without success. When B2 visits the site, he has them run the process, and sees that the bottom sealing bar completes its motion before the top bar. Upon enquiry, it was revealed that, through a maintenance process, the top sealing bar had been replaced, and that the new bar measured under a millimetre thicker than the old bar – sufficient to cause a difference in the high-speed motion of the production line. B2 solves the problem by modifying the parameters on the control system to allow both bars to complete the cycle simultaneously.

7.3.1 Problem environment



Having become agents for a large European machine-building company, the nature of work at the small (<50) local company has begun to change. Offering a service to oversee the European machines in different contexts according to sound technical principles (*situational/purist insight*) requires increased framing over pace, criteria and control (F+) on the part of the servicing consultants.

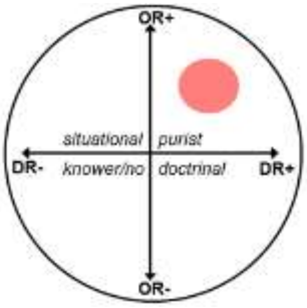
The stakeholder relations have become more complex, and hence more official reporting occurs (DR+). The client manufacturers, with their tight production deadlines and supply-chain

[72] An interesting phenomenon at all the case-study sites is the fact that the titles ‘engineer’, ‘technologist’ and ‘technician’ are NOT indicative of the practitioner’s qualification. They are descriptive of the position, and one finds ‘engineers’ working as ‘technicians’ and vice versa.

interdependencies, manifest strong classification and framing (C+, F+) in all respects, particularly as these are highly regulated, standards-driven pharmaceutical product manufacturers (*doctrinal insight*). As the consulting technologist from a machine-building environment with lateral teams, broad timeline deliverables, and open-plan offices, B2's office environment is weakly classified (C–).

7.3.2 Problem solver

7.3.2.1 General profile: cognitive, experience and mood



At 30 years of age, B2 is the oldest of the participants, having joined the originating programme after working in an engineering environment in his home country in central Africa. One of the programme's high achievers, B2 attained distinctions in all the disciplines, and 63% for the practical technology subjects. As in the case of A4, he has acquired the appropriate discourses both socially and professionally.

A listener and avid researcher by nature, he is a modest, analytical and generous team member. His supervisor claims that 'he always does a proper root-cause-analysis'. He appears to think carefully about any proposition and will, invariably, articulate the underpinning principle, supporting his essentially *purist* orientation. This is his second company since the difficult securing of an in-service training position four years earlier (as a political refugee at the time).

Table 7-3 B2 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
B2	30	M	B	F	81	76	80	63	B-Tech 4yrs	4	Y	Previous engineering work experience in central African country

7.3.2.2 Analytical profile: discourses, semantics and insights

The problem-solving questionnaire (figure 7-9) was completed online and reveals the appropriate sequencing of action taken, underpinned by analytical reasoning. As a visit to the problem site was not feasible, B2 provided supporting evidence. The reports and diagrams demonstrate frequent recourse to principles and their related formulae or procedures. He is comfortable navigating the official standards and user manuals associated with the various technologies. I suspect his French-based schooling enabled a greater degree of ease with the European supplier documentation.

PROBLEM-SOLVING: Process	PROBLEM-SOLVING: Thinking
The client XXX was advised by the machine manufacturer in Germany XXX to replace the motor, then the drive and cable. They have already replaced the motor without success before request our assistance. 1. First we ask the client to run the machine. Then the fault occurs as an overload fault on the top servo motor 2. Ask if no mechanical work or task was perform on the ceiling bar, the answer was they have replaced the ceiling bar 3. Ask to see the old ceiling bars and if they were different to the new ones. They difference was less than a millimetre and therefore negligible. 4. Ask to run the ceiling bars on inching mode. I noticed that the bottom bar had finished its motion while the top one was still in motion and pushing the bottom bar. That was clearly the cause of the overload. 5. Modified the parameter for the top bar end travel position on the HMI, so that both servo end there motion at the same point without collision.	Why did you solve the problem in the manner described? I knew that changing the motor, drive or cable will not solve the issue, if first the cause of the overload was not investigated. What were you thinking at each stage? - Running the machine will allow me to see the fault as it occurs (1) - Investigating if any changes was done on the machine and if that could be the cause (2 and 3) - What could be the source of the overload as nothing then the plastics where passing through the ceiling bar? Running the machine at low speed will allow better observation of the movement then at high speed (4) What did you not know? I haven't work or configure the Allen Bradley servos before and was using the general electro-mechanical principal of electric motor and servo drive.

Figure 7-9 B2 Sample text

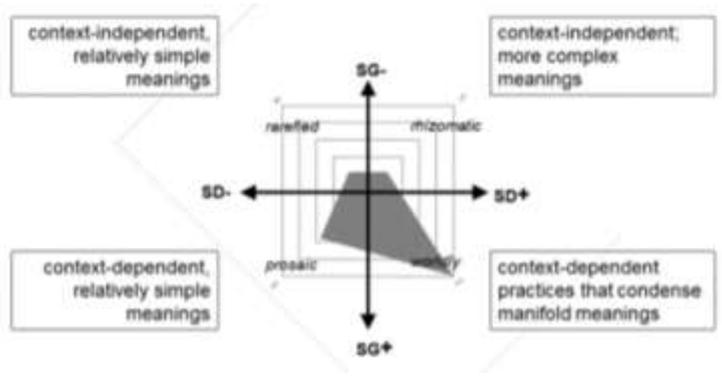


Figure 7-10 B2 Semantic code

The semantic plane analysis reveals a predominance of *worldly* references, but with a fair degree of *prosaic* contextual clarification references in simple language (for my benefit).

7.3.3 Problem-solving process

7.3.3.1 Approach

B2's approach to any problem that falls within his area of responsibility is first and foremost to determine the nature of the particular situation. Each one is different. In this case, here is a production sub-system on a particular machine in a large-scale environment which is not functioning optimally. The practitioner is aware that he needs to take all the variables into account, beginning with context.

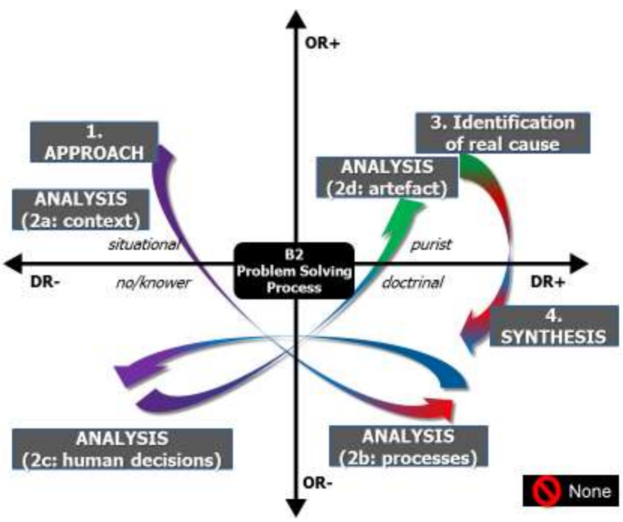


Figure 7-11 B2 Problem-solving process

7.3.3.2 Analysis

The client had already been advised by a remote technician to replace certain items. However, B2's *purist* nature suggested these measures were inadequate in attempting to define the real problem:

> *'I knew that changing the motor, drive or cable will not solve the issue, if first the cause of the overload was not investigated.' (B2-9)*

His contextual analysis moves into the *doctrinal* quadrant when he requests that the system be run 'on inching mode' (i.e. slowly and step-by-step), because 'running the machine will allow me to see the fault as it occurs'.

> *'I noticed that the bottom bar had finished its motion while the top one was still in motion and pushing the bottom bar. That was clearly the cause of the overload.' (B2-15)*

He then shifts his attention to the broader process context, focusing on people in the system. What is it that they may have done to alter the process of the machine? It is here that he discovers that the maintenance team had identified a problem with the top bar, and had replaced it. This was not brought to the remote technician's attention as the bar was thought to be identical. However, B2 examines the specifications for the top bar and discovers it is less than 1mm thicker than the original. His analysis now shifts diagonally from the *knower* into the *purist* quadrant as he explains the difference the fraction of a millimetre made to the process, drawing on the physics and mathematics of force, torque, motion and friction.

7.3.3.3 Synthesis

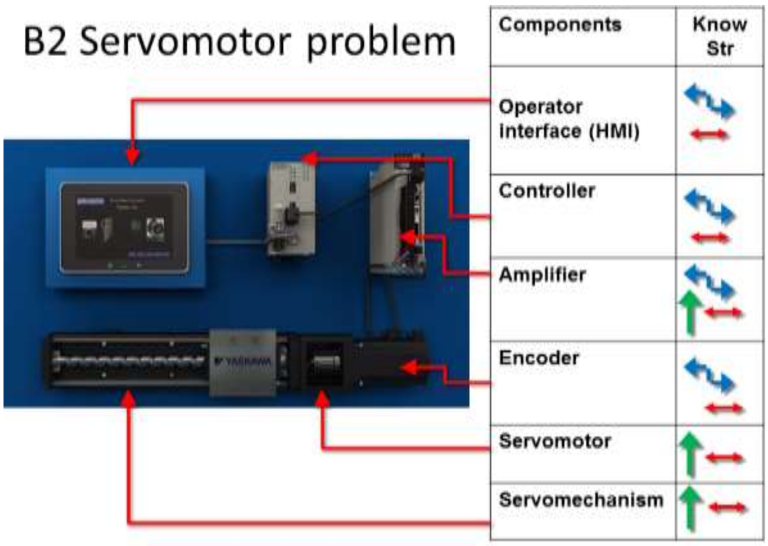


Figure 7-12 B2 Problem features

B2 solves the problem by simply procedurally altering the mathematical (speed and position) parameters for the movement of the top bar on the actual HMI (*doctrinal insight*).

However, this is informed by his understanding of each of the disciplines implied in the servomotor system (*purist insight*).

7.3.4 Problem structure

The technical problem is located in the mechanical domain in relation to machine vision (via the HMI) and actuation processes. These are informed by the hierarchical knowledge structure implied in physics-based motion, torque and friction, all of which are governed by strongly bounded phenomena and related procedures (OR+, DR+). The servomechanism (a mechanical mechanism to drive motion) is powered by the servomotor which is told by the encoder (logic signals) where to go and how fast (mathematically determined). This sets in motion a standardised, *doctrinal* (OR–, DR+) process.

The interrelationship between the servomotor system components (as illustrated in figure 7-12) demonstrates the shift between stronger physics-based and weaker logic-based knowledge forms. The problem thus requires a movement between strong discursive relations (DR+) and weak discursive relations (DR–). The problem as a whole, however, also represents this shift along the discursive relations axis, entailing the identification of *knowers* in the context and their possible impact on the technical processes.

7.3.5 Boundary navigation

The problem-solving trajectory through different *insights* reveals a kind of analytical process that could be equated with *purist* thinking. For this practitioner, each of the contextual and conceptual elements entails distinct 'principles' and associated procedures, even when dealing with unknowns:

> *'I haven't worked with or configured the [brand name] servos before and was using the general electro-mechanical principals of electric motor and servo drive.' (B2-19)*

His grasp of the requirements of the different *insights* is reflected in the appropriate use of discourses at different stages of the explanation, and in different formats. His supervisor commented that 'just by observing and talking to people, he always has a better understanding of the problem'. She also highlighted his ability to 'transfer' his knowledge into different formats, such as the required technical reports. This suggests an ease of 'translation' between DR– and DR+. This case study reveals no evident code clash, and the complexity rating is also at the upper technologist level (15). The relationship between his cognitive profile and the ease of navigation across the discursive relations axis will be discussed in the comparative summary.

7.4 Case study B3: Problem in context

B3 is employed as a graduate student at a University of Technology industrial project unit while completing his B-Tech. One of several projects is to design and build a low-cost platform for experimentation, validation and understanding of data acquisition and signal processing in any integrated system. What this entails is a system of sensors that can connect to a PC so that electro-mechanical data can be collected and interpreted. The data could be anything from temperature to motion and pressure. A major development in automated manufacturing is feedback: getting automatic temperature, pressure or motion readings (to name a few) back into the system not only so that the electro-mechanical processes can respond appropriately, but also to keep track of process data and trends, for example. Such data acquisition systems exist. However, they are prohibitively expensive to smaller local manufacturers, and certainly to students who wish to experiment practically. The project unit focuses on developing affordable local automation solutions, in conjunction with industry partners.

B3 is experimenting with a prototype system to measure temperature changes and gather the data on a computer. He has set up a demonstration kit using the cheapest feasible and available components, all of different origins. The system (figure 7-13) consists of a breakout board with input sensors (temperature) amongst other electronics components, and output wires to an analogue/digital measurement device. All the information is sent to a computer on which a program is installed to engage with the data. Having determined (via Internet search) and acquired all the necessary components and schematic drawings, B3 populates the breakout board and connects it to the digital/analogue device, which is connected to the PC.

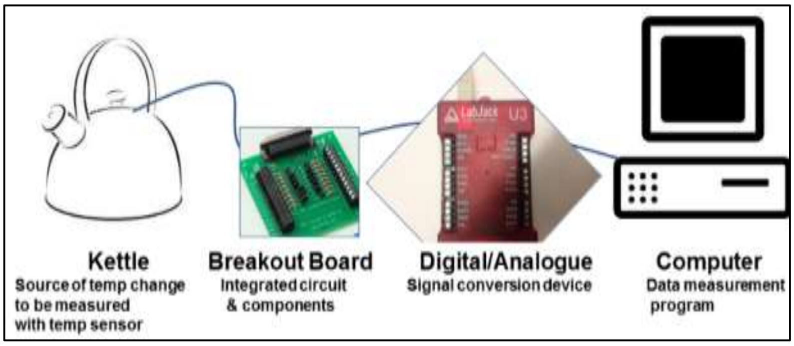
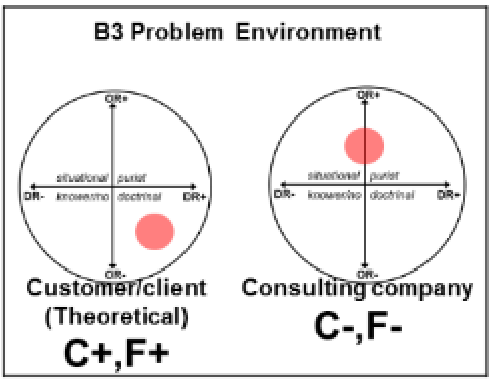


Figure 7-13 B3 Problem scenario

However, no signal is being received on the PC, and within minutes he 'smelt that tell-tale electronic burning smell' (B3-94). He suspects he has misconnected a component called an Op-Amp, because 'the pin configuration on the manufacturer's datasheet was incorrect on the version that was available on the supplier website' (B3-103). However, following investigation, he discovers it is the incorrect configuration on yet another component – a temperature sensor built into a small integrated circuit (IC). He had misinterpreted the schematic connection instructions and had inadvertently connected power to the ground terminal and ground to the power terminal. This had caused the IC to 'blow'. He replaces the IC, connects the pins correctly, and the system functions as required.

7.4.1 Problem environment



B3 works in an open-plan project office, with full access to resources, equipment and Internet (C–). Project progress and deliverables are the preserve of the various project teams, in this case B3 as an individual. There is a final deliverable deadline, but the pace is entirely determined by the practitioner. The criteria are broad, and although B3 has a supervisor, in reality, he is his own boss.

Externally, framing in this context is weak (F^e-). However, graduates in such project/prototyping environments are often tacitly selected on the basis of strong internal framing (F^i+) which matches the Regulative Discourse of such R&D environments: strong allegiance to ethical research, self-regulated research practices, and the valuing of innovation underpinned by disciplinary rigour. The project unit's focus on local solutions thus means the environment is characterised by a *situational/purist insight*. The theoretical customer – small manufacturer or training companies - however, requires a data acquisition system which will function reliably in a procedural (*doctrinal*) manner in a potentially strongly framed manufacturing or production environment (C+, F+).

7.4.2 Problem solver

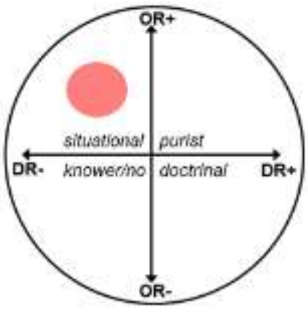
7.4.2.1 General profile: cognitive, experience and mood

B3 is one of the early questionnaire respondents, submitting a meticulously detailed contextual introduction as well as the details of one specific 'micro' problem. Unlike any of the other graduates, he has travelled extensively, worked in Europe in different engineering environments, and is an avid photographer. A high academic achiever across all subject areas, with the highest (86%) being in technology, he is a serious, dedicated and conscientious young man. He is more interested in exploring life than in becoming an engineering practitioner.

Table 7-4 B3 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
B3	28	M	W	E	75	77	76	86	B-Tech	3	Y	Previously employed, and has travelled extensively; amateur photographer

7.4.2.2 Analytical profile: discourses, semantics and insights



Process
1. Just then I smelt that tell-tale electronic burning smell. Straight away, the first thing I did was as a reaction. I unplugged the USB from the computer, because the Labjack and the breakout boards are powered by the USB from my computer. So removing the power was the first step to prevent further damage.
2. have a couple seconds or two of self-irritation at doing something wrong and setting my workload back further.
3. Get my logical problem solving hat on. I unplug the breakout boards and plug in JUST the Labjack and check that it is still all function as expected (Check)
4. now that the problem is determined to have come from the breakout board I need to find out what happened. Initally I resort to a typical visual inspection (can I see anything that is visually blown) and I also resort to the smell/sniff test. Can I identify that way what may be blown...I can smell the tell-tale burnt smell, but because the board is small I cannot narrow it down to an individual component.
5. I re-examine the circuit layout and quadruple check it against the schematic for any inconsistencies.
6. My attention is drawn to the small SOIC Op-Amp chip as the pin configurations on the manufacturers datasheet was incorrect on the verison that was available from RS's website. It was only after going to the Manufacturer (Analog Devics) I got the updated Rev. U datasheet....that had the correct orientation of the pins...So my attention was drawn to this as I thought perhaps

Figure 7-14 B3 Sample text

Of all the questionnaire submissions, B3's is the most narrative. Despite the numbered sequence, he describes the context and his personal responses in detail, including when he drew on which senses to try to identify the source of the problem. His *situational insight* orientation emerges more strongly during the actual re-enactment interview, when – in trying to both explain the existing and solve another problem – he moves back and forth between the devices, his diagrams, and the two different computer screens. On the one hand, there is a constant downloading of different manuals from device manufacturer websites, and on the other, he trawls between different search engines, user fora and websites, typing in search terms. He is heavily reliant on the collective *reservoir* of expertise. Another indication of his *situational insight* orientation is that he seldom reads the device documentation in linear fashion, stating 'I mostly use Control F to find what I'm looking for'. Despite the seemingly simple, narrative, first-person problem description, each statement is laden with context-dependent references with very specific (SD+) meanings.

'I can smell the tell-tale burnt smell, but because the board is small I cannot narrow it down to an individual component.' (B3)

A 'tell-tale burnt smell' implies something very specific in electronics, as does the reference to a 'board'. These 'simple' terms actually condense manifold meanings. The semantic code analysis thus reveals a predominance of *worldly* references, many of which may initially appear innocuous.

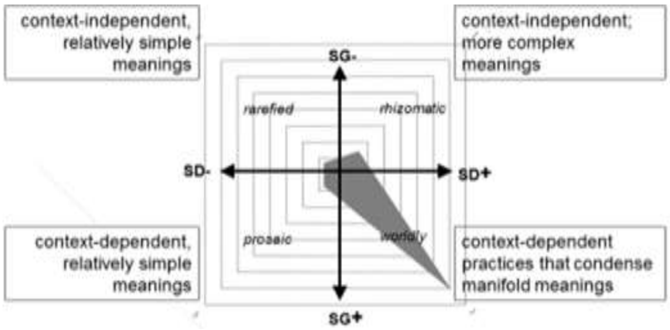


Figure 7-15 B3 Semantic code

7.4.3 Problem-solving process

7.4.3.1 Approach

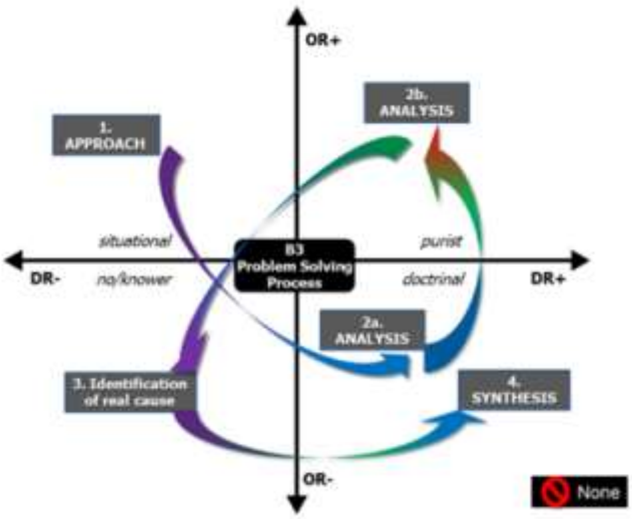


Figure 7-16 B3 Problem-solving process

B3's approach begins with the broader context:

'I've never been able to measure stuff before… You can't just get a multimetre… I mean some of them have temp sensors… but you can't log that data. You can't reference it to anything over time… Industry uses expensive hardware… the point here is to do a low cost version.' (B3-3)

He systematically describes the function of each of the sub-components in his system so that the context of their relationship to the 'blown' sensor is clear (OR+, DR–).

7.4.3.2 Analysis

B3's first analytical reaction to the blown temperature sensor is 'sensory' (very similar to A3's motor problem):

'Initially I resort to a typical visual inspection (can I see anything that is visually blown) and I also resort to the smell/sniff test.' (B3-100)

He follows a *doctrinally*-orientated procedural analysis (OR–, DR+) of his current system and the connections:

'I re-examine the circuit layout and quadruple check it against the schematic for any inconsistencies.' (B3-102)

His first suspicion is that it is the Op-Amp chip. He moves comfortably into the *purist* quadrant (OR+, DR+) explaining that the voltage that gets generated by the sensor is in millivolts, and that an amplifier is necessary to magnify that reading so as to have meaningful data. He clarifies that the reason for suspecting the Op-Amp was that ‘the pin configuration on the manufacturer’s datasheet was incorrect on the version that was available’ on the supplier’s website. After consulting the manufacturer’s website, he corrected the way in which he connected the component, but he felt that because there were two discrepant datasheets, he might still be doing something wrong. This part of the analysis is an acknowledgement that different *knowers* (suppliers, manufacturers, users) have different rationales for their configuration of such components. ‘This is not a theoretical principle at all – it can be arbitrary’ (B3 supervisor). You have to be familiar with how the different suppliers and manufacturers present their information and documentation (OR–, DR–).

This leads B3 to consider all the relevant datasheets from the different manufacturers and suppliers (a time-consuming exercise), and through a systematic, *doctrinal* (OR–, DR+) process of comparison, he discovers he had read the connection of the temperature sensor incorrectly.

> *‘I had read the datasheet thinking that the pin configuration was from above (because that is the way I populate the board with components) but in fact upon closer examination I saw that the pin configuration is from below, the track side.’ (B3-110)*

He had previously used an earlier version of this precise sensor, and had drawn on this knowledge when constructing his circuit. In very fine print on the actual supplier document (figure 7-17) the following statement is visible: - ‘*Note: The LM35DT pinout is different than the discontinued LM35OT.’*

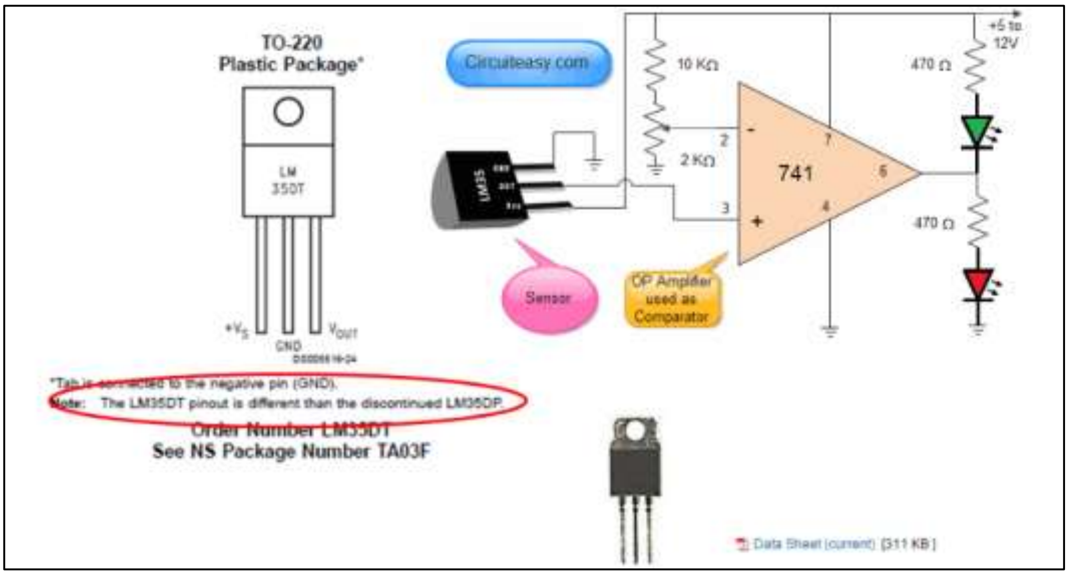


Figure 7-17 B3 Problem identification

7.4.3.3 Synthesis

Solving the problem was as easy as replacing the sensor chip and connecting the pins as per the new datasheet: 'No modification required, I just turned the component around 180°'. In other words, the solution was entirely *doctrinal* (OR–, DR+). However, the supervisor in question felt that this specific 'problem' did not constitute a real engineering problem, and that the broader problem of developing an affordable data measurement and acquisition system had (to date) not been adequately solved.

7.4.4 Problem structure

The manifestation of the problem would be classified as falling within the domain of 'control electronics', with a specific theoretical focus on Ohm's Law and voltage polarity. The three pins on the sensor have a specific physics-based role in the circuit. One is connected to power, the second is an 'output' and the third is the reference voltage (ground). The connections are designed to respond to the logic of the larger circuit/system current flow. This flow is underpinned by two forms of knowledge: the logic *design* of specific components (which *differ* from manufacturer to manufacturer and between versions) and applicable physics. The organising principles are thus weak horizontal and strong hierarchical knowledge structures respectively. Put differently, the theoretical problem structure manifests as a movement between weak (DR–) and strong (DR+) discursive relations. The weak discursive relations implied in the different component configurations in relation to a fixed phenomenon (OR+, DR–) become even weaker when seen in the context of the manufacturer/supplier and user relationship to the problem. In other words, the problem is located between the *knower* and *doctrinal* quadrants.

7.4.5 Boundary navigation

This case study is particularly interesting in that firstly, as previously mentioned, it was not considered a legitimate engineering problem by the supervisor in question, who is an academic at the project unit. I believe this view contributes to the need for a better understanding of real world engineering problem-solving practice, particularly in the South African context. If academics regard engineering problem solving as being more concerned with 'design', then the literature citing industry dissatisfaction[73] with graduate problem-solving abilities is justified, given that very little 'design' occurs in the comprehensive sense intended by the supervisor. It is the contention in this research that problem solving is the overcoming of obstacles to attain a goal, and B3 needed to overcome numerous obstacles at various stages in the attempt to design, build and test an affordable data acquisition system. Secondly,

[73] (CHEC, 2013) (Du Toit & Roodte, 2008) (Felder, 2012) (Jackson S. , 2007) (Griesel & Parker, 2009) (Lang, Cruse, McVey, & McMasters, 1999) (UNESCO, 2010)

this particular case highlights a phenomenon regarding the nature of obstacles that emerged across the 28 final questionnaire submissions – inaccurate or misinterpreted information/documentation on which practitioners are reliant. In both cases (inaccuracy and misinterpretation), what this suggests is that the knowledge required to address a problem dependent on a particular control technology cannot be theoretically deduced unless the practitioner has particularly well-developed or experiential insights into the design thinking behind the particular components.

B3's problem-solving trajectory reveals a potentially iterative sequence of diagonal movements, initially *situational* (OR+, DR–) to *doctrinal* (OR–, DR+) and then *purist* (OR+, DR+) to *knower* (OR–, DR–). The fairly simple context of a misconnected component is not to be underestimated. Systems integrators face multiple such challenges with each new version of a particular technology or protocol (Leonardi, 2011). Each search for the correct 'way' according to the dense accompanying documentation represents additional use of time often not included in project budgets or planning. B3, although expressing frustration at having to wade through documents, navigated the entire epistemic plane with relative ease, and is thus not considered to have experienced explicit code clashing. The level of overall complexity, as in the two preceding case studies in this category, is that of technologist (16).

7.5 Case study B4: Problem in context

B4 is an appropriate case study to set in relation to the preceding three in this category. It certainly marks the most complex of all the case studies, but is one of the few to enable insights into the nature of logic-based problems. Employed as a laboratory technician at a high-end research institute situated at a regional university, B4 is actually completing a Master's in Engineering, having begun his studies at the same originating institution as the other case studies. On the one hand, he has the same relatively weakly framed context as that of B3, having greater autonomy while tacitly being expected to adhere to the institute's values of 'ethical, scientifically-sound, industrial innovation'. His selected problem context is similar to that of B2 in that he is working on a multi-system machine with servodrives, but the problem itself is a logic-based 'communications' problem – as in the case of B1.

The 'machine' in question is a 3-axis 'robot' which is designed to perform manufacturing functions on smaller products. In other words, there is an arm which has a tool mounted on one end, and the arm can move up-down, left-right, and forwards-backwards. The movement along the three axes is physically driven by an electrical actuator set in motion by an attached motor in response to an internal controller which has been programmed. The machine, however, is designed for 'reconfigurable manufacturing'. This means that a number of different products of the same 'family' could be processed by the same system with minimal changes. For each product on the production line, the machine recognises (using identification technology) the different items and responds appropriately. This represents a dynamic new development in manufacturing approaches. Such a 'responsive' system, however, requires a complex communication system and high speed. In other words, more (and changing) information needs to be communicated than in a traditional PLC system, which has a fixed sequence of pre-programmed operations. One method to enable complex communication without a host computer is the use of a Controller Area Network (CAN) 'bus'. Imagine an air-traffic control tower, where every aircraft's movement, path and journey is stored, and every alteration is virtually instantaneously communicated (and verified) through the air-traffic control tower. In addition to having this super-cop traffic controller with its dedicated 'language' and protocol, the machine in question is also using a high-powered, real-time embedded industrial controller – which, however, is not relevant to the problem itself. The entire system is programmed through a Graphical User Interface (GUI) (figure 7-18), in this case a multi-layered computer program system that includes schematics that literally look like the machine and laboratory equipment.

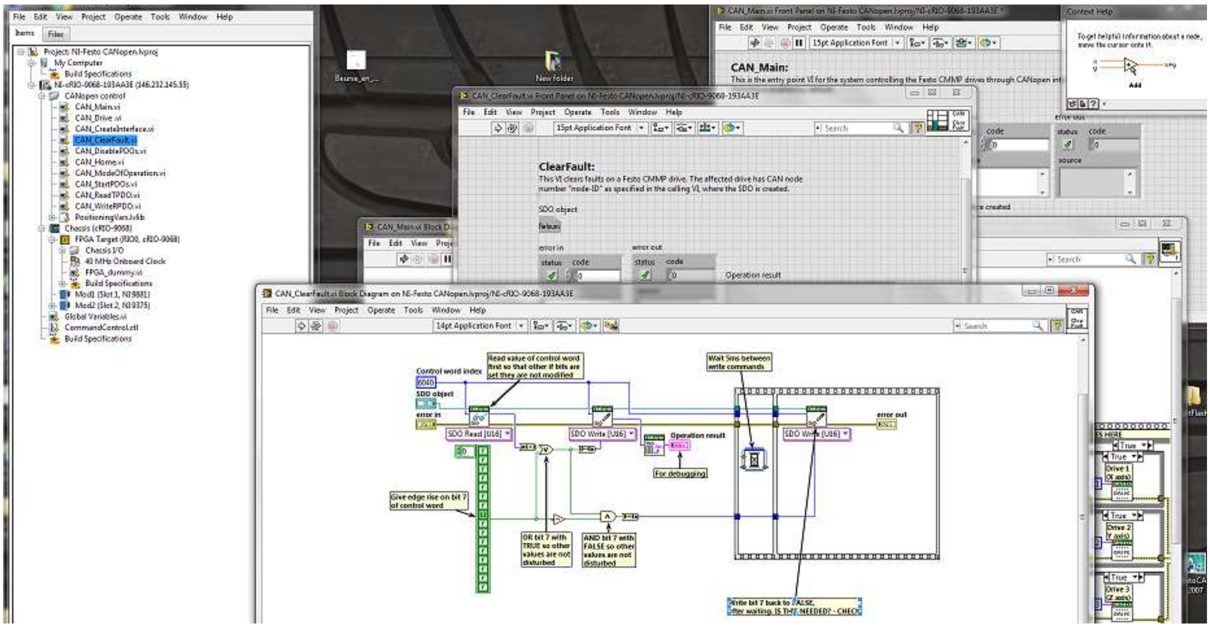


Figure 7-18 B4 GUI Programming environment

B4 had been assigned to take over the development of the machine, as it was not functioning as required and had little accompanying development documentation. In order to save time, he literally began from scratch, dis- and re-assembling the actual machine, reconnecting all the inputs and outputs, and performing the 'hardware configuration'. A problem (one of several) that emerged was 'addressing the drives' (servomotors) via the CAN bus, so that they could receive position commands. In other words, the 'air-traffic controller' needs to know what and where the drives are, and what they are going to do. After struggling to get a single drive to run and accept position commands, 'I kept running into problems to address more than one drive'. Through a process of adding delays to the program so as to observe each step and the resultant action, B4 'identified the subprogram/object that was causing the erratic behaviour' (B4-47).

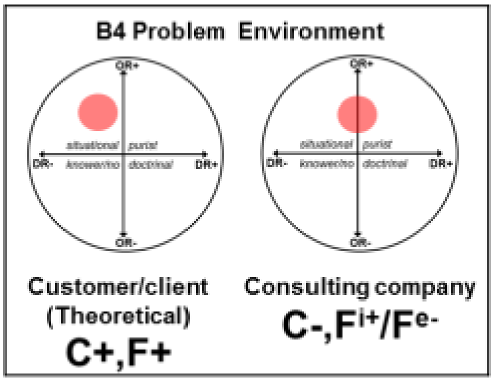
> *'CANopen has a clever addressing system which allows all entities on the system plus their communication objects to be identified by using just the node ID of each device.' (B4-49)*

What this means is that devices – which are seen as Process Data Objects (PDOs) - are allocated an address. When information is transmitted or received it goes to that address on the CAN bus, much like a letter arriving in the mail at a specific house number, street name and suburb etc.

> *'The documentation for the functions than handle the communication with these objects explicitly says that if the PDO address is left blank or made zero, the function automatically calculates the right address based on the node ID.' (B4-57)*

This was not the case. Despite consulting the various vendors, wading through the accompanying documentation, and consulting the various user fora, there seemed to be no solution. The drives were not being ‘picked up’. The solution was to ‘hard code’ the relevant addresses into the ‘blanks’ (which were meant to have automatically deduced the correct ‘address’). In other words, since they were already connected, he located the actual address and physically typed them into the program.

7.5.1 Problem environment



B4 works in an open-plan laboratory with full access to resources, equipment and Internet (C–). Several researchers collaborate on a range of projects in this and other environments. Progress and deliverables are determined by the various teams, and all report to the head of the institute. There are deliverable stage deadlines, but the pace is entirely determined by the practitioner.

Externally, framing in this context is weak (F^{e}-), but slightly stronger than in the B3 case as this is a high-end research unit with a reputation to maintain. Across the board all practitioners in this environment demonstrate strong internal framing (F^{i}+): a drive to innovate at the level of applied science and technology. The research institute’s focus is characterised by a *situational/purist insight*. The theoretical customer here would be a high-end manufacturer, probably of smaller goods, who requires a system that can respond to change without downtime (*situational insight*).

7.5.2 Problem solver

7.5.2.1 General profile: cognitive, experience and mood

My interview with B4 was as impressive as that with A4. He had submitted a superbly detailed, personalised questionnaire (obviously tailored to the research questions and not just a generic report) and had set aside ample time to take me through his machine and the processes behind solving the various problems. The interview process entailed a full orientation of the environment, his colleagues and role. Another high achiever[74] across the majority of subject areas, the 28-year-old Spanish-speaking participant had been engaged in innovation-orientated computer-based work since childhood. My impression – as in the case of A4 - was that here too there was an ideal ‘match’ between a problem solver and his environment. He

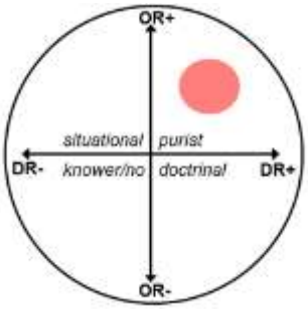
[74] At the time of the interview, B4 had successfully completed additional Bachelor’s in Engineering mathematics courses as a pre-cursor to his Master’s enrolment. Secondly, his first semester mathematics achievement on the original programme was 80%, and the second semester result was compromised by external factors not of his making. He is thus regarded as being a high achiever along with the small group of anomalies.

thoroughly enjoys his job, and the opportunity for research and development of complex systems.

Table 7-5 B4 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
B4	28	M	W	Sp	72	78	87	82	B-Tech 4yrs	3yr	Y	Currently completing an MEng and employed as research technologist at Research Institute

7.5.2.2 Analytical profile: discourses, semantics and insights



The well thought-through, detailed and analytical questionnaire response (figure 7-19) points to an essentially *purist* orientation. The responses bear testimony to a deep understanding of the principles behind the questions, and the relevant procedures in detailing the problem, its context and the problem-solving thinking.

The semantic code analysis (figure 7-20), in addition to the expected *worldly* references, reveals more *rhizomatic* and *rarefied* meanings than any of the other case studies. B4 expanded on the principles behind how the broader systems work in both simple and complex terms. Many of these references are about developments in the field and directions for the future.

4. I advanced through the program in this fashion (adding delays at different points of the program, adding further monitoring features, deploying, running, observing results) until I identified the subprogram/object that was causing the erratic behaviour. Solving this problem requires some background information, provided below:

CANopen has a clever addressing system which allows all entities on the system plus their communication objects to be identified by using just the node ID of each device. It works by adding the node ID to a known constant so when connected to the bus, one does not attempt to communicate with a device but rather with the communication object directly. For example, each drive has 4 "Receive/Transmit Process Data Object". These PDOs have a unique address on the bus (so even if all other drives use all their PDOs on the bus each PDO can still be individually accessed), given by:

RPDO1=200h+NodeID	**TPDO1=180h+NodeID**
RPDO2=300h+NodeID	**TPDO2=280h+NodeID**
RPDO3=400h+NodeID	**TPDO3=380h+NodeID**
RPDO4=500h+NodeID	**TPDO4=480h+NodeID**

The documentation for the functions than handle the communication with these objects explicitly says that if the PDO address is left blank or made zero, the function automatically calculates the right address based on the node ID. Based on this information, I ignored the possibility of the PDOs' address being the problem for a long time, until debugging I arrived to the subroutines that handle the interaction with these objects and was left with no doubt that these were the culprits. To confirm this, I did the following:
5. Since I had the drive objects already hard-instantiated, I hard coded the relevant address for each PDO I needed.
6. Because this worked, I then coded the addressing algorithm to assign the right address to each PDO based on a given node ID. This allowed me to instantiate the drive object normally at a more abstract level.

Figure 7-19 B4 Sample text

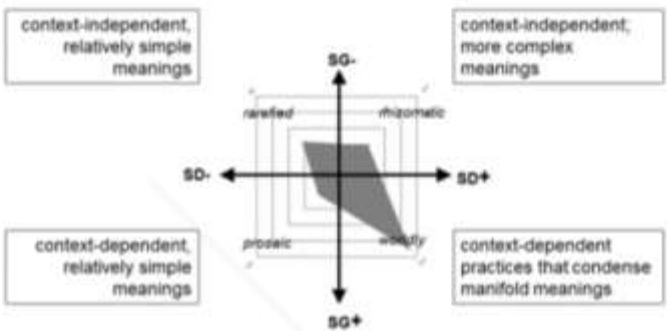


Figure 7-20 B4 Semantic code

7.5.3 Problem-solving process

7.5.3.1 Approach

The problem-solving trajectory (figure 7-21) representing this case study demonstrates a thicker use of process arcs than in the other case studies, particularly in the strong discursive relations (DR+) regions. The intention here is to capture the extent of the detailed, analytical and dense disciplinary-based explanations that emerged in both the questionnaire and interview. Having established the broader context of the machine, its purpose and history (*situational insight*), B4 introduces the 'drive addressing' problem in more abstract terms than most:

> *'I intended to create an abstract "drive" object to which I could simply pass a node ID in order to add more drives to the system. In this way, any number of axes can be added to (or removed from) the system…in line with the project's reconfigurability focus.' (B4-34)*

He establishes that the problem emerges while struggling to get even one drive to connect, run and accept position commands.

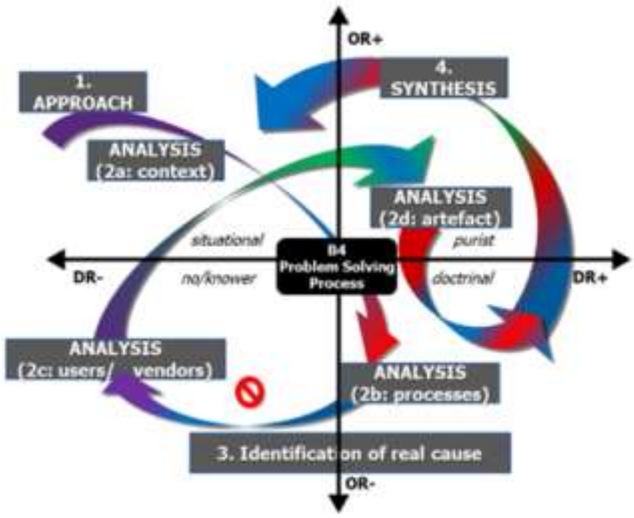


Figure 7-21 B4 Problem-solving trajectory

7.5.3.2 Analysis

B4 proceeds into the *doctrinal* quadrant (OR–, DR+) with an explanation and analysis of the relevant procedures. He set up one drive, following documentation instructions. This meant the drive was wired to the controller and connected through the CAN bus. The CAN bus automatically allocated an 'address' (a node ID) to the drive. In order to get all three drives to run, the procedure should simply have been repeated. However:

> *'I kept running into problems to address more than one drive. Sometimes a drive would register on the bus, and sometimes it would not. Sometimes two drives would move even though only one was commanded.' (B4-35)*

He consulted the drive documentation which explicitly says:

> *'If the PDO address is left blank or made zero, the function automatically calculates the right address based on the node ID.' (B4-57)*

This initiates the analytical move into the *knower* quadrant (OR–, DR–), acknowledging different vendor claims about their products, functionality and compatibility. The different vendors were extensively consulted:

> *'The XYZ people kept just referring me from person to person… and with the previous system we tried, the engineers had the [problem sub-system] for a month and couldn't help.' (B4-95)*

Having failed with the procedural documentation and the people responsible for the development of these complex sub-systems (OR–, DR–), B4 shifts diagonally into *purist* mode, turning his attention to the science behind the artefact (OR+, DR+). He explains the complex addressing system and the concomitant implications for getting the drives to accept position commands:

> *'It works by adding the node ID to a known constant so when connected to the bus, one does not attempt to communicate with a device but rather with the communication object directly. Each drive has 4 "Receive/Transmit Process Data Object" and these PDOs have a unique address such as: RPDO1=200h+NodeID TPDO1=180h+NodeID…' (B4-50)*

Since not only did the drives have to 'register' on the CAN bus but also respond to position commands, the problem now becomes more serious. He proceeded to engage in a procedural (*doctrinal*) debugging process to see what was causing the drive to behave unpredictably. He added 'delays' into the program so that he could literally observe the process at both code and machine action level. This is the same principle as in B2's case where he had the technicians run the machine on 'inching mode'. His observations require a return to the *purist* quadrant:

> *'Due to the drawback of XXX's functions' only being able to exchange 32 bits of data I had a problem with mismatched data lengths (writing 16 bits of position data while the drive expects 32).' (B4-83)*

The drives are from one vendor, but the CAN bus is accessed through a different vendor's software. The two systems have different communication constraints. B4 'decided to stop wasting time trying to find a solution to the reassignment of PDO process values' (B4-83) and to ignore the incorrect documentation.

7.5.3.3 Synthesis

The synthesis of a solution entailed a 'workaround' – a move into the *situational* quadrant: physically assigning each drive its node ID on the CAN bus. Since they were already wired to the system, he could look up their ID and type it into the relevant code section (this is similar to looking up your computer's IP address). He then 'coded the addressing algorithm to assign the right address to each PDO based on a given node ID' (B4-60).

> *'Since the results of the workaround fell within design constraints, I opted to use a bug fix instead of wasting time looking for the proper solution, which may never have been attained.' (B4)*

7.5.4 Problem structure

The problem itself is essentially the failure of documentation (compiled by vendors) to adequately present the appropriate instructions to comply with ostensible functions of the sub-system. B4 sums up the lesson learnt:

> *'On several occasions I followed the procedure exactly as described from each side of the hardware platform … but it did not work as described. Because of this, when considering how to approach a similar problem in future … I will tell myself '**just because a high profile vendor says so it does not mean it is so**'.' (B4-90)*

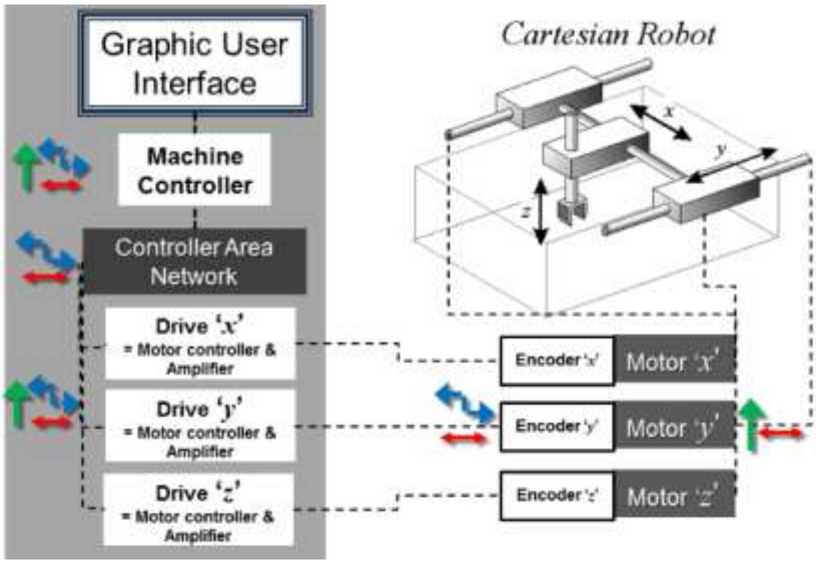


Figure 7-22 B4 Problem features

In navigating the problem, though, structurally it represents the full sweep implied in the epistemic plane. The problem structure is predominantly a logic-based one with a strong mathematical underpinning. In addition to the explanation regarding the Process Data Object (PDO) addressing concept, B4 explains the dilemma in having a shortage of 'bits' to move information between two systems from different vendors:

> *'The PDOs have a maximum carrying capacity of 64 bits (these bits can be used by several process values in groups of 8, since more than one value can be carried by a single PDO) but less than 64 can be used depending on which and how many process values are exchanged.' (B4-65)*

He required more 'bits' and had to 'apply an exponential factor to the position value' to enable the system to work with 'actual and target positions'. This is not directly relevant to the initial step of allocating an address to the drives as it has to do with once the drives are actually moving, but it serves to highlight the necessary recourse to disciplinary thinking in such a problem context. This particular problem demonstrates a higher complexity rating (20) as a result of four of the IEA (2013) problem attributes (appendix B) requiring more complex engagement, namely ‘having no obvious solution’, requiring a ‘first principles analytical approach, entailing ‘infrequently encountered issues’, and being part of a larger system of sub-problems.

As in the B2 case study, the problem (depicted in figure 7-22) entails the physics of motion behind the 3 axes and their motors; the mathematics of the axial movements, speed and data ‘bits’ (these are different kinds of ‘mathematics’); and the logic of not only the control system, but also the CAN bus system. Again, this problem structure requires an iterative, bi-directional and diagonal navigation of the discursive relations axis (DR+ to DR–), moving back and forth between weak and strong horizontal knowledge structures, as well as between weak and strong ontic relations (OR– to OR+).

7.5.5 Boundary navigation

B4 expresses extreme irritation at the vendor inability to assist, and to comply with their own claimed compatibility and accepted standards. His supervisor, however, stated that ‘he really has a well-developed ability to negotiate with the vendors’. Although B4 navigates all the disciplinary boundaries with relative ease, I have indicated the *knower insight* (OR–, DR–) quadrant as a boundary-crossing, code-shifting challenge on the basis of the practitioner’s essentially *purist insight* orientation (OR+, DR+), and the fact of his closing comments about the most important lesson learnt from solving this problem: Don’t trust what vendors say. Although the quadrant is indicated as a challenge, his statement, to my mind, reflects a strong social relations (SR+) element in the *knower* quadrant, as opposed to ‘*no insight*’.

7.6 Category B: Comparisons and discussion

Three of the four preceding case studies in the Modular Systems category are located in the control systems knowledge domain, with B2 being closest to the electro-mechanical domain. Despite the common logic-based knowledge, each case study offered a distinctly different problem-solving trajectory as represented on the relevant case-study epistemic planes. There are, however, significant similarities in this category.

7.6.1 Problem environment differences

The key feature in this category – and one which is echoed throughout each KPE aspect – is the question of straddling opposites, or dichotomies. This is the only KPE category where practitioners are at all times working in two different environments: that of their company/institute 'base' and that of their 'client' (whether theoretical or real). In all cases, the classification, framing and *insight* orientations between the base and the client environments demonstrate significant code differences. All the customers represent strongly classified and framed (C+, F+) manufacturing environments, whereas all the base companies are weakly classified (C–), with more lateral relations, flexible spaces, and more open time frameworks. Secondly, the *insight* orientations between the two environments in all but B4 are polar opposites, manifesting either as weak or strong ontic relations, or strong or weak discursive relations. What this means is that practitioners are either moving between strongly and weakly bounded knowledge claims, or strongly and weakly bounded methodological practices in both the macro working context as well as in the micro problem-solving moments.

7.6.2 Problem-solver differences

As in chapter 6, KPE B problem solvers demonstrate a correlation between academic performance and well-articulated problem-solving processes. As a matter of interest, the number of words submitted in the problem-solving questionnaires was compared to average academic performance, and there is a direct correlation in this limited sample between high performance and high word count, and low performance and low word count. Interestingly enough, only one is a native English-speaker (B3), and all four speak a different mother-tongue. Home language did not impede the generation of a technically detailed English text on the part of the high achievers.

Three of the case studies (B2, B3 and B4) are representative of the 2.9% high mathematics *and* logic anomalies, and (including A4) are the highest achievers of all the research participants.[75] For all intents and purposes they therefore do not represent the norm. However,

[75] These were the only systems integrators of all the original volunteers to submit questionnaires. There were two additional texts submitted by machine builders. However, these were inadequately detailed and attempts to arrange a site visit proved futile as a result of recent management and organisational structural changes.

they represent the best possible cases - given the limitations of the study – through which to examine logic-based problem-solving processes in the most dynamic KPE category of the engineering region in question. The three high achievers also demonstrate fuller and iterative problem-solving process descriptions.

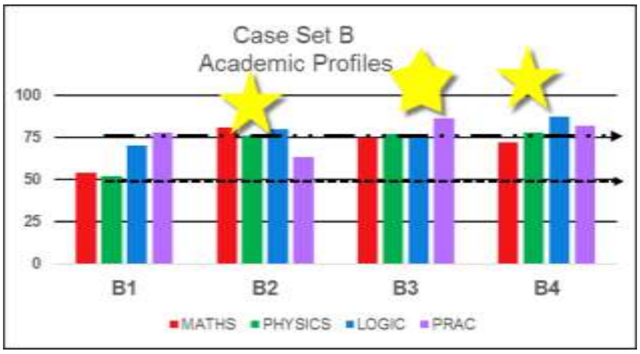


Figure 7-23 KPE B Academic profiles

An interesting observation is that the two systems integrators (B1 and B3), irrespective of company context (commercial or R&D) demonstrate a *situational insight* orientation, whereas the two machine-builders (B2 and B4) demonstrate a *purist* orientation.

As in KPE A, all the cases have a high number of *worldly* (SG+, SD+) references as is to be expected in technical professions. However, both *purists* (B2 and B4) make more non-*worldly* references than the *situational* orientation practitioners. This suggests the *purists* in this category employed more context-independent (SG–) as well as contextually simplified meanings (SD–).

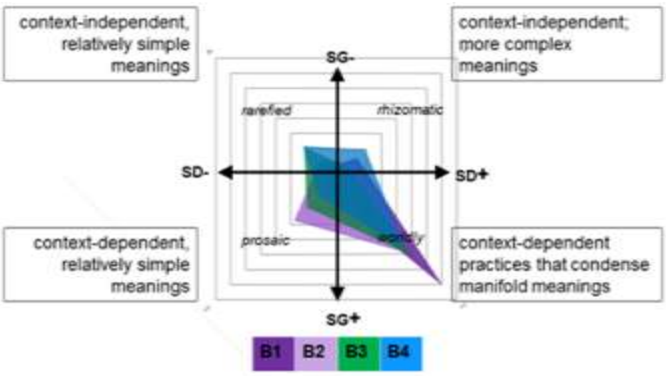


Figure 7-24 KPE B Semantic code comparisons

7.6.3 Problem-solving process comparisons

There are three striking observations with regard to the problem-solving trajectories in this category. First of all, as befits the more logic-based focus, all the practitioners proceed from the *situational* quadrant (OR+, DR–). This is appropriate given the nature of the KPE: custom-made (DR–), contextually-feasible and technically-sound automation systems to enable efficient production. The second observation is that they all move diagonally downward (to the polar opposite: OR–, DR+) to determine the existing or supposed *doctrinally*-orientated procedures on the system in question. Both *purists* (B2 and B4) then move into the *knower* quadrant (OR–, DR–) recognising that before the focus can shift to the epistemic nature of the problem, there is a legitimate need to consider the various *knowers* in the problem situation – whether they be operators or vendors. This move in these two cases would be classified as a strong social relations (SR+) shift as opposed to merely '*no insight* (ER-)[76]. In all these cases, the impetus for or direct cause of the problem lies in the lower left quadrant. People somewhere made decisions to alter machinery without informing the practitioner (B2), or produce documentation claiming certain compatibility capabilities (B4), or change the configuration of an existing component (B3). This holds true even for B1 who states that the PC app 'written by someone' was 'splitting up the barcodes' and thus causing the problem. However, B1 does not have the time (nor possibly the discipline-based insight) to pursue this angle.

The high academic achievers (B2, B3 and B4) then engage in a vertical move on the DR+ side, demonstrating analytical depth as they shift into *purist* (OR+, DR+) mode. The third interesting observation is that all the problem solutions (synthesis stage) lie in either the *doctrinal* or *situational* quadrants, with one each in both sub-category sets (whether R&D versus commercial, or machine builder versus systems integrator). What this seems to suggest is a need to be able to move between diagonal 'poles' from the perspective of both the phenomenon and possible approaches. In other words, here we have not only the shift along the discursive relations axis (between fixed and multiple ways of approaching a phenomenon), but also along the vertical ontic relations axis (between strongly and weakly bounded phenomena). The ability of the three high achievers to navigate the problem-solving arena in iterative diagonal fashion appears to indicate an intuitive response to the codes implied in the different quadrants. These trajectories in relation to the KPE features, and particularly the participant academic performance across the different knowledge structures, were the first indication of possible empirical evidence in this research of the 'generative and structuring properties' of knowledge. This will be returned to in chapter 9.

7.6.4 Problem structure comparisons

The one feature that all four KPE B case studies have in common is that the problem structure is characterised by a *doctrinal* element either in relation to the epistemic basis (OR+, DR+) or the polar opposite, a social basis (OR–, DR–). In the case of B2 and B3, understanding the problems required engagement with fundamental physics principles (hierarchical knowledge structures) with respect to motion and Ohm's Law respectively, and both solutions entailed complying with procedural logic. In other words, the practitioners were not required to make logic choices (DR–) as the systems were already given, and they were required to draw on

[76] The limitations of this research, however, are such that the social relations (SR) are not a primary focus, although this certainly warrants further research.

what was essentially *a priori* knowledge. B1 and B4 were precisely the opposite. The problem structures were essentially *doctrinal* logic-based decisions made by specific *knowers*. This places these two problems on the boundary between strong (DR+) and weak (DR–) discursive relations in the lower half of the plane, the most difficult codes to navigate in engineering. Both solutions could not rely on theoretical *a priori* knowledge, but required innovative *situational* logic-based decisions which led to new *a posteriori* knowledge. To quote B4: 'What do I know? …just because a high profile vendor says so does not mean it is so'.

7.6.5 Closing word on KPE B case studies

What the preceding comparison demonstrates is the necessity and ability to navigate between weak and strong classification and framing conditions, as well as between the different ontic and discursive relations strengths. As in the first category, the higher the academic record, the more detailed the problem-solving description. A pattern to emerge in this category is the iterative diagonal movement between *purist* (OR+, DR+) and *knower* (OR–, DR–) *insights*, as well as *situational* (OR+, DR–) and *doctrinal* (OR–, DR+) *insights*. This suggests an ability to differentiate between strongly and weakly bounded objects as well as strong and weak discursive relations. The anomalous equivalence of high mathematics *and* logic in the three significantly detailed cases appears to support the ability to traverse both epistemic plane axes (OR and DR) with relative ease, recognising at appropriate moments what 'code' is required. This category – as has hopefully been illustrated following the analysis of the four case studies – is significantly different from the first category with respect to practitioner access to the required forms of knowledge. This is also borne out by the complexity rating ranging from technologist to lower-end engineer level. The sheer proliferation of types of components and sub-systems that can fulfil the same function (OR+, DR–) in very different contexts, and each type's accompanying *doctrinal* procedures (OR–, DR+) recalls the claim that 'masses of particulars' (Muller, 2008) need to be acquired in the case of horizontal knowledge structures. The case studies in KPE B demonstrate that these 'particulars' could only be acquired *a posteriori,* and frequently relied on a trial-and-error wading through multiple sources and types of information.

CHAPTER 8: CASE STUDIES – CATEGORY C – DISTRIBUTED SYSTEMS

8.1 Introduction

The focus in the Distributed Systems category is on the production of goods in semi- to fully-automated environments, such as plants and factories which consist of multiple machines and sub-systems. Overall 'process control' is the key objective, with the end goal being to produce goods safely, efficiently, cost-effectively, and to specification. Mechatronics practitioners in these environments are largely concerned with the maintenance and improvement of existing systems and processes. In such environments, the classification of space, stakeholder relations and time is almost always stronger (C+) than in the previously detailed systems contexts. These environments tend to be more formal, and require more stringent documentation and communication processes. As such, external framing is strong (F^{e+}).

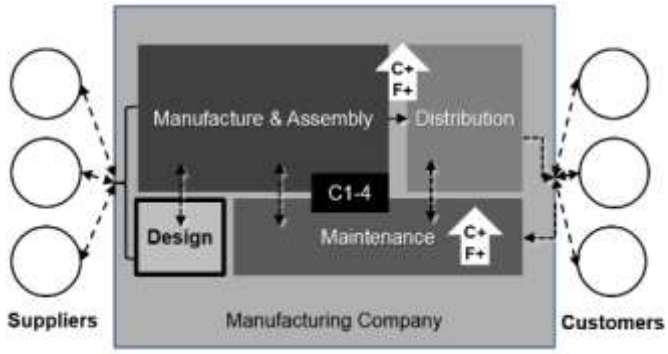


Figure 8-1 KPE C Company 1 & 2 Layout & classification

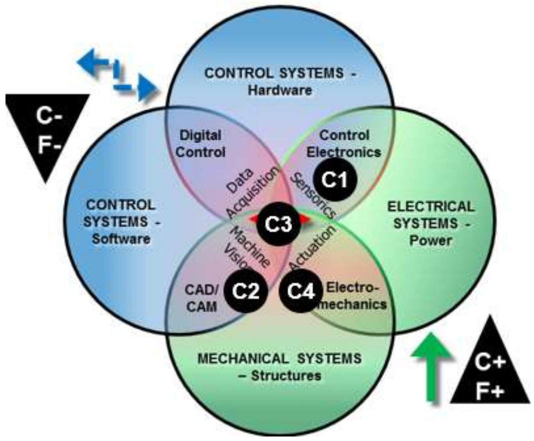


Figure 8-2 KPE C Case-study domains

Each case study in this category focuses on a different area of the mechatronics knowledge domain map (figure 8-2). Given their role in monitoring and improving production processes from a cost and efficiency perspective, practitioners focus on all aspects of the controlled electro-mechanical system and their interrelationships. This chapter presents an analysis of four such Distributed Systems case studies. A comparative discussion section follows the individual analysis of all features of the two selected KPEs and the four practitioners.

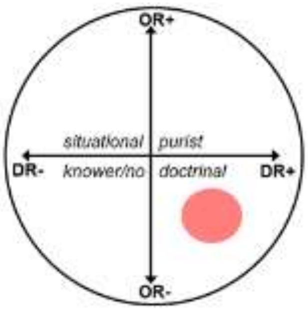
8.1.1 KPE C: Company 1 description

The first case-study site for the Distributed Systems KPE category is a medium-sized automotive safety systems manufacturing plant in the Western Cape. The local subsidiary, with international head offices in both the USA and Europe, has grown progressively smaller as the level of automation has systematically been increased, with currently around 200 local employees. This is a highly regulated and competitive industry, with the local subsidiary competing for business against their Eastern European, African and Australasian counterparts. The Six Sigma-run company specialises in the manufacturing of automotive safety systems designed predominantly in Europe.

Six Sigma has a number of features, including stringent project process methodologies, but the key purpose is to limit the number of failures of manufacturing processes to a 6σ level (near perfection) - 3.4 defects per million. 4 sigma, for example, means 6 parts per thousand are defective. Most companies operate around 3 to 4 sigma. 6σ includes not only statistical analyses of production, but has standard investigation and management strategies. In official 6σ companies, there is usually a clear organisational hierarchy, ongoing official reporting and stringent audit processes.

The manufacturing floor is open plan, and each sub-station or production line has a light stack which indicates the process status. This suggests a more visible 'whole system'. In such environments, the focus of problem solving is more often than not the impact of the outer environment, most notably the 'human element'. Strikes and collective bargaining are a common occurrence.

8.1.2 Dominant KPE *Insight*



The company website promises 'sophisticated systems', 'advanced solutions' and 'intelligent control', and presents numerous technically detailed images and definitions of the various systems. This suggests a *purist* orientation as there is no mention of the *doctrinal* Six Sigma methodology on the formal website. However, actual site processes are stringently driven by the adopted methodology, and all middle and upper management practitioners undergo Six Sigma training.

The dominant *insight* orientation in this local subsidiary is considered to be *doctrinal*: These automotive safety systems are relatively standardised designs implemented following the company's research, prototyping and testing processes (USA and Europe). Local manufacturers follow standardised specifications, and are driven by customer delivery deadlines. The customers are automotive vehicle manufacturers with deadlines of their own. In other words, interdependencies are complex.

8.1.3 Classification & framing of company

The company website differentiates clearly between the types of automotive systems, and the different global subsidiaries. This strong classification of product and subsidiary roles is echoed in the local company layout and management structure. Despite the open-plan central manufacturing factory, the various production lines and areas are clearly demarcated with safety lines painted on the floor (C+), and there are dedicated maintenance, testing and management areas of operation. The production line process boards are kept updated on a shift-by-shift basis, and there are standard daily progress meetings at fixed times across all employee levels. External framing over pace, criteria and control is very strong (F^e+) with a focus on efficient and cost-effective production against strict deadlines. However, the sector has been plagued with strikes and productivity challenges in recent years. Interviews at and researcher familiarity with the local site reveal a disjuncture between external and internal framing at the artisan level. ‘If it doesn't directly influence them it's as if they don't care… there's lots of politics and things like that’ (C2-64). The addition – in 2011 - of a local ‘family tree’ photographic display board at the entrance to the management section suggests an attempt at a more *knower* orientation to deal with productivity challenges.

Table 8-1 KPE C Company 1 - Classification & framing

Knowledge area focus			Manufacturing processes (electro-mechanical and user-orientated control); Improvement methodology: Six Sigma
Business size category			Medium =200
Classification	Space	C^+	Large plant; designated management and support staff offices; boardrooms; formal reception area
	Stakeholder relations	C^+	Clear organisational hierarchy; Formal recorded daily, weekly and monthly reports from all staff levels (operators to senior management)
	Time	C^+	On-going continuous and batch production; shift work;
Framing (external)	Pace	F^{e+}	Dictated by customer orders, highly competitive sector
	Criteria	F^{e+}	International standards driven; major focus on safety
	Control	F^{e+}	International standards driven; highly regulated; bi-annual safety and quality audits

Flexibility with regard to classification emerges at the product level in that this company specialises in different kinds of automotive safety products for a range of customers. They produce batches of a particular product, and then alter the production system slightly to produce a batch with a variation possibly not even visible to the naked eye. These differences in the same kinds of components are captured by way of various item identification systems – such as barcodes or labels. Batch production means that systems have to be reconfigured to allow for a new run. That means there are ‘change over’ times when items are moved, altered or systems can be maintained. Very often system modification is implemented during these short change over periods. Work is therefore relatively cyclical, and management attempts to regulate these to coincide with shift lengths and seasonal variables so as to maximise the use of time.

The three practitioners selected at this company work in relation to different production lines in the central manufacturing area. They have all had experience in the maintenance department, and are all part of ongoing modification projects on specific lines. Many of these lines consist of a mixed automation approach. Some stages are entirely manual, some entirely automated, and some stages are a combination. The latter would be an example where an artisan manually checks individual components that have moved through an automated manufacturing stage or manual stage by using control equipment to automatically measure the component against programmed specifications. The artisan would place the component into a specific machine which takes readings, analyses the data and displays a code on a computer screen. Being responsible for lines which involve all three types of processes requires not only a good all-round sense of mechanical, electrical and control logic, but also contextual knowledge of the people in the system.

8.2 Case study C1: Problem in context

Technician C1 has worked at the manufacturing plant for four years, and his problem is relatively straightforward. A production line is rejecting components due to their ostensibly not meeting the product height specifications. The problem does not even fit on a sigma scale as there are so many apparent failures. Visible inspection of the rejected parts clearly suggests they cannot all be defective. It seems clear that the height-measuring device itself is problematic. This is a sub-system (mounted on the production line) consisting of what are called ‘linear probes’, which ‘touch’ the product and send a signal to the computer to verify whether or not the height is accurate. Imagine a retractable ballpoint pen. You click it and a spring releases the tip and you can write. That becomes the ‘on’ position. You click it again and the writing tip is fully retracted into the ‘off’ position. The ‘on’ and ‘off’ positions of the linear probe checking the height of the components are 10V (volts) and 0V respectively. In other words, it is like a switch in an electrical circuit. When you switch it ‘on’ current flows, and the pre-set voltage is 10V. When nothing is touching the probe, it is at 0V. Now, the linear probes being used in this system are analogue and extremely sensitive. If there is any interference (like other cables nearby, or even the soldering on connective sections), the voltage can fluctuate, because other ‘electricity’ is interfering with the circuit, and the system will read this as incorrect. The specifications for these components are stringent (as people’s lives depend on the accuracy of the equipment in their vehicles), and the height readings are fluctuating. Since C1 has confirmed the height of a number of components, the assumption is that something is interfering with the ‘on’ signal from the linear probes.

Following a rigid 6σ methodology, it is determined that an inappropriate ‘connector bank’ (to reduce cabling) has been supplied by European manufacturers. All cables from the linear probes go to a single connector bank, which in turn is connected to the controller (PLC) by one cable. The connector bank in question is intended for digital inputs and has built in Light Emitting Diodes (LEDs). These, however, cause voltage interference in the highly sensitive analogue probes, and thus cause the height measuring device to reject components. The interim solution is to bypass the connector bank and wire all the linear probe cables directly into the PLC (which causes various delays and slows down overall production process).

8.2.1 Problem environment

8.2.1.1 Classification and framing

Classification and external framing in C1's environment are strong (C+, F^e+). Although the production lines are visible to all, each represents a very specific process on a specific product, the management and documentation of which are highly regulated. C1 reports on processes at fixed daily times following consultation with line supervisors and according to international/local regulatory documentation. When, however, a specific problem emerges, framing over pace weakens as the problems can only be solved within the bounds of human ability and resource availability. This is where internal framing comes into play. As established in section 4.4.3, internal framing is about the company ethos or 'code' - the tacit expectation of certain 'ways of being'. Where the practitioner is able to exercise a degree of autonomy and acts in a manner that echoes the underlying Regulative Discourse (Bernstein, 2000), s/he adopts the pace and criteria that would be valued by the company. The company in question values 'safety first' and systematic 'initiative' (supervisor). C1 upholds these values and exercises strong internal framing over his own processes (F^i+).

8.2.2 Problem solver

8.2.2.1 General profile: cognitive, experience and mood

Participant C1 is a friendly, well-liked and enthusiastic individual. He was the first in-service trainee from the mechatronics programme in question to be recruited by the company, and subsequently to be offered permanent employment – a rarity at the company given its downsizing processes over the past decade. At the time of interview he had been with the company for almost four years. His cognitive profile, based on academic performance, reveals a basic pass in mathematics (50%) and an average 60s in the other academic areas. He worked part-time during his Diploma (which he completed in minimum time).

Table 8-2 C1 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
C1	26	M	C	A	50	60	60	67	Dip 3yrs	4 yrs	Y	1st graduate from the programme in question to be permanently appointed at this company.

8.2.2.2 Analytical profile: discourses, semantics and insights

1.Define .
Loss of production due to high failure rate on product height measurement.

2.Measure.
Data collection, conducted a gage study (measured gage of known value 100 consecutive times)

3.Analyze.
Design of experiments (DOE),
- Replace 1 LVDT probes & redo study.
- Change cable to shielded type for less interference & redo study.
- Hard wire LVDT probe directly to Analogue card, bypassing the connector island & redo study on one probe.

4.Improve.

Temporarily run cable directly from all LVDT Probes to anologue card. (Causes long changeover time)

Long term
Install connector island without LED (The LED on the connector island interfered with the 0-10 Volt range to the analogue card, offsetting the measured value.)

Update all line documentation

Figure 8-3 C1 Sample text

C1's *situational insight* orientation may not appear apparent from the problem-solving questionnaire (figure 8-3), but it emerged during the re-enactment interview. The questionnaire response lists the standard 6σ DMAIC stages, which implies a *doctrinal insight*. However, similar to A1 (chapter 6), C1's interview did not follow a logical sequence. He moved around between concepts and contextual elements, trying to clarify these for my benefit. He only settled into a sequence when the actual artefacts were present. I sensed that the DMAIC methodology gave him a reliable framework or basis from which to operate, but that it was not naturally internalised. His supervisor confirmed this subsequently:

> *'His process is very structured when he understands how the machine operates, but if he's not familiar with the process he jumps around quite a bit.' (C1 supervisor)*

The semantic code analysis (figure 8-4) reveals a predominance of semantically dense terms (SD+) and context-specific references (this sub-system) (SG+). The *rhizomatic* references are the conceptual explanations pertaining to Ohm's Law.

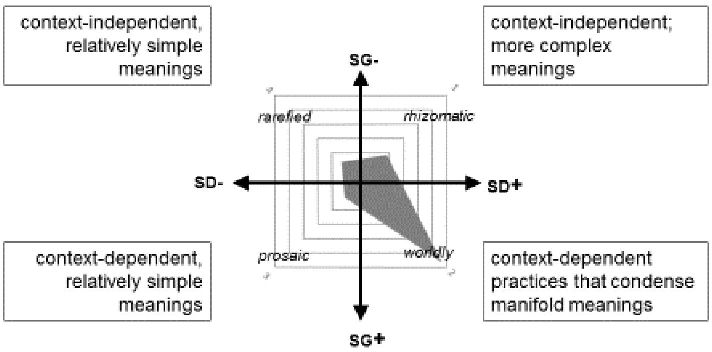


Figure 8-4 C1 Semantic code

8.2.3 Problem-solving process

The problem-solving process captured on the epistemic plane (figure 8-5) indicates two significant boundary-crossing points in relation to the separate axes: that from *doctrinal* (OR–) to *purist* (OR+) on the right (strong DR+), and that from *doctrinal* (DR+) to *knower* (DR–) in the lower half (weak OR-). These will be discussed in detail in the following sections.

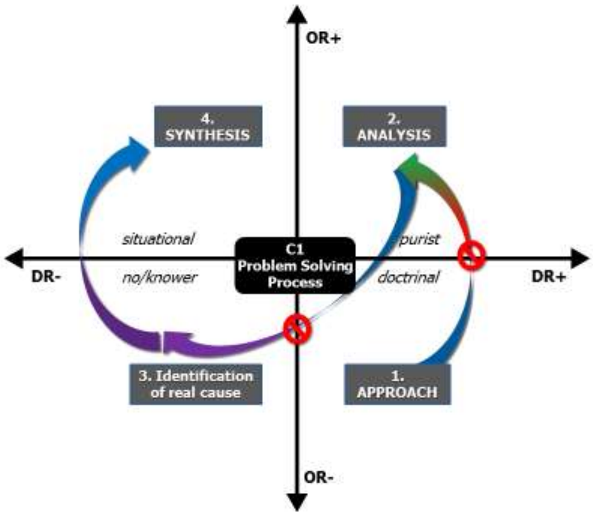


Figure 8-5 C1 Problem-solving process

8.2.3.1 Approach

C1's approach is strongly methodological. The questionnaire response saw him rigidly following the 6σ DMAIC methodology. This is what is expected in this environment, and is usually fruitful. However, in anticipation of the complexity of digital and analogue signalling, I had researched this problem prior to the interview, and had assumed the LEDs (the cause of the voltage interference) were not visible. When faced with the actual artefacts, I could not understand why he had not immediately investigated the very visible LEDs (figure 8-6) as the source of voltage interference on such sensitive probes, particularly given the following statement:

> *'We saw the LEDs were lighting up, getting brighter as you move the [LVDT] probe… The LVDT works as a potentiometer - As you move it the resistance changes, then your PLC will read a 0V as a certain distance, and then 10V as another distance. As you move the probe, the value moves as well.' (C1-25)*

In other words, from the outset with the system running, the LEDs 'lighting up and getting brighter' should have been an indication that a clean on/off signal was not being sent. However, the company's *doctrinal* philosophy dictated that C1 analyse the cause following a set method.

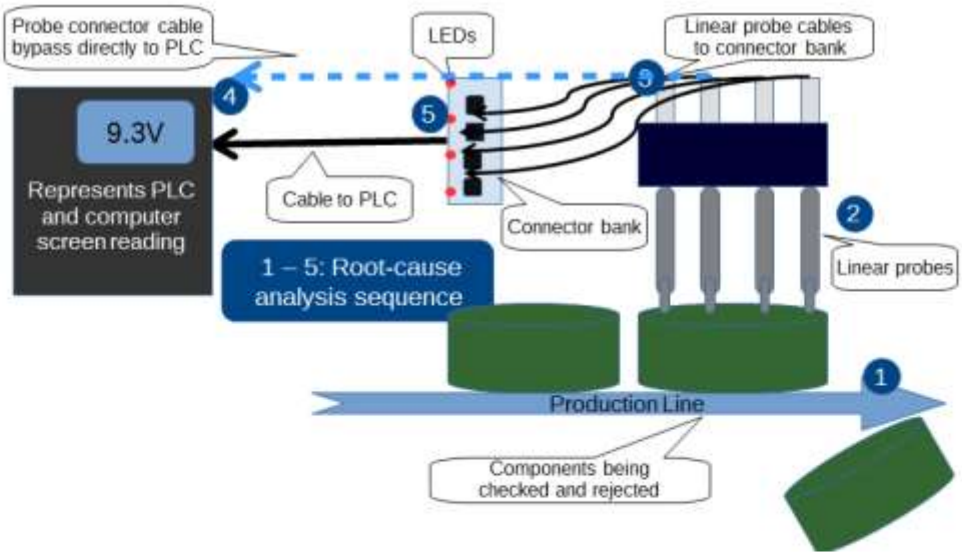


Figure 8-6 C1 Problem schematic

8.2.3.2 Analysis

For the third DMAIC stage - 'analyse' – C1 used an iterative 'Design of Experiment' (DOE) process indicated on figure 8-6. This meant that having identified the problem as being in relation to an inaccurate height-measurement system (1), he started at the linear probe itself (2) and worked his way backwards, replacing each part with a new one (or one known to be working) and testing the system against a known value. He replaced the probes. He replaced the cables (3). He checked the soldering at each connection. The problem persisted - the voltage reading from a component whose height was dead accurate still fluctuated. And so he worked his way towards the connector bank (5) into which the cables from the linear probes were plugged. The next logical step was to determine whether the connector bank was the problem. C1 simply plugged the cables from the linear probes directly into the controller reading the voltages (4). This produced a steady 10V signal. So, the problem was the connector bank (5) - newly supplied (along with the probes) by a leading European manufacturer who has been a supplier of this company for years.

In the explanation of the analysis, C1 moves relatively comfortably between the method and the physics or logic behind each DOE stage, albeit that the physics is very basic and he appears to be strongly reliant on the 'method' he has acquired and clearly had to reproduce over the past four years. During the interview he sketches the problem in terms of Ohm's Law, drawing the different circuits: a digital circuit working between 0V (off) and 24V (on) versus an analogue circuit (0V - 10V). The signal from the probe is an analogue signal, but the connector bank is meant for digital inputs. The LEDs are clearly visible on the system he demonstrates, and when I ask if he could not have calculated the effect of the LEDs beforehand, knowing what he knows about the difference between analogue and digital signals, he laughs uncomfortably:

> *'It's not a common island (or 'bank'), there are various types and **I assumed it was meant to be like that**… European machine suppliers think they're of a high standard.' (C1-106; 70)*

It appears that the European supplier owner has handed over much of the new work to his son. 'This was something new for them', C1 stated. The supervisor admits that checking the newly supplied connector bank documentation had been overlooked.

8.2.3.3 Synthesis

The problem took three days to fix. 'Fix' meaning a return to the previous system - cable directly into PLC while they awaited new and appropriate connector banks. This assumption that new equipment works as per specification is a common theme in this research. C1's problem-solving trajectory sees a *doctrinal* (OR–, DR+) approach, shifting to a *purist* (OR+, DR+) analysis of each of the DOE stages. The movement into the *knower* quadrant with respect to the identification of the cause as being the incorrect supply of a vital component did not entail the kind of miscommunication between suppliers and the company as experienced in case study A3, nor did it mean sustained engagement with the suppliers. It simply entailed electronic communication to bring the delivery of incorrect components to their attention. Again, as with many of the problems encountered, the solution demanded *situational insight* – a solution for here and now in this particular context (OR+, DR–).

8.2.4 Problem structure

The problem would be classified as falling within the domain of 'electronics', with a specific theoretical focus on the difference between analogue and digital signals, and Ohm's Law. This necessitates firstly understanding the logic of the connected components, underpinned by applicable physics (current flow, voltage, resistance). The problem, however, announces itself through mathematics - the incorrect voltage values are being read by the system:

> *'We saw that the voltage change to the PLC was not consistent with the reading that we measured… the system of a linear probe works on resistance… when you press it in full you get 10V… but the LED has a certain resistance as well… so basically its Ohms law.' (C1-25)*

C1's analysis demonstrates the movement from a strong horizontal knowledge structure (mathematics) to a hierarchical knowledge structure (physics) and back to a weak horizontal knowledge structure (logic) – as he systematically checks the logic of the relations between components and the potential impact on the voltage change. The problem structure is thus a movement between weak (DR–) and strong (DR+) discursive relations in relation to a fixed ontological referent (power relations in a circuit as defined by Ohm's Law). However, this analysis was unnecessary. A simple *knower*-orientated inspection of the newly supplied connector bank and its accompanying documentation would have saved three days of analysis. If, for example, he had taken into consideration the fact that a new and younger person was now running the supplier company, he might have checked the component delivery documentation more carefully. The assumption of the reliability of high status supplier products was the actual cause of the problem in this case. This suggests an expectation that the '*knowers*' in the system operate according to standard procedures - strong discursive relations (DR+) - in precisely the same way as the inanimate system is expected to function. Ironically, the movement into the *knower* quadrant is from a *knower* perspective – these are high status suppliers who have always demonstrated certain 'ways of being' that are valued in the sector.

8.2.5 Boundary navigation

In this highly standardised and procedurally codified environment, there are nonetheless more complex stakeholders, requirements, consequences and interdependencies. This places the complexity rating at a value of 15, the upper end of the technologist band. C1 has 'learnt the 6σ approach and applies this - always process first, then part' (C1 supervisor). The *doctrinal* quadrant, however, is not a natural location for his actions, and neither is the *purist.* He has been in the environment for long enough for experience to support his theoretical understanding and vice versa. 'Your theory becomes part of your logic - it can be this, it can't be that…' (C1-107). His supervisor's statement that he 'jumps around' in unfamiliar turf supports the claim that he tends towards weaker discursive relations (DR–). He is ideally a *situational* problem solver. The boundary-crossing challenges are evident throughout his problem-solving description, but they do not represent insurmountable clashes. I would like to suggest his 'persistence' and 'personality' (C1 supervisor) are not only indicative of attributes that are tacitly valued in this context, but have enabled access to the broader *reservoir* of available knowledge in this environment over the years, and that this access has led to experiential '*situational*' problem-solving expertise.

8.3 Case study C2: Problem in context

C2 presents a very interesting problem. At the time of the interview he worked in the maintenance department and was responsible for various optimisation processes identified by technicians or engineers in the plant. This means he engaged with different line operators and technicians on a constant basis. The problem he chose to focus on in his questionnaire is as follows: A certain part that the company manufactures for a client in the Eastern Cape is continuously being rejected by the client's scanning equipment prior to automated assembly as part of a sub-system. The client's scanner reads a barcode to verify that this particular component 'belongs to' the sub-assembly. But there is nothing wrong with the components, the client realises - the problem is the barcode itself. The scanner cannot read some of them as the black and white barcode lines are too close to the black descriptive text on the label.

In the questionnaire and during the interview, however, C2 explains:

> *'The label printer runs out of stickers and the operator does not follow the correct procedure for replacing the roll. [The] printer is then misaligned and maintenance technician then compensate [for the] error by editing label on the PC.' (C–78)*

What happens is that because the printer is not calibrated properly (and is in fact not the ideal printer), when the new label roll is inserted, the stickers (labels) start coming out with 'chopped off' bits of label data. The maintenance technicians then 'edit' the label content on the computer, bringing the label information too close to the barcode (but so that everything will now fit onto the sticker). When the scanner at the client tries to 'read' the barcode, it gives an error reading because it can't distinguish between the black text and the black lines of the barcode.

C2's instruction is to integrate a (costly) vision sensor system into the manufacturing system to ensure the barcode meets specifications. When taken to the site of the problem, I see that the components are manufactured by one automated sub-system; they are then manually taken to an interim station where the printed barcode labels are manually stuck onto each component, before being passed on to another stage. The 'solution' is placed at the interim station: a camera system which has been programmed to measure the spaces around the barcode label and between the barcode and text on the label.

8.3.1 Problem environment

There are significant time, space and stakeholder constraints in the implementation of a solution in the C2 case study. With production deadlines driving cycles (F+), C2 can only integrate the camera inspection system during operator tea and lunch breaks. This gives him 45 minutes per day at the actual problem site. Secondly, the camera inspection system is to be integrated into a space between two production processes:

'Placing of camera affects the program and operator movement and space needs to be considered. [It] needs to be close enough for better image quality, yet not so close as to be damaged by operator during production.' (C2-83)

Thirdly, the camera system needs to be integrated into a foreign manufactured machine for which the original PLC program was never received. In other words, C2 needed to deduce how the program was set up so as to integrate additional program features from the new camera system. These represented significant challenges and manifested as operator and practitioner frustration.

8.3.2 Problem solver

8.3.2.1 General profile: cognitive, experience and mood

C2 is one of the first five participants to have completed the research questionnaire. He was handpicked for this company as he demonstrated great management potential – being articulate, confident and analytical. Although he achieved distinctions for mathematics and logic (making him one of the 2.9% anomalies), he entered the Diploma programme following an access programme year at a different UoT. This means his school-leaving certificate did not entitle him to register for a Diploma initially, and his academic achievement in minimum time is somewhat remarkable.

Table 8-3 C2 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
C2	25	M	W	E	79	71	79	69	B-Tech 4yrs	2.5	Y	Subsequently left the company to pursue R&D interests

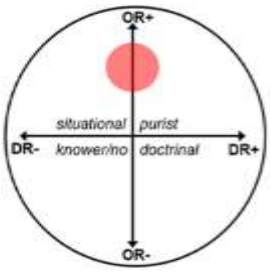
With part-time work experience ranging from volunteer youth programmes to the restaurant trade, he is comfortable in social situations. At the time of the interview he had been with the company for two and a half years. My first impression during the interview was that C2 was somehow uncomfortable and had lost his confidence. His mood, unlike that of his participating colleagues, was distinctly 'down'. This was to be illuminated by the subsequent problem-solving explanation, and the supervisor feedback that 'he is not a natural manufacturing person - he would be more suited to R&D work because he needs flexibility' (C2 supervisor).

8.3.2.2 Analytical profile: discourses, semantics and insights

The problem-solving questionnaire (figure 8-7) is numbered and detailed, but with no indication of the dominant Six Sigma methodology.

PROBLEM SOLVING: Most recent problem faced	PROBLEM-SOLVING: Process
Incorrect printed labels being placed on webbing guide, creating problems when scanned at client. Problem arises when the label printer runs out stickers and the operator does not follow the correct procedure for replacing roll. Printer is then misaligned and maintenance technician then compensate error by editing the label on the PC. This then brings other elements of the label closer to the bar code on the label and the vision sensor at the client sees the element as part of the bar code and gives an error. Use of a vision sensor (camera check) was decided to be implemented into our system to measure/check the distance between the barcode and other elements on the label.	1. Find mounting position for vision sensor (Limited space) 2. Check available input/outputs on PLC of affected station. 3. Familiarize myself with vision sensor and Checker software. (Read operational manual) 4. Familiarize myself with existing program and its logic/operational procedures. The program was uploaded from PLC, thus no comments was available. Integrate vision sensor inputs and outputs into existing program. 5. 12 different labels available, so all 12 needed a separate program on vision sensor and automatic changeover done with operator HMI input. 6. Inform line operators of new changeover procedures, reasoning for modified system and operation. 7. Design and manufacture (manufacturing outsourced) a protective cover for camera. 8. Optimize camera programs. 9. All this needed to be done while production was running. So planning and efficient use of time was very important, especially in my case as I need to leave work earlier to get to class in time.

Figure 8-7 C2 Sample text



His textual contribution and interview suggest a *'situational/purist' insight* orientation. The re-enactment interview supported this. The demonstration of the problem site was not sequential, rather it was responsive to the different factors impacting on the working processes at the site – from the various operators to available equipment and different process explanations.

The semantic code (figure 8-8) reveals a majority of *prosaic* references (SG+, SD-), which are mostly contextual explanations of circumstances related to operator behaviour and difficulties. It was this particular case-study semantic code analysis that alerted me to a possible correlation between high (and equivalent) mathematics and logic achievement in relation to more *prosaic* statements.

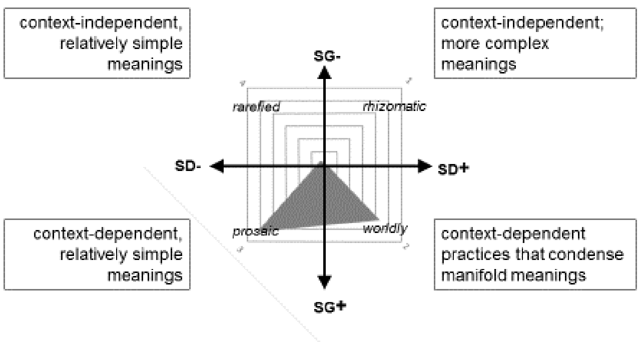


Figure 8-8 C2 Semantic code

8.3.3 Problem-solving process

8.3.3.1 Approach

C2 approaches the problem from a *situational* perspective, stating that the 'problem arises when the label printer runs out [of] stickers and the operator does not follow the correct procedure for replacing [the] roll'. Unfortunately, the printer is not ideal and 'we have ordered new ones, but we can't wait - so we had to put a system in place to make sure the labels are correct'. In other words, in this situation a particular solution was necessary.

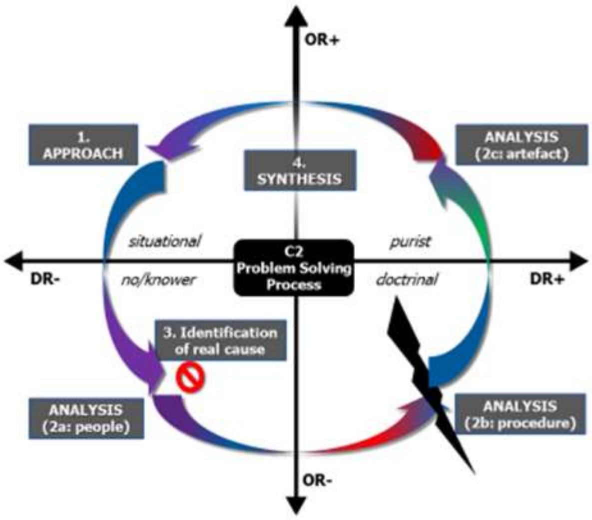


Figure 8-9 C2 Problem-solving process

8.3.3.2 Analysis

Although the *focus* as C2 proceeds into the *knower* quadrant (OR–, DR–) is on operator behaviour, the *basis* of the claims appears to be *doctrinal*:

> *'It is their job to call a maintenance operator and tell them to calibrate the printer first - but they actually got the maintenance technician to change the label itself.' (C2-18)*

The result of their action is that 'this then brings the other elements of the label' too close. And here a disjuncture occurs. The *doctrinally* dictated correct labelling of components is crucial to productivity and client retention. In order to ensure the labels are correct, management decided that a camera inspection system needed to be integrated into the production process. C2 then details a 3rd analysis phase in *purist* fashion, with the technical specifications of the camera system and the particular challenges of the PLC program:

> *'The machine was built in [Eastern European country], so the names of each block were almost useless. I used the HMI program to cross reference with the PLC program different variable blocks to see what variable was used for what hardware input/output.' (C2-89)*

8.3.3.3 Synthesis

The solution in this case was a *situational* one – the integration of a camera system to ensure the labels were correct. However, this was not a solution to the original stated problem: operators not aligning the printer roll correctly and maintenance technicians 'editing' the label. When I queried why operator training was not considered, C2 replied: 'We could have put more effort into the operators' understanding… but, if it doesn't directly influence them, it's as if they don't care. There's lots of politics...' (C3-63). The supervisor confirmed that the solution had to be human-error-proof. Ironically, the newly integrated camera system 'caused friction with the operators because now it has slowed production down' (C2-60).

8.3.4 Problem structure

The problem location and nature depend on the problem definition. If the problem is (as stated) operator behaviour, then it could be described in terms of human 'logic' in a particular context with respect to the relationship between the different component production and labelling stages, and the implications of incorrect product delivery for the business as a whole. This would suggest predominantly weak horizontal forms of knowledge, with weak discursive relations (DR–). However, the problem solution is described in terms of the physics underpinning light sensors to detect the black and white edges on the label, the mathematics of label element proportions, and the logic of the control system into which the camera system is being integrated. The latter problem structure suggests a movement between hierarchical physics knowledge to strong horizontal knowledge (mathematics) to weak horizontal knowledge (logic). In this case, these three knowledge structures each have at least one strong relation: the allegiance to the phenomenon (OR+) or the method (DR+).

8.3.5 Boundary navigation

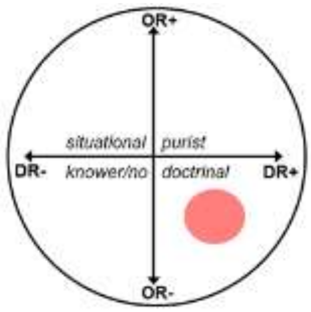
The dilemma in this problem-solving case study is that the original problem was not addressed. However, correct 'problem formulation' (Volkema, 1983) was not the preserve of the technician, and it was his engineering supervisor who suggested and endorsed the proposed solution. I believe that the *doctrinal* orientation of such manufacturing environments predisposes practitioners to predominantly strong discursive relations (DR+) and that the weakening of these can only be tolerated if the ontic relations remain strong (OR+). In other words, there must be a strong anchor in at least one of the relations. It is bad enough, as it were, that the rapid evolution in technologies has weakened discursive relations (multiple ways to accomplish the same objective). Such environments do not appear to have measures in place to deal with weak ontic *and* discursive relations (OR–, DR–). Their very methodology (Six Sigma) is designed to strengthen discursive relations ostensibly underpinned by a philosophy of perfection (which would suggest its intention is *purist* in nature).

Problems of this nature immediately call into question the descriptors applied to technician practice. The analysis against the IEA problem attributes place this particular problem in its context at the lower end of the 'engineer' band (18). My subsequent discussion with outside engineers on the elements in this case study reveals a lone voice. None of the engineers I have consulted has conceded that the problem of operator training could have been addressed in this case. I believe that the solution in this case represents a deliberate attempt to artificially strengthen both the ontic and discursive relations in a climate of ever-increasing technological proliferation and '*knower*' complexities. Furthermore, C2's discomfort at the time of the interview and subsequent resignation from the company suggest a code clash between his way of seeing things and those valued by the company.

8.4 Case study C3: Problem in context

C3 is responsible for the maintenance and improvement of a number of production lines. His stakeholder scope of work involves operators, suppliers and management. Technically, C3 is exposed to mechanical, electrical and control-based problems, and has for the past two and a half years of employment at the company integrated several automation sub-systems to improve existing processes. The problem selected for the research is the force monitoring system on a particular clip used to secure an automotive safety component. The clip is applied using a pneumatic system (pressurised air) and the force with each clip fitting is measured. The consistency and reliability of this force is essential as the clip in question holds an automotive safety device in place that needs to be released upon vehicle impact. The force readings are proving to be inaccurate as a result of the monitoring system not being robust and accurate enough. The solution requires an entire redesign of the clip fitment jigs (devices that hold items in place), the addition of load cells (which measure force) and the reprogramming of the PLC to monitor force measurements and subtract external forces. The new system included an error acknowledgement function as well as a reject bin. The redesign and testing had to be documented to comply with customer specifications.

8.4.1 Problem environment



It has already been established that C3 works in the same *doctrinal* environment as C1 and C2. They all report to the same supervisor. Unlike the C2 case study, the production line in C3's case was halted to allow for the modifications. However, pace and criteria were strongly externally framed (F^e+) as an existing order was in place and the current processes were not meeting specifications.

8.4.2 Problem solver

8.4.2.1 General profile: cognitive, experience and mood

C3 is probably the most typical successful programme candidate, with high logic and technology performance (distinctions), but low mathematics (54%) and physics-based results. What is highly significant in this case is that his father owns a medium (>200) manufacturing company and C3 has gathered part-time work experience there in all the company sections. He took to the research site company like a duck to water, having been inducted into the appropriate value system from an early age.

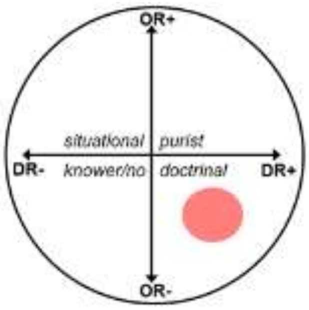
> *'He is driven and motivated to complete his tasks on time - even [using] personal funds in order to get items paid for and delivered on time, if the company system fails.' (C3 supervisor)*

He was regarded as one of the most successful trainees from an attitude and technical ability perspective. He is happy in his environment and is clearly making a good impression on management. He likes rules, citing 'personnel discipline' as his particular challenge. He is the only participant to have a clearly *doctrinal* orientation.

Table 8-4 C3 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
C3	25	M	W	A	54	62	78	84	B-Tech	2.5	Y	Worked part-time in father's manufacturing company (family owned).

8.4.2.2 Analytical profile: discourses, semantics and insights



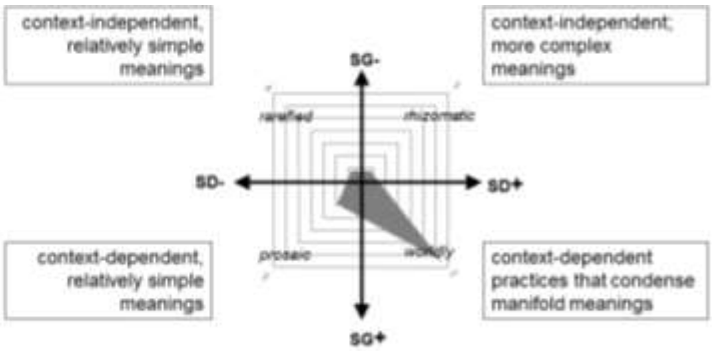


Figure 8-10 C3 Semantic code

C3's *doctrinal* disposition reveals itself in the rigid adherence to appropriate technical terminology (figure 8-11), and a methodically detailed approach to delineating the problem and 'corrective action'. He uses standards-orientated terms and avoids first person references. He relies on industry documentation and specific standards, and this is reflected in his general discourse. His semantic code (figure 8-10) demonstrates a predominance of *worldly* references - contextually technically specific (SG+) and complex (SD+) meanings.

<u>Problem definition:</u> Force monitoring system for fitment of plastic clip to airbag inflator for [redacted]. Initial design of system, accuracy not meeting customers' requirements.

Pneumatic assisted press fitting plastic clips to airbag inflators. Fitment force measured with load cell on each cycle.

Capability of process monitoring system not good at all. Readings very inconsistent and rejecting a lot of parts which isn't rejects.

<u>Corrective action:</u>

a) Redesign of jigs for both clip seating and inflator support in the process. Spring loaded top jig to allow for better self alignment of clip fitment onto inflator during cycle.
b) Multi-point support for inflator on bottom jig to ensure exact orientation for every cycle.
c) Repositioning of load cell monitoring clip fitment force. Load cell integrated to top jig. Reading of measurements only starts after process is stable, with no external interference which can affect readings.
d) PLC program - Complete reprogramming of measuring and process sequence structures.
Reading live value from load cell and subtracting any external forces during the cycle, only indicating actual fitment force.
Controlling and verifying each cycle with set parameters as per drawing and customers specifications.

Figure 8-11 C3 Sample text

8.4.3 Problem-solving process

8.4.3.1 Approach

As is to be expected in the context, and given evidence of his methodical nature, C3 approaches the problem from a *doctrinal* perspective. His first step is listed as 'problem definition', both at a macro and micro level. The former he records as a 'process capability' problem with the micro problem being the 'force monitoring system on' a specific automotive component on a dedicated production line for a long-standing client. His supervisor praises his 'systematic approach':

> *'The pace when he starts seems slow because he spends a good time analysing the context as a whole … but in fact he solves problems faster than the others because of the initial care taken.' (C3 supervisor)*

The Sobek (2004) MIT study found that rigorous 'problem definition' was the crucial stage in effective problem solving. This is the only participant in the Distributed Systems category to effectively define the problem from the outset.

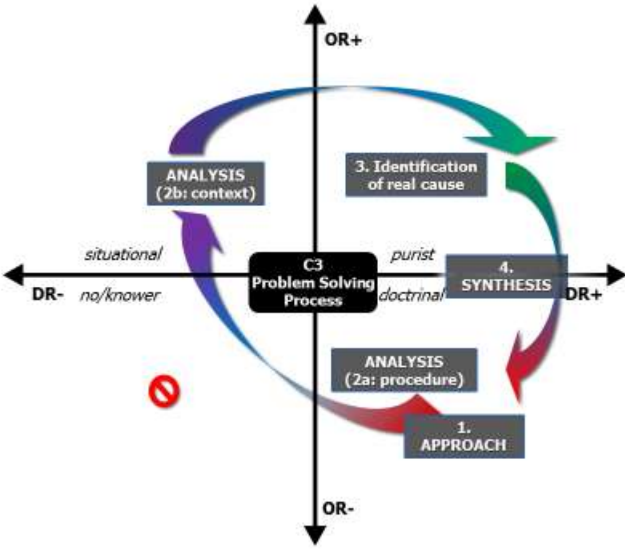


Figure 8-12 C3 Problem-solving process

8.4.3.2 Analysis

As alluded to by the supervisor, C3 systematically analyses the required processes, the context (situation) and the requirements of the artefacts, but 'tends to ignore the people in the system'. The required process (*doctrinal*) is described in technical detail beginning with the pneumatic system that attaches the clips to the automotive safety component and the existing force monitoring measures in place. The analysis shifts to the current *situational* context (OR+, DR–).

> *'The current systems and fixtures are not able to provide the precise accuracy required to meet customer specification. Small improvements or changes won't stabilize the process, and based on systems and process equipment calculations, to achieve what is required major changes had to be made to firstly meet specifications and secondly to ensure capability of process and repeatability.' (C3-9)*

In other words, in this specific situation the customer needs are not being met, so a number of changes need to be made. The third stage of analysis is the epistemic heart of the problem: In order to achieve accurate and consistent force readings, a more reliable mechanism is required. C3 decides – based on Internet research and existing systems at the company – that a load cell would provide the kind of accuracy required. A 'load cell' is like a sensor. It 'is a type of transducer that converts physical force into measurable, quantifiable electric energy'[77]. The load cell is attached to a structural element (in this case, the top jig) to which force is applied. The resistance in the load cell changes as a result of the pressure (when the jig attaches the clip to the component) and this change in resistance is equal to a specific force. This problem is initially an application of mechanical and electrical physics (force and electrical resistance respectively) following the mathematical values specified by the client, and subsequently logic, when the system is programmed to act on the force reading. The correct force reading signals proceed, while the incorrect force reading signals the part should be diverted to the reject bin. Despite the implied disciplinary knowledge, C3 does not go into disciplinary detail.

> *'For each element described the main focus was eliminating external forces or process elements which could influence the actual intended force readings. Also keeping in mind all changes and systems which have to work together and how each change will influence each part of the process.' (C3-14)*

The final stage of analysis details the cause of the problem as inadequate force measurement and broadly demonstrates legitimate procedures in reference to tightly bounded objects, hence a *purist insight* (OR+, DR+).

8.4.3.3 Synthesis

The synthesis of a solution entailed initially integrating load cells into the jig and then the 'complete reprogramming of measuring and process sequence structures' (C3-22). This is followed by process capability testing to ensure repeatability and reliability of results from a mathematical perspective. C3 refers to the equation $\mathrm{F} = p\frac{\pi d^2}{4}$ which was used to control the pneumatic pressure when the clip is attached, and which pressure needs to equate with the force of the fitment. The focus during the solution synthesis is a movement from *purist* to *doctrinal insights*.

8.4.4 Problem structure

The problem at a theoretical level would be classified as falling at the centre of the mechatronics knowledge domains, including the physics of forces and energy (both that of the

[77] (http://www.thomasnet.com/articles/instruments-controls/load-cell-basics)

electrical resistance implied in the use of load cells as well as the 'fluid power' implied in the pneumatic system). The integration of the load cell as a sensor and the alteration of the PLC program to react to the signals requires logic-based processes – a weak horizontal knowledge structure. The acquisition and monitoring of force measurements is dependent on mathematics – a strong horizontal knowledge structure. What is interesting in this case is the maintenance of strong discursive relations (DR+) across all the disciplinary elements. Unlike the previous *situational* logic-based cases (where different options are possible and considered), C3 does not explore any alternatives to the use of a load cell to improve the accuracy of the force measurements, and does not indicate any weakening of discursive relations in his reprogramming of the PLC. The Allen (1966) study indicated that the most successful designs were those where fewer alternatives were considered. This finding suggested practitioner confidence in the original selection of a solution. C3's supervisor confirmed his 'excellent, systematic solution and verification' process, and my impression was that this was a confident practitioner who matched his environment – valuing prescribed procedures and standards.

8.4.5 Boundary navigation

It is interesting that C3's problem-solving trajectory avoids the *knower* quadrant, despite this being in precisely the same environment as the C1 and C2 case studies. There is no mention of people who may be implicated in the problem or problem-solving process. The avoidance of first person and the consistent *doctrinal*-speak suggest the practitioner is more comfortable where the discursive relations are strong (DR+). The only indication of a potential code clash is in his explanation of challenges with regard to 'team work within the department, discipline and order, and the quality of work from fellow team members' (C–30).

It is important to mention that the lack of analytical disciplinary depth during the problem-solving explanation is not a failing in this context. As established in C1's case, this is a highly standardised and procedurally codified environment, and this particular problem complexity rating weighs in at a comfortable technologist level (15). C3 has his priorities straight – get the processes right according to specifications and as efficiently as possible. This environment does not require the kind of *purist* activity that one would find in R&D, for example. There is not the luxury of that kind of time. If one is open to such a *doctrinal* environment, there are sufficient opportunities to acquire experiential knowledge.

8.5 Case study C4: Problem in context

The comparative case study for the Distributed Systems category represents the second largest KPE in the research study. A packaging manufacturer with just under 4000 employees, the company has premises across the country and specialises in the processing of raw materials, recycling, and the production of packaging products. The stock exchange listed company has recently undergone a major rebranding exercise (2012), and – as in the first Contained Systems company – their website now boasts a distinct Triple Bottom Line (TBL) flavour. TBL is 'an accounting framework that incorporates three dimensions of performance: social, environmental and financial' (Slaper & Hall, 2011, p. 4). Given the complexity of globalisation and increased competitiveness, sustainability is the key to economic survival, and performance in the 21st century is increasingly dependent on the 3Ps: people, planet and profits (*ibid*.). TBL brings with it a particularly recognisable marketing and policy discourse. Terms characterising a TBL philosophy are 'environmental friendliness', 'social engagement/responsibility', 'ethical governance', 'transparency' and – in a South African context – 'transformation' and 'employment equity'. This discourse – usually visually accompanied by shades of 'green' - stands in stark contrast to the more technical or scientific discourses evident in traditional modern manufacturing marketing literature.

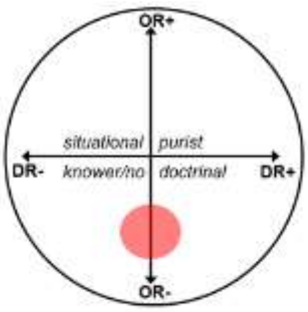
It is important to state upfront that I had not revisited the company website prior to the interview with C4, who worked[78] as a technician at one of the plastic container manufacturing plants in the Western Cape. The original website was lean and practical: nature of business, product range and contact details. Following the interview and noting the similarities between the C4 case study and that of C2, I was not surprised upon revisiting the website to see the transformation. The reasons for the ostensible shift to a people-orientation had been evident in C4's chosen problem, which was complex. The manufacturing plant sees the processing of plastic pellets into the formation of bottles (through a blow-moulding process) and the packaging of these bottles. The existing process had numerous problems: the insertion of the incorrect plastic pellets into the 'hoppers'; inadequate blow-moulding cooling processes; conveyor line blockages; and inadequate quality-control and testing systems. Although the participant was encouraged to focus on a specific micro problem within this larger problem context, references to the interrelationships were unavoidable. C4's role in the company was similar to that of the first three Distributed Systems participants: the monitoring and improvement of production processes.

[78] C4 had handed in his resignation shortly before the interview. As a result, our interview did not take place on site. However, I am familiar with several similar manufacturing sites and their processes as a result of the mentorship of trainees at such sites. The participant's inability to follow the in-situ re-enactment protocol did not impede the data collection process. On the contrary, he provided extensive textual and visual resources.

8.5.1 Problem environment

The local manufacturing site is similar to that of the first KPE in this category. Although the production lines are visible to all, each represents a very specific process and areas are demarcated with safety tape. Production occurs in batches according to fixed cycles and aligned to staff shifts. Classification and external framing are thus strong (C+, F^e+). Whereas safety is the priority in the first company, this manufacturer's focus is productivity and more recently 'quality'. Despite the existence of numerous standards pertaining to the 'physical, mechanical, and chemical properties of a wide variety of materials and products that are made of plastic and its polymeric derivatives'[79], there is far greater flexibility in this sector as compared to automotive or medical manufacturing environments. The implications are that reporting and documentation processes are less internationally standardised and regulated. This implies slightly weaker framing over criteria. However, in a company as large as the one in question, strongly classified stakeholder relations and strongly framed company reporting systems are in place, particularly as they have responsibilities to a shareholder body.

C4's responsibility to act as maintenance and improvement technician meant he was not responsible for actual production, so his reporting was less formal and tended to be verbal daily meetings with his supervisor. What counted was his delivery of solutions – whether mechanical, electrical or control problems – to existing process challenges.



The rebranding to an ostensibly more holistic *knower* orientation, with a claimed focus on 'customers, workforce and shareholders', is challenged by an equal commitment to productivity and profitability. The latter are enabled through historical *doctrinal* processes. Despite the reference to change management in their marketing literature, there is a sense that the good intentions may currently merely be paying lip-service to a global trend in management.

8.5.2 Problem solver

8.5.2.1 General profile: cognitive, experience and mood

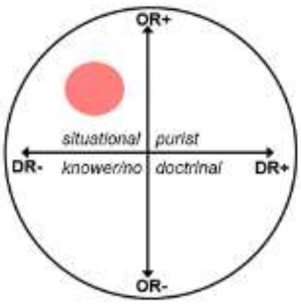
C4 is an engaging, sporty young man with a solid track record in leadership. An above average achiever in the qualification context, he too represents the successful programme graduate norm in achieving distinctions for the logic and technology-based subjects. He has worked as a part-time sound technician since high school and is happiest designing and building new systems. A highlight on his resumé is the rebuilding of his own car.

[79] (http://www.astm.org/Standards/plastics-standards.html)

Table 8-5 C4 Profile

Personal details					Academic Diploma performance					Employment		Comments
Participant	Age	Gender	Race	Language	Mathematics	Physics-based	Logic-based	Technology	Qualification Completion	Duration of Employment	Work Exp prior to /during stud.	Specific personal or contextual factors that may be significant.
C4	24	M	W	A	65	60	81	76	B-Tech 4yrs	1 yr	Y	Was headhunted by a machine building company shortly after interview

8.5.2.2 Analytical profile: discourses, semantics and insights



Unable, for practical reasons, to complete a written questionnaire, C4 opted to go straight into the interview (figure 8-13 is a sample of the transcript), and gave verbal questionnaire responses. The interview could not occur on site, but was accompanied by dozens of photographs of the working processes as well as extensive reports he had compiled. C4's textual contributions and interview indicate a *situational insight* orientation.

1	The idea is to remove the person by installing a camera inspection system
2	because the woman currently standing there putting the glass bottles into a box puts them onto a light box that checks the bottles
3	Several points only became problems after the camera inspection system was installed
4	Before the camera system there had to be a scroll
5	Before the scroll there had to be a bottle rejection system
6	These are things that weren't such big issues if it wasn't for the quality improvement that they wanted at the end

Figure 8-13 C4 Transcript sample

His first priority was to establish the changing context and the various unanticipated factors that kept cropping up and which required responsive solutions. The 'change' here being the shift in focus to 'quality' and not merely 'quantity'. The demonstration of the problem site via the photographs was not sequential, and invariably led to descriptions of operator behaviour.

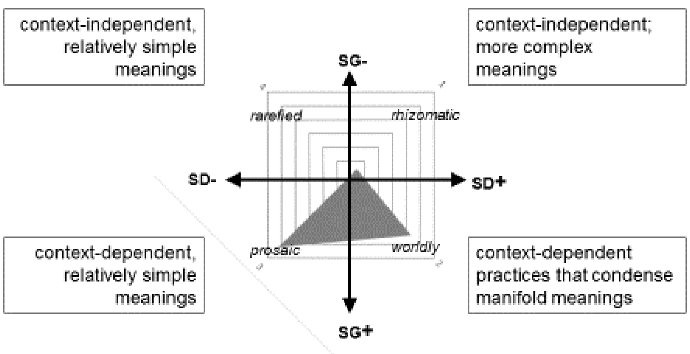


Figure 8-14 C4 Semantic code

The focus on the *situational* context and *knowers* in the system is echoed in the semantic code analysis (figure 8-14) which reveals a predominant *prosaic* code (SG+, SD-) – similar to the C2 case study. Unlike the previous Distributed Systems KPE, the absence of a particular company discourse (such as Six Sigma) is glaring. C4 draws readily on the broader *reservoir* available via the Internet, and also refers to several occasions where he drew on the knowledge and expertise of his supervisor.

8.5.3 Problem-solving process

Although it was difficult for C4 to isolate a specific problem, for the purpose of mapping the problem-solving trajectory, the focus will be on a particular problem where two conveyor belts carrying newly produced plastic bottles merge and cause a bottle neck in the production system.

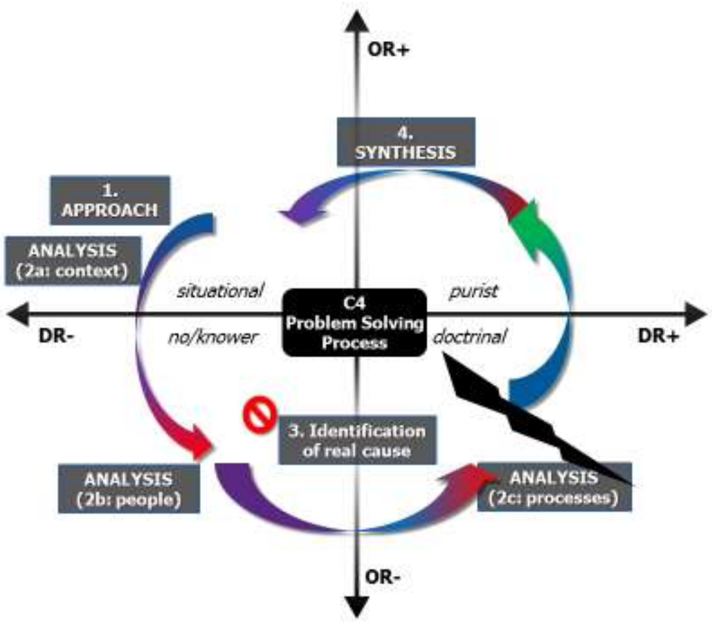


Figure 8-15 C4 Problem-solving process

8.5.3.1 Approach

C4's approach to the problem context in general is *situational*. Here we have a situation where the company is changing its philosophy to focus on quality, but the moment one area is identified where improvement is needed, several interlinked and related processes are affected. Each of these requires an understanding of the roles played by various operators and the current processes in place. One such process is the merging of the two conveyor belts, and which he approaches from a *situational* perspective.

> *'There are two main conveyors running from the machine which have to bottle neck before reaching the main collating table. There was no structure to stop the bottles as they come together so there would be collisions which would cause blockages.' (C4-15)*

8.5.3.2 Analysis

The analysis of this problem moves to the implications for the operators:

> *'So, the operator would either have to stop the machine, or a labourer would have to walk away from packing boxes and would have to unblock the conveyor system.' (C4-19)*

This meant significant production loss. He describes a first intervention which entailed an external contractor merely installing 'stoppers' on each line so that they could alternate. The analysis shifts to the resultant process (*doctrinal* quadrant):

> *'…but he put them on different sections of the lines and as the conveyors were running at different speeds, it was absolutely useless.' (C4-23)*

The problem, in other words, manifests procedurally and has implications for the people in the system. However, the actual cause of the problem is the lack of a disciplinary perspective (*purist*): There are two conveyors running at different speeds and carrying different quantities of bottles which need to merge seamlessly into one line. A physics and mathematics-based analysis of the speed of the conveyors, their timing in relation to each other and the collection of their individual loads could have been the starting point in preventing the constant stoppages. However, C4 finds it difficult to articulate this disciplinary knowledge, but remains focused on procedurally technical details.

8.5.3.3 Synthesis

C4 identifies the solution in the form of two reflective sensors integrated into each conveyor belt. These are connected to the PLC and programmed to respond on a timing basis.

> *'I set a timer that said keep the gate open for three seconds, then the sensor comes into play (a reflective sensor) - the sensors make or break the second timer which closes the gate. As soon as a bottle passes the sensor it breaks the timer and the time is reset to the beginning.' (C4-29)*

In this way the lines alternate feeding bottles onto the single conveyor in a timed fashion. Although not verbally supported with disciplinary analysis during the interview, C4's trial-and-error disposition suggests he has acquired enough experience to intuitively know the principles behind the process (*purist*) and that this is a more feasible solution.

8.5.4 Problem structure

The problem structure in its manifestation is located in the weak ontic relations (OR–) quadrants – people and processes. In other words, if the problem were to be solved by changing the operators' behaviour or that of the process, then the solution would have entailed navigating between strong and weak discursive relations (DR+ to DR–) – between procedural production rules and negotiation of rules governing operator behaviour. However, the most feasible solution lay in the necessary strengthening of ontic relations by considering the principles and associated procedures of the 'inner environment' – a *purist insight* (OR+,DR+). These principles and procedures include the physics laws of motion as well as the physics underpinning reflective sensors, mathematical calculation of frequency of bottle production on the two initial conveyors as well as the timing sequence, and the logic-based opening and closing of the conveyor gates. C4, however, does not consciously move from the hierarchical to strong and weak horizontal knowledge structures respectively. His synthesis of an adequate solution, however, suggests an intuitive movement into the *purist* quadrant based on knowledge acquired *a posteriori* through experience. An interesting feature of this case study is the occurrence of mathematical references (figure 8-15) in the *knower* quadrant. In most of the case studies, mathematics finds itself in the *purist* quadrant (usually in relation to physics or logic calculations), or the *doctrinal* quadrant with respect to logic processes, but here we have the addition of the calculation of the implications of unnecessary human movement in relation to inefficient systems.

8.5.5 Boundary navigation

There is not only a complex set of code clashes in this case study, but also (as in the case of C2) a higher complexity rating (18) as a result of stakeholder involvement and interdependencies. On the one hand, C4 – with his natural *situational* orientation and trial-and-error disposition – is not as comfortable in the more *doctrinal* company operations. Indeed, he only managed to stay with the company for one year before moving on to a Modular Systems company which focuses on the design and building of custom-made packaging machines. By all accounts C4 is much happier in his new company which values his *situational insight* orientation. The code clash in this case is that between two diametrically opposed *insight* orientations. The complex code clashes suggested by the shifting company ethic will be explored in the following comparative summary.

8.6 Category C: Comparisons and discussion

The four case studies in the Distributed Systems category entail forms of disciplinary knowledge central to the broader concept of controlled electro-mechanical systems. Additional complexities in this category are the level of automation at the individual companies; the inevitable reliance on operator/ personnel practices in relation to the manufacturing processes; and the impact of particular company management philosophies. The following sections comparatively summarise the key findings.

8.6.1 Problem environment differences

The case-study environments are characterised by strong classification of spaces, processes, stakeholders and time (C+), accompanied by equally strong external framing over pace, criteria and control (F^e+). In the first company, criteria and control are explicit by way of a particular company philosophy and management system. The strong classification and framing, appropriate to medium-large manufacturing industries, imply the strong discursive relations (DR+) that accompany regulated, *doctrinal* procedures. However, the 'human' factor in all these companies presents a set of challenges that give rise to evident code clashes.

Two of the case studies in this KPE category demonstrate a code clash that occurs on the ontic relations axis (OR). In both C2 and C4, a disjuncture is indicated on the problem-solving map in the *doctrinal* quadrant. Both practitioners' explanations focused on processes (OR–, DR+) and either inappropriate operator behaviour or the negative impact of process/equipment design on operator functioning (OR–). This suggested, to my mind, a need to legitimately recognise the different *knowers* in the potential problem contexts and their need for adequate training as opposed to attempting to bypass the operator in the seeking of a solution. Indeed, C4 started the interview with: 'The idea is to remove the person by installing a camera inspection system' (C4-1). This was precisely the case in C2 – the addition of monitoring devices without accompanying training. In the C4 context, 'removing the person' (and his/her potential mistakes) contradicts the company rebranding exercise and the ostensible shift to strong social relations (SR+) with its focus on *knowers* (OR–, DR–). The shift towards a people-centred TBL ethic has lost sight of the principle that would traditionally have underpinned their endeavours: the efficient and profitable production of goods (OR+). The unfortunate reality in a South African context is a dire shortage of adequately trained engineering artisans, and the simultaneous explosion of technological possibilities. This has led to increasing automation – a necessity for economic survival in the 21st century. At a strategic level in the context of a National Development Plan (NPC, 2011) promoting both social justice and global competitiveness, these companies are caught between two conflicting agendas. I suggest that the social justice implications in these sectors (loss of employment/being replaced by a machine) have driven such companies to superficially adopt an ethical governance and social responsibility mantle. The end-goal or vision has moved into the social relations (SR) realm, losing sight of the epistemic relations (ER) that need to underpin technologically sound and economically viable production. In other words, in these environments the code clash is that between strongly (OR+) and weakly bounded (OR–) phenomena. This has implications for problem solvers in such environments.

8.6.2 Problem-solver differences

All the practitioners, barring C2, have similar cognitive profiles with low physics and mathematics, but higher logic and technology academic records. The interesting difference here is that only one (C3) is perfectly suited to his environment as he shares a predominantly *doctrinal insight* orientation. The remaining three are *situational* practitioners, with C2 also straddling the *purist* quadrant. In other words, these three practitioners are most effective when they are working in the context of more strongly bounded knowledge claims or phenomena (OR+). The impact of this preference on their problem-solving processes in the *doctrinal* environments is clear: C1 is constrained by the rigid methodology and this delays effective problem solving, and both C2 and C4 resigned, not able to navigate the code shift from *situational* (OR+, DR–) to *doctrinal* (OR–, DR+) *insights*.

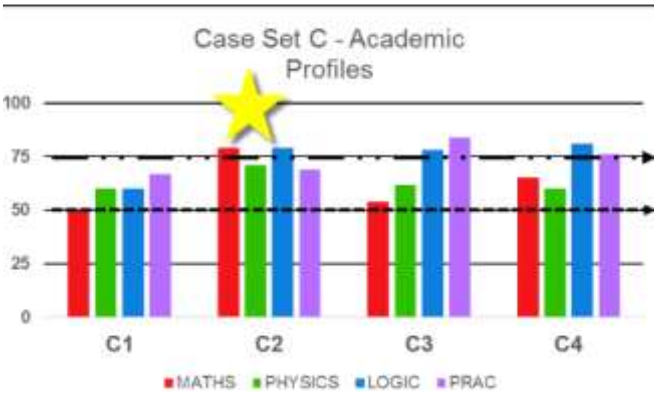


Figure 8-16 KPE C Academic profile comparison

As in the previous two categories, C2 represents one of the anomalous high performers in both mathematics *and* logic. He and the second highest achiever (C4) demonstrated almost identical problem-solving process cycles. C2, however, was capable of more analytical disciplinary insights and articulated these in writing.

The semantic code of each case study reveals the expected predominance of *worldly* (SG+, SD+) references. However, both C2 and C4 – by virtue of their problem contexts, and possibly higher mathematics *and* logic records – each make a significant number of *prosaic* references.

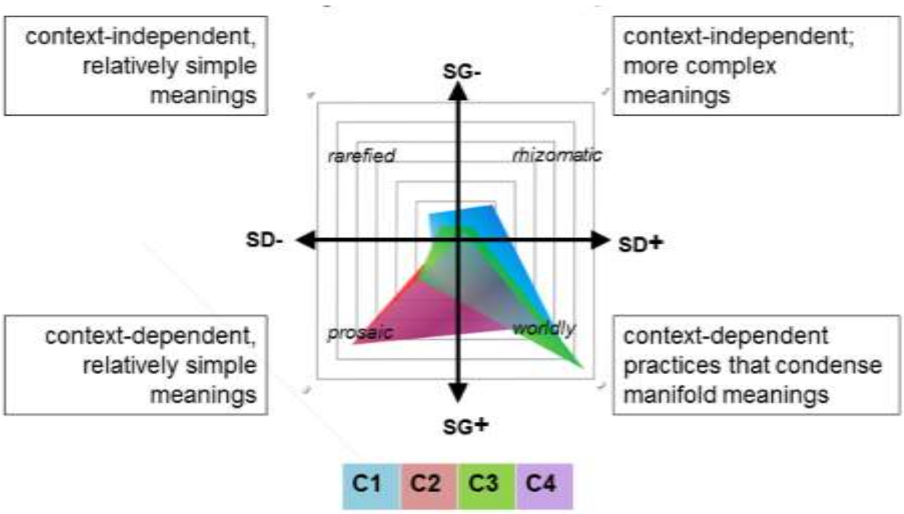


Figure 8-17 KPE C Semantic code comparisons

8.6.3 Problem-solving process comparisons

In this category, all four epistemic relations quadrants are relevant: There are people working on processes underpinned by scientifically/technically-sound principles to fulfil particular production objectives. Two practitioners (C1 and C3) approach the problem with a fixed methodology, from the *doctrinal* quadrant. This is natural for C3, and his problem-solving process is highly effective. It is not a natural starting point for C1, however, and he struggles. C2 and C4, on the other hand, start from their natural inclination in the *situational* quadrant, and do not have effective resources (both personal and environmental) in place to cope with the problems in the *knower* quadrant. It is in this KPE category that the concepts of *focus* and *basis* are critical. In both C2 and C4, although the *focus* is on the *knowers* in the production process where the problems emerge, the *basis* is *doctrinal:* the assumption that the operators will follow protocols in the same way that the inanimate systems function (DR+). Both practitioners' discomfort in detailing the conditions reveals this disjuncture between focus and basis, which effectively speaking means that the second problem-solving analysis stages manifest as a *no insight* orientation (OR–, DR–) with no redeeming shift to the organising principles underpinning the social relations (SR+) element. In other words, there is not an acknowledgement of legitimate *knowers* in the problem-solving context.

8.6.4 Problem structure comparisons

The key finding in this category is the question of problem definition or 'formulation' (Volkema, 1983). As highlighted in the MIT study (Sobek, 2004), those students who spent more time on defining the problem were most successful in solving it. The official problem definition in each of the KPE C case studies was given as a technical problem statement, implying relationships between the three core disciplines: physics (voltage, motion, light); mathematics (power measurements, structural dimensions, speed); and logic (relations between sensors and actuators). The navigation of the three different knowledge structural types, however, is affected by the relationship between practitioner and environment *insight* orientations. C3, who mirrors his *doctrinal* environment (OR–, DR+), is comfortable where there are strong relations in either the processes or phenomenon being addressed. He deliberately avoids the epistemically weak *knower* quadrant. In all the other cases, however, the problem is inadequately defined. If the problem definitions included operator (or supplier, as in C1) behaviour, then the problem structure would take into account human 'logic' in a particular context with respect to the relationship between production processes and human decisions. Such a definition implies predominantly weak horizontal forms of knowledge, with weak discursive relations (DR–). However, as detailed in section 8.6.1 of this chapter, the problem environments do not appear to offer means for practitioners to deal with weak discursive (DR–) *and* ontic relations (OR–). The complexities implied in the navigation of the left-hand quadrants of the epistemic plane also impact on the complexity rating in each of these case studies, with the problems ranging from the upper end of the technologist band (15) and into the lower end of the engineer band (18).

8.6.5 Closing word on KPE C case studies

The question that needs to be asked in this category is whether or not all practitioners – no matter their *insight* orientation – can be trained to cope in such environments. There are two significant challenges here: On the one hand, these types of industries in their traditional roles are the largest employers of mechatronics technicians/technologists, and their *doctrinally* orientated systems require a strong grasp of appropriate business process discursive relations (DR+) where there is no focus on a specific technical phenomenon (the foundation of their training). On the other hand, the global shift towards a TBL business ethic appears to have eroded, I suggest, whatever traditional strong ontic relations underpinned their practices. What such industries appear to lack is a redefinition of purpose in which a strongly bounded phenomenon (that includes the implications of *knowers* in the system) is established.

CHAPTER 9: NEGOTIATING DISCIPLINARY BOUNDARIES

9.1 Introduction

The aim of this research project is to contribute to a better understanding of the negotiation of disciplinary boundaries when different forms of knowledge are integrated in engineering problem-solving practice as observed in industrial settings. The central premise is that different forms of engineering disciplinary knowledge require different ways of thinking – they manifest as different kinds of 'code'. The relationship between the engineering practitioners, artefacts and environments may be such that navigating the problem-solving situation entails explicit 'code shifting', and in some cases actual 'code clashes' (Maton, 2014). The previous three chapters have detailed the analyses and comparative category findings across 12 case studies in three mechatronics engineering Knowledge Practice Environments (KPEs). Each environment has distinctive features associated with the scale, type and conditions of work. These features were broadly analysed according to three category types (chapter 4) using the Bernsteinian concepts of classification and framing. The three data chapters (chapters 6 to 8) focused on the application of theoretical concepts and tools drawn primarily from Legitimation Code Theory (LCT) Specialization and Semantics, which illuminated specific KPE features pertinent to practitioner problem-solving practices.

The purpose of this chapter is to fulfil the stated research design intention (chapter 5) of 'producing patterns of problem-solving practice' which may contribute to our understanding of 21st century multidisciplinary engineering complexity, particularly at the level of 'technician', and the potential implications for the engineering curriculum and associated pedagogy. Taking an 'integrated systems' approach, this chapter consolidates the findings across the KPE categories, each representing a different 'module' in the problem-solving research 'system'. The aim is to identify patterns with respect to the relationship between the key components of the 'inner/outer' problem-solving system and the conditions for 'goal attainment' (Simon, 1996). The chapter is designed around a discussion of the research sub-questions:

- Do mechatronics engineering technicians manifest particular patterns in navigating between different forms of knowledge when addressing engineering problems?
- Does an overarching pattern emerge which could be described as potentially archetypal?
- How are the disciplinary forms of knowledge brought into relationship with each other in the problem-solving process?
- What level of understanding is necessary in order to solve that particular problem?
- What is the relationship between the elements in the problem-solving context and their impact on the problem-solving process?

The questions have been grouped into three categories. The first deals with the patterns in relation to three ‘outer’ environment features in each KPE, and whether or not there are patterns that could be described as typical or representative. The second category for discussion revolves around the ‘inner’ environment of the problem: the question of knowledge. It focuses on disciplinary interrelationships in the problem-solving moment and what/how it is that practitioners know and do not know. The third discussion category deals specifically with the question of problem-solving conditions that both reveal and illuminate code shifting and code clashing. Each of the three discussion sections will begin with a summary of key findings across the KPE categories drawn from the data chapter consolidation sections.

It is important to remember that this is a limited qualitative study with a small number of case studies. Caution needs to be exercised in the temptation to generalise findings. However, there are significant findings that warrant attention when considering curriculum and pedagogic design aimed at a more informed understanding of actual professional engineering practice. A second point that needs to be reiterated is that all the participants are considered highly successful in relation to national statistics for engineering graduates. Their contributions afford the research an invaluable opportunity to understand the complexities entailed in engineering knowledge practices.

9.2 Problem-solving patterns in context

As established in chapters 2 and 5, there are a number of key elements in the problem-solving situation, whose interrelationships may be interpreted as different kinds of patterns.

Simon’s (1996) ‘inner/outer’ distinction provided the starting point for the Knowledge-Practice Environment (KPE) case-study framework (figure 9-1). This section will discuss any patterns that emerge in relation to the ‘outer’ KPE components which may be significant to the problem-solving process, namely: the problem environments, the nature of the problem solvers, and the general problem-solving patterns.

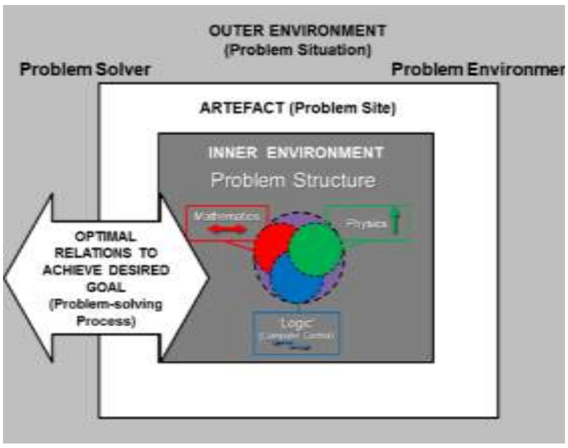


Figure 9-1 KPE Case-study framework

9.2.1 Problem environment patterns

The following is a summary of problem environment differences across, within and between the three KPE categories, and which are captured in figure 9-2:

- The scale of the problem and context appears to dictate the strength of classification and framing of objects, stakeholders and processes. Stronger classification and framing conditions imply the need for stronger discursive relations to regulate a greater number of potential *knowers* or unknowns with more possible solutions. In other words, there appears to be a tendency to counterbalance the unknowns with more rigid or *doctrinal* rules.
- KPE A: R&D Contained Systems work generally occurs in smaller scale environments which are more weakly classified and framed, allowing greater practitioner autonomy and greater access to the collective *reservoir* of expertise via colleagues and online user fora. Small, team-orientated environments can support practitioners with different discursive relations orientations and strengths.
- KPE B: Modular Systems practitioners straddle two environments simultaneously (their company and their client), usually weakly and strongly classified and framed respectively. The *insight* orientations between the two environments are generally diametrically opposed – *situational* and *doctrinal* respectively.
- KPE C: The Distributed Systems environments - larger in scale - are strongly classified and framed, requiring adherence to regulated *doctrinal* processes. These environments appear to have become more cognisant of '*knowers*' in their processes, leading to a shift in business philosophy in some cases. However, the dominant *doctrinal insight* orientation does not appear (as yet) to support a true *knower* orientation (strong social relations).

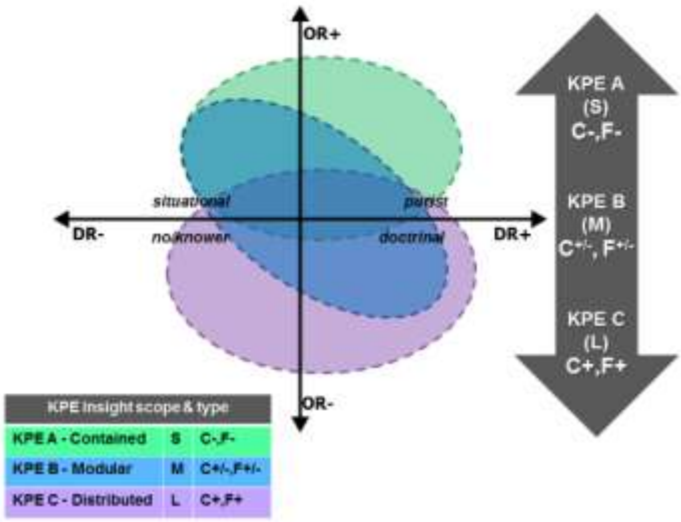


Figure 9-2 KPE *Insight* scope and type

The smaller the company, the more likely there is to be a greater deal of methodological freedom and allegiance to phenomena, hence their position higher up on the ontic relations axis. In such environments, practitioners tend to approach the problem from their own natural (problem solver) *insight* orientation (either *doctrinal* or *situational*). Where there is a supportive team-orientated environment, the team as a whole can enable the collective straddling of the discursive relations axis. In other words, strong *doctrinal* practitioners can lend the team methodological rigour, whereas the *situational* practitioners can enable a more flexible view of the methodological choices. The one feature to emerge from KPE A is the relative centrality of *purist* principles underpinning the core business of designing, producing and maintaining dedicated devices for a specifically defined customer.

The larger the environment, the more strongly classified and framed, and the more likely there is to be a dominant methodological problem-solving system in place (*doctrinal*). The apparent shift to a people-orientated philosophy appears to be a response to productivity and worker-orientated challenges in the South African manufacturing sectors. However, this shift currently seems at odds with the focus on rigid procedures and profitability from a clearly *doctrinal* perspective. For practitioners to be successful in such environments, they need to recognise and realise strong discursive relations rules.

The middle category, KPE B, by sheer virtue of practitioners working into two different contexts, sees the movement between the types of environments characterised by KPE A and KPE C. This means the ability to shift between strongly and weakly classified and framed environments. This ability is echoed in the data which show the necessity of moving diagonally from a *situational* perspective to a *doctrinal* one. Recalling the MEFSA definition of mechatronics engineering as 'the concurrent design, manufacture, integration and maintenance of controlled dynamic electro-mechanical systems' and increasingly complex 21st century engineering contexts, I suggest that KPE B is an emerging representative category. Based on this, **a potentially archetypal pattern is the ability to move between the *situational* and *doctrinal* requirements of different engineering environments**.

9.2.2 Problem-solver patterns

The comparison of problem solvers (figure 9-3) within and across the different KPE categories takes three aspects into account: cognitive profile, experience and mood. With respect to the relationship between academic performance and problem solving, the following factors are significant:

- The higher the academic performance, the fuller the problem-solving process description and cycle.
- Six of the participants are representative of a mere 2.9% of graduates on the base qualification (over a 6-year period) who achieved distinctions in both mathematics *and* the logic-based subjects (referred to as 'high achievers' in this study). All the high achievers, barring B3, have a *purist* or dual orientation that overlaps the *purist* quadrant. B3 is the only *situational* high-achieving practitioner.

- Six of the participants are representative of the norm[80], which is lower mathematics and higher logic-based and/or practical technology-based subjects (referred to in this study as 'normative achievers'). All six are either *situational* or *doctrinal* practitioners, and each type finds the other environment conditions problematic. In other words, the normative problem solvers fall into two distinct categories on either side of the discursive relations as well as the ontic relations axes.

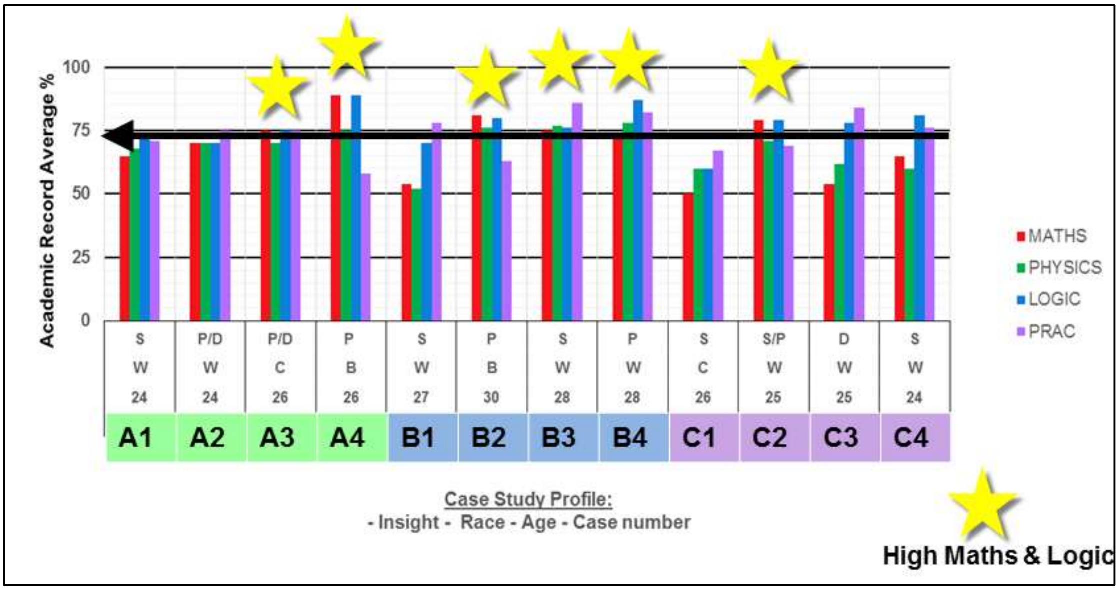


Figure 9-3 Problem-solver profile comparisons

When set in relation to the semantic code analyses, what becomes evident is a greater range of references beyond the *worldly* (complex, context-dependent meanings) for the high achievers. There are two phenomena here. Firstly, all the practitioners (irrespective of their cognitive profile) who engaged with stakeholders (operators and suppliers) who impacted on the problem-solving processes by way of their own action or implied action (documentation generation) used more *prosaic* references. In other words, during the interview the stakeholder implications were described in relatively simple, context-dependent terms. However, the high achievers also used *prosaic* references to translate dense technical concepts into simpler meanings for my benefit as non-engineering researcher. This latter category also tended to include more *rhizomatic* references to talk about the complex principles behind certain aspects of the problem, and in some cases a few *rarefied* references around their own general, non-context-dependent practices. The semantic code patterns suggest a relationship between the high achievement in mathematics *and* logic and a more holistic ability to make meaning around a particular defined context drawing on an expanded reference framework. In general, the

[80] The majority of graduates on the originating qualification demonstrate a typical high achievement in logic and low achievement in mathematics. This is thus regarded as the 'norm'.

range of references in the case of the high achievers is broader, more elaborated, and takes into account not only my presence as non-engineering researcher, but also the nature of the research questions. The practitioners in the normative group are slightly more restricted to the technical context.

All the participants had some form of home or work experience prior to their studies that predisposed them to deciding to enter the field of mechatronics engineering. For the most part, this was either by way of early induction into the world of computers and/or gadgets. Their duration of formal work experience ranged from six months to four years at the time of the interview, and only participant A2 (with the lowest at six months) appeared to be most affected by lack of work experience. This, however, could also be due to the fact that he is the only participant to have completed his qualification in a more theoretical programme at a traditional university.

All the participants referred to challenges in their working environments that could be an indication of a certain 'mood'. As a general rule, the smaller the environment, the more available the personal support and access to the collective *reservoir* (particularly on the Internet) in these particular case studies. The larger and more regulated the environment, the more challenging it is experienced by practitioners with a *situational* or *situational*/*purist insight* orientation. In other words, practitioners for whom the strength of the ontic relations is key to successful practice appear to find the *doctrinal* conditions constraining. Three of the *situational* participants (B1, C2, and C4) have subsequently resigned from such *doctrinal* environments. I will return to these cases in the section on code clashes.

A potentially archetypal pattern to emerge with regard to problem-solver comparisons is the relationship between high mathematics *and* logic achievement, a broader *semantic code,* and fuller problem-solving cycles and descriptions.

9.2.3 Problem-solving patterns

The visual summary (figure 9-4) is merely intended to capture overall patterns across the categories at a glance. Across the board, all the participants either approach a problem from a *situational* perspective or a *doctrinal* perspective, demonstrating a strong allegiance to either the phenomenon in question or a certain methodology.

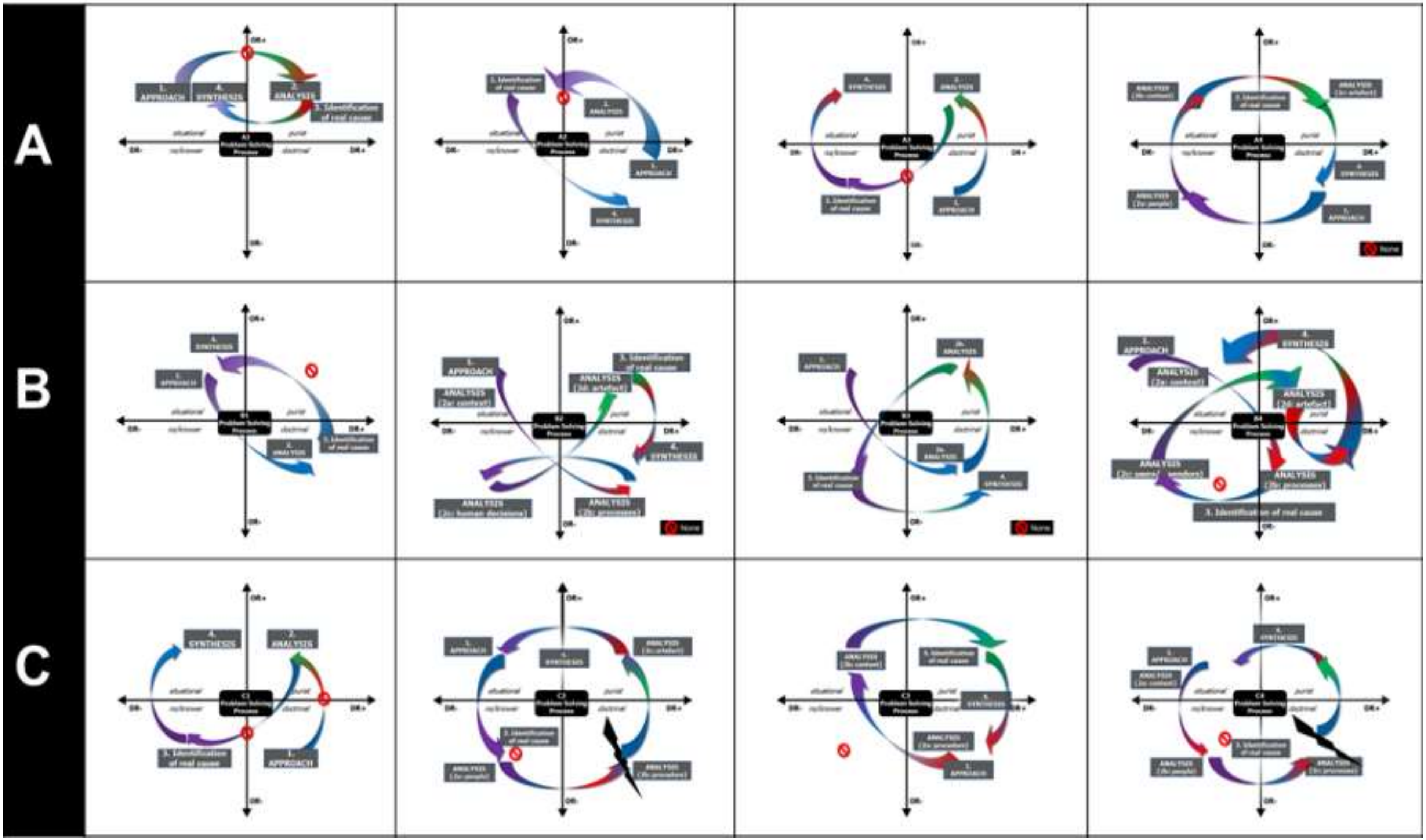


Figure 9-4 Problem-solving pattern comparisons

- KPE A: All practitioners in KPE A approach the problem in relation to their own discursive relations orientation, supporting the claim that such environments are more flexible and allow greater individual autonomy with regard to methods. The problem-solving analysis and synthesis stage patterns are bound by the requirements of the problem structure (which all the practitioners recognise, but do not necessarily fully realise) and those of the dominant basis of legitimacy in the environment. In R&D (A1 and A2) - where no external stakeholder engagement takes place - the dominant *insight* orientation is *situational*/*purist*, whereas in maintenance (A3 and A4) - which includes external stakeholders - the dominant *insight* orientation is *doctrinal*, but also requires navigation of the *knower* quadrant.
- KPE B: Irrespective of their personal preferences, all practitioners in KPE B approach the problem from a *situational* perspective, as the nature of their project-based work involves different environments on a daily basis. This means every situation must first be assessed in relation to a defined objective (strong ontic relations). Secondly, all practitioners in this category engage in diagonal code shifting, moving productively between *situational* and *doctrinal*, as well as *knower* and *purist insights*. Three of the practitioners are also capable of vertical shifting (B2, B3, and B4). The normative achiever in this category (B1) only moves between the *situational* and *doctrinal*.
- KPE C: The pattern that emerges in KPE C is potentially a cyclical one covering all *insight* quadrants. Given that such environments are strongly *doctrinal*, but have a greater number of stakeholders and variables, an ideal pattern may well be that represented by the A4 case study (albeit that he is in the Contained Systems category): a macro-to-micro cyclical clockwise movement beginning with a meaningful methodological *(doctrinal insight*) analysis of the processes, people (*knower insight*) and possibilities (*situational insight*) around the problem in question, before zooming in to the epistemic heart of the problem (*purist insight*). An alternative to this is the anti-clockwise cycle taken by C2 and C4, beginning with the situation, the possible contributing factors, people and processes. In both these cases, however, the environments did not offer appropriate mechanisms to address the real problems situated in the *knower* quadrant.

Taking all the ‘outer’ environment factors into account appears to enable a more efficient focusing on the ‘inner’ principles underpinning the problem artefact/site. Where practitioners attempt this cycle from a *doctrinal* perspective in an anti-clockwise fashion (A3 and C1), they inevitably need to detour into the *knower* quadrant and have found this to be the source of the problem. The avoidance of (C3) or inability to shift productively into the *knower* quadrant (C2 and C4) is a key finding in KPE C.

Of great significance to the research intention is the discovery of iterative diagonal shifting that emerged in all the Modular Systems case studies – KPE B. As detailed in chapter 7, all practitioners here begin with the situation and then shift into the required processes. The *purist* practitioners then move into the *knower* quadrant, and repeat the diagonal into the *purist* quadrant to determine the underpinning disciplinary manifestation of the problem. The *situational* practitioners avoid the *knower* quadrant, but end up having to move there (or could have moved there, as in the case of B1). The *purist* participant trajectory prior to engaging with the sciences underpinning the problem recalls the Sobek (2004) study findings where it was found that problem definition at the *conceptual system* level has a more positive impact on project quality than 'engineering analysis at the … detailed levels' (p. 11). The data suggest that the *purist* practitioners in KPE B grasp that the conceptual system implies all variables, including people in the system.

All the solutions in KPE B are either *situational* 'work-arounds' or *doctrinal* applications of misunderstood or misrepresented procedures. This ability to shift diagonally is a requirement of the nature of work in this category, as the company and client contexts are polar opposites. However, the *iterative* ability to shift between diametrically opposed *insights* is only evident among the high achievers. I will return to this in the following section on knowledge.

The preceding summary and discussion has attempted to answer the two research sub-questions:

- Do mechatronics engineering technicians manifest particular patterns in navigating between different forms of knowledge when addressing engineering problems?
- Does an overarching pattern emerge which could be described as potentially archetypal?

We have seen that there are identifiable patterns in three distinct contexts as defined by the KPE categories. A potentially archetypal overarching pattern across contexts does not exist. However, an overarching pattern *principle* emerges: All four *insight* quadrants are relevant in most engineering problem-solving contexts, where the *basis* of practice at any particular *focus* stage in the problem-solving cycle is a recognition and realisation of a particular *insight* 'code' held to be legitimate in that context. Where the *basis* is at odds with the *focus*, we see a distinct code clash. This will be discussed in the third section.

9.3 Problem-solving 'knowledge and knowing'

The second category for discussion revolves around the 'inner' environment of the problem: the question of knowledge. One of the original impetuses for this research was the observation of polarised student performance in the mathematics and logic-based subjects of the originating programme (chapters 1, 4 and 6). Their subsequent performance in various industrial environments suggested it was imperative to understand the differences between the disciplines underpinning multidisciplinary engineering practice, as they seemed to impact on individual practice in different ways in diverse contexts. Prior social realist-based research (Wolff, 2011) had determined that the three core disciplines in mechatronics engineering represented three distinct knowledge structures:

- Physics: Hierarchical knowledge structure
- Mathematics: Horizontal knowledge structure (strong 'grammaticality')
- Logic: Horizontal knowledge structure (weak 'grammaticality')

The focus in this section of the discussion is on the relationships between these forms of knowledge in the problem structures as described in the three data chapters (6 – 8); the available knowledge domains and frameworks on which practitioners draw; and the nature and implications of the different disciplinary organising principles. This section will attempt to answer the following research sub-questions:

- How are the disciplinary forms of knowledge brought into relationship with each other in the problem-solving process?
- What level of understanding is necessary in order to solve that particular problem?

9.3.1 Problem structures

All the case-study problems entail a relationship between logic, physics and mathematics. Some problems 'announce themselves' through physics (mechanical motion/force or electrical current/voltage) in relation to mathematics (too much/little). These relationships are both subservient to and guide the overall visible structural logic of the system (what is mechanically or electrically connected to what). The initial 'design logic' of the structure of the system would have been based on the designer's choices dictated by the laws of physics - mechanical motion and spatial affordances/constraints, and electrical current/signal behaviour – supported by the relevant mathematics to determine optimal spatial, temporal and behavioural relations. The research data suggest that problems in the visible structural relations or power relations **can be theoretically deduced** by drawing on the *same* disciplinary knowledge as that of the original designer. The practitioners generally deconstruct the logic of the structural and power connections, and then mathematically refine optimal relations based on the relevant laws of physics and mathematical procedures.

Where the problem manifests as a 'control logic' problem, the data show that the practitioner does not necessarily know what the original physics/mathematics-based decisions were, as these are less visible and dependent on internal control system structures. The control systems are designed on integrated circuits contained in electronics systems or programmable logic controllers. Mechatronics technicians/technologists do not build these control systems – they use an existing system to enable the larger visible structural components of different types of gadgets/machines to communicate electro-mechanically with each other. The communication protocols are based on information (user documentation and software) which clarifies what the controller can do and how it can be connected. The practitioner accesses the control logic system via a graphic user interface (a computer program). Each GUI has its own rules. There are general principles in engaging with the control logic. The programming platform:

- generally has functions to configure the hardware (set up physical relations and states of the equipment) and the software (what the different processes need to be);
- may be accessible via a 'tree structure' with folders or files for sub-programs;
- may use lines to visibly indicate some forms of connection;
- and may allow different kinds of programming languages in the sub-routines.

Other than these general principles, each programming platform and language has its own rules, with its own naming conventions and specific purposes. In all the logic-based problem structures, practitioners indicated that unless he had worked with the actual (or a similar enough) control system before, he needed to learn the rules of the specific system from scratch, relying heavily on documentation detailing how the control system works. There are two major challenges in solving logic-based problems: Firstly, the rapid developments in the field imply constant changes which may not necessarily be documented accurately (Briand, 2003), and secondly, designers/suppliers of these systems do not necessarily have the expertise to understand different contextual applications. For this reason, the most reliable source of support is either prior individual experience or that of the global community on the various Internet user fora. These factors automatically imply more complex stakeholder involvement, greater interdependencies and less standardised or adequately documented codes of practice (IEA, 2013), thus rendering problematic the 'well-defined' descriptors which establish the criteria for technician problem-solving practice.

A summary of problem structure findings from each category (situated across the knowledge domains in figure 9-5) establishes the following:

- KPE A: The case studies in the Contained Systems category entail forms of disciplinary knowledge more closely situated within the physics-based domains of 'control electronics' and 'electro-mechanics'.
- KPE B: The four Modular Systems case studies tend towards the logic-based knowledge domains. The one feature they all have in common is that the problem structure is characterised by a *doctrinal* element either in relation to the epistemic basis (*purist*) or the polar opposite, a social basis (*knower*). In other words, these are methodological problems based on principles or vendor decisions.

- KPE C: The Distributed Systems case studies entail forms of disciplinary knowledge central to the broader concept of controlled electro-mechanical systems in particular contexts that include human behaviour. However, the official problem definition in each of these case studies was given as a technical problem statement, implying relationships between the three core disciplines: physics (voltage, motion, light); mathematics (power measurements, structural dimensions, speed); and logic (relations between sensors and actuators).

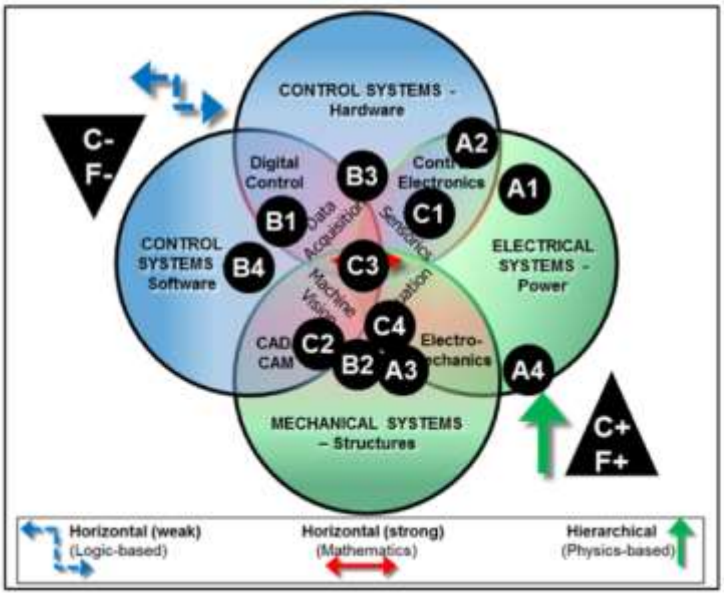


Figure 9-5 Case-study problem-solving knowledge domains

Each of the core disciplines, as detailed in chapter 3, has distinctive organising principles. Hierarchical physics-based knowledge subsumes concepts that can be accessed via specific principles and formulae. Working effectively with this kind of knowledge requires the sequential and analytical depth characteristic of a *purist insight*. The applicable mathematics here – a horizontal knowledge structure with strong 'grammaticality' - is formulaic or *doctrinal*, requiring the identification of a specific mathematical language (algebraic, geometric, or simple arithmetic in many cases) and the linearly procedural application of its specific rules to a particular problem, but which application would be the same for any problem. The logic of controlled electro-mechanical systems, however, is a horizontal knowledge structure with weak 'grammaticality'. There is always an allegiance to a particular phenomenon (strong ontic relations) – the logic must be in relation to fulfilling a particular objective. However, the choices determining how this is done are legion (weak discursive relations) and almost entirely context-dependent – *situational insight*. When, however, a particular choice is made, the rules underpinning that selection may become more *doctrinal*. Working with this kind of knowledge requires an ability to shift between weak and strong discursive relations, but being governed by a defined purpose (strong ontic relations). Once the purpose is a given (for example, the system has been set up to fulfil that purpose), then the programming process can become entirely routine (*doctrinal*).

9.3.2 Knowledge domains, frameworks and knowing

Where the focus of the problem is underpinned by a particular physics element, in all cases prior knowledge of the requisite disciplinary fundamentals was not only necessary to solve the problem, but was available *a priori* in established knowledge domain frameworks, such as those frameworks provided by Newton's laws of motion and Ohm's Law. A few of the *situational* practitioners (A1, B1, C1) demonstrated a less firm grasp of the *purist* elements of the problem, but could solve it by drawing on these accessible knowledge frameworks. In other words, they could recognise the required knowledge and work this out ('realise' it) because the knowledge is commonly available and agreed on by all in the field. The reason for this lies in the nature of the ontic relations with respect to physics-based knowledge[81]. Ontic relations describe the strength of the bond between a knowledge claim and its object of study. All the common physics-based concepts in the region in question manifest a strongly bounded relationship between the phenomenon and any commonly understood claim about it, whether that claim be an observation or demonstration of cause and effect, or an actual formula. This makes such knowledge more accessible to anyone who can grasp the sequential underpinning (or subsumed) concepts.

In contrast, where the focus of the problem is a particular logic-based technology, this knowledge could only be gleaned *a posteriori* through engagement and experience – whether that of the practitioner or the available *reservoir*. A finding that emerged across the 28 questionnaire submissions was inaccurate or misinterpreted information/documentation on which practitioners are reliant. Whether inaccuracy and misinterpretation, what this suggests is that the knowledge required to address a logic-based problem using a particular control technology **cannot fully be theoretically deduced** beyond the broad principles unless the practitioner has particularly well-developed or experiential insights into the *design-thinking* behind the particular components. Only B4 attempted (and was able) to deconstruct the logic-based problem theoretically (*purist insight*), but his working conditions supported the time that this demanded[82]. For the most part, the logic-based problem structures were as a result of *doctrinal* decisions made by specific *knowers* in a field of practice that is not 'relatively autonomous' and in which there is no 'consensus' beyond certain principles (Maton & Moore, 2010, p. 6). This means these problems are located on the boundary between strong and

[81] Note this is with reference to the fields of recontextualisation and reproduction. Physics in the field of production is a different matter.
[82] It is also worth noting that of all the case studies B4 is working closest to the field of production.

weak discursive relations in the lower half of the epistemic plane. In other words, the nature of the ontic relations in the case of control logic is different from that of engineering physics-based knowledge. When considering the control logic to meet the needs of a particular situation, the initial concepts are far more loosely bounded than in the case of physics. There are general principles at work, and the claims made about specific control logic phenomena can be misunderstood by an outsider from a different control logic paradigm. It is only when a practitioner has been inducted into the particular logic paradigm (through experience) that s/he will experience the ontic relations as strong, but within a particular context – this specific 'brand' or type. Where the practitioner knew to consider the nature of particular *knowers* behind the logic-based decisions[83], he is regarded as dealing with that aspect of the problem from a legitimate *knower insight* basis, whether he liked what they have done or not (as in the case of B4).

I suggest that engineering mathematics demonstrates a third and more multifaceted type of ontic relations. This is supported by the data which show mathematics references across all the *insight* quadrants. Where the physics phenomenon is captured in a particular formula which has to be mathematically processed, the allegiance is always to the principle of the physics phenomenon in question (in other words, strong physics-determined ontic relations) and the mathematics is merely the *doctrinal* application of the relations set up within the formula. Examples of these occurred mainly in KPE A and KPE C (A1, A3, C1, and C3). Where a logic-based potential set of relations already exists in a control system and instructions are communicated using mathematical algorithms determining sequence, rate, speed and position, the end-user (such as our mechatronics practitioners) mainly works at the arithmetic level. S/he enters values into a pre-existing framework (the 'language' and conventions of which s/he will have had to learn). The ontic relations with respect to mathematics in this case demonstrate allegiance to the logic-based phenomenon. Such examples were evident in KPE B (B2 and B4). The designer of such control systems or computer programs, however, draws on a vast range of mathematical algorithms, and *creates* his/her own algorithms, which ascribe to the 'laws' of what the mathematics can actually do. Although, of course, subservient to the purpose of the system (determined by physics laws and logic decisions), the ontic relations in this third type of mathematical application are more strongly bounded by the mathematical

[83] In other words, practitioners get to know how reliable suppliers' documentation is, what kind of purposes their products claim to fulfil and the nature of their particular discursive conventions.

phenomena themselves[84]. This might have been observed in a case where integral or differential Calculus was explicitly used to monitor and regulate behaviour in a system[85].

KPE C presents the most complex problems from a contextual perspective, as defined by the IEA (2013) problem attribute descriptors: a broader range of stakeholders, consequences beyond the local, and interdependencies within larger systems. The very nature of such environments suggests any technician required to work beyond 'discrete components of engineering systems' (*ibid*.) will be working within 'systems within complex engineering problems' *(ibid.)*, and thus at least at the level of a technologist. Although the technical problems in KPE C entail the same knowledge structures as the preceding categories, these problems are located in relation to a more complex constellation of *knowers* – including operators, colleagues, management, suppliers and clients. Generally, the sciences underpinning the problems themselves are better defined and governed by standardised processes. Secondly, the technologies used in large manufacturing environments already imply some form of available external expertise (such as the systems integrators or machine builders from KPE B who may have been called upon to supply these systems). This means the focus in KPE C is more on alignment of all the systems including people to enable efficient *processes* to produce goods. The data from this category demonstrate that the knowledge elements with respect to *knowers* in the larger system cannot be known *a priori.* However, there is an assumption (and a desire, it would appear) that the *knowers* will follow the *doctrinal* processes of the inanimate systems. In other words, when the *focus* is ostensibly on *knowers* in this category, more often than not the *basis* is in fact *doctrinal*. This renders such action as being from a *no insight* perspective, and sets up the conditions for code clashing. Despite the occurrence in KPE C of similar discipline-based problems to the other contexts, the focus on alignment of people and processes challenges the nature of the ontic relations in this context. Traditionally, as described in chapter 8, manufacturing had as its core mission the efficient production of technically-sound goods, underpinned by strong ontic relations with respect to the implied sciences. The shift in focus to 'people, planet and profits' (Slaper & Hall, 2011) has brought about, I suggest, not only a weakening of the ontic relations, but a need to redefine what exactly these may be. I will return to this shortly.

9.3.3 Structuring effects of disciplinary knowledge in context

What are the implications of these different organising principles? All the practitioners fall into either a weak or strong discursive relations dominant *insight* orientation, barring A4 and C2

[84] This is borne out by a study reporting engineering students' problem-solving difficulties differentiating between the single solution governed by mathematical operation versus dual solutions in dynamic systems problems (Craig & Cloete, 2013).

[85] Mechatronics engineering practitioners routinely work with computer software that performs Calculus type operations – they very seldom do the actual calculations themselves (Hoffman, 2011).

who straddle the ontic relations axis. The normative *situational* achievers are all better at logic-based work, which has already been established as more open-ended and variable. They all tend to prefer trial-and-error 'learning-by-doing' and are described by their supervisors, variously, as being 'hands-on' or even 'all over the show'. This suggests a responsiveness to the way in which the logic-based knowledge initially announces itself – a world of choices. It is echoed in the participants' non-linear problem descriptions, as well as in their seemingly more *laissez faire* approach to the working environment (even in their dress code).

In contrast, the strong discursive relations practitioners (four of whom are *purist*-orientated high achievers, and two being *doctrinal*-orientated normative achievers) manifest a preference for defined rules both in their written submissions and interviews. There is evidence in their numbered, orderly submissions of a procedural coherence appropriate to one of two contexts: the problem or the environment. The coherence of the *doctrinal* submissions appears to be influenced by the external environment – that of the work place, where an accepted methodology has been recognised and acquired by the practitioner. The evaluative rules in strongly *doctrinal* environments dictate an allegiance to standardised, regulated methodologies.

The coherence of the *purist* submissions seems to be dictated by their own inner sense of how the problem should be described, and this appears aligned to the problem structure itself. They draw deductively upon available frameworks (that already dictate certain ways of making meaning) when describing the problem-solving process and analysing the causes. There are analytically detailed movements between the hierarchical physics knowledge structure, and the strong (mathematics) and weak (logic) horizontal knowledge structures from these high-achieving *purists*. There seems to be not only the recognition and realisation of how a particular kind of knowledge works, but also the articulative capacity to detail this knowledge.

The preceding descriptions may be seen as examples of the structuring effects of knowledge (Bernstein, 2000). However, it is clear that not all the participants are responsive to the structuring effects of *all* the implied disciplines. Their particular preferences (except in the case of A4 and B2) affect their journey across the different codes. A1, for example, pulls his *situational* orientation into the *purist* quadrant as he grapples with Ohm's Law in an almost trial-and-error manner; C3 moves into the *situational* quadrant with his dominant *doctrinal* orientation, and does not dilly-dally about deciding on an efficient solution for a particular situation that could have had other solutions – he is ruthless in his *doctrinal* precision; B4 engages grudgingly (and justifiably so) with the '*knowers'* upon whom he is dependent for reliable information, expecting them to do their jobs with the same principled *purist* orientation he upholds. The same might be said for A3 in his international dealings.

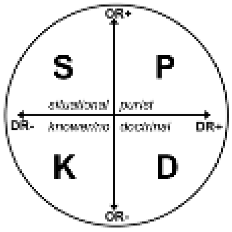
The ability to successfully navigate all the codes underpinning the different *insights* seems to be linked to the anomalous high academic achievement in both mathematics *and* the logic-based subjects. The high achievers demonstrate an ability to move comfortably between a strong horizontal knowledge structure (mathematics), with its strong discursive relations, and a weak horizontal knowledge structure (logic-based), with its initial weak discursive relations. This movement is also reflected (in the semantic code analyses) in the ability to navigate comfortably between complex and simple meanings. This code-shifting behaviour is both conscious and signposted in various ways, on which I will elaborate in the following section. The ability to navigate these codes, I would further like to suggest, cannot be accomplished through 'limited theoretical knowledge', as defined by the IEA (2013) in the 'well-defined' problem-solving category. Rather, what is required is 'a detailed knowledge of principles and applied procedures and methodologies in defined aspects of a professional discipline with a strong emphasis on the application of developed technology and the attainment of know-how, often within a multidisciplinary engineering environment' *(ibid.).* This suggests that these practitioners are, at the very least, working at the level of technologist.

This section of the chapter has sought to answer the following research sub-questions:

- How are the disciplinary forms of knowledge brought into relationship with each other in the problem-solving process?
- What level of understanding is necessary in order to solve that particular problem?

What has been established is that the disciplinary forms of knowledge are brought into relationship with each other in a manner that echoes their interrelationship in the physical system: The elements of the system are both subservient to and guide the overall visible structural logic dictated by the laws of physics and supported by the relevant mathematics to determine optimal relations. In the problem-solving moment, the successful practitioner navigates these forms of knowledge - in no particular order – by shifting between three different *insights*: *situational*, *purist* and *doctrinal.* Secondly, whereas the physics and mathematics-based knowledge required to solve the problem is available *a priori*, the context-specific logic-based knowledge is generally acquired *a posteriori* other than at a generic principle level. The level of understanding required to solve these mechatronics engineering problems cannot be described as 'limited theoretical knowledge', nor the depth of analysis (IEA attribute number 2) as 'standardised'.

9.4 Code shifting and code clashing



This discussion section specifically addresses the question of code shifting and code clashing. The case studies have been summarised in table 9-1, indicating the dominant problem-solver, structure and environment *insight* orientations, as well as the axis on which the code-shifting challenges were most apparent and the specific quadrants which represent the site of the code clash for a particular problem solver.

As a general finding, *situational* practitioners found it most difficult to cross into the strong discursive relations quadrants (*purist* and *doctrinal*). In addition to this challenge, two normative achievers (C1 and C4) also found the movement into the weak ontic relations quadrants problematic. The *purist/doctrinal* practitioners found the movement into the weak discursive relations quadrants challenging. Two high achievers with a *purist* orientation (B4 and C2) found the movement from strong to weak ontic relations to be challenging.

Table 9-1 Case-study code-shifting and code-clashing summary

Case	High achiever (H)/ Normative achiever (N)	Problem-solver orientation	Problem structure location	Problem environment orientation	Code-shift challenge (axis)	Code-clash location (*insight*)
A1	N	**S**	**S**/**P**	**P**/**D**	DR– to DR+	**P**
A2	N	**P**/**D**	**S**	**P**/**D**	DR+ to DR–	**S**
A3	H	**P**/**D**	**K**	**D**	DR+ to DR–	**K**
A4	H	All	**P**/**D**	All	None	None
B1	N	**S**	**K**/**D**	**S**/**P**	DR– to DR+	**P**
B2	H	**P**	**P**/**D**	**S**/**P**	None	None
B3	H	**S**	**K**/**D**	**S**/**P**	None	None
B4	H	**P**	**K**/**D**	**S**/**P**	OR+ to OR–	None
C1	N	**S**	**P**	**D**	DR– to DR+ OR+ to OR–	**P** & **K**
C2	H	**S**/**P**	**K**	**D**	OR+ to OR–	**K** & **D**
C3	N	**D**	**P**/**D**	**D**	DR+ to DR–	**K**
C4	N	**S**	**K**/**D**	**K**/**D**	DR– to DR+ OR+ to OR–	**K**

Although most of the cases demonstrate code-shifting challenges, these were not necessarily regarded as code clashes. Where the code clash is indicated as either *situational* (S) or *purist* (P), this is as a result of particular problem-solver orientations. It will be seen from the above table that the dominant location of the majority of actual code clashes occurs in relation to the *knower*/*no insight* (K) quadrant. This section of the chapter will focus on three specific case studies, one from each KPE category, which demonstrate the structuring effect of the environment and the impact on problem-solving processes with regard to the question of code shifts and clashes.

9.4.1 The code-shifting facilitative environment

A common feature of the smaller or R&D environments (all A, B3 and B4) is the availability of mentorship and support that either facilitates explicit code shifting or compensates for code preferences through the establishment of multifaceted teams. Interestingly, these environments are generally weakly classified and framed and yet the knowledge focus is often on the more strongly classified and framed physics-based domains. The freedom of the environment in such cases – supporting greater practitioner autonomy – can be seen as a constraint for the normative *situational* practitioners in that they may flounder methodologically (as in the case of A1). A case worth using as an excellent exemplar of an explicitly signposted, multifaceted and facilitative environment is that of A4. The medical device maintenance technician, as detailed in chapter 6, works in an environment which explicitly values 'sound scientific, professional and moral principles'. These values are echoed in the environment itself (figure 9-6).

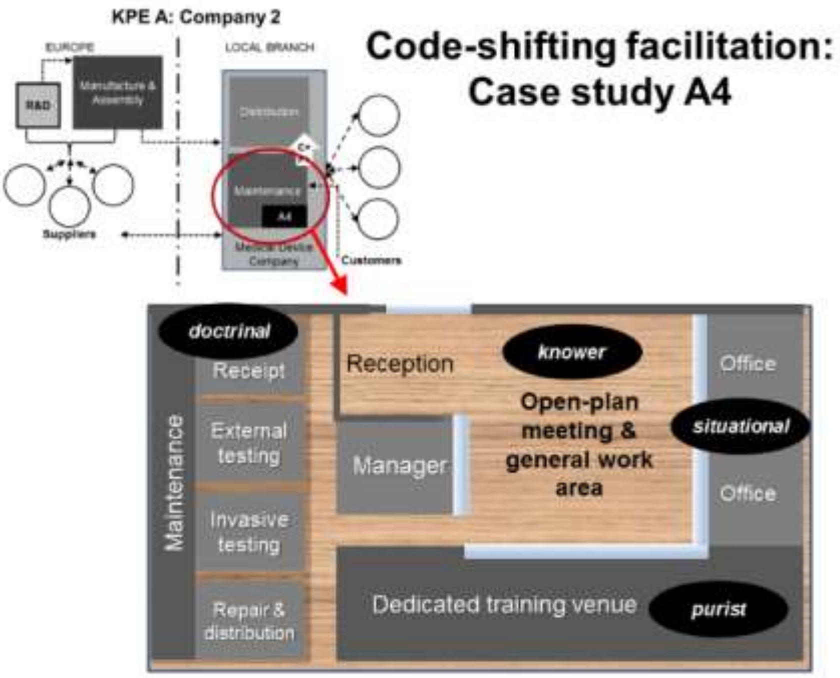


Figure 9-6 A4 Code-shift facilitating environment

The reception area leads into an open communal *knower*-orientated space for informal meetings, refreshments and general administrative work. This area is visible (through glass partitions) to the surrounding dedicated management and training spaces. The *purist*-orientated training takes place in a specific venue, where the signage implies an allegiance to the principles underpinning both scientific and humane practices. The core business of device maintenance is set aside in a *doctrinal* wing, with explicitly signposted and sequenced venues that accommodate a natural workflow. The arrangement of this wing was initiated by the practitioner himself. Each of the areas at the company as a whole enables explicit code shifting by virtue of its position, content and signage. I believe that the holistic, successful, macro-to-micro problem-solving process undertaken by this practitioner was further facilitated by the infrastructural features of this specific environmental context, and that these demonstrate a company that explicitly recognises and realises different forms of legitimate practices, which, in turn, are recognised and realised by the practitioner. In essence, this represents a 'code match' (Maton, 2014).

9.4.2 The code-clashing environment

In all the KPE categories, there were examples of companies whose business philosophies had either recently shifted towards an ostensible *knower*-orientation (A3, B1 and C4) or who had long been grappling with the regulation of human behaviour (C1 – C3). In all these cases, the key issue is the desire to improve their processes and remain competitive, while simultaneously aligning their activities to the principles of the National Development Plan (NPC, 2011) and similar global policy documents. These policies promote development and longer-term sustainability by focusing on 'people, planet and profits' (attributed to John Elkington in 1994) in the measurement of business performance according to the 'triple bottom line (TBL)' (Slaper & Hall, 2011). The dilemma from an economics perspective is that 'the 3Ps do not have a common unit of measure' (*ibid.,* p. 4). I suggest that the dilemma from an engineering knowledge perspective is the inability to define the nature of the ontic relations according to some common unit of measure when not only are three significantly different disciplines called upon in the engineering problem-solving moment, but also the entire sphere of human behaviour, which operates according to an entirely different set of organising principles.

The code-shifting challenge for a number of the *situational* and *purist* practitioners (B4, C1, C2 and C4) was the loss of strong ontic relations. Since three of these occur in the third KPE category, it is worth taking a closer look. Both KPE C companies are in the process of increasing automation (in other words, possibly downsizing) and are facing a lack of sufficiently skilled employees (a very real challenge in the South African context). Traditional processes in these companies are *doctrinal*, but orientated originally towards strong ontic relations and discursive relations (*purist*) with respect to the basic engineering sciences underpinning electro-mechanical production. Not only have they had to contend with rapid logic-based technological developments (which sees a shift towards weak discursive relations), but they also need to contend with the social context. However, the dominant methodology is still *doctrinal*, and this is the *basis* of all activity, no matter the ostensible *focus*. This suggests, to my mind, a confusing environment within which to operate for practitioners who favour strong and clearly understood ontic relations. Both C2 and C4 detailed (at length) the 'operator behaviour' problems, because 'they don't do what they're supposed to do' (C2), but went on to detail technical ‘policing’ solutions (in alignment with company requirements) which did not solve the original problem. This artificial maintenance of strength on either the ontic relations or discursive relations axis manifested as a distinct code clash for these particular practitioners, who subsequently went on to resign from such environments.

This is not to suggest that such environments cannot work. Both C1 and C3 are cases in point. The former has adapted to the *doctrinal* environment over time. C3, on the other hand - with his natural *doctrinal* disposition – is well-suited to his environment. How sustainable his avoidance is of the human elements in the problem-solving equation may be a matter for debate. In these examples of code-shift facilitating (A4) and code-clash manifesting (C) environments, we have seen a further layer of elements which have a structuring effect on sociocultural practices.

9.4.3 The code-shifting practitioner

There were a number of striking examples of tacit, but signposted code shifting across the case studies. B4 is one such example which deserves elaboration. His adoption of discipline- and *insight*-sensitive discursive conventions was apparent both in writing and during the interview. The following are a few features of his code-shifting technique which manifested discursively:

- 1st-person (active) descriptive paragraphs situating the problem in context
- Passive sections detailing system features
- Parenthetical informative or explicative details
- *Purist* and formulaic analyses of the logic-based science and mathematics
- Numbered, sequential *doctrinal* processes
- Italicisation and punctuation of own thoughts as quotations when expounding on engagement with *knowers* (suppliers)

The ability to shift between appropriate discursive conventions is a feature of all the high achievers. This speaks to the recognition and realisation of the different knowledge structures and their location at any given point within a particular *insight*. In other words, these practitioners select the most appropriate (and generally recognised as legitimate) *basis* for different claims depending on the *focus* of the problem-solving stage. There is *focus-basis* alignment. It is quite possible to speak about any of the engineering problem-solving aspects from any *basis.* This was more evident in the *situational* practitioner contexts, where the *purist* or *doctrinal* explanations during the problem analysis stage tended to be more narrative, for example.

The final section of this chapter has focused on the fifth sub-question and sought to examine the relationship between the elements in the problem-solving context and their impact on the problem-solving process. The data examples cited point to the significance of the environment with respect to enabling explicit code shifting or presenting conditions that manifest as distinct code clashes for particular practitioners. There are two primary code-shifting challenges for the case-study practitioners, each in relation to a specific epistemic relations axis: The discursive relations axis represents a code shift between single and multiple methods; and the ontic relations axis represents a code shift between defined and ill-defined phenomena. In order for practitioners to navigate these axes, they need to recognise – firstly – their own dominant *insight* orientations, and secondly, have access to the 'rules of the code' at any particular point in the problem-solving process *in context*. In other words, they need to be able to recognise and realise the appropriate code conventions, as held to be legitimate both from the perspective of the disciplinary basis as well as that of the environment. The environment can support and reinforce access to these rules. Where the environment is not clear on the phenomena being addressed, or there is a *focus-basis* misalignment, practitioners will not necessarily navigate the epistemic plane successfully, and thus not effectively solve real world engineering problems.

9.5 Implications of the research for engineering curriculum and pedagogy

Thus far, this chapter has sought to answer the research sub-questions. The central overarching research question, however, includes the question of the potential implications for curriculum and pedagogy:

What are the patterns of disciplinary boundary negotiation in multidisciplinary engineering problem-solving practice, (and what are the implications for the redesign of Diploma curricula and pedagogic practice to facilitate more effective problem solving)?

In summary, the research data show problem-solving patterns which demonstrate a symbiotic, structuring relationship between problem solver, problem structure and the problem environment. Each of these may manifest as having a different dominant *insight* orientation, with each *insight* representing a different kind of code as to the '*what'* and the '*how'* of the problem. The inner environment of the problem is a disciplinary reflection of the controlled electro-mechanical system: The elements of the system are both subservient to and guide the overall visible structural logic dictated by the laws of physics and supported by the relevant mathematics to determine optimal relations. Set in relation to the outer environment, solving the problem requires the explicit navigation of different 'codes' across the problem-solving stages over a period of time. Each code has different rules. Successful practitioners recognise and realise the different code conventions, and engage in code-shifting practices that may be evident both in the way they navigate the physical environment as well as in their discursive conventions. Using the theoretical tool as a metaphor here, the successful practitioner maintains stronger ontic relations with respect to the phenomenon in question – the problem – and stronger discursive relations with respect to the problem-solving stages – that each stage has ‘rules’. Secondly, the successful engineering problem-solving practitioner needs to be aware of his/her own *insight* orientation and the potential implications of different kinds of environments and different problem structures. A third factor is the recognition that whereas the physics and mathematics-based knowledge required to solve the problem is available *a priori*, the context-specific logic-based knowledge is generally acquired *a posteriori* other than at a generic principle level. This implies the conscious shift from stronger to weaker discursive relations, which the data show to be the most common code-shifting challenge, and which also signals a more complex level of problem solving than captured in the ‘well-defined’ descriptors applicable to the level of technician.

9.5.1 Enabling explicit code shifting

We now turn to a few of the possible implications of these findings for the engineering curriculum and pedagogic practice. First of all, although this small qualitative study makes no claims to generalisability, I do believe that the theoretical tools have sufficiently illuminated features of the complexity of engineering problem-solving practice to be able to make a few suggestions. Engineering curricula, as detailed in chapter 2, ascribe to a common set of competency ‘outcomes’ which ‘seek to cover the three broad categories (as dictated by national HE policy) that indicate a commitment to graduate development of the requisite ‘knowledge, skills and citizenship’’ (Wolff & Hoffman, 2014, p. 83). These outcomes could individually be aligned to different *insight* orientations, from the *purist*-based ‘application of mathematics, natural science and engineering sciences’ to the *doctrinal* ‘use [of] appropriate techniques, resources, and modern engineering tools’ and the *knower*-orientated ‘understanding of the impact of engineering activity on the society’ (ECSA, 2012).

The issue is not that there are different kinds of knowledge and practices in engineering (one look at both the competency criteria and the traditional silo curriculum pays testimony to this fact). On the contrary, the issue is the evidence that engineering practitioners are found wanting in the ability to apply this knowledge (Griesel & Parker, 2009) – and the contention in this research is that **such application requires the ability to consciously shift *between* the different forms**. It is this shifting that is not explicit in the curriculum, and it is this very shifting that implies a more complex level of practice. Opportunities to enable code-shifting are provided in ‘project-based’ subjects, for example, but there is no explicit induction into what is required to be able to recognise and realise the different forms of code in a single problem-solving moment. And herein lies our first challenge as engineering educators: making the codes explicit. However, this task requires an understanding and appreciation of the different ‘codes’.

9.5.2 Valuing disciplinary differences

A second challenge from an engineering curricular and pedagogic perspective is the nature and role of the disciplines. Mathematics is 'the largest stumbling block causing dropout in freshman year' (Bernold, Spurlin, & Anson, 2007, p. 264). The findings in this research study of a correlation between mathematics *and* logic performance in relation to code-shifting behaviour suggest we have not sufficiently grasped the significance of mathematical ways of thinking in engineering practice. In denouncing the 'divorce of mathematics from physics' in education (Hestenes, 2010, p. 2), the author argues for a mathematical model-orientated approach to engineering mathematics education. He suggests:

> '…if mathematics is "the language of science," then the *referents of mathematical models must be mental models.* Likewise, *the proper referents of scientific models must be mental models of physical situations*, which are only indirectly related to real physical systems through data, observation and experiment. This implies a common cognitive foundation for math, science and language…' (*ibid*., p. 7) (author's emphasis)

The disciplinary nature of mathematics is such that it represents different strengths of ontic relations at different moments in the engineering endeavour. The application of mathematics can be governed by physics phenomena, logic relations and mathematical phenomena. These require different kinds of mathematical thinking and discursive practices. I believe the tentative suggestions regarding differentiating between the different ontic relations 'codes' with respect to mathematical application support the notion of a meaningful relationship between mathematics, physics and logic. The primary focus in engineering mathematics teaching on computation or application to existing formulae (*doctrinal insight*) denies students the opportunity to develop higher-order relational ways of thinking in mathematics (which bears a close resemblance to 'logic-based' thinking at a more principled level).

There is a further implication of understanding the roles of the different disciplines in problem-solving practice. Given that the engineering qualification exit level outcomes call for application, demonstration and comprehension of a range of forms of knowledge, skills and attributes, this implies students are required to articulate these in some form. That the high achievers in this study demonstrated articulative capacity sensitive to different forms of meaning-making, I suggest, points to an uninterrogated relationship between mathematics, logic *and discursive practices*. Mathematics and logic in this research were found to be defined by differences in strengths along both the discursive relations and ontic relations axes – moving between fixed ways and many ways of approaching phenomena which in themselves are characterised by a shift in how strongly they are bounded (see 9.3.2). What these findings suggest is that the different engineering disciplines play a vital role in shaping practices that extend beyond the technical. Valuing and understanding these differences (and making them explicit) has implications for enabling successful problem-solving practice in sociotechnical environments.

9.5.3 Understanding contextual complexity

The third challenge lies in contextual complexity. There are levels of complexity in the real world problem-solving environment that the curriculum does not and cannot take into consideration. To do so would require the simulation of contexts that can only exist in the real world of work, and which would require periods of learning that extend beyond the parameters set by qualification duration. I suggest, firstly, it is the naïve simulation of context in problem-based/project-based learning which has led to a loss of the strength of ontic relations in the attempt to expand the range of discursive relations. In other words, in a real world problem-solving context, the ‘what’ of the problem has a relationship with the ‘how’ that is determined by the entirety of the Knowledge-Practice Environment. Without a meaningfully defined and consensus-based objective in relation to its possible approaches (in context), HE can only resort to ‘drilling’ different methods out of context if it wishes to simulate the real world. This is precisely the criticism of ‘competency-based training’ (Wheelahan, 2007) which does not enable conceptual thinking.

A key issue with regard to the question of complexity is in relation to the qualifications occupying the space between conceptual and contextual coherence curricula (Muller, 2008), specifically the Diploma in Engineering. Theoretically and empirically, this research project has determined that the application of logic-based knowledge requires shifting along both the discursive and ontic relations axes. This has implications for the qualification descriptor of ‘well-defined’ problems, given that the ontic relations axis represents how strongly bounded a particular phenomenon is. The rapid emergence of different logic-based technologies and the data in this research suggest that in 21st century multidisciplinary engineering practice dependent on computer technologies, the ‘problem’ cannot be easily defined as ‘well-defined’. I suggest that the context-specific focus on Diploma student engagement with particular forms of technologies (in a field characterised by redundancy and obsolescence) needs to be rethought. Hestenes’ (2010) allusion to the ‘common cognitive foundation for math, science and language’ (p. 7) provides a starting point for a more conceptual approach to both strengthening awareness of the organising principles underpinning the different disciplines as well as the ways in which they impact on each other. In other words, given that it is the Diploma technicians who operate at the coal-face of rapidly evolving artefacts in the empirical space, we must find ways to enable greater conceptual grasp.

The apparent complexity with regard to *knowers* in the real world problem-solving situation has implications for what it is that HE can accomplish. The increasing awareness of 'people and the planet' is a factor in the engineering problem-solving equation which stretches both the discursive relations and ontic relations continua well into the 'weak' domains. As in Bernstein's characterisation of 'regions', this continuum-stretching with respect to the question of knowledge implies a weakening of the epistemic relations and the loss of a 'relational idea' (Bernstein, 1975, p. 93). There are two key challenges in this regard that apply to HE. On the one hand, the recognition that the weak ontic relations and discursive relations together (*knower insight* OR–, DR–) imply a different set of organising principles (social relations) may well be the starting point for redefining the nature of epistemic relations in engineering knowledge practices for the 21st century. Ignoring these different organising principles in the less considered quadrants renders existing practices as having *no* legitimate basis. On the other hand, while practices in a number of the research contexts manifest as *focus-basis* misalignment precisely because of the uninterrogated relationship between the epistemic relations and the social relations underpinning engineering practice, HE cannot hope to prepare graduates for dealing with such challenges if industries themselves are not clear on the 'what' and the 'how' of the problem.

So, if HE cannot simulate the real world and provide enough realistic examples of ways of approaching different problems in different contexts in the face of a rapidly evolving technological landscape, what is our role? I suggest our role is to step out of contexts and understand them from a more conceptual perspective. This can be accomplished through providing opportunities to interrogate complexity from a more conceptually-informed basis. Here is an ideal opportunity to make explicit the difference *and* relationship between *theory and practice*. The relation between an abstract formulation of different kinds of problems in types of 'messy' contexts and the empirical actualisation of that formulation represents the 'space of possibles' (Bourdieu, 1991, cited in Maton, 2014, p. 7). It is the duty of engineering education to enable access to this space if our graduates are to cope in what will become even more complex sociotechnical practice environments.

We have seen that research *can* describe features of this complexity, and can highlight *focus-basis* relationships. The conceptual language presented in this research project – primarily the concept of the *epistemic plane* – offers a set of tools to potentially conceptualise complex engineering problem-solving environments for the purpose of teaching and learning. This conceptual language is not intended to be a prescriptive 'how-to' – rather, it serves as a lens through which to interrogate practices and the nature of different disciplines in different contexts. Such a model may usefully be employed to elicit important aspects for consideration in the conception, design and implementation of applied projects in engineering education.

CHAPTER 10: CONCLUSION

10.1 Thesis summary

The research presented in this thesis was sparked by a desire to understand why it is that HE appears to be failing in its ability to produce 'problem-solving' engineering graduates. This widespread perception is supported by an extensive body of literature detailing low retention and throughput in engineering qualifications, attempts to redesign 'relevant curricula', and industry reports on graduate inabilities to apply knowledge. Against a background acknowledging increasing 21^{st} century complexity in the engineering profession, the research 'problem' of understanding what is entailed in engineering problem solving was introduced in chapter 1. The contention is that HE is failing as a result of not understanding the theory/practice relationship and the nature of engineering problem solving from the perspective of 'knowledge'. Chapter 2 presented an overview of the literature on the emergence of engineering education as we know it today, its recognised forms of knowledge, the development of the profession, and a review of problem-solving research literature. What was clear from the literature was a glaring absence of awareness of the different disciplines underpinning engineering practice and the implications of their different organising principles for problem solving. Social realism and the key analytical tools were introduced in chapter 3 as providing the conceptual basis through which to examine the different engineering forms of knowledge and their relationships with each other. Following the introduction and conceptualisation of the empirical research site – multidisciplinary mechatronics engineering – in chapter 4, chapter 5 presented a novel and pragmatic research design 'modular systems' framework through which to rigorously examine engineering problem-solving practice. Chapters 6 to 8 presented the analysis of 12 case studies: novice mechatronics engineering practitioners in three significantly different types of South African industrial sites. Each site was characterised as a Knowledge-Practice Environment, constituted by a problem solver in a problem environment facing a problem to be solved that revolved around the disciplines of mathematics, physics and logic. Based on questionnaire texts and a re-enactment protocol, the KPE elements and processes were analysed using the Legitimation Code Theory tools of Semantics and Specialization (epistemic relations). The research focused on illuminating patterns of disciplinary boundary negotiation, and these were discussed in chapter 9 along with implications for engineering curriculum and pedagogy.

Limitations of the study include the fact that analysing practitioner problem-solving practices was dependent on their 'articulative capacity'. A number of the original volunteers (50) either expressed an inability to describe their problem-solving processes or this was evident in submissions where the question 'How did you solve the problem?' was answered with a single sentence, such as 'I asked my supervisor'. The ability to articulate the problem-solving process in such a way that some form of disciplinary engagement was evident was a key methodological decision in order to more effectively interrogate problem solving from a disciplinary knowledge perspective. In this research project, unfortunately, there were no useful submissions by local black South African students (who represented 14% of the volunteering group). However, the 12 cases included representatives of all population groups in Africa (black, coloured, and white) with four different home languages. A second limitation is the fact that none of the female engineering graduate volunteers managed to submit questionnaires. Given that they represent less than 10% of the mechatronics qualification cohorts, and that few are actually working as mechatronics practitioners (which is an area that warrants further research), the lack of a female case study should not come as a surprise.

Despite the limitations and the small number of thesis case studies (drawn from 28 phase one participants), the findings are drawn from the entire range of potential practice sites, which represent significantly different and representative multidisciplinary engineering contexts. The very fact that there *are* patterns that emerge - despite the nature of specific contexts and particular practitioners - suggests a number of ‘pattern principles’ and findings that may prove relevant to at least interrogating the assumptions underpinning our current engineering education practices.

10.2 Key research findings

The analysis of the different features of the problem-solving process reveal the following broadly-stated patterns:

Environment: The different practice environments are characterised by the difference between greater allegiance to phenomena or methods, with smaller companies tending towards the former, and larger companies towards the latter. This manifests as environments requiring practices based on *situational insights* and *doctrinal insights* respectively. These *insight* orientations are diametrically opposed, and represent the two environments in which systems integrating practitioners (the core role of a mechatronics graduate) are required to work simultaneously. In other words, the different environments characterising the field regard as legitimate two significantly different approaches to problem solving. Practitioners based in one environment and who service the other are required to navigate between two opposing *insights*.

Problem solver: There is a relationship between high mathematics *and* logic-based academic achievement, articulative capacity, and fuller problem-solving cycles and descriptions. This pattern emerged across all contexts. Such practitioners were most successful in recognising the legitimate *basis* of practice at all stages of the problem-solving process. Problem solvers with low achievement in mathematics and high achievement in logic (which represents the norm on the originating qualification) displayed a distinct preference for their basis of practice (*situational insight*), and this revealed code-shifting challenges.

Problem-solving process: Each category reveals a different pattern. In smaller (Contained Systems) environments, the problem-solving trajectory is determined by the practitioner preferences in response to their perception of the problem structure; in larger (Distributed Systems) environments, the process is dictated by methods regarded as legitimate in that environment. A potentially archetypal pattern of successful problem solving that emerges in the small and large contexts is a macro-to-micro clockwise cycle through all *insights* starting in the *doctrinal* quadrant. In all the Modular Systems contexts, the problem structure (in context) appears to dictate the problem-solving process. An archetypal pattern that emerges here is the iterative diagonal shifting between both sets of diametrically opposed *insights*.

Problem structure: The problem structures all entailed a relationship between physics, mathematics and logic. These disciplinary forms of knowledge demonstrate different relationships between the phenomenon being addressed and its legitimate approaches. This is theoretically described in this research as having different sets of ontic and discursive relations relationships. The problem-solving process requires recognising the disciplines and their interrelationship in the physical system. The elements of the system are both subservient to and guide the visible and invisible structural logic dictated by the laws of physics and supported by the relevant mathematics to determine optimal relations in a particular context. The successful problem-solving practitioner navigates these disciplines - in no particular order - through a conscious shifting between different realisations of both allegiance to phenomena and the legitimate ways of approaching those phenomena. Simply put, the practitioner changes his/her way of thinking and acting depending on the particular phenomenon in focus at a particular moment during the problem-solving process. The practitioner shifts between different *insights* ('codes') in relation to the disciplines suggested by the problem structure in context. A second knowledge-related finding is that whereas the physics and mathematics-based knowledge required to solve the problem is available *a priori*, the specifically required logic-based knowledge is generally acquired *a posteriori.*

The overarching *principle* is that all four *insight* quadrants are relevant in most engineering problem-solving contexts, and the successful problem solver recognises and realises the legitimate *basis* of practice at any particular *focus* stage in the problem-solving cycle, where the *basis* is held to be legitimate in relation to the problem and/or the environment.

Code shifting and code clashing: All these patterns can be explained by examining the nature of the two axes of the epistemic plane. There are two primary code-shifting challenges, each in relation to a specific epistemic relations axis: The discursive relations axis represents a code shift between single and multiple methods; and the ontic relations axis represents a code shift between defined and ill-defined phenomena. The most common code-shifting challenge *dictated by practitioner preference* is along the discursive relations axis. This simply says that some practitioners tend to be more comfortable with either limited/fixed methods or open/multiple methods. In the right environment, such practitioners can flourish. The most common code-shifting challenge *dictated by the environment* is along the ontic relations axis. This suggests the loss of consensual focus on the 'what' of the problem and manifests as a *focus-basis* misalignment. In other words, in complex contexts there are environments in which it is not clear what the real focus is – the science underpinning the manifestation of the problem or the contextual factors that give rise to the problem in the first place. These latter factors are as a result of *knowers* in the problem-solving equation. This marks a move away from the epistemic relations (the focus of this research project) and towards the social relations, which operate according to an entirely different set of organising principles.

The group of high-achieving practitioners in this research who navigate seamlessly between the different ways of thinking are able to do so as a result of shifting their thinking between weaker and stronger discursive relations. It is significant that they do so without losing sight of the phenomenon (maintaining stronger ontic relations) or by legitimately recognising the different organising principles required for effective practice when considering *knowers* in the problem-solving situation. In other words, they do not expect the *knowers* to behave like the objects in the system, and they tailor their approaches appropriately.

The apparent code-shifting requirements, together with the weakening of discursive relations (as the range of methods increases) and the weakening of ontic relations (as the demands of the environments shift away from the epistemic basis) literally expand the scope of engineering problem-solving practice. This challenges the current descriptors defining the role and level of an engineering technician in a multidisciplinary region.

10.3 Recommendations for engineering education

The UNESCO (2010) report's recommendation that in order to stop losing potential recruits, engineering education needs to shift from the 'Humboldtian fundamentals approach' (p. 32) supported my own initial conviction that I was going to find an answer to the 'mathematics' problem in engineering education. An internal study on graduate performance in industry on the originating programme had revealed that the majority of successful systems integrators consistently had below average results (even failing) for engineering mathematics and the physics-based subjects, but had achieved distinctions in the logic-based subjects. However, the data in this study suggest the need to reconceptualise the role of mathematics, in particular, with respect to the possible 'structuring' effects of knowledge. Secondly, the holistic research methodology employed in this project revealed that the possible reason for the success of systems integrators who had performed poorly in mathematics (and physics) was their being located in the right kinds of environments – those which value *situational insight* – in other words, environments where the objective is clear and multiple approaches are encouraged. The research data suggest that where mathematics plays a vital role is in its ability – *in relation to logic* – to enable the practitioner to recognise and realise (both in practice and discursively) the different disciplinary organising principles and associated ways of making meaning. These are practitioners who can both see and express their problem-solving processes[86].

The implications of the research findings, detailed in section 9.5, led to three key recommendations for engineering education:

- The necessity to enable explicit code shifting between different ways of approaching different phenomena in engineering problem solving.
- The recognition that the different organising principles in the core engineering disciplines enable the development of significantly different ways of thinking and meaning-making. The possession of the recognition and realisation rules associated with these different disciplines enables more effective problem solving.
- Engineering education cannot (and should not) hope to simulate real world problem contexts. Students may be far better served through the development of a more conceptual grasp of complex problem-solving contexts.

The finding of the significance of *a priori* access to the physics and applicable mathematics knowledge in successfully solving engineering problems leads me to conclude, contrary to the UNESCO (2010) report and progressivist trends, that the 'fundamentals' are essential. In all cases in this study where the practitioners had a less firm grasp on the fundamentals, the problem-solving process was impeded. The *a posteriori* acquisition of context-specific logic-based knowledge is further support of the need for a more conceptual approach to teaching logic-based systems. In the absence of an epistemologically-orientated curriculum, the alternative is to provide guaranteed access to mentorship and support in carefully selected and willing environments – a return to the so-called 'shop culture' of old. Though this ethic is evident in the smaller environments, it does not seem practicable in the larger scale productivity-focused environments.

[86] It is worth noting that two of the original questionnaire submissions which could not effectively describe the problem-solving process were submitted by South African black students who had achieved distinctions for mathematics, but had low performance in the logic-based subjects.

10.4 Contribution to the field

This research has not looked at a new problem. The ‘problem’ of the inability of HE to adequately equip (and retain) engineering graduates is well established. As is the ‘problem’ of increasing engineering graduate inability to solve problems. So, too, the ‘problem’ of increasingly complex 21st century practice contexts. What this research has done is to look at an old problem in a new way. First of all, the research methodological design (mimicking the empirical site) represents a novel and pragmatic systems approach to understanding problem solving *from a disciplinary knowledge perspective* by considering complex behaviour in complex contexts. Problem-solving research to date has not considered the significantly different forms of disciplinary knowledge and their impact on human processes in real world contexts. Secondly, the new and emerging social realist-based Legitimation Code Theory framework is finding its way into every imaginable practice sector as a result of its ability to both illuminate and transcend sociocultural practices. It offers dimensions and languages that enable researchers not only to see practices in hitherto unexplored ways, but also to explain those practices as part of the ‘structured and structuring structures’ (Bourdieu, 1994, p. 170 in Grenfell, 2014) in society. This research has been the first of its kind to thoroughly explore and extend the Specialization dimension of epistemic relations.

The research findings have demonstrated that it is the comprehension of the individual nature of and explicit shifting between different forms of disciplinary knowledge that enable effective problem solving. It suggests that we are missing an invaluable opportunity to draw on the affordances of the different disciplinary forms in enabling a more conceptual understanding of the role of knowledge (theory) underpinning practice. Secondly, the research has highlighted the unavoidable reality of both epistemic and social relations in the practice space, and that effective practitioners need to recognise the different organising principles of these two sets of relations. It is hoped that this research can enable the beginning of an informed dialogue between stakeholders involved in the design of engineering curricula and pedagogic practice to better meet the needs of society as well as do justice to knowledge itself.

10.5 Further research

The relationship between performance in the mathematics and logic-based subject areas in engineering education deserves attention. Given the common prior curricular experience in the research case studies (barring A2), it may well be that these subjects were taught in certain ways that enabled or constrained the kind of thinking required. I believe it would be of value to conduct a larger scale comparative study on the relationship between mathematics and logic academic performance and the impact on, for example, capstone project success, or, ideally, industry perception of successful problem solving.

The research finding that high performance in mathematics and logic was accompanied by iterative code shifting as well as articulative capacity warrants further research. It speaks to the need to interrogate why none of the South African black students managed to participate on the research project, despite being academically successful. This success, however, was in the disciplines with stronger discursive relations, suggesting a tendency towards rule-bound knowledge. Given that the technologies in such regions as mechatronics engineering demonstrate practices based on ever weakening discursive relations, and that there may be parallels between these weak discursive relations and those associated with non-technical sociocultural practices (such as, for example, horizontal discourse practices), it may be necessary to pay greater attention to developing the recognition and realisation rules in the non-disciplinary parts of the curriculum.

Bibliography

Allen, T. (1966). Studies of the problem-solving process in engineering design. *Transactions on engineering management, 13*(2), 72-83.

Andersson, S., Chronholm, J. A., & Gelin, B. (2011). Student retention in engineering education - Examples of how it looks and what can be done. *Utvecklingskonferensen för Sveriges ingenjörsutbildningar*, (pp. 53-57). Retrieved June 1, 2012, from http://www.ep.liu.se/ecp/075/011/ecp12075011.pdf

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education*, *87*(2), 121-132.

Baird, F., Moore, C. J., & Jagodzinski, A. P. (2000). An ethnographic study of engineering design teams at Rolls-Royce Aerospace. *Design Studies*, *21*(4), 333-355.

Bankel, J., Bergren, K.-F., Engstrom, M., Wiklund, I., Crawley, E., Soderholm, D., . . . Ostlund, S. (2005). Benchmarking engineering curricula with the CDIO syllabus. *International Journal of Engineering Education, 21*(1), 121-133.

Barnett, M. (2006). Vocational knowledge and vocational pedagogy. In M. Young, & J. Gamble (Eds.), *Knowledge, Curriculum and Qualifications for South African Further Education.* Cape Town: HSRC Press.

Barnett, R. (2000). Supercomplexity and curriculum. *Studies in Higher Education, 25*(3).

Bellotti, T. (2006). Lecture notes on Immanuel Kant's Critique of Pure Reason (Peter Rickman 1995).

Bernold, L., Spurlin, J., & Anson, C. (2007). Understanding our students: a longitudinal study of success and failure in engineering with implications for increased retention. *Journal of Engineering Education, 96*(3), 263-274. Retrieved June 17, 2012, from http://www.jee.org/2007/july/2.pdf

Bernstein, B. (1975). *Class, codes & control* (Vol. III). London: Routledge.

Bernstein, B. (1977). *Class, codes and control, Volume III: Towards a theory of educational transmissions.* London: Routledge & Kegan Paul.

Bernstein, B. (1990). *Class, codes and control, Volume IV: The structuring of pedagogic discourse.* London: Routledge.

Bernstein, B. (1996). *Pedagogy, symbolic control and identity: Theory, research, critique.* London: Taylor & Francis.

Bernstein, B. (2000). *Pedagogy, symbolic control and identity: Theory, research, critique, rev. edn.* London: Rowman & Littlefield.

Bishop, R. H. (Ed.). (2002). *The Mechatronics Handbook.* Retrieved December 15, 2010, from Media Fire: http://www.mediafire.com/?ese8srfvtkudtve

Blackie, M. (2014). Creating semantic waves: using Legitimation Code Theory as a tool to aid the teaching of chemistry. *Chemistry Education Research and Practice, 15*, 462-469. doi:10.1039/c4rp00147h

Bordogna, J., Fromm, E., & Ernst, E. (1993). Engineering education: Innovation through integration. *Journal of Engineering Education, 82*(1), 3-8.

Brezillon, P. (1999). Context in problem solving: a survey. *The Knowledge Engineering Review, 14*(01), 47-80.

Briand, L. (2003). Software documentation: how much is enough? *Software Maintenance and Reengineering* (pp. 13-15). Seventh European Conference: IEEE.

Caelli, K., Ray, L., & Mill, J. (2003). 'Clear as mud': toward greater clarity in generic qualitative research. *International Journal of Qualitative Methods*, 1-13.

Carvahlo, L., Dong, A., & Maton, K. (2009). Legitimating design: a sociology of knowledge account of the field. *Design Studies, 30*(5), 483-502.

Case, J. (2011). Knowledge matters: interrogating the curriculum debate in engineering using the sociology of knowledge. *Journal of Education*(51), 1-20.

CHE. (2009, October). Higher Education Monitor. Council on Higher Education.

CHE. (2013). *A proposal for undergraduate curriculum reform in South Africa.* Pretoria: Council on Higher Education.

CHEC. (2013). *Pathways from university to work.* Cape Town: Cape Higher Education Consortium.

Chlpeková, A., Večeřa, P., & Šurinová, Y. (2014). Enhancing the effectiveness of problem-solving processes through employee motivation and involvement. *International Journal of Engineering Business Management*. doi:10.5772/59431

Clarence, S. (2014). *Enabling cumulative knowledge-building through teaching: a Legitimation Code Theory analysis of pedagogic practice in law and political science*. Rhodes University.

Craig, T., & Cloete, T. (2013). Observations and conclusions of dynamics students' mathematical fluency. *Conference of the South African Society for Engineering Education*, (p. 39).

Crawley, E. (2001). *The CDIO syllabus: a statement of goals for undergraduate engineering education.* Massachusetts: Massachusetts Institute of Technology.

DHET. (2012). *Green Paper for post-school education and training.* Pretoria: Department of Higher Education and Training.

DHET. (2013). *White Paper for post-school education and training.* Pretoria: Department of Higher Education and Training.

Disco, C., Rip, A., & van der Meulen, B. (1992). Technical innovation and the universities: divisions of labour in cosmopolitan technical regimes. *Social Science Information*, 465-507.

Du Toit, R., & Roodte, J. (2008). *Engineering professionals: crucial key to development and growth in South Africa.* Pretoria: HSRC.

ECSA. (2012). *5 new engineering technology qualification standards.* Engineering Council of South Africa.

Eisenhardt, K., & Graebner, M. (2007). Theory building from cases: Opportunities and challenges. *Academy of management journal, 50*(1), 25-32. Retrieved March 3, 2015, from http://aom.org/uploadedFiles/Publications/AMJ/Eisenhart.Graebner.2007.pdf

Feisel, L., & Rosa, A. (2005). The role of the laboratory in undergraduate engineering education. *Journal of Engineering Education, 94*(1), 121-130.

Felder, R. (2012). Engineering Education: A Tale of Two Paradigms. In McCabe, B, Pantazidou, M, & Phillips, D (Eds.), *Shaking the foundations of Geo-Engineering education* (pp. 9-14). Leiden: CRC Press. Retrieved June 17, 2012, from http://www4.ncsu.edu/unity/lockers/users/f/felder/public/Papers/TwoParadigms.pdf

Felder, R., & Brent, R. (2005). Understanding Student Differences. *Journal of Engineering Education, 94*(1), 57-72. Retrieved June 17, 2012, from http://www4.ncsu.edu/unity/lockers/users/f/felder/public/Papers/Understanding_Differences.pdf

Fisher, G. (2011). *Improving throughput in the Engineering Bachelors degree.* Engineering Council of South Africa.

Funke, J., & Frensch, P. (1995). Complex problem solving research in North America and Europe: An integrative review. *Foreign Psychology, 5*, 42-47.

Gardner, K., Rush, A., Crist, M., Konitzer, R., & Teegarden, B. (2011). *Cognitive patterns: problem-solving frameworks for object technology.* Zurich: Global Text.

Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., & Trow, M. (1994). *The new production of knowledge: The dynamics of science and research in contemporary societies.* Sage.

Grenfell, M. J. (Ed.). (2014). *Pierre Bourdieu: key concepts.* London: Routledge.

Griesel, H., & Parker, B. (2009). *Graduate Attributes: a baseline study on South African graduates from the perspective on employers.* HESA & SAQA.

Hanrahan, H. (2014). The evolution of engineering knowledge. In M. Young, & J. Muller (Eds.), *Knowledge, expertise and the professions* (pp. 109-127). New York: Routledge.

Hestenes, D. (2010). Modeling theory for math and science education. In *Modeling students' mathematical modeling competencies* (pp. 13-41). US: Springer.

Hoffman, F. (2011, November 29). Diploma graduate assessment. (K. Wolff, Interviewer)

Hood, S. (2014). Ethnographies on the move, stories on the rise: An LCT perspective on method in the humanities. In Maton, K, Hood, S, & Shay, S (Eds.), *Knowledge-building.* London: Routledge.

IEA. (2013). *Graduate Attributes and Professional Competency Profiles.* International Engineering Alliance. Retrieved from International Engineering Alliance: http://www.ieagreements.org.

Isen, A., Daubman, K., & Nowicki, G. (1987). Positive affect facilitates creative problem solving. *Journal of personality and social psychology, 52*(6), 1122-1131.

Jackson, S. (2007, Winter/Spring). *Waking up to the 'Quiet Crisis' in the USA.* Retrieved April 1, 2013, from College Board Review: www.rpi.edu/homepage/quietcrisis/CBReview

Jenkins, R. (2002). Practice, Habitus and Field. In R. Jenkins, *Pierre Bourdieu* (pp. 66-102). London: Routledge.

Johnson, R., & Onwuegbuzie, A. (2004). Mixed methods research: a research paradigm whose time has come. *Educational Researcher, 33*(7), 14-26.

Jonassen, D., Strobel, J., & Lee, C. (2006). Everyday problem solving in engineering: lessons for engineering educators. *Journal of Engineering Education, 95*(2), 139-151.

Joseph, M. (2002). *The Trivium: The Liberal Arts of Logic, Grammar, and Rhetoric.* Philadelphia: Paul Dry Books.

Kant, I. (1787). *Critique of Pure Reason.* (J. Meiklejohn, Trans.) Hazelton: An Electronic Classics Series Publication.

Kemmerling, G. (2011). *Kant: Synthetic a priori judgements*. (Britannica, Producer) Retrieved April 15, 2015, from The Philosophy Pages: http://www.philosophypages.com/hy/5f.htm

Kilpert, L., & Shay, S. (2013). Kindling fires: examining the potential for cumulative learning in a journalism curriculum. *Teaching in Higher Education, 18*(1), 40-52.

Kraak, A. (2000). *Changing modes: New knowledge production and its implications for Higher Education in South Africa.* (A. Kraak, Ed.) Pretoria: HSRC.

Kuhn, T. (1962). *The structure of scientific revolutions.* University of Chicago Press.

Lajoie, S. (1993). Computer environments as cognitive tools for enhancing learning. In S. Lajoie, & S. Derry (Eds.), *Computers as cognitive tools* (pp. 261-288). New Jersey: Lawrence Erlbaum Associates, Inc.

Lang, J., Cruse, S., McVey, F., & McMasters, J. (1999). Industry expectations of new engineers: a survey to assist curriculum designers. *Journal of Engineering Education, 88*(1), 43-51.

Leonardi, P. M. (2011). Innovation blindness: Culture, frames, and cross-boundary problem construction in the development of new technology concepts. *Organization Science*, *22*(2), 347-369.

Lundgreen, P. (1990). Engineering Education in Europe and the U.S.A., 1750-1930: The rise to dominance of school culture and the engineering professions. *Annals of Science, 47*, 33-75.

Mahembe, E. (2011). *Literature Review on Small and Medium Enterprises' Access to Credit and Support in South Africa.* Pretoria: National Credit Regulator.

Markie, P. (2015). *Rationalism vs Empiricism*. Retrieved April 20, 2014, from Stanford Encyclopedia of Philosophy: http://plato.stanford.edu/entries/rationalism-empiricism/

Martin, J., & Maton, K. (Eds.). (2013). *Linguistics and Education: Special issue on cumulative knowledge-building in secondary schooling, 24(1)*, 1-74.

Maton, K. (2009). Cumulative and segmented learning: exploring the role of curriculum structures in knowledge building. *British Journal of Sociology of Education, 30*(1), 43-57.

Maton, K. (2013). Making semantic waves: A key to cumulative knowledge-building. *Linguistics and Education, 24*, 8-22.

Maton, K. (2014). *Knowledge and Knowers: Towards a realist sociology of education.* London and New York: Routledge.

Maton, K. (2015, February 3). [LCT] Changing terms - 2 semantic codes. *LCT Theory Group*.

Maton, K., & Lamont, A. (2010). Unpopular music: Beliefs and behaviours towards music in education. In R. Wright (Ed.), *Sociology and Music Education.* London: Ashgate.

Maton, K., & Moore, R. (2010). *Social realism, knowledge and the sociology of education: Coalitions of the mind.* (Maton, K, & Moore, R, Eds.) London: Continuum.

Maton, K., & Muller, J. (2007). A sociology for the transmission of knowledges. In F. Christie, & J. Martin, *Language, Knowledge and Pedagogy.* London: Continuum.

Maxwell, J. (1992). Understanding and Validity in Qualitative Research. *Harvard Educational Review, 62*(3), 279-297.

Maxwell, J., & Loomis, D. (2003). Mixed methods design: An alternative approach. In A. Tashakkori, & C. Teddlie (Eds.), *Handbook of mixed methods and social behavioural research* (pp. 241-272). Thousand Oaks: SAGE.

Morrow, W. (2009). *Bounds of democracy: epistemological access in higher education.* Cape Town: HSRC Press.

Muller, J. (2008). Forms of knowledge and curriculum coherence. *ESRC Seminar Series, Seminar 2: Epistemology and the Curriculum.* University of Bath.

Nowotny, H., Scott, P., & Gibbons, M. (2003). Introduction: Mode 2 revisited: The new production of knowledge. *Minerva, 41*(3), 179-194.

NPC. (2011). *National Development Plan Vision 2030.* National Planning Commission.

Onwuegbuzie, A., & Leech, N. (2005). On becoming a pragmatic researcher: the importance of combining quantitative and qualitative research methodologies. *International Journal of Social Research Methodology, 8*(5), 375-387.

Paton, B., & Dorst, K. (2011). Briefing and reframing: A situated practice. *Design Studies*, *32*(6), 573-587.

Popper, K. (1962). *Conjectures and refutations: the growth of scientific knowledge.* New York: Basic Books.

Programmable logic controllers. (2011). Retrieved June 29, 2011, from All about circuits: http://www.allaboutcircuits.com/vol_4/chpt_6/1.html

Rip, A. (2002, February 16). Science for the 21st century. *Sciences and Arts debate*. Hollandsche Maatschappij der Wetenschappen.

Sadovnik, A. (2001). Basil Bernstein (1924-2000). *Prospects: the quarterly review of comparative education, XXXI*(4), 687-703.

Sciulli, D. (2005). Sciulli, D. (2005). Continental sociology of professions today: Conceptual contributions. *Current sociology, 53*(6), 915-942.

Shay, S. (2008). Beyond social constructivist perspectives on assessment: the centring of knowledge. *Teaching in Higher Education, 13*(5), 595-605.

Shay, S. (2012). Conceptualizing curriculum differentiation in higher education: a sociology of knowledge point of view. *British Journal of Sociology of Education, 34*(4), 1-20.

Shay, S., & Steyn, D. (2014). Enabling knowledge progression in vocational curricula: Design as a case study. In Maton, K, Hood, S, & Shay, S (Eds.), *Knowledge-building.* London: Routledge.

Sheppard, S., Colby, A., Macatangay, K., & Sullivan, W. (2007). What is engineering practice? *International Journal of Engineering Education, 22*(3), 429-438.

Shooter, S., & McNeil, M. (2002). Interdisciplinary collaborative learning in Mechatronics at Bucknell University. *Journal of Engineering Education, 91*(3), 339-344.

Simon, H. (1978). *Herbert A. Simon - Biographical*. Retrieved January 24, 2015, from Nobelprize.org: http://www.nobelprize.org/nobel_prizes/economic-sciences/laureates/1978/simon-bio.html

Simon, H. (1996). *The sciences of the artificial* (3rd ed.). Cambridge, Massachussetts: The MIT Press.

Slaper, T., & Hall, T. (2011, Spring). *The Triple Bottom Line: What is it and how does it work?* Retrieved April 27, 2015, from Indiana Business Review: http://www.ibrc.indiana.edu/ibr/2011/spring/article2.html

Smit, R. (2012). Transitioning disciplinary differences: does it matter in engineering education? Draft paper for Knowledge in the Curriculum symposium.

Sobek, D. K. (2004). The engineering problem-solving process: good for students? *American Society for Engineering Education.* ASEE.

Sternberg, R., & Frensch, P. (Eds.). (1991). *Complex Problem Solving: Principles and Mechanisms.* Lawrence Erlbaum Associates, Inc.

Steup, M. (2015). *Epistemology*. Retrieved from Stanford Encyclopedia of Philosophy: http://plato.stanford.edu/entries/epistemology/

Szentirmai, L., & Radacs, L. (2012). Improvement of academic and research standards of Higher Engineering Education in light of Bologna process. *10th IEEE International Conference on Emerging eLearning Technologies and Applications* (pp. 381-386). Slovakia: ICETA.

Turns, J., Atman, C., Adams, R., & Barker, T. (2005). Research on engineering student knowing: trends and opportunities. *Journal of Engineering Education, 94*(1), 27-40.

UNESCO. (2010). *Engineering: issues, challenges and opportunities for development.* Paris: UNESCO Publishing.

Usher, R. (1996). A critique of the neglected epistemological assumptions of educational research. In D. Scott, & R. Usher (Eds.), *Understanding educational research* (pp. 9-32). London: Routledge.

Vandor, L. (2001). *Legal Counsel: Frequently Asked Questions about the Law (Vol. 2). .* ECW Press.

Vogt, C. M. (2008). Faculty as a critical juncture in student retention and performance in engineering programs. *Journal of Engineering Education, 97*(1), 27-36. Retrieved June 23, 2012, from http://www.jee.org/2008/january/5.pdf

Volkema, R. J. (1983). Problem formulation in planning and design.*Management Science*, *29*(6), 639-652.

Wang, Y., & Chiew, V. (2010). On the cognitive process of human problem solving. *Cognitive Systems Research, 11*, 81-92.

Wheelahan, L. (2007). How competency-based training locks the working class out of powerful knowledge: a modified Bernsteinian analysis. *British Journal of Sociology of Education, 28*(5), 637-651.

Wiltschnig, S., Christensen, B. T., & Ball, L. J. (2013). Collaborative problem–solution co-evolution in creative design. *Design Studies*, *34*(5), 515-542.

Winberg, C., Engels-Hills, P., Jacobs, C., Garraway, J., & Winberg, S. (2012). 'I take engineering with me': theory and practice in an engineering curriculum. *Knowledge & Curriculum in HE. CHED symposium UCT*. Cape Town.

Wolff, K. (2011). Integrating multidisciplinary engineering knowledge in a final year technical university diploma programme: an analysis of student praxis. University of Cape Town.

Wolff, K. (2012). A community-of-practice approach to multidisciplinary engineering assessment. *HELTASA 2012 Conference*. Unpublished.

Wolff, K. (2013). 'Reservoirs' and 'Repertoires': epistemological and discursive complexities in multidisciplinary engineering practice. *Journal of Academic Writing, 3*(1), 84-94.

Wolff, K., & Hoffman, F. (2014). Knowledge and knowers in engineering assessment. *Cristal, 2*(1), 74-95. doi:10.14426/cristal.v2i1.19

Wolff, K., & Luckett, K. (2013). Integrating multidisciplinary engineering knowledge. *Teaching in Higher Education, 18*(1), 78-92.

Wright, J. (1999). *The debate over which PLC programming language is state-of-the-art.* Retrieved June 26, 2011, from http://atmae.org/jit/Articles/wrig0899.pdf

Young, M., & Muller, J. (2007). Truth and truthfulness in the sociology of education. *Theory and Research in Education, 5*(2), 173-201.

Zhang, G., Anderson, T., Ohland, M., & Thorndyke, B. (2004). Identifying factors influencing engineering student graduation: a longitudinal and cross-institutional study. *Journal of Engineering Education, 93*(4), 313-320.

Appendix A: Exit Level Outcomes

Exit Level Outcomes: Diploma in Engineering (ESGB May 2012)	
1	Apply engineering principles to systematically diagnose and solve well-defined engineering problems.
2	Apply knowledge of mathematics, natural science and engineering sciences to defined and applied engineering procedures, processes, systems and methodologies to solve well-defined engineering problems.
3	Perform procedural and non-procedural design of well-defined components, systems, works, products or processes to meet desired needs normally within applicable standards, codes of practice and legislation.
4	Conduct investigations of well-defined problems through locating and searching relevant codes and catalogues, conducting standard tests, experiments and measurements.
5	Use appropriate techniques, resources, and modern engineering tools, including information technology, prediction and modelling, for the solution of well-defined engineering problems, with an understanding of the limitations, restrictions, premises, assumptions and constraints.
6	Communicate effectively, both orally and in writing, within an engineering context.
7	Demonstrate knowledge and understanding of the impact of engineering activity on the society, economy, industrial and physical environment, and address issues by defined procedures.
8	Demonstrate knowledge and understanding of engineering management principles and apply these to one's own work, as a member or leader in a diverse team and to manage projects.
9	Engage in independent and life-long learning through well-developed learning skills.
10	Comprehend and apply ethical principles and commit to professional ethics, responsibilities and norms of engineering practice within own limits of competence.
11	Demonstrate an understanding of workplace practices to solve engineering problems consistent with academic learning achieved.

Appendix B: Case study problem-solving range

The International Engineering Alliance (2013) Graduate Attributes & Professional Competencies: Section 4.1 Range of Problem Solving

	Attribute	Well-defined Problems (Technician) Value = 1 per attribute	Broadly-defined Problems (Technologist) Value = 2 per attribute	Complex Problems (Engineer) Value = 3 per attribute	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
1	**Preamble**	Engineering problems having some or all of the following characteristics:	Engineering problems which cannot be pursued without a coherent and detailed knowledge of defined aspects of a professional discipline with a strong emphasis on the application of developed technology, and have the following characteristics	Engineering problems which cannot be resolved without in-depth engineering knowledge, much of which is at, or informed by, the forefront of the professional discipline, and have some or all of the following characteristics:												
2	**Range of conflicting requirements**	Involve several issues, but with few of these exerting conflicting constraints	Involve a variety of factors which may impose conflicting constraints	Involve wide-ranging or conflicting technical, engineering and other issues	1	1	2	2	2	2	2	2	2	2	2	2
3	**Depth of analysis required**	Can be solved in standardised ways	Can be solved by application of well-proven analysis techniques	Have no obvious solution and require abstract thinking, originality in analysis to formulate suitable models	2	2	2	2	2	2	2	3	2	2	2	2
4	**Depth of knowledge required**	Can be resolved using limited theoretical knowledge but normally requires extensive practical knowledge	Requires a detailed knowledge of principles and applied procedures and methodologies in defined aspects of a professional discipline with a strong emphasis on the application of developed technology and the attainment of know-how, often within a multidisciplinary engineering environment	Requires research-based knowledge much of which is at, or informed by, the forefront of the professional discipline and which allows a fundamentals-based, first principles analytical approach	2	2	2	2	2	2	2	3	2	2	2	2
5	**Familiarity of issues**	Are frequently encountered and thus familiar to most practitioners in the practice area	Belong to families of familiar problems which are solved in well-accepted ways	Involve infrequently encountered issues	2	2	2	2	2	2	2	3	2	2	2	2
6	**Extent of applicable codes**	Are encompassed by standards and/or documented codes of practice	May be partially outside those encompassed by standards or codes of practice	Are outside problems encompassed by standards and codes of practice for professional engineering	1	1	2	1	1	1	2	2	1	2	1	2
7	**Extent of stakeholder involvement and level of conflicting requirements**	Involve a limited range of stakeholders with differing needs	Involve several groups of stakeholders with differing and occasionally conflicting needs	Involve diverse groups of stakeholders with widely varying needs	1	1	3	2	2	2	2	2	2	3	2	3
8	**Consequences**	Have consequences which are locally important and not far-reaching	Have consequences which are important locally, but may extend more widely	Have significant consequences in a range of contexts	2	2	3	3	2	2	2	2	2	2	2	2
9	**Interdependence**	Are discrete components of engineering systems	Are parts of, or systems within complex engineering problems	Are high level problems including many component parts or sub-problems	2	2	2	2	2	2	2	3	2	3	2	3
	TOTAL - LEVEL OF COMPLEXITY				**13**	**13**	**18**	**16**	**15**	**15**	**16**	**20**	**15**	**18**	**15**	**18**

Appendix C: Questionnaire

Engineering Problem-solving Questionnaire:

<table>
<tr><td rowspan="9">Personal & company details
CONFIDENTIAL</td><td>Surname, Initials</td><td></td></tr>
<tr><td>Student # (If applicable & still registered)</td><td></td></tr>
<tr><td>Employer
Name of the company</td><td></td></tr>
<tr><td>Supervisor
The person to whom you report directly</td><td></td></tr>
<tr><td>Mentor
If you have one/different from supervisor</td><td></td></tr>
<tr><td>Company business description
What is the core business of your company?</td><td></td></tr>
<tr><td>Employment start date
When did you start working for this company?</td><td></td></tr>
<tr><td>Current work context
Describe briefly your current work focus (eg. Specific client project). What are your responsibilities?</td><td></td></tr>
<tr><td>Key challenges in your current work
What are the key challenges you are experiencing in your work at the moment? (They could be professional, technical, economic, or personal in nature)</td><td></td></tr>
<tr><td rowspan="3">TECHNICAL PROBLEM SOLVING</td><td>Most recent problem faced
Identify and briefly describe a recent problem you encountered and solved on your project/in your current work.
• It could be a problem that took a few seconds or minutes to solve.
•
• It must be a technical problem connected to any aspect of electro-mechanical control
•
• It can include networking, programming, data acquisition, process control, mechanics, electrical, electronics, pneumatics, hydraulics…
•</td><td></td></tr>
<tr><td>Problem-solving process
What did you do to solve the problem?
Try to describe this in sequence using 1, 2, 3…
Please be as technically specific as possible</td><td></td></tr>
<tr><td>Problem-solving thinking
Why did you solve the problem in the manner described? What were you thinking at each stage? What did you know? What did you not know?</td><td></td></tr>
<tr><td>Problem-solving description notes</td><td colspan="2">• You can describe the problem-solving process any way you like.
• If you are comfortable with writing it in 1,2,3 notes, then do so in the questionnaire as requested
• If it is easier to draw or sketch on paper, then do so and scan it to pdf, and email to me (wolff.ke@gmail.com) with your surname in the file name.</td></tr>
</table>

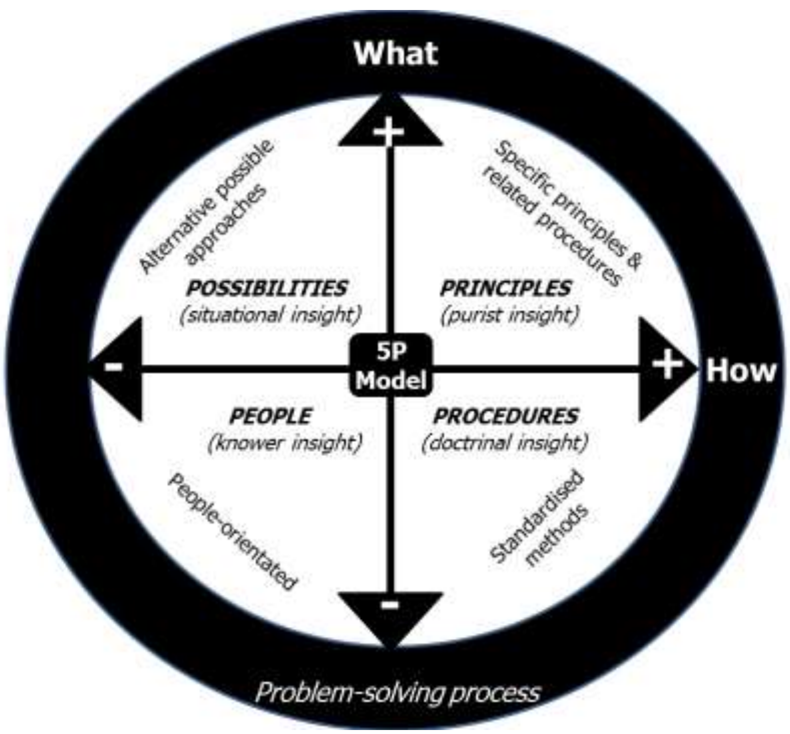
Thank you for your participation

Appendix D: The 5P model

In order to obtain expert verification of the problem-solving process, the epistemic plane was translated into a simplified schematic intended to be meaningful for non-sociological practitioners. The ontic relations axis is translated as the strength of the phenomenon - 'what' the focus of the knowledge claim is, and the discursive relations axis is translated as 'how one talks about or represents the claim'. The quadrants are translated as follows:

- OR+, DR+ *purist* = 'principles' (specific principles and related procedures)
- OR–, DR+ *doctrinal* = 'procedures' (standardised methods)
- OR–, DR– *knower/no* = 'people' (people-orientated)[87]
- OR+, DR– *situational* = 'possibilities' (alternative possible approaches)

The 5P model schematic (the 5th 'P' representing the 'problem') was used in conjunction with the descriptive summary of each practitioner's problem and problem-solving process.



5P Model: Simplified problem-solving analysis schematic

(modification of the epistemic plane (Maton, 2014))

[87] The concept of '*no insight* orientation was not included on the 5P model. However, the difference between '*knower*' and '*no insight* was deduced by differentiating between 'focus' and 'basis'.

Appendix E: Case study B3 sample detailed data analysis

Phase 1 text: Questionnaire section

Process
1. Just then I smelt that tell-tale electronic burning smell. Straight away, the first thing I did was as a reaction. I unplugged the USB from the computer, because the Labjack and the breakout boards are powered by the USB from my computer. So removing the power was the first step to prevent further damage.
2. have a couple seconds or two of self-irritation at doing something wrong and setting my workload back further.
3. Get my logical problem solving hat on. I unplug the breakout boards and plug in JUST the Labjack and check that it is still all function as expected (Check)
4. now that the problem is determined to have come from the breakout board I need to find out what happened. Initally I resort to a typical visual inspection (can I see anything that is visually blown) and I also resort to the smell/sniff test. Can I identify that way what may be blown...I can smell the tell-tale burnt smell, but because the board is small I cannot narrow it down to an individual component.
5. I re-examine the circuit layout and quadruple check it against the schematic for any inconsistencies.
6. My attention is drawn to the small SOIC Op-Amp chip as the pin configurations on the manufacturers datasheet was incorrect on the verison that was available from RS's website. It was only after going to the Manufacturer (Analog Devics) I got the updated Rev. U datasheet....that had the correct orientation of the pins...So my attention was drawn to this as I thought perhaps

The questionnaire response was added to the interview texts and coded similarly. The two texts were used to inform each other and the overall problem-solving process analysis.

Phase 2 text: Interview transcript

Coding categories

EPISTEMIC CONCEPTS							OTHER	
MATHS	PHYSICS	STRUCTURES	POWER	LOGIC	CONTROL	SYSTEM	**CONTEXT**	**ACTION**
MAT	PHY	STR	POW	LOG	CTR	SYS	CON	ACT

PROBLEM-SOLVING STAGES		
APPROACH	**ANALYSIS**	**SYNTHESIS**
APP	**ANA**	**SYN**

Coding values: Semantic codes

-1, -1	**SG-/SD-**	**SG-/SD+**	**-1, +1**
D	***Abstract concept; common words***	***Abstract/Principle; complex term***	**A**
Rarefied	Voltage is the product of current multiplied by resistance	V=IR	***Rhizomatic***
+1, -1	**SG+/SD-**	**SG+SD+**	**+1, +1**
C	***Real world; common meaning***	***Real world; complex meaning***	**B**
Prosaic	Here there is a surge of power because this component allows…	Resistance at this point measures Xohms	***Worldly***

Sample text (B3) – (next page)

B3 Interview April 2014	PROBLEM-SOLVING STAGES				ANALYSIS									
Other	APPROACH	ANALYSIS	SYNTHESIS		EPISTEMIC CONCEPTS							OTHER		
Background (BG), motivation (MOT)	**APP**	**ANA**	**SYN**		MATHS	PHYSICS	STRUCTURES	POWER	LOGIC	CONTROL	SYSTEM	CONTEXT	ACTION	
		PS Stage	Dialogue Sequence		MAT	PHY	STR	POW	LOG	CTR	SYS	CON	ACT	
			DS		SEMANTIC PLANE CODES							SEMANTIC WAVE		
Description/(*Prompt*)	**Insights coding notes**		**DS**	**Transcription**	**SG Value**	**SD Value**	**A: -1,+1**	**B; +1,+1**	**C: +1,-1**	**D: -1,-1**	**EPISTEMIC**	**SG**	**SD**	**Semantics Coding Notes**
KW: *Tell me about your problem*	SIT,	BG	1	Well, okay, first … I've never been able to measure stuff before	-1	-1	0	0	0	1	MAT	-2	-4	By implication 'measure stuff' here means collect data with digital equip
		BG	2	This would be great.	1	-1	0	0	1	0	ACT	-4	-2	Ie Judgement based on accomplishment of project
		BG	3	You can't just get a multimetre… I mean some of them have temp sensors…	-1	1	1	0	0	0	CTR	2	2	General procedure
	General 'problem'	BG	4	but you can't log that data. You can't reference it to anything over time…	-1	1	1	0	0	0	LOG	5	4	Principle of this logic system, and conceptual density; 'log' means sth specific in this context
	Aim of current project	MOT	5	Industry uses expensive hardware… the point here is to do a low cost version	1	-1	0	0	1	0	SYS	3	2	Interpretation of need
		BG	6	The labjack comes with basic SW for data capture	1	1	0	1	0	0	STR	2	4	Denser concepts = 'labjack, SW, data capture have specific meanings
		BG	7	Its got about 15 channels that you can read information from	1	1	0	1	0	0	LOG	2	4	
		BG	8	Its also got a built-in temp sensor	1	1	0	1	0	0	PHY	1	2	
		BG	9	The problem is the sw is very basic	-1	-1	0	0	0	1	LOG	1	2	
		BG	10	You cant stop and start easily	-1	-1	0	0	0	1	LOG	2	4	Starting & stopping' here mean sth very specific
		BG	11	I still need to play with starting and stopping via the digital inputs	-1	1	1	0	0	0	LOG	2	4	Starting & stopping' here mean sth very specific
Problem context - practical		BG	12	because then you can write a separate program	-1	-1	0	0	0	1	LOG	2	2	
		BG	13	and start recording and stop recording the data stream	-1	1	1	0	0	0	LOG	2	4	Starting & stopping' here mean sth very specific
		BG	14	But at the moment we are just clicking start and clicking stop	1	1	0	1	0	0	LOG	1	2	
		BG	15	and exporting to a text file	1	1	0	1	0	0	LOG	1	4	Specific conceptual meaning
		BG	16	and then you need to import the text into Excel or Matlab	1	1	0	1	0	0	LOG	1	4	Specific conceptual meaning
		BG	17	But then the problem is the resolution is super high, the data strings are huge	1	1	0	1	0	0	LOG	3	4	Specific conceptual meaning
		BG	18	and then you have to process the data to get it to a rate that is acceptable to what you need in your application	1	1	0	1	0	0	MAT	4	4	Specific conceptual meaning
		BG	19	So there are interface issues between the very basic sw that they get vs the very expensive sw that you can buy that factories or NI use	-1	1	1	0	0	0	STR	2	4	Specific conceptual meaning

Start of a different problem	SIT, 'zooming in'	APP	30	The first thing w as to get it to w ork… w ith the kettle	1	-1	0	0	1	0	ACT	-1	-2	Experimental action
		APP	31	using a current clamp sensor to measure the real-time current usage of a appliance	1	1	0	1	0	0	POW	2	4	Specific conceptual meaning
		APP	32	and plot this data over time to	1	1	0	1	0	0	LOG	2	4	Specific conceptual meaning
		APP	33	verify the amount of pow er consumed.	1	1	0	1	0	0	MAT	3	2	Measurement of a process
		APP	34	initial analysis of the data show s sharp increases and decreases forming a sine w ave	1	1	0	1	0	0	CTR	3	2	Interpretation of data
		APP	36	but at a frequency that does not make sense (period of w aves at 6s)	1	1	0	1	0	0	MAT	3	6	Symbolic data representation w ith specific conceptual meaning
		APP	37	Initially I started straight aw ay in ruling out w hat could not be w rong.	1	-1	0	0	1	0	ACT	-4	-2	Judgement action
Analysis of one problem	DOC, each item, each connection, and then data	ANA	38	I ruled out that the kettle w as faulty (as it boiled the w ater as usual)	1	-1	0	0	1	0	STR	1	2	Observation in context
		ANA	39	I ruled out that the sensor w as faulty (as it w as brand new	1	1	0	1	0	0	POW	1	2	Observation in context
		ANA	40	The next logical step w as to assume that either I w as connecting the sensor to the labjack incorrectly	1	1	0	1	0	0	LOG	2	2	Process
		ANA	41	or the softw are w as configured incorrectly	1	1	0	1	0	0	CTR	3	4	Specific conceptual meaning
		ANA	42	or perhaps the data I w as receiving w as correct and I had assumed the w rong thing	1	-1	0	0	1	0	MAT	3	2	
		APP	43	The next steps take a lot longer than a couple minutes to solve as it requires reading through the extensive pdf manuals	1	-1	0	0	1	0	ACT	-2	-2	Research

Moving tow ards synthesis of a solution to a particular aspect		SYN	107	So you need to have a secondary thermocouple so that you can put in a reference object, like cold w ater that you know is near 0 degrees	1	1	0	1	0	0	LOG
		SYN	108	And then calibrate it according to that	1	1	0	1	0	0	MAT
		ANA	109	But because w e don't know w here this (thermocouple) came from… this is from a multimetre temp sensor, w e don't know w here it w as calibrated	1	1	0	1	0	0	MAT
		SYN	111	We had to assume w hat the temp w as and then adjust the formula so that w e get the right values	1	-1	0	0	1	0	MAT
		SYN	112	But that isnt the right w ay of doing it	-1	-1	0	0	0	1	CON

Early analysis approaches

Semantic profile over time: 6-scale as per MPhil thesis (note: not employed in PhD research, rather used to ‘see’ based on existing framework).

Weaker	Abstraction	Making statements about the underlying principles or concepts that are non-context-bound
	Generalisation	Drawing a general conclusion to make statements about the system in a broader or cross-context
	Judgement	Drawing a specific conclusion, making a decision that affects the thinking/working process
	Interpretation	Identifying a problem; interpreting something as significant and requiring action; (drawing a parallel with other systems/machines; use of metaphor)
	Summarising description	Object-orientated summary/ overview of machine/system/process
Stronger	Reproductive description	Object-orientated procedural description of machine/ system/ process