

THE NATURE OF PROFESSIONAL REASONING:  
AN ANALYSIS OF DESIGN IN THE  
ENGINEERING CURRICULUM

by

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## **Abstract**

Access to the practice of a profession is controlled by formal education structures. These structures are intended to induct future professionals into the specialised knowledge, skills and values that underpin that profession. Yet, despite meeting the academic requirements of a professional degree, many graduates struggle to 'apply' specialised knowledge when confronted with problems in professional practice. This is a study of the nature of knowledge as it is mobilised in professional reasoning.

The case studied was located in engineering education, because knowledge relations tend to be more explicit in education than in practice. The data were collected from design projects located in two differently structured curricula in civil and mechanical engineering curricula. The research questions that directed the study were:

1. What is the nature of the reasoning involved when specialised disciplinary knowledge is recruited to develop specific, often concrete, artefacts?
2. What is the logic of progression in a trajectory of engineering design tasks in terms of the relation between knowledge and artefact?

The study draws on two intellectual fields: models of professional reasoning and design thinking on one hand, and social realism in the sociology of education on the other. These traditions take different positions on professional reasoning. Design thinking is concerned with contextual detail and case precedent, while social realism in the sociology of education is concerned with conceptual coherence within knowledge specialisations and the power of generalisation. Both offer important insights into professional reasoning, but alone neither is adequate.

The analysis was done using the semantics dimension of Legitimation Code Theory, LCT (Semantics), which required an adaptation in order to fully describe the significance of contextual detail evident in the data. The findings showed that specialised knowledge and contextual detail interact far more dialectically than previously assumed. This provides empirical insights for structuring curricula. Students can be more intentionally inducted into recontextualising academic knowledge for the purpose of solving contextually emergent problems. Theoretically the study contributes to the social realist school within the sociology of education by revealing its blindness to contextual detail and consequently offering a fuller understanding of the nature of regions. This has implications for other studies of professional knowledge and education.



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## Glossary of terms

The following terms have been defined in terms of the way in which they have been used in this thesis:

**Artefact** (see also artefact prescription and solution specification): an artificial object or process intended to fulfil a specific function in particular context under certain conditions.

**Artefact prescription**: the identification of a type of artefact with the potential to fulfil a required function in a particular context, it is associated with the output of conceptual design.

**Course**: refers to a module in a curriculum, a contained unit involving transmission of a section of knowledge along with assessment (cf subject).

**Conceptual design**: used to indicate the conception of a type of artefact in response to the emergent need.

**Context** (context description): a description of or reference to the context in which the designed artefact is intended to fulfil a specific function.

**Detailed design**: used to indicate the process of reasoning involved in specialising a prescribed artefact type to perform its intended function in a particular context.

**Disciplinary knowledge** (disciplinary 'knowledges'): knowledge defined within a specialised disciplinary field, using specialised terms and legitimate relations defined between terms. Although the term 'specialised knowledge' is preferred in the social realist tradition in sociology of education, disciplinary knowledge is used to make a distinction from the development of a specific solution, a process of specialisation to the particular.

**Inference**: the process of reasoning followed when an artefact type (prescription) is specialised for a specific function in particular context under certain conditions. Relates to detailed design.

**Material relations** (ontic relations): knowledge of and about external, ontologically real objects in the world, including for example case based knowledge, and knowledge about artefacts and how they function. Material relations are those concepts by which we make sense of an object in the world.

**Solution specification**: the detailed description of the designed artefact in the form of technical drawings or performance characteristics, it is associated with the output of detailed design, and may include for example performance characteristics and/or technical drawings for the purpose of manufacture or construction.

**Solution specialisation**: the inferential process of developing an artefact proposal to perform its specific function in a particular context.

**Subject**: refers to a disciplinary field, for example fluid mechanics or dynamics (cf. course)

**Symbolic relations** (discursive relations): specialised concepts and formal relations of legitimate combination defined internal to a particular disciplinary field.

## **LCT (Semantics) conventions**

SG: semantic gravity

SG+: stronger semantic gravity

SG-: weaker semantic gravity

SD: semantic density

SD<sup>d</sup>: semantic density of the discursive relations

SD<sup>o</sup>: semantic density of the ontic relations

↓: Weakening semantic relations, for example, SG+↓SG- means stronger semantic gravity weakening to weaker semantic gravity

↑: Strengthening semantic relations, for example SD-↑SD+ means weaker semantic density strengthening to stronger semantic density



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# Chapter 1 Introduction

Education is so often positioned as the gateway to social mobility. Work hard at school; gain access to a 'good' college; secure a degree; and the doors of the world are open to you. But sociologists studying education have persistently argued that rather than transforming society, education reproduces social inequality (Bernstein, 1981; Bourdieu & Passeron, 1977), with perhaps just a sufficient number of individuals breaking through the social barriers to maintain the hope of education for social mobility. Bernstein (2000) convincingly argued that the reason education continues to reproduce social inequality is that the construction of curricula, and the recontextualisation into classroom practice, embed ideological influences that unintentionally benefit some students at the expense of others. Kotta's (2011) South African study of engineering students in two sequential chemical engineering design courses showed that when pedagogic relations break down, the students who most struggled to meet the course requirements were 'black'<sup>1</sup>. South African society is still largely socially segregated on the basis of race. This is not a study of social segregation, but the example does serve to illustrate Bernstein's point that tacit evaluative criteria underpinned by invisible ideological principles privilege different groups differently. Explicating 'what matters', and the effect of recontextualisation on 'what matters', is a first step in broadening access to educational success for more students (and in this case to the skills necessary to effectively practice a profession).

South Africa's apartheid history shows a significant differential university participation rate (access) between 'black' students and 'white' students, compounded further by differential graduation rates (success). This has continued well into the democratic era and indicates the persistent effects of social inequality (CHE, 2013; Kotta, 2011; I. Scott, Yeld, & Hendry, 2007; Shay, Wolff, & Clarence-Fincham, 2016). The importance and urgency of effective education for all is well expressed by Muller (2000, p. 37): unless the marginalised have a chance to enter the functional economy, crime and violence become an inevitable result.

Many impoverished students in South Africa see a professional education as a means of economic emancipation for themselves and their families. Professional education therefore plays a very important role in social transformation – and as a developing country with tremendous pressures on the economy, as an important economic development driver (Fisher & Scott, 2011; Saint, 2009; Trani & Holsworth, 2010). Education, positioned as skills development essential to a country's economic development, drives a relevance agenda. Education should be relevant for the students and to the world for the purpose of preparing for a job, leading to a prevalent concern over 'graduate attributes' and employability (Barrie, 2007; Bridgstock, 2009; Griesel & Parker, 2009). And yet anecdotally there are many

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<sup>1</sup> 'Black' is a racial category applied to people in South African. Because Apartheid was based on racial classifications, the categories are still applied today in an effort to measure transformation in the form of more equitable access across all race groups.

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concerns raised over graduates' apparent inability to make the transition from university to effective professional practice.

One of the characteristics of professions is that they are built on bodies of specialised knowledge, which are formally transmitted and examined for admission to the profession (Abbott, 1988; Beck & Young, 2005; Schein & Kommers, 1972). Professional knowledge is required to solve problems within the jurisdiction of the profession. And professional education is therefore largely (but not exclusively) about transmitting those bodies of knowledge, along with the attitudes, values and ethics associated with the profession (IEA, 2009; Schein & Kommers, 1972). Educational reforms based on the development of professional skills and attributes, the notion of the development of the whole 'being' or 'becoming' (R. Barnett, 2009; Dall'Alba, 2009), are reported to have improved 'graduates' attributes' or 'enabling skills' such as teamwork, communication and business skills (J. King, 2007; R. King, 2008). However, empirical studies of recently graduated professionals suggest that even with a strong grasp of their professions' theoretical foundations, their ability to use the knowledge in practice is inadequate (Christiansen & Rump, 2007; Smeby & Vågan, 2008; Winberg, 2007). In the case of engineering for example, reports on the quality of engineering education indicated a significant improvement in enabling skills over the last 20 years, but have consistently bemoaned the inability of graduates to use theoretical knowledge to solve problems they encounter in professional practice (Grinter, 1955; J. King, 2007; C. R. Mann, 1918). What then in the nature of professional knowledge makes the shift from the academic context to the professional context so difficult?

While much is made of education's importance in what is termed a 'knowledge economy', theorists associating themselves with a social realist turn in the sociology of education argue that knowledge itself has been stripped from education in the thrust for employability (Muller, 2000; Wheelahan, 2010; Young, 2008). These theorists argue that broadening access to specialised, abstract, theoretical knowledge is a democratic right and at the heart of social transformation. The basis of their argument is that abstract knowledge is transferable across contexts. It is this transferability that enables us to think beyond the limits of what already is (Bernstein, 2000), the knowledge that allows societies to have conversations about themselves and to recognise their potential for change (Wheelahan, 2010). And while they acknowledge the social basis for the production of knowledge, they also argue that the social processes by which canons of knowledge are produced contribute some level of objectivity (Young & Muller, 2013). This theoretical movement is founded on the work of British sociologist Basil Bernstein (2000, 2003a, 2003b, 2003c, 2003d), who was concerned with why education persistently reproduced social inequality. Bernstein believed that an adequate model of knowledge transmission and acquisition would enable broadened access to specialised knowledge, and consequently disrupt the reproductive nature of education.

This study investigates the nature of knowledge as it is mobilised in professional reasoning. It focuses on the structure of the conceptual relations internal to specialised disciplinary knowledge and their relations to practical problems in the world; specifically on how

knowledge is used in relation to contextually rich problems constructed in professional curricula. Although the study is limited being located in the curriculum and not in practice, knowledge relations tend to be more explicit in an educational context than in practice. The case study selected for this research is engineering education, with the assumption that as a science-based profession founded on a well-established body of specialised knowledge, scientific reasoning in relation to contextual problems would be more apparent in the data. Finally, design projects within these curricula were chosen as the most likely curriculum texts to find interactions between abstract and generalisable disciplinary knowledge and specific, contextually rich design problems. Engineering design is characterised as the application of multiple knowledge disciplines (including sciences and engineering sciences informed by economic, environmental and aesthetic considerations and social insights) to develop an artefact (object or process) for meeting some contextually emergent problem. And engineering design is seen to epitomise engineering practice, even when engineers might not specifically be design engineers.

The empirical problem that defines this study is the persistent challenge facing graduate professionals when they enter practice, and their struggle to mobilise the knowledge gained in academia to address professional problems. There is an apparent disjuncture between knowledge structured in the curriculum and knowledge used in practice. Drawing on a knowledge perspective and the contributions of the social realist school within the sociology of education to investigate the case of engineering design in the curriculum, this problem was recast in the form of two research questions:

1. What is the nature of the reasoning involved when specialised disciplinary knowledge is recruited to develop specific, often concrete, artefacts?
2. What is the logic of progression in a trajectory of engineering design tasks in terms of the relation between knowledge and artefact?

Social realist scholars in the sociology of education have made significant contributions to understanding the development of disciplinary specialisations (insulated internally coherent knowledge structures) (Moore & Muller, 2002; Muller, 2011), their transformation into curricula (selection and sequencing of knowledge from vast canons of available knowledge) (Beck, 2002), and implementation in classrooms (classroom practice) (see for example the collection of papers in Muller, Davies, & Morais, 2004). This research has been dominated by studies of disciplines, what Bernstein (2000) termed 'singulars'. Bernstein (2000) distinguished 'singulars' from 'regions' where regions are typified by professions and vocations. Those who have studied professions and vocations (see for example Wheelahan, 2010; Young & Gamble, 2006; Young & Muller, 2014b), typically argue that specialised knowledge precedes its application to contextual problems (Beck & Young, 2005; Muller, 2000).

## **1.1 Professional education: Developing the skills to use disciplinary knowledge.**

Two intellectual fields inform this study; design research informed predominantly by Simon (1981) and Schön (1983) on one hand and sociology of knowledge in the social realist tradition after Bernstein (2000) on the other. These intellectual traditions take opposing positions on the nature of professional reasoning. Design thinking theorists are typically concerned with contextual detail and case precedent, while social realism within sociology of education is concerned with conceptual coherence within bodies of disciplinary knowledge and the power of generalisability. Although often contrasted, both Schön (1983) and Simon (1981) offer important insights into the relation between the contextual detail inherent in context (the environment from which a perceived problem emerges) and artefact (the intervention developed to address the identified need) in the process of design. Design thinking theorists are typically concerned with contextual detail and the co-evolution of problem space and solution space. On the other hand the knowledge perspective in social realism within sociology of education is concerned with the internal relations of conceptual coherence defined within bodies of disciplinary knowledge. In terms of professional knowledge, disciplinary knowledge precedes any contextually emergent problem and is imposed onto the problem in order to solve it (Beck & Young, 2005; Young & Muller, 2014a). Both fields offer important elements of professional reasoning, but neither is adequate to fully describe the nature of professional reasoning.

Abbott's (1988) three modes of professional action - diagnosis, treatment and inference - are introduced, partially forging a link between the two intellectual fields. Abbott identifies two distinct organisational structures that professional knowledge takes. In the first instance, case-based knowledge organised by prevalence in the case of diagnosis, and efficacy in the case of treatment. Both are rooted in contextual examples and specific cases, and are strongly aligned with Schön (1983). The other structure that knowledge takes refers to the organisation of academic knowledge, based on legitimated internal rules of conceptual coherence and rationality, which is the basis of inference. The latter is the position taken by sociology of knowledge theorists. Abbott (1988) recognises that both knowledge structures are evident in professional reasoning, but argues that knowledge in its academic form does not lend itself directly to practice.

## **1.2 Theoretical framework: Social realism in the sociology of education**

Although informed by design and design thinking research, this study is located in the sociology of education in the social realist tradition (Moore, 2013b; Sayer, 2010). The theoretical foundations of this study lie in the work of Basil Bernstein (2000, 2003a, 2003b, 2003c, 2003d), and those who have contributed to it over the years (see for example Maton, 2014; Moore, 2013a; Muller, 2009; Wheelahan, 2010; Young, 2000, among others). These theorists have consistently argued that sociology of education lacks a theory of knowledge.

Consequently, Bernsteinian analyses of education have tended to prioritise internal relations between conceptual ideas within insulated disciplinary knowledge specialisations (Beck & Young, 2005). In the case of professional or vocational knowledge, the coherent network of internal relations between concepts takes precedence over their external application to contextually specific problems; and conceptual generalisability over contextual specificity (see for example the collection of papers in Young & Muller, 2014b). Disciplinary knowledge comes first, followed by external application. Wheelahan (2010) is a notable exception in her critique of the limitations of the rationalist base founded on Durkheim (1995) which tends to undervalue the ontological aspects of context. Nonetheless, the knowledge perspective on professional education offers an understanding of what it means to apply disciplinary knowledge for solving contextually specific problems.

A number of intertwined concepts have a particular prominence in this study, and are worth mentioning in the introduction. The first relates to Bernstein's pedagogic device (Bernstein, 2000, 2003d), a model for the construction of a curriculum as a process of dislocating knowledge from its field of production (and in the case of professional knowledge also from the field of professional practice (M. Barnett, 2006)) and relocating it into a curriculum. This involves selecting and sequencing knowledge (and skills and values), dislocating them from within canons of disciplinary knowledge (and established professional procedures) and relocating them within a curriculum designed to transmit and acquire knowledge (and skills). From a sociological perspective Bernstein (2000) argues that this process is ideological, and in his terms, involves the embedding of an instructional discourse into a regulative discourse. In other words, what is selected and how it is sequenced depends both on (often implicit) theories of teaching and learning, and social norms of behaviour, along with the 'content' to be transmitted and acquired. But in the construction of the curriculum, the instructional and regulative discourses become one discourse, normalising ideological positions. This has an important implication for social transformation. Because engineering design in a curriculum is not the same as engineering design in professional practice, the recontextualising agents (the people constructing the design projects in the curriculum) bring to the construction of the projects their implicit view of the structure of knowledge. This will always differentially advantage different sectors of society. For example, those familiar with the ideological basis of the recontextualisation are more likely to read the tacit signals about what counts in design than those socialised differently. This study attempts to identify trends in the recontextualising choices; the view being that if we are more explicit about the curriculum choices we are making, we are in a better position to broaden access to 'what matters' to more students.

The second key idea relates to establishing boundaries around disciplinary knowledge. The more insulated a discipline is from other knowledge, both specialised and unspecialised, the stronger the classification (Bernstein, 2000). Bernstein saw the insulation of knowledge from other knowledge, other disciplines and the everyday or common knowledge, as the means by which it was specialised. It is by the separation of knowledge that rules of coherence and adequacy are established. It is by the abstraction from the contextually specific that the power

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of generalisation is extended. The empirical case in this study, the application of disciplinary knowledge to solve contextually specific problems, is about crossing these boundaries.

Most of Bernstein's (2000) work was located in schools and involved the analysis of knowledge structured as disciplinary subjects, developed in the field of production in the form of singulars. Singulars refer to 'differentiated knowledge' separated from other 'knowledges' and from the mundane concerns of the world; strongly classified disciplines (Young & Muller, 2013). In his brief references to professional knowledge Bernstein drew a distinction between singulars and regions, where regionalisation of knowledge is the integration of singulars for the purpose of their application to the world. In this formulation, knowledge in its separate and abstract form is necessarily prior to any application of knowledge to the concerns of the world (Bernstein, 2000, pp. 81-86; Muller, 2009). But Bernstein's (2000) formulation of regions is sparse, an incomplete sketch untested empirically and inadequate for analysis. Muller (2007, 2016) drew on Bernstein's distinction between internal relations and external relations to elaborate the distinction between the internal relations of disciplinary knowledge and the external relations of knowledge to specific contexts. In LCT (Semantics), one of a number of dimensions of Legitimation Code Theory (LCT), Maton (2013, 2014) offers semantic gravity as one conceptualisation of the relation between internal systems of meaning and their external referents.

Engineering design conceptualised as the application of scientific knowledge to solve real problems typifies a region. It draws on multiple disciplines simultaneously, and forces knowledge into contact with the contextually specific. In design, the purpose lies in integration of knowledge and specialisation to the particular, rather than in the separation of knowledge and its abstraction to the general. While the social realist school within the sociology of education introduces very useful analytical tools with which to analyse knowledge, this empirical case pushes the theoretical position. Consequently, this study makes both an empirical and theoretical contribution. Empirically the study contributes to an understanding of the relations between abstract knowledge and concrete particulars, and the effect of recontextualisation on these knowledge relations for the purpose of designing professional curricula. Theoretically the study contributes to a theory of knowledge capable of describing professional knowledge in action.

### **1.3 The empirical case: Three trajectories of engineering design**

The empirical setting for this research was engineering design located in two different engineering curricula: mechanical engineering and civil engineering. To investigate the nature of reasoning in engineering design and identify the potential for developing a more intentional curriculum trajectory of learning, a number of design projects were identified. Engineering design is organised differently in the two curricula, offering a useful basis of comparison. In mechanical engineering, engineering design is a distinct subject stream, and

consists of a sequence of four courses<sup>2</sup>, a full-year course in second and third year (Design 1 and Design 2 respectively), and two semester courses in fourth year (Product Design followed by Systems Design). These courses build on the foundational first year drawing course. In civil engineering, engineering design is embedded within disciplinary courses, and most courses include some sort of design project in addition to the standard conceptual knowledge examination, for example Structures IV includes a design project along with structural engineering knowledge. The program culminates in a final six-week fulltime block design course. Since the research began with a basic assumption that engineering design involves an inherently different knowledge relation than do typical science and engineering sciences, the differing design organisation in the two curricula (one embedded and the other distinct) offered a useful basis for comparison.

### 1.3.1 An overview of the two engineering curricula

The design projects are embedded in traditional engineering curricula. For the purposes of providing a curriculum overview, four kinds of courses were identified. *Science* courses are those courses taught in the science faculty, aligned with science disciplines, and include for example mathematics and physics courses. *Engineering sciences* are those courses taught in the engineering faculty, and while quite similar to the pure sciences, draw their disciplinary base from engineering research rather than science research and seem to have a different 'flavour' from science. But within the engineering sciences, each curriculum consists of a collection of disciplinary streams. In mechanical engineering these may include: mechanics, dynamics, thermodynamics, fluid mechanics, manufacturing and management. In civil engineering curricula, the engineering sciences are roughly split into two fields: structural engineering including structural and geotechnical engineering; and urban engineering including hydraulics and hydrology, water and wastewater treatment, surveying, transportation engineering, urban infrastructure and management. *Complementary* courses are external to both science and engineering, but complement engineering, for example economics and accounting, languages, sociology or humanities courses. *Engineering design* seems to have quite a different nature from the other courses. Where science, engineering science and complementary disciplines are structured around a particular conceptual framework, engineering design tends to be structured around problems, drawing on a range of disciplines for solution. Its integrated structure and association with the essence of engineering practice make engineering design the object of this study.

#### **Year 1**

In the two curricula investigated, the first year is dominated by science (physics, mathematics and chemistry). They include three engineering courses, engineering drawing, introduction to engineering and engineering statics. For many engineers, engineering drawing is seen as the first design course since it develops one of the main design tools. The introductory

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<sup>2</sup> The term 'subject' will refer to disciplinary specialisations, which I distinguish from 'courses' as credit-bearing modules located within subject streams. For example in this study in the case of the mechanical engineering curriculum, the subject of design is taught in four sequential design courses.

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engineering course includes elements of everything considered relevant to engineering, from computing, writing and experimental skills, through general engineering terminology and some basic engineering theory. The first year has been excluded from the analysis because any design component was judged as drawing on insufficient disciplinary knowledge for the purpose of this study.

### *Year 2*

The second year begins a transition from science to engineering science courses, and in mechanical engineering the first design course forms the spine around which the other courses are aligned. Civil engineering does not have a design course, but the first two design projects are introduced in the second semester, one in structures and the other in the surveying course, followed by a 10-day 'engineering camp' in which students complete a design project.

### *Year 3*

The transition from science to engineering science courses is completed in the third year, and the complementary courses are typically offered in third year. Again, mechanical engineering includes a single, whole-year design course consisting of a number of design projects, while in civil engineering most of the engineering science courses include a design project. For example, hydrology introduces different hydrological models, but includes the design of a system of culverts to attenuate the flow in a specific catchment area. Urban Water Services is entirely structured around three design projects, one for each of the water services studied, with disciplinary knowledge introduced in support of the project requirements. There are two structures courses and each embeds a design project.

### *Year 4*

In both curricula the fourth year offers specialised engineering science courses and a design course/s. In the first semester mechanical engineering students do a product design course followed by a second-semester systems design course. In civil engineering the final structures course includes a significant structural design project, and Urban Design and Management includes a design. The second semester includes a large team design project, done in a five-week block.

## **1.3.2 The study: Research design and data selection**

Seventeen design projects with associated sample solutions were selected from these two curricula. It is important to note that each project was developed within different courses by different 'recontextualisers' (academics), each to develop skills and knowledge particular to the course objectives. These objectives are not necessarily specifically aligned with the research objectives of this study. Consequently, the implications of this study should in no way suggest a critique of specific projects or recontextualising agents. Rather, the study is concerned with the overall possibilities, opportunities and challenges for developing the skills needed to use specialised knowledge for solving contextually specific professional problems.

Design projects were the most likely curriculum events in which to find examples to investigate the knowledge relations between abstract theory and concrete specifics.

The theoretical framework used in this study followed Bernstein's typical research process. Consistent with his methodology, a dialectic relationship between theory and data was set up. Although the theoretical concepts preceded the mapping of the empirical data, the empirical data in turn made demands on the theory, requiring modifications and adjustments to the theory. This set up an iterative cycle of data analysis and theoretical development. The methodology is articulated in detail in chapter 4. It also has significant implications for the way the thesis is structured.

## **1.4 A roadmap to the thesis**

The rationale for this study was to develop a better understanding of why graduate professionals struggle to use specialised knowledge to solve practical problems, with a view to proposing ways in which curricula can more intentionally develop this skill. The case study selected was engineering design, and the data was constructed from seventeen design projects in two engineering degree programs located in a research-intensive university. The study draws on two substantial but distinct intellectual fields, research in design, design thinking and professional knowledge (Abbott, 1988; Schön, 1983; Simon, 1981) on one hand and sociology of education after Bernstein (2000) on the other. The thesis is structured to develop the empirical case in relation to each of these two fields and then to draw them together at the end.

An overview of the two bodies of literature is presented in chapters 2 and 3 respectively. Chapter 2 is structured around the object of study, a case study of engineering design education positioned as preparation for professional engineering practice (Dym, Agogino, Eris, Frey, & Leifer, 2005; Sheppard, Macatangay, Colby, & Sullivan, 2008). More generally the literature includes design thinking (Cross, 2007), the relationship between science, technology and engineering (Kline, 1995; E. Layton, 1971; Pitt, 2011), and the nature of professional reasoning drawing on Abbott (1988), Schön (1983) and Simon (1981).

The social realist tradition of sociology of education is presented in chapter 3. The chapter provides a broad overview of the intellectual field, its central concerns and key theoretical concepts. The purpose is to locate the study rather than to describe the specific conceptual tools drawn on in the analysis. Instead, the conceptual tools are introduced in detail at the start of each of the analysis chapters. This allowed me to position the study as a contribution to the theoretical field as a whole, as distinct from the empirical contributions to understanding the nature of reasoning in design and the effect of curriculum choices.

Chapters 2 and 3 lay the foundations for the research design presented in chapter 4, which elaborates the relationship between the theoretical field and the empirical study. Although theory-led, the research is not theory-determined as indicated the need to modify and

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specialise the conceptual tools available in social realist school within the sociology of education to adequately describe the empirical data.

The analysis is presented in two parts. The first part of the analysis, presented in chapter 5, follows a narrative style, providing rich detail on the two capstone design courses. It draws on insights from Simon (1981), Schön (1983) and Abbott (1988) and weaves in aspects of control over knowledge selection, sequence and the basis of evaluation (Bernstein, 2000). This analysis shows the dialectical relation between knowledge and context, counter to the more intuitive 'application of knowledge', or the notion of internal, conceptually coherent knowledge relations imposed on external referents as preferred by social realist analyses in sociology of education. It also demonstrates that recontextualising choices set up vastly different knowledge requirements, unintentionally modifying this dialectic. The analysis therefore served to identify significant features of the nature of reasoning relevant to the second part of the analysis, and to identify useful units of analysis within each project.

Although very useful models for structuring design thinking, the first phase of analysis demonstrates the limitations in the current models, especially in relation to the significance of disciplinary knowledge. Chapter 6 therefore shifts to an analysis of the knowledge relations in the design projects using LCT (Semantics), a tool developed within the framework of Legitimation Code Theory (Maton, 2013, 2014). LCT (Semantics) was selected because the relation between knowledge and the object of knowledge is explicit in semantic gravity, and because semantic density implies inherent complexity, a logical principle of progression. But as with the models of design reasoning, LCT (Semantics) has its own blind spot: the significance of contextual detail on the demands made of disciplinary knowledge. This necessitated an adaptation of LCT (Semantics). Because the adaptations to semantic gravity and semantic density emerged as part of the analysis, LCT (Semantics) is presented in chapter 6 rather than in chapter 2 with the theoretical framework.

Semantic gravity was specialised to avoid any association of strong semantic gravity with the familiar, an *unintentional* tendency in some LCT (Semantics) analyses (see for example Blackie, 2014; Georgiou, Maton, & Sharma, 2014). Semantic density was developed to distinguish between the complexity of the knowledge relations required to develop an adequate design, and the complexity of the detail and purpose of the artefact itself. The necessity to develop semantic density relates to the blind spot that the social realist school within the sociology of education tends to have towards the influence of contextual complexity on the demands of insight into disciplinary knowledge. This study therefore also challenges the theoretical tradition that informs it, and offers insight into the nature of 'regions', not yet adequately described in the field.

Chapter 7 presents a discussion of the findings. Firstly the empirical findings are discussed in relation to the two research questions and their implications for developing professional curricula. Secondly the implications of the empirical case on the theoretical field are discussed.

The study helps to articulate some often tacit or assumed aspects of the nature of professional reasoning. It challenges the (often implicit) assumption that specialised disciplinary knowledge is superior to situated knowledge, an assumption that is evident in much of the work done in social realism in sociology of education after Bernstein (2000), as discussed in chapter 3. Simultaneously it recognises the limitations of situated learning that takes no account of specialised disciplinary knowledge and its potential for transferability an implication of much of the rhetoric behind studies of graduate attributes and the role of design in the preparation of engineering graduates for professional practice, as noted in chapter 2.

Using LCT (Semantics), this study makes a theoretical contribution to the conversations within the broader field of social realism in the sociology of education. It shows that a far more dialectical relation between contextual specifics and theoretical generalisations needs to be considered if students are to learn to use knowledge for solving contextual problems. The study shows how difficult contextual complexity is to work with. These insights provide opportunities for us to be more intentional about broadening access to the power of disciplinary knowledge by suggesting more choices in designing curricula. This study therefore makes a contribution both to an empirical understanding of the nature of professional reasoning, and the influence of recontextualisation choices (how projects are constructed to mimic 'real' problems) on the nature of reasoning. It also makes a theoretical contribution to LCT (Semantics) and more broadly to the social realist school within sociology of education in developing a more adequate model of professional knowledge in action, and the nature of 'regions' – those disciplines that face both inwards towards specialised knowledge and outwards to the contextual particularities of the world. The modified LCT (Semantics) concepts were developed into an external language of description that has application across studies of professional and vocational knowledge and curricula that might also be considered a methodological contribution. These contributions are elaborated in the conclusions presented in chapter 8.

## Chapter 2 Professional reasoning in engineering design

The problem addressed in this study emerged from an enduring concern that graduate engineers seem unable to use the theoretical knowledge learnt at university to solve the problems presented in professional practice (Grinter, 1955; J. King, 2007; R. King, 2008; C. R. Mann, 1918; Sheppard et al., 2008). But the problem of applying academic knowledge to solve professional problems is also of concern in other professions (see for example Smeby and Vågan (2008) on medicine, Breier (2004) on law and Schön (1983) on architecture, psychotherapy, engineering, town planning and management). In this study the problem is conceptualised as the nature of reasoning between theoretical knowledge, structured by rules of conceptual coherence for the purpose of generalisation, and contextual problems, emergent from specific instances requiring disciplinary integration for the purpose of specialisation towards a solution. Engineering design constructed as a curriculum subject was selected as the case study for a number of reasons, but it is important to emphasise that this is not a study of engineering design. It is a study of knowledge, especially disciplinary knowledge, as it is used to solve contextually specific problems.

Education tends to require an elaboration of reasoning that might be more tacit in professional practice. Although the selection of an educational context as opposed to a professional context does impose limitations on the study, engineering design was selected because it is usually assumed to mimic professional practice. In addition, the study also offers insights into implications of curriculum choices on the preparation of graduates for professional practice. While engineering students spend the bulk of their time learning engineering sciences, practice requires the integration of disciplines, in context, including social, economic and ethical considerations (Sheppard et al., 2008). Design courses usually (although not exclusively) provide the opportunities for students to integrate knowledge and use it to address complex contexts (Dym et al., 2005). The literature review therefore begins with an overview of the role of engineering design in preparing engineering graduates for professional engineering practice.

The engineering education literature reviewed is dominated by studies in the United States, United Kingdom and Australia. This is not only because these countries have a rich history of published engineering education research in English. It is also because the data analysed was from South African engineering degree programs based on a similar curriculum structure and subject to the same accreditation requirements under the Washington Accord<sup>3</sup> (International Engineering Alliance, 2009). Engineering degree programs in the European Union on the other hand tend to show far more variability in structure and content even as they move

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<sup>3</sup> The Washington accord is an agreement between signatory countries to recognise all engineering degree programs meeting the agreed accreditation requirements as educationally equivalent.

towards educational parity through the Bologna Process (Bucciarelli, Coyle, & McGrath, 2009). A number of other intellectual fields offer insight into the problem of knowledge application to solve contextually specific problems. Design thinking research addresses design more generally, including for example product design, graphic design and fashion design in addition to engineering design (see Cross, 2007 for a history of this field). Central to design reasoning, especially in engineering design, is the relationship between science, engineering and technology, a relationship between different structures of knowledge and a physical artefact (or process) (Galle & Kroes, 2014; Kline, 1995; E. Layton, 1971). The final section of the literature review presents three models of professional knowledge. Both Simon (1981) and Schön (1983) present design as the model of professional reasoning. While their models are often contrasted (Dorst & Dijkhuis, 1995), they also have significant similarities. A third model of professional reasoning is presented by Abbott (1988) who draws on medical and legal metaphors to describe professional reasoning. These three models are further elaborated in Chapter 5 as they form the basis of the analysis of the two capstone design projects.

## **2.1 Engineering education: Preparation for professional practice**

Access to the practice of most professions is controlled through formal education in bodies of disciplinary knowledge seen to inform the effective practice of that profession as defined by the profession (Abbott, 1988; Schein & Kommers, 1972). This implies disciplinary knowledge specialised for particular problems emergent from specific contextual concerns. On the other hand universities (particularly research intensive universities) are primarily concerned with the production and transmission of disciplinary knowledge, knowledge defined by internally, conceptually coherent knowledge relations. This implies disciplinary knowledge generalisable across contexts. Professional education, especially when offered within research-intensive universities faces a tension between specialised disciplinary knowledge aimed at generalisability on one hand and aimed at specificity on the other. The challenge is evident in Noble's (1977, pp. 24-28) discussion of the tension faced by the early engineering schools in America in dealing with academic respectability versus meeting the demands of engineering industries. In a similar discussion Seely (1999) comments on the tension between 'practical' engineering based on rules of thumb and design experience, and the influence of European engineers with their scientific and mathematical expertise. Noble (1977) and Lundgreen (1990) argue that the scientific base of engineering was introduced in the universities under pressure for legitimacy and social advancement of the professionals. On the other hand, Seely (1999) argues that the introduction of mathematics and scientific fundamentals was always a call to generalisable knowledge for the purpose of addressing specific problems; "... the construction of better bridges, not the generation of better theories of bridge design or materials behavior" (Seely, 1999, p. 287). Harris, Grogan, Peden, and Whinnery (1994) make the same argument in their reflections on the Grinter report<sup>4</sup> (1955).

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<sup>4</sup> The Grinter Report was an investigation of engineering education in the United States commissioned in the 1950s by concerned engineering employers. The committee responsible for the report was chaired by LE Grinter.

Also see Harwood (2006) for a comprehensive review of history of engineering education across four countries and the range of factors that are attributed to shifts between practice and theory orientations within engineering curricula.

This tension between 'theory' and 'practice' places professional education at universities in a difficult position. As educational objectives they conflict. The first is concerned with abstract knowledge constructed as separated disciplines, separated from the concerns of the world and aimed at generalisability. The second is concerned with the concrete particulars of contextually emergent problems in the world, requires integration of disciplines, and is directed at specialisation to the particular. This tension between abstract, generalisable knowledge and its application in particular contextual problems is at the heart of professional education.

Using engineering as a case study, a review of a number of engineering education reports over the last hundred years across the United States (Clough, 2005; Grinter, 1955; C. R. Mann, 1918), Great Britain (J. King, 2007; Spinks, Silburn, & Birchall, 2006) and Australia (R. King, 2008) show surprising consistency in the conception of the engineering profession and the requirements of engineering education set up to meet these requirements. They all regard mathematics and science, along with economic and liberal arts, as foundational knowledge, but always for the purpose of technical analysis and design. These reports were commissioned by professional bodies, and the interests of employers and industry expectations of graduates dominate the views presented on the purpose of engineering education and the proposals for reforms in education. The same position also dominates much of the engineering education research by academics in universities with few dissenting voices (cf. Conlon, 2008); that the role of engineering education is predominantly preparation for professional engineering practice, which is perceived as the integration of technical knowledge and professional skills to address problems faced in the world (see Bingham, Southee, & Page, 2015; Bucciarelli, 2003; Jonassen, Strobel, & Lee, 2006; Sheppard et al., 2008 for a small sample of this literature).

As far back as the Mann report in 1918, including the Grinter Report in 1955 and the more recent reports (J. King, 2007; R. King, 2008), we see a distinction made between skills related to scientific and technical competence associated with problem-solving and technical analysis (technical skills), and skills related to the social aspects of practicing in a profession – including effective teamwork, leadership, communication etc. (professional or enabling skills).

Any attempt to specify the content of an engineering curriculum must be preceded by the development of a clear understanding of the objectives of such professional education. These objectives are two-fold and are based on the technical and social responsibilities that must be assumed by graduates expecting to enter the engineering profession ... The first objective, the technical goal of engineering education, is preparation for the performance of the functions of analysis and creative design ... The second objective, the broad social goal of engineering education, includes the development of leadership, the inculcation of a deep sense of professional ethics, and the general education of the individual. (Grinter, 1955, p. 75)

Growing interest in the perceived gap between engineering education and the needs of industry during the 1990s saw two parallel trends developing: one in the engineering education research agenda and the other in the accreditation criteria for engineering programs. Studies on graduate competence in the workplace, and the importance of developing graduate attributes (Jolly, Radcliffe, Crosthwaite, & Humphries, 2002; G. Scott & Yates, 2002) resulted in many proposals for incorporating the development of professional, enabling, or interpersonal skills into the curriculum in an integrated manner - often with the introduction of more design (Burton & White, 1999; Marra, Palmer, & Litzinger, 2000; Seely, 1999; Sheppard et al., 1997). The growing importance of professional skills in engineering curricula can also be seen in the shift in the accreditation of engineering degree programs away from the prescription of content towards an outcomes-based system. This movement, based on the attainment and demonstration of specified graduate attributes, resulted in a number of professional engineering bodies adopting the ABET (Accreditation Board for Engineering and Technology) style of outcomes-based accreditation (International Engineering Alliance, 2009) after the United States (Felder & Brent, 2003) for example in Australia (R. King, 2008) in 1999 and in South Africa in 2000. The same drive towards graduate attributes defined as outcomes is also evident in the Bologna process (Heitmann, 2005).

These curriculum reforms and accreditation changes have been justified based on a perception that the needs of industry are changing as a result of the rapid increase in knowledge in recent times, the increasingly complex problems that modern engineers face in relation to social, economic and environmental challenges, the contextually embedded nature of engineering professional problems, and the need for graduates to be ready to address these sorts of complex problems when they graduate (see for example Bingham et al., 2015; Heitmann, 2005; Lucena, Downey, Jesiek, & Elber, 2008; Sheppard et al., 2008). Yet both the Mann (1918) and Grinter (1955) Reports describe the needs of industry in the same way and acknowledge the importance of the integrations of professional and technical skills (see Seely (1999) for an analysis of the Grinter Report).

Many of the more recent educational reforms have been directed at introducing the integration of professional and technical skills, which is often loosely associated with some form of problem-based learning (PBL). Case (2011) argues that most would more accurately be termed project-based learning because projects run in parallel with traditionally structured technical courses. These projects are presented under a range of labels, including for example design-based learning (DBL) (Chandrasekaran, Stojcevski, Littlefair, & Joordens, 2013), Conceive-Design-Implement-Operate (CDIO) (Edström & Kolmos, 2014) and project-centred curriculum (PCC) (Crosthwaite, Cameron, Lant, & Litster, 2006). Typically these project courses are associated with first-year introductory design courses (Aloul, Zualkernan, Hussein, El-Hag, & Al-Assaf, 2015; Burton & White, 1999; Marra et al., 2000; Sheppard et al., 1997), service-learning courses (Huff, Zoltowski, & Oakes, 2015; Litchfield, Javernick - Will, & Maul, 2016; Shuman, Besterfield-Sacre, & McGourty, 2005), industry placements (L. Mann, Howard, Nouwens, & Martin, 2009) and capstone design courses.

Norback, Rhoad, Howe, and Riley (2014) reviewed over 1900 papers related to capstone design projects published between 1997 and 2012.

In addition to developing professional skills, it is assumed that technical knowledge will be applied (seemingly without difficulty) to solve contextual problems (Bingham et al., 2015; Chandrasekaran et al., 2013; Veldman, De Wet, Ike Mokhele, & Bouwer, 2008). The integrated nature of these problems depend on the open-ended and ill-defined nature of the problems posed, the assumption that they require the integration of multiple disciplines including social and economic insights, that they usually involve teamwork and therefore communication, and that they result in divergent solution possibilities. These courses are often set up as a counter to disciplinary engineering science courses, characterised by well-defined, predetermined convergent problems (Dym et al., 2005). Although most often associated with design learning, others have offered more general approaches to addressing the challenge of integrating professional and technical skills. Jonassen et al. (2006) describe ways of introducing 'everyday problems' across the curriculum. Bucciarelli (2003) proposes introducing design-like approaches to disciplinary reasoning in disciplinary courses and provides an example in mechanics.

Despite on-going education reforms there is still concern over the performance of graduates when they first enter professional practice (Baytiyeh & Naja, 2012; Newberry, 2007; Sheppard et al., 2008; Walther & Radcliffe, 2007). There are reports suggesting that graduates are more proficient in the social, enabling or professional skills than before, and acknowledgement that they have a solid foundation in mathematics and science (J. King, 2007; R. King, 2008). But these reports still raise concerns with graduates' ability to recruit the specialised knowledge that they have acquired through their education to address the problems they face as they enter professional practice.

Although industry is generally satisfied with the current quality of graduate engineers it regards the ability to apply theoretical knowledge to real industrial problems as the single most desirable attribute in new recruits. But this ability has become rarer in recent years... (J. King, 2007, p. 7)

... most employers consulted in the study have agreed that today's graduates have superior verbal communication and team skills than their predecessors. On the other hand, many employers have referred to students having less ability to 'work from first principles' (R. King, 2008, p. 18).

This is not a new problem and has been expressed as far back as 1918 in the Mann report:

One of the most common complaints of employers is that even college graduates have serious difficulty in applying theory to practice. (C. R. Mann, 1918, p. 88)

There are a number of unresolved tensions beneath the proposed requirements of engineering education that may go some way to suggesting why educational reforms have not resolved the problem of graduates' apparent inability to apply knowledge in solving professional problems. Firstly, although there appears to be general agreement that engineering education is principally intended to prepare graduates for practice, there are surprisingly few empirical studies of professional engineering practice evident in the engineering education literature (Trevelyan, 2009).

Those rare studies of engineering practice show how incredibly intertwined social skills are with technical skills (Bucciarelli, 1994; Faulkner, 2007; Trevelyan, 2009). Trevelyan (2009) found that professional engineers spent about 60% of their time communicating, mostly informally but related to making sense of technical issues and requirements or trying to convince others about them, and only about 20-30% of their time on explicitly technical issues (design, coding and calculations). Bucciarelli's (1994) in-depth ethnographic study of three design cases set in professional practice highlighted design as predominantly about negotiating meaning across individuals in teams, each with his/her own disciplinary and component priorities. Based on interviews with recently graduated chemical engineers working in practice, Martin, Maytham, Case, and Fraser (2005) argue that confidence in technical knowledge and skills was a requirement for effective communication and interpersonal skills, which in turn set the foundations for effective teamwork and management. Even so, as Faulkner (2007) pointed out, the engineers in her study tended to foreground their scientific and technical skills with pride and relegate their social skills to the background.

Secondly, despite the intertwined nature of professional and technical skills, a great deal of attention to preparation for engineering practice focuses on the development of the social, enabling or professional skills without explicitly considering the technical context of these professional skills. Many of the studies of engineering practice based on interviews and surveys with graduates focus on the importance of enabling skills in professional practice. For example Baytiyeh and Naja (2012) stated that Lebanese engineering graduates reported difficulty with communication, taking responsibility and working under pressure. Huff et al. (2015) and Litchfield et al. (2016) reported that graduates claimed to learn more about professional skills in service-learning courses. But what most of these studies fail to identify is the intertwined nature of social skills with technical issues. For example very little attention is paid to what the team might be working on and how, what the individuals may be communicating about, what level of technical expertise is required (or not) to manage a project. The study by Gilbuena, Sherrett, Gummer, Champagne, and Koretsky (2015), was situated in a simulated professional laboratory with senior students and focused on the role of informal feedback on the development of professional skills, but the data presented in their paper showed that the professional skills were all associated with technical issues.

Thirdly, as Trevelyan (2009) has argued, the dominant view of practice held by engineering educators tends to be of technical problem-solving (Jonassen et al., 2006) or design (Dym et al., 2005; Sheppard, Colby, Macatangay, & Sullivan, 2007) based on scientific and mathematical proficiency, even though there is an acknowledgement of associated disciplinary insight into economic and social factors. For example Pawley's (2009) in-depth interviews with a number (albeit a small number) of engineering educators suggests that the pervasive view of engineering held by educators is some combination of engineering as 'the application of science and math' to 'solve problems' usually related to 'making things'. Yet there is surprisingly little literature on the nature of what it means to use knowledge in contextually particular problems. In a study of recently-graduated nurses and physicians,

Smeby and Vågan (2008) offer a very useful insight, usually overlooked in the engineering education literature. They attribute the apparent knowledge gaps between academic learning and professional practice (the theory-practice gap) to the differences between how knowledge is structured and used in an academic learning setting and in professional practice. Knowledge needs to be recontextualized from the one setting to the other. Sheppard et al. (2007) touch on the challenge that teaching and learning occurs in a context different from practice, but do not elaborate on the implications. In a simulated industrial project Kittleson and Southerland (2004) explicitly looked for technical knowledge. They investigated concept negotiation using discourse analysis, but found very little in the way of discussion about making sense of theoretical concepts in relation to their problems. They attributed the absence of much concept negotiation to an engineering 'Discourse' (after Gee, 1999) founded on a realist ontology and objectivist epistemology, a sense that knowledge is truth and equally accessible in the same ways to everybody. This suggests a general inattention to the complexity of using theoretical knowledge in contextually specific problems.

Even those critical of the limitations of a technical, rational perception of engineering (Faulkner, 2007; Trevelyan, 2009; Winkelman, 2006) don't actually deny the importance of technical and scientific expertise. Rather, they critique the way in which engineering has become subject to science and to some extent management, or the economic imperative (Johnston, Lee, & McGregor, 1996; Noble, 1977). They argue that science is presented as objective and perfect, somehow pure, while the other aspects of engineering, ethics, social insights and empathy, and aesthetic judgement are peripheral and secondary (Faulkner, 2007; Winkelman, 2006). Winkelman (2006) points out that science and mathematics, while dominant in the curriculum, are not subject to critique in comparison to those disciplines positioned peripherally in the curriculum. Conlon (2008) calls for less focus on ability and more attention to the social responsibility required of engineering solutions. All call for a more balanced and integrated definition of engineering, which needs to be translated into more balanced and integrated curricula.

Many argue that design projects provide opportunities for this more integrated approach, including the assumption that design projects will assist students to learn to use disciplinary knowledge in context. While many may acknowledge the importance of disciplinary knowledge, few actually examine that knowledge explicitly, rather focussing on professional skills (Bingham et al., 2015; Burton & White, 1999; Chandrasekaran et al., 2013; Marra et al., 2000; Sheppard et al., 1997). Seron and Silbey (2009) position design as a balance of theory and practice, "... to bridge the space between expert knowledge and professional discretion" (Seron & Silbey, 2009, p. 113) in order to acquaint students with the ambiguity of real problems and teach them discretionary judgement. But it does beg the question of the basis of that judgement when design is introduced before students have the theoretical knowledge needed with which to judge. In a review of two panel discussions of student experiences of capstone design projects, Norback et al. (2014) identified 11 challenges, only one of which related to technical knowledge. Although there was very little elaboration, students reported that they found it difficult to apply their knowledge.

Although integrated contextual projects are seen as a bridge between theory and practice, there are a number of well-documented problems associated with these approaches in already overloaded engineering curricula. Sheppard et al. (2008) concern themselves with the complexity and integrated nature of practice, and the ethical obligations of the professional. They recognise the importance of technical expertise but argue that in overloaded curricula, the opportunities for critical thinking and integration of knowledge, available in laboratory work and design projects, is far too limited. Similarly Dym et al. (2005) point out with all the conflicting learning objectives embedded in design it is no wonder that instructors struggle to teach to these objectives and that students struggle to meet them all. Driven by the outcomes-based accreditation processes it is evident that many of the requirements (both technical and professional) are assessed in (especially capstone) design courses (Shuman et al., 2005). These studies suggest that while specialised disciplinary knowledge is recognised as important, when integrated into projects with multiple learning objectives and assessment criteria, the use of specialised knowledge in relation to contextually specific problems may get lost.

Linder and Flowers (2001) draw attention to the separation of engineering science and design in the curriculum, and further argue that most junior design courses focus on teaching generic design methods, addressing contextually situated problems, but tend not to draw on technical knowledge. They argue that it is therefore unsurprising that when the students in their study entered capstone design courses they were unable to draw on technical knowledge. They struggled to identify relevant knowledge, and few are able to construct knowledge into a form applicable to their specific problems without substantial assistance. The separation of courses in specialised technical knowledge from courses in design compounds the difference between knowledge structured for conceptual coherence and knowledge structured for contextual relevance.

The difference in knowledge structured for learning concepts from knowledge structured for solving contextually detailed problems is also acknowledged by Jakobsen and Bucciarelli (2007). They point out that theory needs to be restructured and integrated before it can be used to solve design-like problems. They argue that rather than stripping the irrelevant aspects of the context, students need to use the context to discern what theories to use and how to contextualise them. Smeby and Vågan (2008) make a similar point in relation to recently graduated doctors and nurses. It is not that they lack the academic knowledge, but rather that academic knowledge needs to be recontextualised before it can be 'applied' in practical situations. Christiansen and Rump (2007) also examined the theoretical knowledge requirements engineers draw on to solve practical problems. In an empirical study, engineering graduate students and professional engineers were provided with a simulated production problem, involving three different potential faults. The participants were provided with a description of the process, technical drawings and a number of sources of data notionally extracted from the faulty process. They were asked to diagnose the problem. The more experienced engineers were able to identify the technical problems more

comprehensively than the students, through a process of integrating the data sources to make sense of the underlying principles of operation alongside their general experience of the practical side of production processes. The students on the other hand tended to struggle to contextualise and integrate the data and information provided, and their more limited practical experience constrained their understanding. Rather than attributing the limitations of novices to a lack of practical skills or theoretical knowledge, Christiansen and Rump (2007) recognise the deeply theoretical nature of the expertise drawn into the context for the purpose of diagnosing the problems. These studies all highlight the uncertainty and ambiguity that detailed context adds to a problem, and the discretionary judgement required to identify the disciplinary knowledge that is relevant to the problem and specialise it to the problem – all aspects not evident in sanitised disciplinary problems in traditional engineering science courses.

In summary, engineering design, seen as the defining feature of engineering practice, plays a central role in engineering curricula. Design projects require the integration of technical and professional skills. Design projects require students to integrate the multiple disciplines previously learned in isolation. Design projects that incorporate complex contextual problems require scientific, economic and social insights. However, while a great deal of research and education reform addresses the importance of developing professional skills, there is far less attention to the interwoven nature of disciplinary knowledge within the web that is professional practice.

Some studies do raise important aspects about the nature of reasoning with knowledge in relation to contextually specific problems. Firstly, when the context is left intact (rather than stripped as it is in many engineering science problems), the context adds uncertainty and ambiguity to the problem, requiring discretionary judgement (Jakobsen & Bucciarelli, 2007; Seron & Silbey, 2009). Secondly, discretionary judgement draws on disciplinary expertise in addition to practical insights (Christiansen & Rump, 2007). Thirdly, uncertainty and ambiguity makes the identification of relevant knowledge less obvious than when problems are already formulated and predetermined, usually designed to test conceptual knowledge (Linder & Flowers, 2001). Fourthly, when used in ambiguous complex contexts, academic knowledge needs to be reformulated (Jakobsen & Bucciarelli, 2007). And finally, all the attention placed on professional skills in design projects has tended to distract from the complexity of using theoretical knowledge, and the way in which students struggle with it (Dym et al., 2005; Shuman et al., 2005).

A final note, although there is a general call to better prepare graduates for practice, most of studies of graduate preparedness are based on employer or graduate *perceptions*. This begs the question: Are graduates really underprepared for industry? To what extent are industry expectations unrealistic? To what extent are these studies conflating 'work-readiness' with 'experience' gained in practice? Some of this research tends to be very uncritical of underlying assumptions and to be under theorised with respect of broader societal influences and power relations.

## 2.2 Design thinking research: The process of design

Design research covers a broader range of design disciplines than engineering design, including for example architecture, product design, industrial design, fashion design and choreography to name a few. Design is broadly presented as neither art nor science, but rather a third way of knowing that incorporates elements of both art and science (Cross, 2001; Eder, 1995). This intellectual field has become associated with 'design thinking', and has expanded beyond traditional design disciplines, for example design thinking has been applied to business and management (Brown, 2009) and information technology (Lindberg, Meinel, & Wagner, 2011).

Design theorists generally argue that design follows a process of reasoning that is distinct from other problem-solving processes (see for example Visser, 2009). And much of the design literature has been concerned with formalising the nature of design thinking, defining a process specific to design and articulating methodologies to facilitate the process (see for example Dorst, 2010 for a brief synthesis of design thinking characteristics). Simon (1981) and Schön (1983), both prominent design theorists, have suggested that design provides a model of professional reasoning. Design thinking research does offer some useful insights, but as a new intellectual field, determining a particular model of the design process has been elusive. Most theorists conclude that design is simply too complex, with too many variations to categorise. And as Dorst (2008, p. 5) so eloquently points out:

... it takes only an afternoon to explain one of the design process models to a group of design students. But knowing that model doesn't make these students designers at all...

In his brief history of design research, Cross (2007) discusses the origins of the discipline in operations research and the decision-making techniques that were so successfully implemented during World War II, coupled with creativity techniques. This became epitomised in Herbert Simon's (1981) quest for a science of design<sup>5</sup>. But by the 1970s, design as a linear, rational, technical, decision-making process was being critiqued for the inability to deal with what became known as 'wicked' as opposed to 'tame' problems (Rittel, 1973). 'Wicked' problems were regarded as those complex problems that are ill-defined; for which no standard solution exists. The requirements, which develop with a developing understanding of the problem, inherently conflict, and they generally require novel or creative insights. During the 1980s there seemed to be a split developing between systematic design methodologies favoured by engineering and industrial designers on one hand and resistance to it from architecture and planning on the other. During the 1980s and 90s more attention was being paid to the creative, artistic, intuitive processes inherent in design, a movement usually associated with Donald Schön's (1983) 'reflective practitioner'.

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<sup>5</sup> Drawing on fields of artificial intelligence and computer-aided design, Simon sought to enhance the rigour and formal intellectual content of a science of design in order to give it academic respectability. He identified two key requirements: a means of making rational choices between given alternatives (eg linear programming); and a means of determining the optimal option amongst alternatives.

Design theorists often set Simon's (1981) more linear process associated with technical rationality in opposition to a more cyclic process of intuitive leaps between problem and solution associated with reflective practice after Schön (1983). Many design researchers have aligned themselves with this more fluid view of the design process (see for example Adams, Daly, Mann, & Dall'Alba, 2011; Dorst & Dijkhuis, 1995). Simon's model is usually dismissed as too restrictive or limited to problems for which a solution has already been defined, while Schön's model is seen to be more representative of the reflective conversation between problem setting and solution development (Adams et al., 2011; Dorst & Dijkhuis, 1995). However, Meng (2009) has argued that Simon has been misrepresented in the design literature and that a more careful reading of his work, especially the later edition (Simon, 1981), shows that he was far more open to the role of intuition and intuitive leaps, the limits of optimisation, and the non-linearity of shifting goals throughout the design process. As models of professional reasoning, the section that follows on professional knowledge will elaborate on Simon (1981) and Schön (1983) in more detail.

A number of design thinking research themes offer further insight into the nature of design, and by extension professional reasoning (after Simon (1981) and Schön (1983)). Protocol studies of 'expert'<sup>6</sup> designers prevalent in the 1990s suggest that when faced with complex problems, designers rarely follow the strictly linear process from problem to solution associated with well-defined problems. Instead, 'experts' work with problems and potential solutions in parallel, often using complexities in defining the problems to explore possible solutions (Cross, 2004), and maintaining a balance between predictability and ambiguity (Yilmaz & Daly, 2016).

Ethnographic studies of engineering designers highlight the social nature of design. For example, Bucciarelli (1994) argues that design does not take the neat form of a process often described by designers after they complete a design. He points out that design is no longer an individual exercise; it always involves many people. Each person brings their own perspective on the problem, largely driven by interests that are rooted in their own expertise and their role or reason for inclusion in the design team, as well as personal and political influences. He therefore sees design more as a 'shared vision' achieved through negotiation until sufficient consensus is achieved. His starting point is that no object of design is fully understood by any one person; rather that it is the manifestation of many different understandings culminating in a product.

In the simplest terms, design is the intersection of different object worlds. No one dictates the form of the artefact. Hence design is seen as a social process of negotiation and consensus, a consensus somewhat awkwardly expressed in the final product. (Bucciarelli, 1994, p. 20)

Many researchers compare the differences between scientific processes and design processes, the former intended to understand and describe in general terms, symbolically, while the

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<sup>6</sup> It should be noted that Visser (2009) and Lawson (2004) have critiqued these studies of expert designers because few studies have been done with truly 'expert' designers. Instead, senior students are considered 'experts'.

latter intended to create something new and particular that does not yet exist (Galle & Kroes, 2014, 2015; Owen, 2007; Simon, 1981). Others, for example Farrell and Hooker (2012), contend that the process of science is no different to the process of design because they see a scientific theory or principle as the symbolic artefact as a result of a process of 'design'. Certainly there are substantial similarities between the ethnographic studies of practicing design engineers (Bucciarelli, 1994) and practicing scientists (Latour, 1987), but in an engineering curriculum, where science is so often presented as objective, accurate and certain (Faulkner, 2007; Johnston et al., 1996; Jonassen et al., 2006; Sheppard et al., 2008), design does have a considerably different sense of uncertainty, fluidity and creativity.

A useful thread in design thinking for this study are the attempts to capture and categorise both the essence of design and the variations amongst its forms, suggesting significant elements of professional reasoning. *Abductive* reasoning, as distinct from inductive or deductive reasoning, is also considered a distinctive feature of design thinking (Dorst, 2010, 2011). Where induction involves determining general laws from particular observations and deduction involves predicting a particular performance based on general laws, abduction is described as the creation of something new, imagining both the general principle of operation and its particular performance simultaneously and before the artefact exists. Design is categorised as cycles of deductive and abductive reasoning (see for example Dong, Garbuio, & Lovallo, 2016 for an interesting discussion on the process of developing and selecting concepts). Distinctions between *divergent* and *convergent* problem solving are also drawn in the design literature, with design categorised as cycles of divergent and convergent thinking (Yilmaz & Daly, 2016), a more nuanced view than that presented in the engineering education literature that valorises divergent reasoning over convergent reasoning (Dym et al., 2005; Jonassen et al., 2006). Secules, Gupta, and Elby (2014) showed how coaching interventions could drive an *integrated* or *fragmented* approach to design. Each of these dichotomies raises aspects of design.

Rather than setting up dichotomies, some authors plot features of design thinking on continua, recognising both underlying principles and variation across these principles. Owen (2007) compared disciplines across two axes, representing a process axis, *analytic* (separating into parts orientated towards discovery) or *synthetic* (integrated into the whole orientated towards creation); and a content axis, *symbolic* (abstracted concepts and their relations) or *real* (concrete artefacts and processes). For example, in a comparison between science and design he positions science as an analytic-symbolic discipline and design as a synthetic-real discipline. Owen (2007) then calls for a balance between science and design in engineering. Dong, Maton, and Carvalho (2015) attempt to identify underlying principles that drive variation across design. Drawing on concepts from Legitimation Code Theory (LCT) (see Maton, 2014, for a comprehensive overview of LCT) they suggest mapping the relative importance of social and epistemic (knowledge) elements in design and the relation between abstracting principles and specialisation to contexts. Their studies locate engineering design as dominated by epistemic relations (knowledge relations) leaving social relations less

significant; what they label a 'knowledge code' (Carvalho, Dong, & Maton, 2009). They argue that design spans the whole continuum across abstraction and concretisation.

Another approach taken in the design literature relates to the various elements involved in design and their interaction. Dorst and van Overveld (2009) identify four elements of design practice, namely the *design problem*, the *design activity*, the *designer* and the *design context*. They attempt to map the interrelations between each part. Visser (2009) identifies potential variables to distinguish the differences that the form of design activity can take based on the *process* (time and team; tools; view of user); the *designer* (expertise; personality; routine); and the *artefact* (social embeddedness; development over time; nature (spatial/temporal)). The relationship between the artefact and the context in which it is intended to function plays an important role in distinguishing design from other disciplines. Simon (1981) introduced design as intentional control of interface between the inner environment (the structure of the artefact) and the outer environments (the context in which it operates) so that the artefact performs its intended function in the context of its operation. Kroes (2002) drew a further distinction between the external context of operation (the function) and the purpose for which the artefact was designed (the intention), what he termed the dual nature of technical artefacts, both physical objects and intentional objects.

Crismond and Adams (2012), in a project described as a scholarship of integration after Boyer (1990), draw on the extensive design literature to identify what they call 'dimensions of informed design'. They propose a matrix of nine design strategies, which map to these dimensions. They do recognise the difference between doing design and developing a curriculum for the purpose of teaching and learning design and consequently consider the issue of educational progression. Associated with each design strategy is a comparison between the behaviours of beginning (novices with no design experience) and informed designers (not expert, but with some formal training and experience). Their paper is primarily addressed to engineering design educators and it is not surprising that the findings have strong resonances with the engineering design education literature. The focus is on the process and skills required to design, and leaves disciplinary knowledge (they call it domain knowledge), while not absent, largely tacit. For example, the dimension "making knowledge-driven decisions" maps onto all but one of the nine design strategies, and "connecting and reflecting on knowledge and skills" maps onto all nine strategies. But the knowledge tends to be presented as existing, unproblematically, as domain knowledge. Identifying what knowledge is relevant or how that knowledge might be specialised to the problem at hand tends not to be considered.

An important form of knowledge that Crismond and Adams (2012) do mention relates to case-based knowledge contained in other design solutions. Visser (1998) presents a comprehensive description of the difference between 'analogic reasoning' and 'reuse', different ways in which solutions or parts of solutions are transferred to solve new problems. This transfer of contextual knowledge is prevalent in the literature (see for example Cross, 2003; Lawson, 2004). Schön (1983) speaks of building up a repertoire of familiar case

examples, of problems and solutions, failures and successes. Previous problem situations are then used as part of understanding new, unique problems. The engineering graduates in the study by Martin et al. (2005) reported that one of the biggest challenges they faced when they first entered the workplace was a lack of familiarity with the specific artefacts and processes they encountered. This underlines the importance of knowledge of the contextual specifics associated with professional problems, as distinct from the generalisability of abstract knowledge.

Although there are mentions of disciplinary knowledge (Bucciarelli, 1994; Cross, 2003) in the design literature, and it is evident in the data presented (even if not formally acknowledged) (Dorst & Dijkhuis, 1995; Schön, 1983), the recruitment of disciplinary knowledge in the solution of design problems tends to be implicit, and consequently, mostly invisible. In one of the few studies of the influence of domain knowledge on design performance, Yu, Honda, Sharqawy, and Yang (2016) analysed 22 students (both undergraduate and post doctoral) with a range of exposure to desalination plant design, as they performed parametric design using a simulation package. Their results do indicate that disciplinary knowledge improved the efficiency of the designs, but the study is quite limited in that it focuses on concept selection and specification, a deductive stage of design in the context of a relatively convergent problem. It gives no indication of disciplinary insights at the more creative/abductive stages of the design.

In summary, even though specialised disciplinary knowledge remains largely unexamined in the design research literature, there are nonetheless important characteristics of design thinking significant to this study. What is clear from this literature is the importance of the role of the context in which the artefact functions (Dorst & van Overveld, 2009; Kroes, 2002). A related theme is case-based reasoning, or familiarity with concrete examples (Lawson, 2004; Schön, 1983; Visser, 1998). This indicates an important distinction between artefact and context, both 'concrete' (Kroes, 2002; Schön, 1983; Simon, 1981). Counter to concrete detail are abstract aspects of a process (Owen, 2007) associated with a comparison between specific detail and general principles (Dong et al., 2015). Most suggest shifts between the various modes of reasoning in different stages in the design: shifts between convergent and divergent reasoning patterns (Yilmaz & Daly, 2016), between inductive and deductive reasoning, but also abductive reasoning (Dong et al., 2016; Kroes, 2002), always in shifting cycles, neither exclusively one nor the other.

### **2.3 Disciplinary knowledge in design: Relations of science to engineering and technology**

As discussed above, while design research highlights the importance of contextual detail and shifting processes of reasoning, the specifics of the role of disciplinary knowledge is largely left unexamined. Similarly engineering education research does recognise the importance of projects where students are expected to integrate disciplinary knowledge when solving complex problems that mimic professional engineering practice. But the research tends to

focus on the importance of professional skills and leaves the interwoven dependence between professional skills and disciplinary knowledge more tacit. This section is intended to draw more explicitly on science. It addresses the relations between science and engineering, and between science and technology, relationships that remain quite problematic.

As much as design does not define all of engineering, engineering does not define all of technology. There are however similarities between engineering, technology and design in terms of the relations between science and the creation of technological artefacts (see for example D. Layton, 1993; E. Layton, 1971; Pitt, 2011; Vincenti, 1990). Much like engineering, technology is often presented as the result of the application of science: first the scientific principles and then their application. E. Layton (1974) and Johnson (2011) have critiqued these accounts claiming that they imply that technological development involved no knowledge at all. Johnson (2011) argues that the great Roman engineering feats cannot be attributed to trial and error alone, but that they must have drawn on principles. It is just more difficult to determine the principles of design from existing artefacts, while scientific articles make the principles explicit (E. Layton, 1971; McClellan & Dorn, 2006).

The denial of a thought component to technology is thus the consequence of adopting a theory of the relationships of science and technology. This theory holds that scientists generate new knowledge which technologists then apply. Two assumptions are critical here. The first is that technological knowledge is essentially identical with natural philosophy. The second is that this knowledge has been produced by scientists since 1800. Logical deduction from these premises leads to an absurdity: that prior to 1800 technology involved no knowledge at all. (E. Layton, 1974, p. 31)

Although philosophers studying technology generally agree that neither technology nor engineering are applied science (Kline, 1995; D. Layton, 1993; Pitt, 2010), the nature of the relationship between engineering, technology and science remains contentious (van de Poel, 2010).

The construction of engineering and technology as applied science is a relatively new development associated with complex social processes for securing status on one hand and funding on the other (Johnson, 2011; Kline, 1995). Histories of technology and engineering (see for example Derry & Williams, 1993; Kirby, Withington, Darling, & Kilgour, 1956; McClellan & Dorn, 2006) challenge the notion that science precedes technological development and point out that many technological advances preceded scientific advances. They suggest rather that technological progress and scientific progress (certainly prior to the 'scientific revolution' in the 19th century) occurred independently of one another. Instead the technology and science literature argues for a far more interwoven and reciprocal relationship between science and technology (E. Layton, 1971). Scientific research is constrained by technical advances in instrumentation (Pitt, 2010) and technological advances often provide new challenges for scientific investigation (E. Layton, 1974). Both draw on similar knowledge and methods (E. Layton, 1971) and consequently inform each other.

The case is generally made for technological knowledge and scientific knowledge taking a different form, predominantly because of their different purposes and consequently their

different values (E. Layton, 1971; Pitt, 2011). It also results in a different organisation of the knowledge (D. Layton, 1993). The purpose of science is to produce knowledge based on an understanding of the natural world and described in principles that are general and abstract. The purpose of technological knowledge is the creation of something new, which is artificial and requires principles specialised to particular applications. Simply put, the purpose of science is knowing and the purpose of technology is doing (D. Layton, 1993; E. Layton, 1971).

A number of characteristics of technological knowledge have been identified in relation to this purpose of technology. The creation of a technological artefact may draw on scientific principles but it also requires what D. Layton (1993) calls functional knowledge, knowledge of what artefacts and parts of artefacts can do. In a similar sense E. Layton (1971) references Koyre (1948) as defining a systematic form of 'common sense' thinking, but related to the art and visual reasoning rather than simply unspecialised reasoning.

A common distinction relates to the different requirements for generalising in science and specialising to the particular in technology.

If neither the design nor the separate parts are new, we have ordinary engineering. The designer simply adapts known means to a given end; he may build a truss bridge of familiar design and materials, the sole novelty being in adapting these to the *particular case*. (E. Layton, 1974, p. 38, emphasis added)

De Vries (2010) provides an interesting take on the form that generalisations take in engineering in a discussion of the difference between abstraction (eliminating aspects of reality to get a deeper understanding of what remains) and idealisation (an approximation of reality by introducing simplified but inaccurate approximations). Both are engineering science techniques, but both are limited in the extent to which they can be generalised, in the first instance because the complexity of interacting parts cannot be entirely eliminated without changing the nature of the interactions, and in the second because the idealisation needs to be sufficiently accurate to still hold true when implemented. Pitt (2011) further suggests rather provocatively that engineering science is arguably more certain, and when it works, is more accurate than scientific knowledge. On the other hand, E. Layton (1971) argues that the complexity of artefacts requires a more approximate approach and less mathematical rigour than 'pure' science.

The idea of integration of parts and ideas is also seen as an element of technology,

... dovetailing a number of separate discoveries or insights into a *complex whole* capable of functioning as a working system. (E. Layton, 1974, p. 39, emphasis added)

a process described by D. Layton (1993) in terms similar to the way in which abduction is defined in the design thinking literature, and founded on principles of judgement as much as truth.

This very brief dusting of literature of philosophy and culture of technology and science does serve to highlight the reciprocal relationship between generalising principles of science and functional knowledge of artefacts. It also points to the influence of complex artefacts, made up of multiple interacting parts, on the demands and limits of science in the process of their design.

## 2.4 Models of professional reasoning: Bringing Simon, Schön and Abbott together

In this section three key theorists in the field of professional knowledge, Herbert Simon (1981), Donald Schön (1983) and Andrew Abbott (1988) are brought together with some of the central ideas presented in the previous section. This section sets up the basis of the analysis of the two capstone design projects presented in Chapter 5.

Both Simon (1981) and Schön (1983) have made substantial contributions to design research, but they both position themselves with professional knowledge and action.

Everyone designs who devises courses of action aimed at changing existing situations into preferred ones. The intellectual activity that produces material artifacts is no different fundamentally from that that prescribes remedies for a sick patient or the one that devises a new sales plan for a company or a social welfare policy for a state. Design, so construed, is the core of all professional training; it is the principle mark that distinguishes the professions from the sciences. (Simon, 1981, p. 111)

As already mentioned the design research community tends to set a linear rational model of design proposed by Simon (1981) in opposition to the more intuitive cyclic model of reflective practice proposed by Schön (1983). Nonetheless they have very important aspects in common. Both see professional practice as a process of understanding a situation, identifying what is not desirable and changing it into a (hopefully) more desirable situation. In this process both distinguish between the context and the artefact, both 'real' in the sense that they exist, or when implemented will exist. But where Simon (1981) addresses the general physical laws to which both are subject, Schön (1983) emphasises the repertoire of exemplars that a designer builds up and their relation to each unique design situation. Despite this apparent difference, Simon (1981) acknowledges the limitations of our knowledge of the physical laws, and even when the properties of component parts might be well understood, when put together it is not always possible to predict how the assembly will behave. He introduced the idea of *satisficing* – less precise than optimisation, but based on a judgement of 'better than' not just adequate. Likewise, Schön (1983) is not as blind to specialised knowledge as sometimes suggested

I propose that engineering design is understandable as a reflective conversation with the materials of a situation, a kind of process similar to the ones we have already observed in architecture and psychotherapy. Although it cannot be reduced to the application of general rules and theories, on the model of applied research, *some of its main features are constant and amenable to description*. (Schön, 1983, p. 172, emphasis added)

and his description of expert reasoning does indicate disciplinary insight. See for example the well-known conversation between Quist and his student Andrea, where the master (Quist) models his reasoning process to his student (Andrea). It is an example taken from architecture

and underpins the principle of geometric coherence, a principle significant to architecture (Schön, 1983, pp. 82-104).

Both Simon (1981) and Schön (1983) recognise the need to simplify the contextual detail (be it of the context or artefact) in order to manage a design, a process of imposing subjective judgements onto an objective reality (Dorst, 2010). Schön (1983) calls this a process of problem setting, or problem *framing* (the terminology taken up by the design thinking community),

When we set the problem, we select what we will treat as the "things" of the situation, we set the boundaries of our attention to it, and we impose upon it a coherence which allows us to say what is wrong and in what directions the situation needs to be changed. Problem setting is a process in which, interactively, we *name* the things to which we will attend and *frame* the context in which we will attend to them. (Schön, 1983, p. 40)

while Simon (1981) refers to it as abstracting,

... we are seldom interested in explaining or predicting phenomena in all their particularity; we are usually interested in only a few properties, abstracted from the complex reality. (Simon, 1981, p. 20)

... Most of the complex structures found in the world are enormously redundant, and we can use this redundancy to simplify the system. But to use it, to achieve the simplification, *we must find the right simplification*. (Simon, 1981, p. 228, emphasis added)

I would argue that Simon (1981) and Schön (1983) describe two sides of the same coin, Simon (1981) emphasising disciplinary insights and the power of abstract knowledge, Schön (1983) emphasising the importance of contextual familiarity and the power of a repertoire of exemplars. But both, albeit subtly, acknowledge the other side of the coin. Winch (2010) proposes that professional and vocational expertise combine rich practical familiarity, but overlaid with the idea of inference to give reflection a more principled basis, and more explicitly acknowledges the role of expert disciplinary knowledge in reflective practice.

Andrew Abbott (1988) offers one way in which to reconcile these two positions very productively. Professionals draw on two forms of knowledge, structured in fundamentally different ways. The first, the primary focus of Schön's (1983) work, relates to repertoires of case knowledge, knowledge founded on familiar contextual details, categorised by types. This knowledge is organised in a hierarchy of prevalence (problem types): how common a problem type is; or efficacy (solution types), how effective past solution types have been. These types do not necessarily exist in their entirety; parts of problem types or solution types may be combined in new situations, or to address novel problems.

What I want to propose is this: The practitioner has built up a repertoire of examples, images, understandings, and action. It includes sites he has seen, buildings he has known, design problems he has encountered, and solutions he has devised for them. The supervisor's repertoire includes patients he has seen or read about, types of stories he has heard psychodynamic patterns associated with them, interventions he has tried, and patients' responses to them. A practitioner's repertoire includes the whole of his experience insofar as it is accessible to him. (Schön, 1983, p. 138)

The second form of knowledge that Abbott (1988) proposes is a significant focus of Simon's (1981) work. It is abstract in nature, generalisable and therefore able to reveal underlying regularities not evident in contextually constrained practicalities, and organised not by a

## CHAPTER 2

hierarchy of types, but by logical connections between abstract concepts, and an internal rational system based on conceptual coherence.

The character of the abstract classification system is thus dictated by its custodians, the academics, whose criteria are not practical clarity and efficacy, but logical consistency and rationality. Professional knowledge exists, in academia, in a peculiarly disassembled state that prevents its use. (Abbott, 1988, p. 53)

Abbott (1988) proposes a model for professional practice based on what he calls three 'modalities of action', namely diagnosis, inference, and treatment. Diagnosis and treatment are associated with case typologies and inference is associated with abstract knowledge. He does not suggest that the three modalities are individual acts, or that they necessarily follow a set sequence. Instead they can occur in any order, at any time, and often simultaneously. For example, in medicine doctors may treat in order to diagnose.

Simon's (1981) external environment and Schön's (1983) problem space both refer to a rich context. The context is real, complex and subject to emergence as a result of contingent mechanisms, some of which we understand and can predict, some less predictable, some encountered before, some new. In order to design, both recognise the need to simplify the context in order to manage it, a process of abstracting only what is significant to the problem (Simon, 1981), a process of framing (Schön, 1983). In his diagnosis modality, Abbott (1988) includes both aspects in two phases, *colligation*, a process of stripping the context of its complexity by identifying what matters to the problem in the context and abstracting it from the context, and *classification* where the 'problem' is categorised against a catalogue of problem types organised by prevalence.

Like diagnosis, treatment involves identifying a treatment types from a catalogue of possible treatments, organised by their efficacy in other cases. But where diagnosis required colligation, treatment requires prescription, adjusting the treatment to the specifics of each context. Like Schön (1983), Abbott (1988) sees diagnosis and treatment progressing hand in hand, diagnostic classifications associated with treatment prescriptions. But it is also akin to design at the thin interface between inner and outer environment (Simon, 1981).

Abbott (1988) claims that professionals only resort to inference, chains of abstract conceptual reasoning based in academic logic, when routine diagnosis-treatment pairs are not obvious or fail. But Schön (1983) argues that all contexts are unique and consequently all treatments require reflective action. Perhaps prescription, tailoring the treatment to the vagaries of each case, is adequate to address Schön's concern. However, Simon (1981) would no doubt insist that even in quite routine design, managing the interface between the inner and outer environment requires some reliance on abstract models defined within conceptually organised inferential chains that describe the physical properties of context and artefact.

Abbott's (1988) three modalities of professional action can be seen to incorporate significant aspects of professional reasoning from both Simon (1981) and Schön (1983), while elaborating them in ways often only implicit in both. Abbott (1988) formalises the distinction between abstract knowledge, organised on principles of rationality and separate from

contextual limitations, from typologies of specific exemplars of both contexts and artefacts. In diagnosis he brings together the simplification of a context and the abstraction of significant features. But for both Simon (1981) and Schön (1983) modelling and adapting the artefact solution also involves a similar process. Inference (Abbott, 1988) gives voice to Simon's (1981) call for rational decision-making informed by predictions of artefact performance on context based on theoretical models of physical laws where possible. And treatment (Abbott, 1988) recognises both the role of practical experience of case histories and the need to modify such cases to particular situations for particular requirements.

## **Chapter 3 Social realism in the sociology of education**

This study is undertaken within the social realist approach to sociology of education, an intellectual field founded on the work of Basil Bernstein and currently more formally developing its sociological foundations in social realism<sup>7</sup> (Maton, 2014; Moore, 2013b). This chapter provides a broad overview of the field as it currently stands, introduces its Bernsteinian roots along with conceptual tools that he developed; introduces Legitimation Code Theory (LCT), an offshoot founded on the ideas of Bernstein and Bourdieu (Maton, 2014); and presents some of the central tenets of social realist sociology. Because this study follows a Bernsteinian approach to research, a theoretically informed, empirically grounded methodology, the conceptual coherence of the study within the broader body of specialised knowledge is central to the research design. Therefore this theoretical overview ranges beyond the specifics of the conceptual tools mobilised in the analysis.

### **3.1 The emergence of a social realist approach in sociology of education**

Social reproduction theorists like Pierre Bourdieu and Basil Bernstein have convincingly argued that education systems are the dominant mechanism for the reproduction of social inequality. Dominant social groups define what knowledge counts and control access to that knowledge. Since the early 1970s, educational reform movements like those based on the new sociology of education (see Young, 1971 for examples) and various forms of post-structuralist and post-modernist theories have attempted to disrupt this reproduction on the basis of discrediting the knowledge base of traditional education (Maton & Moore, 2010; for a critique of 'voice discourse' see Moore & Muller, 1999; and Young, 2000). The explanation for the differential success of different groups within the education system was seen as the privileging of the knowledge valued by the powerful classes over the knowledge of others. Their argument is that the reason that the powerful have access to 'powerful knowledge' is that they legitimate it as powerful and discredit the knowledge of others. Since all knowledge is socially constructed, under certain conditions of history and experience, all knowledge is culturally biased and there is no basis on which to judge various truth claims. Knowledge collapses onto experience, and formal knowledge becomes merely the knowledge of the powerful.

It was not working-class pupils who were failing to achieve in terms of the academic curriculum as was maintained by mainstream researchers. From the perspective of the sociology of knowledge, it was the academic curriculum, historically constructed to preserve the status quo of a class society, which systematically ensured that the majority of working-class pupils were failures. (Young, 2000, p. 525)

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<sup>7</sup> As opposed to the philosophical foundations of social realism found in the work of the likes of Margaret Archer.

The emancipatory project of progressive movements like the New Sociology of Education attempted to deny the 'power' of traditional knowledge in favour of legitimating all knowledge. However, from a social realist perspective, which acknowledges knowledge as an object with emergent properties of its own, sometimes unintended, some knowledge *is* more effective, more coherent and more accurately describes the world than other knowledge. And, they argue, there are means to judge 'better' knowledge (Young, 2000). Denying the power of some knowledge over others therefore runs the sociological risk of perpetuating the exclusion of some groups from epistemic access to 'powerful knowledge'.

The powerful are so not because they can arbitrarily impose their knowledge/culture as 'powerful knowledge/culture', but because they enjoy privileged access to the knowledge/culture that is powerful in its own right. (Moore, 2013b, p. 18)

In the sociology of education, the social realist approach makes knowledge itself an object of study, not only the social interests of power between groups. The emancipatory project of the social realist school of sociology of education shifts to broadening access for all to knowledge that makes a difference. Knowledge is considered a system of making sense of the world. Knowledge has an internal structure and organisation. Formal knowledge, produced within an intellectual field, and subject to rules of evidence and conceptual coherence, is considered more reliable than knowledge constructed individually without the formal structures of legitimacy that give it a measure of objectivity (Moore & Muller, 1999; Young, 2000).

Within the social realist school in the sociology of education are those whose approach has strong affinities with the philosophy of critical realism, which strengthens the emphasis on the distinction between 'the world' (ontology) and 'knowledge of the world' (epistemology) (for example Maton (2014), Moore (2013b) and Wheelahan (2010)). For these theorists knowledge always relates to an object of knowledge, which is considered ontologically real, and therefore has the potential to 'act back' on our knowledge of it and thereby modify our knowledge (Wheelahan, 2010).

... while 'knowledge' is reduced to knowing, 'what is being learned' (that which is being mentally processed) is typically understood as the world rather than a system of knowledge about the world - the physical world rather than physics, the social world rather than sociology ... (Maton, 2014)

For an extensive description of critical realism see Archer, Bhaskar, Collier, Lawson, and Norrie (1998). For an introductory text on critical realism see Danermark, Ekstrom, Jakobsen, and Karlsson (2002). The philosophy of critical realisms is founded on a realist ontology, which holds that objects are real and exist independently of our knowledge of them. A weak form of epistemological relativism is an acknowledgement that our knowledge is never complete, certain or fixed, but judgemental rationalism (the formal rules of conceptual relations or 'grammar' as Bernstein (2000) calls it) provides a rational basis on which to judge the relative 'truth' of different meanings (Archer et al., 1998).

For these theorists within the social realist school of sociology of education, the distinction between ontology and epistemology is central. When the two are conflated, for example

when regularities observed in empirical data have been accorded the limits of reality, or objects of knowledge are reduced to our experience of objects mediated through self-interested lenses, ontology is reduced to epistemology and any form of objective judgement is rejected. Although subscribing to a realist ontology, they accept a weak form of relativist epistemology, acknowledging the social construction of knowledge. While primacy is in some sense given to ontology (Moore, 2013b), it is a depth ontology, where a distinction is made between three levels of reality. Experiences of which individuals become aware (empirical domain) are a subset of broader events (actual domain) in which the experiences occur as a result of causal mechanisms that underpin all possible events, and interact in contingent ways such that some events do occur in a certain time and space and others do not (real domain). Where empiricism seeks to reveal regularities at the level of the empirical, critical realism seeks to identify the causal mechanisms at the level of the real, which, although themselves not observable, account for the regularities observed at the level of the empirical, and simultaneously recognise alternative possibilities (Danermark et al., 2002).

But just because knowledge and systems of knowledge are ontologically real, it does not make them permanent or immutable. An element of a stratified ontology is also the distinction between the transitive and intransitive domains of reality. While the physical world may remain relatively unchanged regardless of our knowledge of it, knowledge occupies a transitive domain of the real, subject to change, modification or rejection. Nonetheless, theorising within a disciplinary tradition is subject to rules of evidence and rules of relevance within an established and legitimated community of practice. Social realists within sociology of education agree that knowledge produced formally within communities of knowledge produces is more reliable than knowledge produced individually (Young, 2000; Young & Muller, 2007)

In the previous chapter I showed that much of the engineering education literature on engineering design fails to consider the structure and organisation of engineering knowledge and its application in design (c.f. Dong et al., 2015 who show that different design disciplines value different principles and that theories of design span a range of semantic gravity, from case based to generalisable theory). It is consequently blind to epistemic relations and more importantly different epistemic relations, for example between engineering sciences and design and between academic knowledge organised in specialised disciplines and reorganised in relation to complex objects. Specifically the present study takes as its object of study engineering knowledge and the relationship of this knowledge to the world that it models in the process of design and in the curriculum constructed for inducting students into the professional practice of engineering. More broadly this research asks questions of professional knowledge and professional education and the relationship between disciplinary knowledge in its abstracted conceptual form and the specialisation into a context defined within the complexity of the world. Underpinning the study is a recognition of the sociological processes involved in the construction and transformation of this knowledge, and the transmission and acquisition of, particularly, the manner of transformation of the knowledge from its abstracted to applied form.

## 3.2 Introducing Bernstein

In this chapter I turn to ideas founded on the work of Basil Bernstein (2000) as a means of analysing the structure and organisation of knowledge, and the manner of its transmission and acquisition. Although Bernstein never categorised himself as a social realist, theorists following in his tradition have argued that his theories are consistent with a sociological version of social realism, and are therefore compatible with it (Maton, 2014; Maton & Moore, 2010; Moore, 2013b).

Bernstein, a scholar working on the outskirts of sociology of education in Britain in the latter half of the twentieth century, was primarily concerned with the unequal distribution of knowledge between social groups and the manner in which the structure of pedagogic discourse perpetuated differential transmission and acquisition. But unlike the reproduction theorists of the time, Bernstein was searching for a model that could both describe the reproduction of social inequality as well as its potential for change (Moore, 2013a, see especially chapter 4). In Wheelahan's words:

Basil Bernstein (2000) argued that fair access to theoretical knowledge was important for democracy because it is the means society uses to conduct its conversation about itself and about what it should be like. Society uses theoretical knowledge to imagine alternative futures through thinking the unthinkable and the not-yet-thought. This is why theoretical knowledge is socially powerful knowledge. Access to abstract theoretical knowledge is thus a question of distributional justice, and curriculum in all qualifications should be structured so that they provide students with this access. (Wheelahan, 2009, pp. 228-229)

From this same perspective Gamble (2014) argues that curriculum design needs to be based on introducing students to the internal structure of whichever disciplinary specialisation they are learning. It is in this spirit that this study seeks to analyse the structure of specialised discourses and their relation to contextual particulars in the practice of engineering design. By making the nature of the knowledge relations more explicit, it is proposed that engineering educators can be more intentional about structuring curricula to introduce all students to the nature of reasoning required to use specialised disciplinary knowledge to address practical problems.

In order to develop the theoretical foundations of this study, some background to the development of Bernstein's thought is provided here. His theories were deeply influenced by Durkheim's (1995) separation of the sacred (the inner, the unseen, the explanation of our experience of the world) and the profane (the outer, the experience of the world) and the relationship between the two (Moore, 2013a). From a sociological perspective, Durkheim recognised the way in which religion regulated consciousness by studying religion in 'primitive societies'. He drew parallels with the way in which education regulates consciousness, our understanding of what we see and experience. The earliest religions were symbolic systems that regulated peoples' understanding of the world. They provided explanations for peoples' experiences in the world in terms of 'things unseen'; but they also controlled both access to these symbolic relations and decided who had the power to define these relations. Durkheim recognised this as the basis of scientific reasoning - the regulation

of the relation between the mundane (the world) and things unseen (ideas, conceptual relationships, and systems of meaning). In modern societies, although systems of legitimate meaning are more pluralistic, the control over legitimate meaning parallels that of early religious societies through formal academic education (Bernstein, 2000; Moore, 2013a).

For to explain is to connect things to other things; it is to establish relationships between things that make them appear to us as functions of one another and as vibrating sympathetically in accordance with an internal law that is rooted in their nature. Sense perception, which sees only from the outside, could not possibly cause us to discover such relationships and internal ties; only intellect can create the notion of them. When I learn that A regularly precedes B, my knowledge is enriched with a new piece of knowledge but my intelligence is in no way satisfied by an observation that does not carry a reason with it. I begin to understand only if it is possible for me to conceive of B in some way that makes it appear to me as not foreign to A but united with A in a relation of kinship. The great service that religions have rendered to thought is to have constructed a first representation of what the relations of kinship between things might be... As soon as man became aware that internal connections exist between things, science and philosophy became possible. Religion made a way for them. (Durkheim, 1995, p. 239)

Systems of theoretical knowledge are, for Bernstein from Durkheim, analogous to systems of religion. They form the basis of reasoning about the world, for making connections between the world and our ideas about the world. They also set up a system for control over symbolic power; an hierarchical structure of knowledge production, recontextualisation and reproduction (Bernstein, 2000). This system controls the way in which we make sense of the world and therefore our consciousness; it controls access to this way of making meaning and it sets up an internal hierarchy of adepts within the system and externally to those excluded from it. From this reasoning, Bernstein constructed his ideas about legitimate knowledge relations, processes of controlling legitimate meaning and the basis of the transmission and acquisition of these symbolic systems, in essence, the basis of controlling the distribution of labour and perpetuating social differentiation.

Two aspects of Bernstein's reasoning are foundational to this study. The first relates to the distinctiveness of the separation of systems of symbolic meaning in disciplines (amongst other things), what Bernstein (2000) called classification, or the strength of boundaries between things. Bernstein argued that classification is what gives a system of meaning power: the power to define itself, and the power to develop. It sets up legitimate internal conceptual relations based on rules of rational coherence. It separates systems of meaning that enable abstract concepts to connect apparently unconnected things in the world. Adepts inducted into this system of meaning develop a specialised consciousness capable of transcending contextual and experiential constraints, and thereby identifying what has not yet been experienced and to imagine new possibilities (Wheeler, 2009).

Associated with classification is framing, the system of control. Framing defines the system of control within systems of the transmission and acquisition of knowledge. Internal framing of a pedagogic exchange defines who controls what within the exchange, the transmitter or the acquirer. Aspects of framing include who determines and sequences what counts as legitimate knowledge within a pedagogic exchange; who sets the rate of exchange; who defines what counts as realization of having acquired new knowledge; and who sets up the social relation between transmitter and acquirer.

Although Bernstein developed code theory to describe modalities of pedagogic practice in the classroom (the introduction of classification and framing appears in the final chapter of *Class, Codes and Control Volume I* (Bernstein, 2003a), first published in 1971), the principles of power in separation and control are also evident in much of the development of his later theories. He used principles of classification to compare 'traditional' and 'progressive' curriculum structures (Bernstein, 2003c, pp. 85-115), and changing strengths of classification is central to his distinction between disciplines and professions (Bernstein, 2000, pp. 7-11; 81-86).

The second aspect lies in the pedagogic device, a model of symbolic control exemplified in the formal education system (Bernstein, 2000, pp. 25-39, 113-120; 2003d, pp. 165-218). Bernstein distinguished three 'fields', which he argued were related hierarchically to each other, and operated differently from each other, both in terms of their rules of control (of access and internal hierarchy) and their organisation and structure of symbolic meaning. Most significantly, the pedagogic device illustrates how and why engineering design in a classroom is not, and cannot be, the same as professional engineering practice. Curriculum choices not only select and sequence knowledge differently to the way in which knowledge exists in practice and in an intellectual field; the way in which curriculum choices are made always involve ideological choices which impose their own structure on the curriculum structure (Bernstein, 2000).

### **3.2.1 Power and control: Classification and framing**

Code theory, the categorisation of pedagogic practice in terms of classification and framing, has roots in Bernstein's abiding concern for understanding the mechanisms by which education reproduces social inequality. Rather than ascribing relations of social reproduction solely to external relations to race, class, gender etc, Bernstein wanted to be able to describe the internal relations of the system of social reproduction in a form sufficiently abstract to recognise both its mechanisms of reproduction and the potential for disruption of social reproduction. He wanted to be able to describe the way in which systems of meaning are produced (and controlled); constructed into various forms for the purpose of transmission and acquisition; and selectively transmitted and acquired. He wanted to show how different groups of people have differential access to systems of meaning and to explain the processes of constructing and realising what counts as legitimate meaning. But he also wanted to explain why some people managed to transcend this differentiation, which is what Moore (2013a, p. 56) claims “defines him most distinctively as the theorist of disruption and interruption rather than reproduction”.

Bernstein's theoretical development began with describing language characteristics of different groups of children in terms founded on Durkheim's model of religious thought. These he termed elaborating (initially elaborated) and restricted codes. He argued that the codes emerged from principles of authority experienced in the home (positional or personal)

and predisposes (rather than being strictly deterministic) children to particular orientations to meaning. A restricted code is based on condensed symbols, draws heavily on metaphors and tends to sensitise its users to particularistic meanings embedded in a particular context. This is associated with the mundane, rooted in specific contextual experiences. In contrast, an elaborating code is based on articulated meanings, draws on rationality as the basis of its meaning relations, and tends to sensitise its users to universalistic meanings that transcend contexts (Bernstein, 2003a, pp. 136-137).

Where codes are elaborated, the socialized has more access to the grounds of his own socialization, and so can enter into a reflexive relationship to the social order he has taken over. Where codes are restricted, the socialized has less access to the grounds of his socialization, and thus reflexiveness may be limited in range. *One of the effects of the class system is to limit access to elaborated codes.* (Bernstein, 2003a, p. 136)

Schooling, particularly at the higher levels of education, is based on an elaborating code, the articulation of reasoning and the relations between concepts. Therefore children predisposed towards an elaborated orientation to meaning by virtue of their home and community are at an advantage when they enter school. Since access to higher levels of education is based on access to systems of rational and articulated meaning, progression in school is about the transmission and acquisition of an elaborated orientation to meaning, in the form of an elaborating code. The point is that differently positioned social groups *tend* to enter school differentially prepared to work with an elaborating code.

The concern with elaborating and restricted codes is to a major extent, though not exclusively, to do with *entry* into modalities of pedagogic discourse, and through them, to knowledge. (Moore, 2013a, p. 60)

It is important to note that despite the unfortunate label, restricted codes are not inferior to elaborating codes. For example, practitioners working in highly specialised contexts tend to shift to a restricted code. A familiarity with a shared context can lead to highly condensed and contextually specific meanings (Moore, 2013a). But an elaborating code is necessary in the process of transmission and acquisition of specialised disciplinary knowledge.

Bernstein's focus then shifted to describing the various forms taken by elaborating codes in classroom practice. His reasoning, in contrast with reproduction theorists, was that in order to make claims about reproduction (and transformation) one needed to be able to precisely describe any particular practice and compare it to alternative modes of that practice. His approach was to develop a systematic means to categorise different pedagogic code modalities in order to rigorously describe and compare different pedagogic practices, and to identify potential codes not available in a particular data set. His reasoning was that underpinning the visible pedagogic interactional practices and the realisation of 'texts' (any production of written, spoken, or gesture open to evaluation) are the invisible features of specialised meaning and hierarchical social positioning.

The features that create the speciality of the interactional practice (i.e., the form of the social relationship) regulates orientation to meanings, and the latter generate through *selection* specific textual productions. (Bernstein, 1981, p. 329).

It is important to highlight Bernstein's position (often overlooked by critics) that he always pointed out that these chains were not an inevitable consequence of social position, but rather a result of relations of power and control.

These coding orientations are in no sense inevitable consequences of any position. Coding orientations are not intrinsic to different positions. Whether they become so depends upon the distribution of power. Thus the distribution of coding orientations depends upon the distribution of power created by the principles regulating the social division of labor. (Bernstein, 1981, p. 333)

In order to establish the principle on which power relations position people, Bernstein used the concept of classification (introduced previously), a principle of separation that sets up a space for disciplinary specialisation, based on general concepts abstracted from empirical experience and related by formal, rational, conceptually coherent links. Classification refers to relations between categories, the degree of insulation from other categories, rather than to the contents of any category.

There are two basis rules that are sufficient to generate this whole section of the model. Where we have strong classification, the rule is: things must be kept apart. Where we have weak classification, the rule is: things must be brought together. But we have to ask, in whose interests is the apartness of things, and in whose interest is the new togetherness and the new integration? (Bernstein, 2000, p. 11)

The insulation of a category from other categories is what establishes its opportunity for specialisation. The insulation sets up the boundaries for specialisation and the boundaries facilitate the recognition of any specialisation (be they agents or discourses). Classification is therefore associated with the discernment of what may be included and excluded, and how 'things' within a category may or may not be connected and hierarchically positioned in relation to each other within in any category. Although classification is associated with power relations, and therefore the arbitrary social distribution of categories of people, Bernstein goes on to suggest the possibility of a necessary specialisation in the case of disciplinary discourses (Bernstein, 1981, p. 337).

Pursuing the notion of classification of specialised disciplinary discourses constructed into subjects or subject streams within a curriculum, the principle of classification provides the basis of 'recognition rules', which define what may legitimately be put together within a particular discourse. Strong classification implies that legitimate texts are based on sharply distinct discourses with well-defined internal rules of relation, while weak classification suggests that legitimate texts tend to incorporate influences from other discourses, less clearly defined, which make the boundaries of legitimacy more ambiguous to determine.

The principle of the classification generates through its insulations the specialty of the categories and the markings of that specialty. The markings of the categories, from the point of view of the acquiring subject, provide a set of demarcation criteria for recognizing the categories in the variety of their presentations. The sets of demarcation criteria provide a basis for the subject to infer recognition rules. The recognition rules regulate what goes with what: what meanings may be legitimately put together, what referential relations are privileged/privileging. The recognition rules regulate the principles for the generating of legitimate meaning and in so doing create what we have called the syntax of generation of meaning. (Bernstein, 1981, p. 339)

Hugo (2013)<sup>8</sup> identifies three dimensions of classification, evident in Bernstein's work, but never as explicitly distinguished: the relation between the specialised discourse and the everyday; the relation between different discourses; and the relation between the various sections within a discourse. For each dimension, the boundary between the two can be firmly maintained, or weakened to bring the two together.

Where classification regulates *what* meanings may be put together to construct a legitimate text and thus provides the recognition rules, framing regulates *how* these meanings can be put together to construct a legitimate text. Framing provides the 'realization rules' (Bernstein, 1981, p. 342). Where classification is related with power, the power to maintain or change the insulation of boundaries, framing is related to control, the control over the form that the pedagogic interaction takes. However, as much as the classification principle circumscribes the limits of legitimate texts, the form that they can take has the potential to change or challenge the classification principle.

In terms of framing, a pedagogic practice can be categorised as strongly or weakly framed, where strong framing means that the transmitter controls the exchange while weak framing means that the acquirer controls the exchange. However Bernstein is clear that in the case of weak framing, control only appears to shift to the acquirer because evaluation always lies with the transmitter. Rather he seems to imply that the evaluation merely becomes more ambiguous. Bernstein identified five basic aspects of the pedagogic exchange over which the transmitter or acquirer can have control, and these can vary independently of one another. There is the control over the content (selection); the sequence in which the content is transmitted/acquired (sequencing); the time allocated to the transmission/acquisition (pacing); who decides what really matters (the evaluative criteria); and the manner of the relationship between the transmitter and acquirer (the social base). Each aspect can have its own framing value, so, although selection may be strongly framed (what is transmitted is explicitly determined by the transmitter), the pacing may be weakly framed (the acquirer may be able to slow or speed up the pace of the exchange). If one accepts that theoretical knowledge is powerful in its potential to recognise connections and imagine new things, then one can recognise the role of the transmitter (the adept within a system of meaning) in transmitting the legitimated system of meaning.

Research in schools suggests that strong framing over selection, sequencing and the evaluative criteria reduces ambiguity for the acquirer, while weak framing over pacing and the social base invites the acquirer into the new discourse (see for example the collection of papers in Muller et al., 2004). On the other hand Gamble and Hoadley (2011) suggest their work indicates that strong framing over the social base may assist working class children access into an elaborating code because it is closer to a form of positional control more prevalent in working class homes.

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<sup>8</sup> Although Hugo was describing classroom practice (in the field of reproduction) these three classification dimensions resonate with classification in the curriculum and the parent discipline.

While pedagogic modalities were developed to describe classroom practice (Bernstein, 1981), Bernstein (2000, pp. 9-11) also used classification to compare different curriculum constructions, distinguishing between collection codes and integrated codes. The principles of classification are also the basis of his distinction between singulars (strongly classified disciplinary specialisations) and regions (the weakening of boundaries between disciplines and between the world in the formation of professions). It therefore seems reasonable to apply classification and framing principles to design tasks at the level of curriculum. The analysis presented in chapter 5 weaves in principles of classification and framing to show how recontextualisation choices modify knowledge relations within design projects.

In summary, classification defines the strength of boundaries around categories, be they people or discourses. Strong classification refers to strongly differentiated categories implying that legitimate text (performance) is clearly defined within a category; weak classification refers to weakly differentiated categories implying integration and consequently more ambiguous legitimate texts. Strong framing refers to explicit control of the relations within or between categories; weak framing refers to more implicit control of these relations, allowing for more input from the acquirer, but also resulting in more variation and potentially more ambiguity.

### **3.2.2 Construction of pedagogic discourse: The pedagogic device**

In order to understand engineering design as a curriculum subject, and its relation to design as a discipline and design as a professional practice, Bernstein's pedagogic device (Bernstein, 2000, 2003d) provides a powerful starting point. The pedagogic device distinguishes between knowledge in its disciplinary form, and knowledge in the curriculum. The former is defined by a canon of conceptually related and coherent ideas, realised through social practices of evaluation. Pedagogic discourse is constructed into a curriculum for the selective transmission and acquisition of specialised disciplinary knowledge. The disciplinary discourse is 'recontextualised' and therefore changed, into a pedagogic discourse. This is an explicit recognition that engineering education is not engineering practice and that there are significant limitations in trying to replicate professional practice in a pedagogic context. Rather, the construction of a curriculum – the selection and organising of the specialised knowledge and skills – is an ideological site of struggle, and any particular form that a curriculum takes should not be considered either necessary or neutral. The pedagogic device offers both a means to recognise the dislocation and relocation of knowledge into curriculum form and a set of principles to describe the embedding of knowledge within particular ideological norms.

The pedagogic device analytically separates three fields, the field of production, the field of recontextualisation and the field of reproduction, and positions these fields hierarchically in relation to each other. Different agents operate within each field, and the relations between agents and legitimate practices are subject to different 'rules', what Bernstein terms grammars, within each field. These rules function to determine legitimate texts and practices,

and to position people differently within each field, they provide the basis of internal order and relations (Bernstein, 2000, pp. 25-38; 115-120; 2003d, pp. 143-182).

As a sociological model of the processes of production, recontextualisation and reproduction of knowledge, the pedagogic device provides a description of a generative mechanism at the level of the real<sup>9</sup> with the power to explain empirical observations of knowledge production, curriculum constructions and pedagogic actions, as well as to suggest alternative possibilities. At its heart are two knowledge dislocations in which knowledge undergoes reordering and shifts, first from any disciplinary discourse into an 'imaginary' pedagogic discourse and then into a pedagogic practice. This process of transformation is not neutral, rather it

... creates a space for the play of ideology. ... The pedagogic device is thus a symbolic ruler of consciousness in its selective creation, positioning, and oppositioning of pedagogic subjects. It is the condition for the production, reproduction, and transformation of culture. The question is: whose ruler, what consciousness? (Bernstein, 2003d, p. 189)

Significantly, the pedagogic device provides a model to describe the embedding of social order into the educational system. It can show how differently constructed curricula serve different groups of students differently. It is in this, the explication of the manner in which social reproduction happens by education, that Bernstein's theories differ from those of, for example Bourdieu<sup>10</sup> (Maton, 2014; Moore, 2013a).

However, Bernstein developed the pedagogic device in the context of school knowledge, traditionally organised around disciplinary subjects imposed on teachers, it therefore does have limitations for this study. Firstly, this study shifts to knowledge in higher education, where the knowledge producers, recontextualising agents and teachers are usually one and the same person (Ashwin, 2012). Secondly, it considers professional knowledge, with its influences from the field of professional practice as well as the disciplinary canon. Bernstein did not consider the influence from the field of professional practice in the pedagogic device, except perhaps in his later distinction between 'singulars', 'regions' and 'generics' (Bernstein, 2000, pp. 52-53). M. Barnett (2006) expanded Bernstein's pedagogic device to account for the influence of workplace knowledge and practices in vocational curricula. He suggests a form of double recontextualisation: both from the canon of disciplinary knowledge and from the norms and requirements of workplace practices. But his work was more related to workplace skills than with knowledge relations per se.

### ***The field of production: systems of specialised meaning***

Within the pedagogic device the field of production is preeminent; it is the field in which the canon of a discipline's knowledge is produced. Within each discipline there is a system of coherent meaning founded on coherent inferential chains of reasoning between concepts and procedures (see Winch (2010) for inferential reasoning within systems of knowledge in

<sup>9</sup> Critical realism subscribes to a depth ontology, the empirical, the actual and the real as described in section 3.1.

<sup>10</sup> Where Bourdieu showed *that* education systems reproduce social inequality, Bernstein's work was aimed at showing *how* education systems reproduce social inequality. Bernstein thus showed that the system does have some (albeit limited) potential to interrupt social reproduction.

disciplines as well as vocations). Each discipline has principles of validity against which knowledge claims are tested. These include the practical efficacy to explain certain phenomena (relation to their intransitive empirical objects), the coherence with which they relate to other concepts within the discipline (relation to the transitive conceptual relations) as well as their support from a legitimated community of experts (social relations) (Young, 2000). The objectivity of knowledge claims provided by a community of knowledge producers in pursuit of truth rests on the induction of these participants into an established disciplinary body of knowledge, and rigorous processes of review with the potential for overturning prior knowledge claims (Young & Muller, 2007). Bernstein called these the distributive rules and was particularly concerned with the symbolic power relations that were set up by any community of knowledge producers (Bernstein, 2000).

Despite the cultural and historical influences on knowledge production and its inevitable fallibility, social realists in education have argued that the very social processes of its production provide a measure of objectivity to knowledge because of a commitment to truth and the rigours of peer review (Young, 2000; Young & Muller, 2007). Rather than debunk disciplinary knowledge on the basis of the distributive rules, they argue for extending access to the processes and rigours of knowledge production through immersion in the discipline and a commitment to truth. However, Wheelahan (2010, p. 40), points out that this position is based on the rationalism of Durkheim and tends to focus on the structures of knowledge, and their social construction, leaving the influence of objects of knowledge more implicit. She makes a case for explicitly recognising the contribution of critical realism to address the epistemic relations between the objects of knowledge and our knowledge of objects in addition to the social relations of knowledge practices:

A focus on the epistemic is needed if we pursue truthfulness in which knowledge can be demonstrated to be true based in the available evidence that we have, even if new evidence leads to its revision. Bringing the social and epistemic together provides the basis for critiquing curriculum so that knowledge is judged by the extent to which it provides access to its objects, as well as the extent to which the curriculum provides students with access to the structures of knowledge and systems of meaning. (Wheelahan, 2010, p. 47)

In a profession like engineering, which relies heavily on the physical laws defined within the sciences in order to predict the potential performance of a physical artefact intended to function to some purpose, the epistemic relation to its object of knowledge is particularly important. Also when a designed artefact is implemented in the world, it operates in ways emergent from its internal structure in relation to its context of application; it does not necessarily function as it was intended as a result of our predictions based on our knowledge. And further, unpredicted performance in turn challenges established knowledge.

### ***The field of recontextualisation: constructing the curriculum***

The field of recontextualisation is subject to the field of production. It is from the field of production that specialised knowledge and skills are selected and sequenced into a curriculum. Bernstein points out that the pedagogic discourse constructed in the curriculum is not the same as the disciplinary discourse from which it was recontextualised. It has a different structure as a result of the recontextualisation and is subject to different rules.

Bernstein defined the rules of recontextualisation as the principle by which the instructional discourse (specialised competencies and forms of consciousness) is embedded in the regulative discourse (principles of order, relations and identities or forms of consciousness). But it is the regulative discourse that provides the principles of selection and order (Bernstein, 2003d, p. 183).

In the field of production, the distributive rules control the relation between the world and our ideas about it, who has access to the construction of these relations and consequently who has control over legitimate meaning-making. When specialised meaning in the form of conceptual relations and knowledge practices are selected from the field of production and reassembled in the field of recontextualisation, the relations change. A new order is imposed on the knowledge practices, knowledge relations and the social relations. This order over the instructional discourse (the content of the pedagogic discourse) is provided by the regulative discourse, which includes social relations, constructions of identity and theories of instruction. A new discourse, based on the primary discourse, but ordered differently, is created.

Pedagogic discourse is a principle for appropriating other discourses and bringing them into a special relation with each other for the purposes of their selective transmission and acquisition. Pedagogic discourse, then, is a principle which removes (delocates) a discourse from its substantive practice and context, and relocates that discourse according to its own principle of selective reordering and focusing. In this process of the delocation and the relocation of the original discourse the social basis of its practice, including its power relations, is removed. In the process of the de- and relocation the original discourse is subject to a transformation which transforms it from an actual practice to a virtual or imaginary practice. (Bernstein, 2003d, pp. 183-184)

The instructional discourse is not only subject to choices of inclusion and exclusion of knowledge from within the disciplinary discourse. It is also subject to choices regarding the sequencing of the transmission of that knowledge at a particular depth and breadth that can be accommodated in a defined time. Moreover, it is embedded into a regulative discourse that includes the norms of conduct and expectation depending on the various institutions and processes of transmission. These serve different groups in different ways (Bernstein, 2000). For example Wheelahan (2010) describes the regulative discourse underpinning the current curriculum focus on modularised and fragmented competencies and work-readiness, especially in vocational education as neo-liberalism:

The regulative discourse provides the principle of recontextualisation which is used to selectively appropriate concepts and then reassemble them as the instructional discourse so that the appropriated discourse is ideologically congruent with the regulative discourse (Bernstein 2000: 32-33). The parameters of the regulative discourse are shaped by the particular model of social order, which in this case is neo-liberalism. (Wheelahan, 2010, p. 132)

### ***The field of reproduction: transmission and acquisition in the classroom***

The field of reproduction refers to the field in which knowledge transmission and acquisition is enacted in pedagogic practices. Here the criteria for performance are condensed into the evaluative rules. Instructional content defined in time and space and embedded in regulative norms and practices by the pedagogic discourse constructed in the field of recontextualisation, is again recontextualised into the field of reproduction and realised in the

evaluative rules. Although the field of reproduction is largely omitted from this study, it cannot be entirely ignored because, as Bernstein points out, “Evaluation condenses the meaning of the whole device” (Bernstein, 2000, p. 36).

### **3.3 Structure and organisation of professional knowledge**

In the previous chapter it was argued that engineering design is typically considered to epitomise the nature of professional engineering practice. Engineering design is characterised as recruiting multiple disciplinary specialisations, ranging from 'pure' maths and science, different engineering sciences to economic, environmental and social sciences. It recruits these specialisations to inform the solution of specific, contextually emergent problems in the world. The classification of the disciplinary specialisations is weakened in two regards. Firstly the boundary between the abstract, conceptually coherent discipline and the everyday concerns in the world (albeit professionally defined concerns) is weakened. Secondly the boundary between the disciplines is weakened as they are brought into contact with each other and potentially integrated. The importance of case-based knowledge, knowledge of past problems and solutions, is also important in design; knowledge which according to Abbott (1988), has a substantially different structure than academic knowledge. In addition, one of the challenges identified in teaching and learning design is the integration of conceptually disparate knowledge and skills, including professional skills, design thinking methodologies, and disciplinary specialisations. As a recontextualised subject in the curriculum, design is therefore internally fragmented, further weakening the classification, resulting in ambiguous and even conflicting evaluative criteria.

The principles of recontextualisation, classification and framing therefore offer analytic tools with the potential to untangle and precisely describe the complex interactions involved in constructing engineering design tasks for the purpose of preparing engineering graduates for professional practice. But, engineering design, recontextualised as a curriculum subject, also provides a very interesting empirical case with which to push the theoretical field.

#### **3.3.1 Characterising the professions: A shift from singulars to regions**

Bernstein's distinction between disciplinary discourse (parent discourse in the field of production) and pedagogic discourse (a recontextualised discourse in the curriculum) lies in the logic of the discourses. The parent discourse cannot be derived from the recontextualised pedagogic discourse, because the regulative (moral) discourse is what gives the new discourse its structure (order, relation and identity) (Bernstein, 2000, p. 34; 2003d, p. 184). On the other hand Muller (2007) points out that Bernstein was perhaps making too strong a point, since there is at least some predictability in performance of students in school subjects, their university equivalents and performance in their fields of production. Muller goes on to suggest that Bernstein's shift to discourses and knowledge structures in his last works indicates that perhaps he too began to realise the importance of the parent discourse. Muller leaves us with the following important questions about disciplinary discourses:

## CHAPTER 3

Does knowledge structure constrain pedagogic structure, does it place any onus on the way that the 'what is to be learnt' is recontextualized? Do these internal characteristics of knowledge structures place limits on the form their curricular offspring optimally could and should take? (Muller, 2007, p. 79)

Gamble (2014) pursues this line of reasoning when she argues that curriculum logic should follow the disciplinary logic. That is, the structure and logic of the parent discourse should be introduced from the beginning of the curriculum trajectory. She argues that symbolic knowledge is based on particular structural relations, basically how parts relate to the whole. After Durkheim, she argues that in order to make connections between parts, they first have to become theoretical objects, abstracted from particular empirical cases to general types or classes. Particular instances need to be recognised as an exemplar of the general type. This leads to an argument that rather than assuming that learners will intuitively grasp the organisation of theoretical knowledge from concrete examples, they would be better introduced to the whole structural organisation from which they should identify exemplars. This is contrary to the dominant rhetoric around student-centred learning, where the curriculum is structured from the familiar to the esoteric, with an assumption that general principles can be recognised from the empirical examples. But what then is the logic and structure of professional knowledge?

As discussed in chapter 2, Trevelyan (2009) pointed out that there are relatively few studies of engineers in practice. Those that do exist (for example Bucciarelli, 1994; Faulkner, 2007; Johnson, 2009) all show a complex social process of negotiation, and messy uncertain knowledge relations. But they also recognise theoretical insights, if not necessarily in as much formal disciplinary analysis as seen in curriculum structures. Indeed Moore (2013a) argues that there is a shift from elaborating code (formal explication of the conceptual relations) in education to its restricted form (condensed and unarticulated) in the practice of the discipline. One of the limitations of this study is that it too is located in the curriculum, not in practice, and therefore substantially modifies the social influence and tends to 'sanitise' the theoretical needs of the tasks. But engineering design projects do attempt to mimic the complexity of practice. Within the limitations of the curriculum, they present the contextual uncertainty and complex integration inherent in professional practice. Therefore as Muller (2007) suggests, Bernstein's (2000) models of disciplinary structures provide an entry into professional knowledge structures.

Bernstein (2000, 2003d) distinguished between singulars and regions. He defined singulars as disciplines, separated and strongly insulated from other disciplines and from the mundane concerns of the everyday (strongly classified). Singulars look inwards towards themselves, concerned with defining coherent structures of meaning built on conceptual chains of reasoning. These are in turn defined by legitimated rules of internal rational connections. It is their insulation that gives them the power to define what counts as legitimate disciplinary knowledge. They refer only to external references in terms of themselves. He defined regions as constructed of recontextualised singulars, facing both inwards to their foundational singulars and outwards to the concerns of the world. Regionalization therefore represents a

weakening of the classification, both in terms of relations between singulars and in relations to the external referents.

For Bernstein, with roots in Durkheim (1995), the purpose of education is to induct adepts into systems of meaning that specialises consciousness, which develops an internal commitment to a system of meaning and structures identity. It is only once the inner (the sacred) has been specialised that it is safe to confront the outer, the profane (Beck & Young, 2005). This model positions singulars necessarily prior to regions, both in terms of knowledge production and in terms of transmission and acquisition of the inner consciousness, a commitment to the moral order of 'sacred' knowledge, albeit a more secular principle internal to any knowledge specialisation (Muller, 2011). This establishes the

Word before the world. (Muller, 2011, p. 16).

Beck and Young (2005) extended Bernstein's analysis of the inner and outer to professional education. They argue that a professional education develops a commitment to a sacred inner identity, and identity based on established disciplinary knowledge and a code of ethics. They claim that well-established professions coalesce into regions that resemble singulars, in that strong boundaries develop around the established body of professional knowledge. They argue that well-established professions maintain relative autonomy through specialising a professional identity and controlling access to the community of professionals by formal education and licensing structures. We can certainly recognise this organisation of knowledge within engineering curricula and curriculum reform debates over the years. The earliest curriculum debates in engineering were around strengthening the scientific foundations particularly at the start of the degree. Later the debates shifted towards engineering design, seen as the application of sciences to 'real world' contextual problems. The importance of a code of ethics is also evident in the conversations about engineering education.

By positioning singulars necessarily prior to regions, Bernstein (2000) made the production of specialised knowledge the province of singulars. His concern with the relation between context (or object of knowledge) and meaning was in the direction of generalising and abstracting beyond the context. Consequently his focus on the development of knowledge and the principles of organisation of knowledge was within singulars. He was less concerned with regions and the organising of knowledge for the purpose of specialising abstract and generalised knowledge to the particular contextual case of application. This model of professional knowledge describes knowledgeable action as the application of specialised (sacred) knowledge to solve the problems in the world (profane). But as the history of technology theorists have convincingly demonstrated, technological inventions did not all emerge out of established scientific knowledge (McClellan & Dorn, 2006), nor could technology have developed without any form of generalisable knowledge (Johnson, 2011; E. Layton, 1974).

In addition, what the idea of the knowledge base of regions being founded on inward-looking singulars and the idea of knowledge being applied to the world fail to recognise, is the manner in which the world acts back on the knowledge and our understanding of it. This

potentially feeds into the production of new knowledge. It speaks not only to the limitations of the social relations in the production of knowledge which neglects the contribution from the field of professional practice, but also to the neglect of the epistemic relations, the way in which the complexity of the real world responds regardless of how we think it might respond. This is an important argument that Wheelahan (2010) makes.

While singulars and regions provide some insight into the relations between inner systems of 'sacred' knowledge and outer concerns of the 'profane', this model provides little insight into the internal structuring principles of specialised knowledge itself.

### 3.3.2 Discourses and knowledge structures

It was only towards the end of his life when Bernstein (1995, 1999) turned more formally to articulating principles internal to the organisation of knowledge in the parent discourse. Bernstein saw two 'fractures' that he attempted to describe. The first relates to the specialisation and differentiation of knowledge, between the everyday and official knowledge. Bernstein called these horizontal and vertical discourses, respectively. He drew the second distinction within vertical discourses where he distinguished between knowledge structures. The first is based on a hierarchical development of knowledge (hierarchical knowledge structures), where new knowledge extends and subsumes prior knowledge and produces more condensed and abstracted concepts, epitomised in physics. The second is based on a horizontal development of knowledge where new knowledge accumulates alongside existing knowledge in the form of a new language (horizontal knowledge structures), epitomised by the social sciences. Although his work on discourses and knowledge structures appear to be ideal type descriptors, it is important when reading Bernstein to recognise that he always worked towards describing underpinning principles rather than ideal types (Moore, 2013a).

The basis of the distinction Bernstein made between discourses lies in their organising principles, either organised around the functional necessity of the context of its application in the case of horizontal discourses, or organised around meaning in the case of vertical discourses (Bernstein, 1999, pp. 72-80; Moore, 2013a; Muller, 2016). The most fundamental distinction is that horizontal discourses are trapped in their context of application; they are only relevant within particular contexts. Vertical discourses are transferable across contexts because they are based on a conceptual principle rather than a functional necessity. Moore (2013a) argued that education systems were necessarily about the transmission and acquisition of an elaborating code, which is associated with vertical discourses, whether they have hierarchical knowledge structures or horizontal knowledge structures.

Breier (2004) pointed out the difficulty of identifying *distinctly* horizontal or vertical discourses as types in her study of labour law. She drew on what she called 'localizing' or 'generalizing' strategies (after Dowling, 1998 cited in Breier, 2004) as a proxy for relating the general legal principle to the personal or specific experience of a particular legal case.

Gamble (2004) studied craft knowledge, which Bernstein (2000, p. 168) had positioned as a vertical rather than horizontal discourse, albeit on the cusp of horizontal discourse. She also sees the fundamental distinction as being the difference between the general and the particular. From this position she is able to define craft knowledge as a 'specialised' form of knowledge that is 'general' in the sense that in order to master the craft, one has to understand (albeit tacitly) that an artefact is a generalised 'type' of artefact subject to certain rules of form rather than as a 'particular' instance. A particular organisation of parts must conform to type to be considered a legitimate artefact.

In order to solve contextually specific problems, engineers recruit a range of knowledge. This study focuses only on the recruitment of vertical discourses, on one extreme the sciences, vertical discourses with hierarchical knowledge structures, on the other extreme case based knowledge, vertical discourses based on knowledge of 'types' much like the craft knowledge that Gamble (2004) studied. The former knowledge structures align with Abbott's (1988) mode of 'inference'. The organisation of the latter knowledge structure aligns with the organisation of what Abbott describes in his modes of diagnosis and treatment, and what Schön (1983) refers to in his repertoire of past sites, problems and solutions. A necessary familiarity with the way in which parts interact and function as an integrated unit, what D. Layton (1993) termed functional knowledge, also has resonances with this organisation of knowledge. Although associated with contextual knowledge, these theorists describe particular instances abstracted to a 'type'. This suggests vertical discourses rather than any assumption of horizontal discourses.

Muller (2007) and Maton (2014) have pointed out that Bernstein's work on describing disciplinary knowledge structures and their growth was in an early stage of development. Both have developed Bernstein's initial work on characterising knowledge structures, but by different routes. Muller (2007, 2009) worked more directly with Bernstein's vocabulary, introducing 'verticality' to describe the process of integrating and subsuming theories within hierarchical as well as horizontal knowledge structures. He used 'grammaticality' to describe the internal relation of concepts to one another within one particular disciplinary specialisation, and externally to describe the relation between theories and their external referents (Muller, 2007). He then pulled these concepts from the field of production into the field of recontextualisation as principles of curriculum logic in the form of conceptual coherence and contextual coherence respectively (Muller, 2009).

In contrast, Maton (2014) developed a new language in Legitimation Code Theory (LCT), arguing that LCT integrates and subsumes the work of both Bernstein and to some extent Bourdieu. Where Muller stayed true to Bernstein's construction of the pedagogic device, and developed different terminology in each field, Maton argues that LCT can be used at any level of the device, obviously with the appropriate specialisation that a project might need. I have chosen to work with LCT (Semantics), one of the dimensions of LCT that explicitly models relations between the general and the particular, and the condensation (integration) of meaning.

### 3.4 Legitimation Code Theory (LCT) and the professions

LCT consists of five dimensions, each based on two principles of legitimation. Only two of the dimensions have been significantly developed to date, LCT (Specialization) and LCT (Semantics)<sup>11</sup> (see Maton, 2014 for a comprehensive exposition of Specialization and Semantics). LCT (Specialization) compares the basis of legitimation of knowledge practices in terms of social relations (SR) and epistemic relations (ER). All practices include both SR and ER, but their relative significance within different practice varies, that is SR and ER vary independently along two continua, usually represented on the two axes of a Cartesian plane. LCT (Semantics) tends to focus on epistemic relations and compares the basis of legitimation of the epistemic relations in terms of their context dependence (semantic gravity, SG) and condensation of meaning within symbols, gestures etc (semantic density, SD). Although Semantics has been extended beyond epistemic relations to include for example axiological condensation (Maton, 2014, pp. 148-170), in this study the analysis is limited to the Semantics of the epistemic relations. In all dimensions of LCT, a stronger dependence on a particular principle of legitimation (for example ER or SG) is indicated by '+', and a weaker dependence on that principle by '-'. Therefore a practice that is legitimated by a less focus on ER and more dependence on SR is indicated by ER-/SR+, what has become known as a knower code, while a practice legitimated by both social and epistemic relations (ER+/SR+) is termed an elite code.

In a study of different design professions (engineering, architecture, media and fashion), engineering was identified as a knowledge code, indicating that legitimation of engineering practices is based far more on accumulation and application of knowledge (ER+) than on personal attributes (SR-). By comparison, fashion design was categorised as a knower code because a sense of taste and style (SR+) play a far stronger role in legitimation than formal knowledge (ER-). Architecture and media design were categorised as elite codes (ER+/SR+) (Carvalho et al., 2009). Engineering design categorised as a knowledge code (ER+/SR-) is somewhat contentious; in a study of the assessment of tasks undertaken by student engineers working in practice, Wolff and Hoffman (2014) argued that when tasks become more complex there is a tendency for the social relations to become more significant and in some cases to dominate the epistemic relations, a shift from a knowledge code to a knower code.

LCT (Semantics) provides an alternative lens on knowledge practices. Semantic gravity, the relative dependence of meaning on context, has an intuitive resonance with the relation of abstract knowledge (transferable across contexts) to problems emergent from particular contextual specifics. In this relation the knowledge in its abstract and generalisable form would be coded with stronger semantic gravity, because it is intended to transfer across contexts, having less dependence on any particular context to make sense. On the other hand the problem is specific to a particular context, and understanding the problem is very strongly dependent on that particular context, and is therefore coded as having a stronger semantic

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<sup>11</sup> There has more recently been a growing interest in LCT (Autonomy) and LCT (Temporality), which has not been included in this study.

gravity. Semantic density, the relative condensation of meaning in symbols, gestures etc, suggests the relative complexity of ideas (and things) and their relation to each other. On one pole of the continuum of semantic density lies a single idea or concept, disconnected from its intellectual field, coded as weaker semantic density. On the other pole is the condensation of multiple ideas into a single term, phrase or equation. Maton (2014) uses the example of the word gold, a word that has significantly different semantic density in different communities of practice. To the layperson, 'gold' condenses relatively few concepts (SD-), while to a chemist 'gold' condenses substantially more specialised meaning (SD+). In relation to vocational education and design in particular, Shay and Steyn (2016) introduce the strengthening of semantic density as the *compounding* of meaning, the integration of terminology, with practices and forms of representation, on a scale of descriptive (SD-) to symbolic (SD+). Semantic density has more recently been described in terms of relative complexity, where SD+ indicates complex relations between multiple components or concepts and SD- indicates fewer relations and consequently less complex meaning (Maton & Doran, 2017).

Although specialization codes are clearly significant in engineering practice and in engineering education, this is a study of the epistemic relations. LCT (Semantics), with semantic gravity providing an analytical tool for analysing the significance of context in professional reasoning, and semantic density providing some measure of complexity, was therefore selected as an appropriate analytic tool to address the research questions. However, like most social realist accounts of sociology of education, many LCT studies have tended to underplay the significance of complexity inherent in material detail by focussing on the SG+/SD- and SG-/SD+ semantic codes. While neither the intention of semantics, nor theoretically inevitable (Maton, 2013 is very clear that the SG+/SD+ and SG-/SD- semantic codes are possibilities even if not normally illustrated) there is nonetheless a *tendency* to associate weaker semantic gravity (context independence) with stronger semantic density (more complex meanings) (see for example Blackie, 2014; Maton, 2013). The case of engineering design, where the context is central to meaning (stronger semantic gravity) and adds significant complexity to the problem (stronger semantic density), provides a theoretically possible, but an as yet unexamined empirical case.

LCT tends to prioritise 'abstract' knowledge over contextual knowledge. There is a tendency to associate weaker semantic gravity (context independence) with stronger semantic density (more complex meanings) (see for example Blackie, 2014; Maton, 2013). The case of engineering design, where the context is central to meaning (stronger semantic gravity) and adds significant complexity to the problem (stronger semantic density), provides a theoretically possible, but an as yet unexamined empirical case. In order to facilitate readability, the elaboration and development of LCT (Semantics) is presented in chapter 6 along with the analysis of the data.

## **Chapter 4 Research Design**

The practical problem addressed in this study is the apparent disjuncture between engineering education and professional engineering practice reported as the under-preparedness of graduate engineers when they enter their profession. Much of the current research in engineering education addresses aspects of doing and being (see for example Adams et al., 2011). The research and associated educational reforms involving more integrated practices and a focus on enabling skills appear to have resulted in an improved perception by employers of graduates' personal attributes such as communication and teamwork skills (R. King, 2008). But the challenge faced by graduate engineers to translate academic knowledge into useful insights for solving professional problems, reported since the early part of the twentieth century (C. R. Mann, 1918) persists today (J. King, 2007; R. King, 2008). It is this problem, the application of academic knowledge in the solution of professional problems, that this study addresses.

As noted in the previous chapter, the problem is addressed from within the social realist approach to the sociology of education (Moore, 2013b), a theoretical tradition that attempts to make knowledge visible by making it the object of study (Maton, 2014; Muller, 2000; Wheelahan, 2010). The theoretical position is founded on the work of Basil Bernstein, whose intellectual project was to articulate models of transmission and acquisition of discursive practices that could account for the persistent exclusion of certain sectors of society from access to specialised knowledge, its associated symbolic power and social advancement, as well as the potential for change (Bernstein, 2000). But it is his crucial distinction between knowledge as an established intellectual field and knowledge recontextualised into curriculum (Bernstein, 2003d), and his later work on knowledge discourses and knowledge structures (Bernstein, 1999, 2001) that informs this study. The study also draws on other scholars who have extended his work, including especially Muller (2009, 2016) and Maton (2014).

Following the basics of qualitative research design, this chapter presents the elements of research design suggested by, for example Maxwell (2012) and Durrheim (1999). Research design is therefore the iterative and interdependent relationship between the purpose or goal, the formalised research question/s that address that goal, informed by the conceptual (or theoretical) framework into which the research falls. These elements are both informed by and inform the methods of data collection and analysis, under consideration and constraints of reliability and validity.

### **4.1 Research questions**

The empirical problem, designing curricula for teaching and learning the skills to apply that knowledge to solve contextually embedded problems faced in professional practice, was

recast into theoretical form from a Bernsteinian perspective. Taking engineering design as a model of professional reasoning, this is a study of the relations between abstract knowledge (specialised theoretical concepts related by internal rules of conceptual coherence) and contextually embedded problems, and the logic of curricula that develop these relations. Two specific research questions were developed with a view to articulating the nature of professional reasoning for the purpose of informing more intentional curricula.

1. What is the nature of the reasoning involved when specialised disciplinary knowledge is recruited to develop specific, often concrete, artefacts?
2. What is the logic of progression in a trajectory of engineering design tasks in terms of the relation between knowledge and artefact?

This research is intended to contribute both to the empirical problem of developing engineering design curricula for teaching and learning to use knowledge in engineering design, as well as to the theoretical conceptualisation of what Bernstein called 'regions' (Bernstein, 2000).

## 4.2 Methodology

I use the term methodology here in the same sense as Crotty (1998), as a strategy that draws together the research design and provides the reasoning for the selection of data and methods employed in the research. The methodology followed in this study is similar to the methodology that Bernstein used to approach his research project over the years. Although Bernstein was not particularly clear about his methodology, especially in his earlier work, in his final book he does provide a retrospective reflection on the research process that he followed throughout his career (Bernstein, 2000, pp. 123-126 and 131-139).

Central to Bernstein's methodology is a distinction between what he called an internal language of description ( $L^1$ ), or the abstract concepts internal to the model, and an external language of description ( $L^2$ ), or the precise descriptors by which these concepts can be recognised in an empirical context, specialised to that context.  $L^1$  provides the internal logic of the theoretical model, the syntax (sets of theoretical concepts) and the grammar (rules which define the legitimate ways in which the theoretical concepts can be logically related).  $L^2$  provides the external logic, the relations between  $L^1$  and the empirical case.  $L^2$  defines the grammar or rules that link  $L^1$  and empirical data.  $L^2$ , the external language of description, is a set of descriptive principles for transforming the information available in the empirical context into theoretically relevant data, without constraining the data to what was defined by the theory. In other words, to operationalize the abstract concepts ( $L^1$ ) in any specific empirical setting requires the development of a specific 'translation device' ( $L^2$ ), or what Moore and Muller called a 'data near device'.

The external language must not only be able to describe what is outside the theory in terms relevant to the theory, but also somehow be capable of recognising what is beyond the theory. It must submit to an external ontological imperative that allows that which is outside to 'announce

itself' (loc cit), and hence open the categories of the external language, but also the conceptual relations of the internal, to possible modification. (Moore & Muller, 2002, p. 634)

The external language of description is critical to the validity of the research findings. It needs to be precise enough to recognise in an empirical setting what is relevant to the theory and what is not. Yet it needs to be sufficiently open to recognise not only what the conceptual theory predicts, but also what it does not. It is the 'discursive gaps' between the model ( $L^1$ ) and the principles of description ( $L^2$ ) (Moore & Muller, 2002), and between the excess of an empirical setting (real context) and the construction of data extracted from that context (Ensor & Hoadley, 2004) that affords data the potential to modify the theory.

In Bernstein's inimitable style, the complexity of this task is illustrated in the contradictory instructions for the development of an external language of description.

The external language of description ( $L^2$ ) must be derived from the internal language, otherwise it will not be possible for this internal language to describe anything except itself. (Bernstein, 2000, p. 135)

but

Crucial to the procedure is that it [ $L^2$ ] is constructed independently of the  $L^1$ , that is, independent of the theory and the derived model. (Bernstein, 2000, p. 138)

At the root of this contradiction lies the dialectical relation between the internal conceptual language and translation device for the construction of data from the empirical context. The external language of description relates to the theoretical model, but needs to be sufficiently independent of it to allow the data to challenge the model.

This methodology philosophically aligns with the social realist theoretical perspective (Moore, 2013b; Sayer, 2010). From a social realist position our knowledge of the world, or the conceptual models that we create in order to make sense of the world, are transitive and socially mediated. But, because the world itself is independent of our knowledge of it, our conceptual models are not constructed independently of the world they explain. Reality acts back on our understanding of it and operates to correct our conceptual models. Epistemological constructivism is weakened in the face of ontological realism.

The output of the research is a theoretically informed conceptual model, developed between building theoretical relations and empirical specifics. The model should be conceptually coherent within the discipline to which it contributes. It should be theoretically abstract enough to transfer across contexts and describe phenomena beyond the specific empirical context of its development, and at the same time allow specialisation into specific empirical cases.

### **4.2.1 Theoretical framework**

The theoretical framework in which this study is located, the social realist approach to sociology of education founded on the work of Basil Bernstein, has been elaborated in detail in the previous chapter. It also guides the methodological choices as described above.

The internal language of description ( $L^1$ ), the concepts drawn on to develop a model to describe the knowledge relations involved when specialised disciplinary knowledge is recruited to solve contextually embedded problems, was drawn from the theoretical field in which the study is located. This field provided insights into the distinction between the structures of specialised knowledge, strongly insulated from external concerns of the world. It provided ways of describing the relations internal to the specialisation and external to the knowledge, a conceptualisation of meaning as the imposition of networks of conceptual relations reflected onto external artefacts. It provided a conceptual language with which to investigate notions of complexity.

But, because the concepts available in the theoretical framework proved inadequate to describe important features of the data, models drawn for design thinking (Schön, 1983; Simon, 1981) and professional knowledge more generally (Abbott, 1988) were translated into terms coherent with the Bernsteinian framework – but extending it. A central aspect of validity relates to the coherence of the theoretical concepts mobilised for the study within the broader intellectual field.

#### 4.2.2 Data selection, collection and analysis

The methodology has much in common with case study methodologies. It is qualitative research, where the case/s selected are intended to study a particular phenomenon in depth, but the phenomenon is embedded in a complex context, and the boundaries of the context are unclear and need to be defined for the study. Data selection, collection and analysis are informed by theoretical insights, and the purpose of the study is to describe significant features extracted from the context and to develop and explain causal links (Yin, 2009). But where triangulation between different data sources is a key element of 'reliability' in case study research (Yin, 2009), the methodology used in this study follows the argument presented by Sayer (2010) in relation to the realist approach to social science. Sayer argues that regularity between variables is inadequate to make causal claims and instead describes a form of inference called *retroduction*, “in which events are explained by postulating (and identifying) mechanisms which are capable of producing them” (Sayer, 2010, p. 107). He explains a social realist method of research as the search for causal explanations for the emergence of certain observations or experiences, not as regularities but as possibilities under certain circumstances. Social realist methods develop the relations between a theoretical model (causal mechanisms at the level of the *real*) and observations or experiences constructed as data (the selection of *empirical* instances from particular emergences of *actual* events under the confluence of causal mechanisms) (Sayer, 2010).

The importance of the case selected relates to aspects of generalisability of the research. The social realist position locates generalisability beyond the case in the retroduction of causal mechanisms, descriptions that are sufficiently abstracted from specific instances to generalise across contexts. Flyvbjerg (2001), in his example of the black swan, points out that carefully

selected cases can be generalisable in their own right; a single black swan is sufficient to refute the general claim that all swans are white.

### ***The case of design in the engineering curriculum***

The case selected for this study is engineering, a so-called 'science-based' profession in which the application of well established bodies of scientific knowledge is likely to be more evident in solving professional problems. Chapter 2 showed that within an engineering curriculum, engineering design is seen to epitomise the practice of engineering as the application of science to solve specific problems and therefore offers what Flyvbjerg (2006) calls a 'paradigmatic' case, an exemplar of a particular practice.

The specific cases selected were engineering design curriculum trajectories located in two different engineering curricula, mechanical engineering and civil engineering at the University of Cape Town. The selection of the site was due to both ease of access and because engineering design is organised differently in the two curricula. In mechanical engineering, engineering design is a distinct subject stream, and consists of a sequence of four courses, a whole (full year) second-year course (Design 1), a whole third-year course (Design 2), and two half (semester) courses in fourth year (Product Design followed by Systems Design). In civil engineering, engineering design is embedded within disciplinary courses that include some sort of design project in addition to the standard conceptual knowledge examination. The program culminates in a final semester five-week block design course. Since the research began with a basic assumption that engineering design requires an inherently different knowledge relation than do typical science and engineering science subjects, the different organisation of design in the two curricula (one embedded and the other distinct) offered an interesting basis for comparison, maximising the variation across the two cases (Flyvbjerg, 2006).

### ***Units of analysis***

Where the science and engineering science subjects are structured around disciplinary theories, or coherent systems of conceptual meaning, engineering design is usually structured around design projects. When engineering design is a course in its own right as in the mechanical engineering curriculum, the assessment events tend to be one or more design projects, in addition to an examination. When engineering design is embedded in disciplinary subjects, the design component consists of a design project, and the examination focuses on the disciplinary knowledge. The unit of analysis for this study was therefore the design project, and the data set is made up of sequences of design projects through each curriculum.

The information collected for each project consisted of the 'design brief' and solution possibilities. The 'design brief' is the project instructions presented to the students. It is the project description, which includes a user need set within a context constructed by the lecturer. The design brief may include explicit requirements for a solution and constraints on a solution, or leave these open to interpretation from the description of the context. Where possible a solution memorandum was used in order to understand the knowledge

requirements for the solution. However, because design projects are usually open-ended with divergent solutions, it is unusual for the design to have a single prescribed solution, and in most cases there is no clear solution memorandum. Instead examples of 'good' student submissions (judged on the basis of the grade assigned to the task) were used as a proxy for a solution memorandum. Where possible, assessment comments on these designs were considered in terms of what they meant for expectations of an adequate solution, not as measures of knowledge acquisition. Although student work is located in the field of reproduction from a Bernsteinian perspective, these solutions were viewed as curriculum texts, or samples of solutions, rather than in terms of any form of student learning attainment. The construction of the data therefore viewed both the design brief and the solution possibilities as curriculum texts located in Bernstein's field of recontextualisation, rather than as products of Bernstein's field of reproduction.

Each project was analysed in terms of four distinct units of analysis. The brief provided a description of the *context* in which a designed artefact was expected to function, and the requirements of the *artefact* itself. The memorandum provided an indication of the details of the designed artefact presented as a completed *solution*, as well as the nature of the *inferences* required to develop a solution. These units of analysis emerged as part of the initial analysis of engineering design in relation to the established models of design (Schön, 1983; Simon, 1981) and professional knowledge (Abbott, 1988) which is presented in chapter 5.

### **Data Selection**

A wide range of projects was available for selection. The projects selected for the research were chosen in the first instance by a sequence of subjects that are representative of progression in each of the curricula. From there, the lecturers in each subject were consulted in an effort to identify specific design projects representative of engineering design.

Table 4.1 shows the design projects selected, their location in the curriculum sequence, and the name of the courses from which they were selected. In Mechanical Engineering a sequence of three design projects was selected in each of Design I and Design II. They represent a progression of representative projects through the year. The Product Design and Systems Design courses are each structured around a single design project. In Civil Engineering, only the final (capstone) project is located in an engineering design course, and the course was structured around a major design project that ran full time for five weeks. Prior to that project, all design projects were embedded in disciplinary courses. Because the civil engineering curriculum is loosely structured around a structural and urban stream of courses, one course with its associated design project was selected from each stream per semester. Details of each project are provided in appendix 2.

**Table 4.1 Data: design projects and trajectories**

	Civil Engineering		Mechanical Engineering
	Structures	Urban	
<b>YR2</b> S1			<b>M1</b> Bearing selection and mounting <b>M2</b> PRS for domestic appliances
<b>YR2</b> S2	<b>S1</b> Parking structure (Structures I)	<b>U1</b> Bikeshare scheme (Engineering Camp)	<b>M3</b> Gearbox design (Design I)
<b>YR3</b> S1	<b>S2</b> Steel shed (Structures II)	<b>U2</b> Flood attenuation culvert (Hydrology)	<b>M4</b> Wheel support assembly <b>M5</b> Multi-tool
<b>YR3</b> S2	<b>S3</b> Concrete slab (Structures III)	<b>U3</b> Sewage reticulation (Urban Water Services)	<b>M6</b> CCTV tower (Design II)
<b>YR4</b> S1	<b>S4</b> Parking garage (Structures IV)	<b>U4</b> Emmarentia Dam road (Urban Design and Management)	<b>M7</b> Multitask micro-machine (Product Design)
<b>YR4</b> S2	<b>C5</b> Future foreshore (Design Project)		<b>M8</b> Power plant specification (Systems Design)

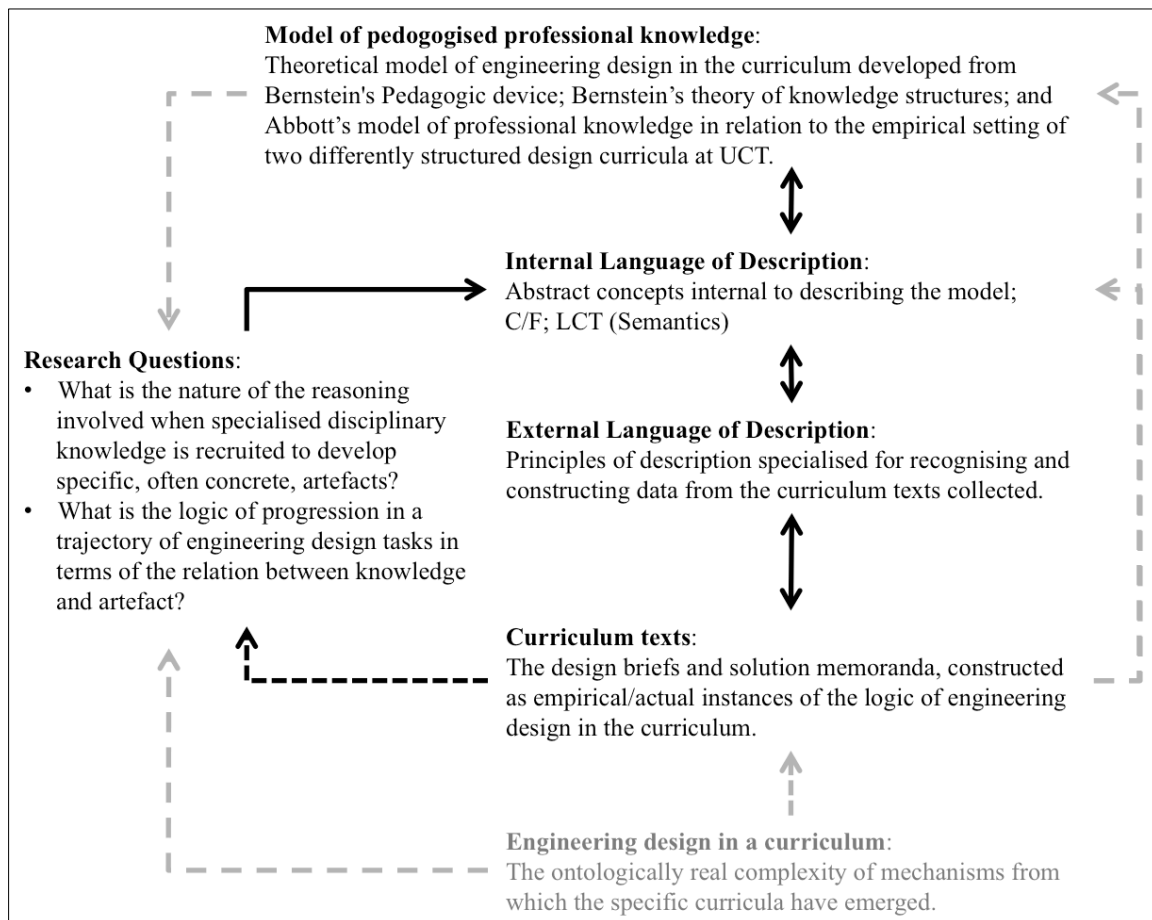
**Data construction and analysis**

The development of the external language of description ( $L^2$ ), the principles by which the empirical information is constructed into data, also provides the basis of comparison between data. Maton and Chen (2016) describe this complex and iterative process, which begins with an immersion in the empirical site and selected information. The information is described in its own terms, but is simultaneously theory-laden (neither theory-neutral nor theory-determined) but inevitably informed by the theoretical backdrop (Sayer, 2010), in this case social realist tradition in sociology of education. Relevant theoretical concepts ( $L^1$ ) begin to emerge from the empirical descriptions in relation with the theoretical framework.

In this study, the boundedness of specialised disciplinary knowledge was different to the integration and openness of the knowledge in relation to an artefact (classification). The way in which knowledge was prescribed or left to the discretion of the students was clear in the design briefs (framing). There were clear differences in how the framing functioned to simplify both the contextual features of the task, and the conceptual requirements of the task, but independently of each other. Semantic density offered a conceptual tool to describe relative complexity, but not adequately to distinguish between contextual and conceptual features. Semantic gravity provided a route into this distinction, but inadequately on its own.

With empirical descriptions on one hand and a battery of theoretical concepts on the other, the external languages of description ( $L^2$ ) began to be developed. They required on-going

refinement as empirical data and theoretical concepts were drawn into relation with one another, more data challenging existing categories and more nuanced insights into the concepts refining the data categorisation. It was during this process that the inadequacies of the  $L^1$  became evident, requiring extension. The data had more to say than the theory could describe. This process is illustrated in figure 4.1.



**Figure 4.1 Overview of the research design**

The development of the external languages of description will be presented in the analysis in Chapter 6. This has been done for the sake of readability, keeping the details of the conceptual relations and the development of the data analysis together, and because the development of  $L^2$  is an analytical output rather than a theoretical imposition on the data.

Following the development of the theoretical model ( $L^1$ ) into five significant conceptual elements in conjunction with the translation device ( $L^2$ ), each of the four units of analysis (the context, the artefact, the solution and the inferences) were coded for each of the 17 design projects. The full analysis is presented in appendix 2. In each case the project was analysed in its own right to determine its structure and organisation of knowledge (research question 1). Each project was then considered in relation to the other projects in terms of its position in the sequence of projects to determine rules of progression (research question 2).

### 4.2.3 Validity and reliability

The problems of modelling reliability and validity on the norms of quantitative research are well established for qualitative research (see for example Corbin & Strauss, 2008; Denzin & Lincoln, 2005; Flyvbjerg, 2006; Lincoln & Guba, 1985). Drawing on Golafshani's (2003) discussion, *reliability* relates to credibility in terms of neutrality or conformability, consistency or dependability and applicability or transferability, and *validity* relates to quality, rigour and trustworthiness.

An important aspect of the consistency and rigour of this research lies in its conceptual coherence within the intellectual tradition, and the internal coherence between concepts used to describe and analyse the data. Even when models outside of the tradition have been incorporated, they have been translated into terms consistent with the theoretical framework.

The way in which the analysis was conducted, which allowed the data to 'speak back' to the theory through the  $L^2$ , to push beyond the prescriptions of the model, is an argument for the neutrality of the research. This required a commitment to both the coherence of the theoretical framework and to the integrity of the data. One of the important aspects behind the credibility of the extension of the theory lies in the symmetry of the  $L^2$  that was developed. The new aspects of the theory were developed as a mirror to the existing theoretical concepts in relation to the data that extended beyond the theory.

The question of generalisability lies in the social realist argument that the specifics of the empirical case have been sufficiently abstracted (simplified from and lifted out of the complexity of the concrete example) to apply to other cases. The rigorous construction of the external language of description provides a means of comparison between cases, and the development of the theoretical concepts offers new insights for other contexts.

Nonetheless, the analysis is based on an interpretation of the empirical case, albeit in terms of a rigorous, descriptive  $L^2$ . It is neither complete, nor neutral. In an effort to be clear about the interpretations that I have made, I have provided rich detailed descriptions of each project, each concept, each category and the reasoning for the coding. The full coding of each project is presented in appendix 2, but there are also elaborations in the narratives presented in chapters 5 and 6 as appropriate.

## 4.3 Research Ethics

Prior to the commencement of this study, the University in accordance with their requirements for ethical research granted ethical clearance. This included a formal presentation of the research proposal, explicit consideration of any ethical dimensions of the study and associated processes for informed consent and practices to protect anonymity. The informed consent forms approved by the relevant committee are included in appendix 1.

Beyond the formal procedures there are two elements of ethics to this research project. The first relates to the commitment to rigour, truth and objectivity (as far as possible) in the research. The second relates to the potential to cause harm to any of the participants in the research. In terms of the first aspect, all principles of research as laid down by university policy, basic research textbooks and those implicit in the intellectual field have been adhered to.

In terms of the second aspect, although this project relies predominantly on the study of documents rather than on human subjects, it is none the less recognised that this research is quite closely linked to human subjects and perhaps requires more explicit sensitivity, particularly in terms of its interpretive nature. Of particular import are:

- sensitivity to the professions of civil and mechanical engineering and its practitioners
- sensitivity to the potential to cause harm to my colleagues and their students from whom the documents have been sourced.

My colleagues produced the documents analysed in this study. I have relied on their trust in my integrity for access to these documents, and have in cases needed to clarify with them aspects of the design projects. While my primary purpose has been research, this information simultaneously straddles our shared practice. I face a particular ethical dilemma in terms of my position as a researcher who owes allegiance to the generosity of my participants and my role as academic development lecturer in the department with responsibility for improving teaching and learning and curriculum practices in the department. In the later role I find myself in the difficult position of having what might be considered illegitimate access to potentially bad educational practices. This needs to be dealt with in a very sensitive manner. Two measures were implemented, the first relating to anonymity and the second to informed consent and voluntary participation.

The simplest solution of maintaining anonymity has not been entirely possible in a small department where the level of analytical detail required makes identification of those responsible for the practices obvious to a number of people. What remained was full disclosure at the outset, in this context involving a discussion of the use of the data with my colleagues. Implementing voluntary participation has meant allowing colleagues the opportunity to request the omission of any data or associated interpretations should they perceive it as potentially incriminating. Therefore the analysis and discussion of the design projects were presented to the participants for their approval prior to submission of the thesis.

The use of student scripts as proxies for a range of potential design solutions also required informed consent. However, in the case of student solutions, anonymity is far more straightforward to assure. Solutions do not include personal details and in each project many of potential solutions exist, not linked to any one student. In all cases where student work has been used, it is work considered to be available to scrutiny by external parties. Where student work has been presented in the document, the respective students have granted consent.

## Chapter 5 The capstone design projects

The analysis is presented in two chapters. The first, chapter 5, follows a narrative style, describing and comparing the two capstone design projects in relation to models of design (Schön, 1983; Simon, 1981) and modalities of professional action (Abbott, 1988). These models were introduced in chapter 2, but are elaborated in section 5.2. The effect of recontextualising choices defined in terms of Bernstein's (2000) concept of framing (described in chapter 3) are woven into the narrative. This chapter functions to illustrate the key aspects that were identified as significant within the data and sets up the development of the units of analysis for the following chapter. Chapter 6 develops a fine-grain analysis of all the projects investigated based on a modified LCT (Semantics) (Maton, 2014) analysis and addresses the question of progression.

The analysis in this chapter focuses on the two capstone design projects. Each project represents the endpoint of design in an engineering curriculum. In the case of mechanical engineering, it is the eighth in a sequence of 8 projects. In the case of civil engineering it is the ninth project following two parallel trajectories of 4 projects each; one trajectory in structural engineering and the other in what is loosely termed urban engineering: civil engineering directed towards the urban environment. Although many of the aspects presented in this chapter were identified in other projects, for the sake of a coherent overview, they are presented in relation to the two capstone design projects.

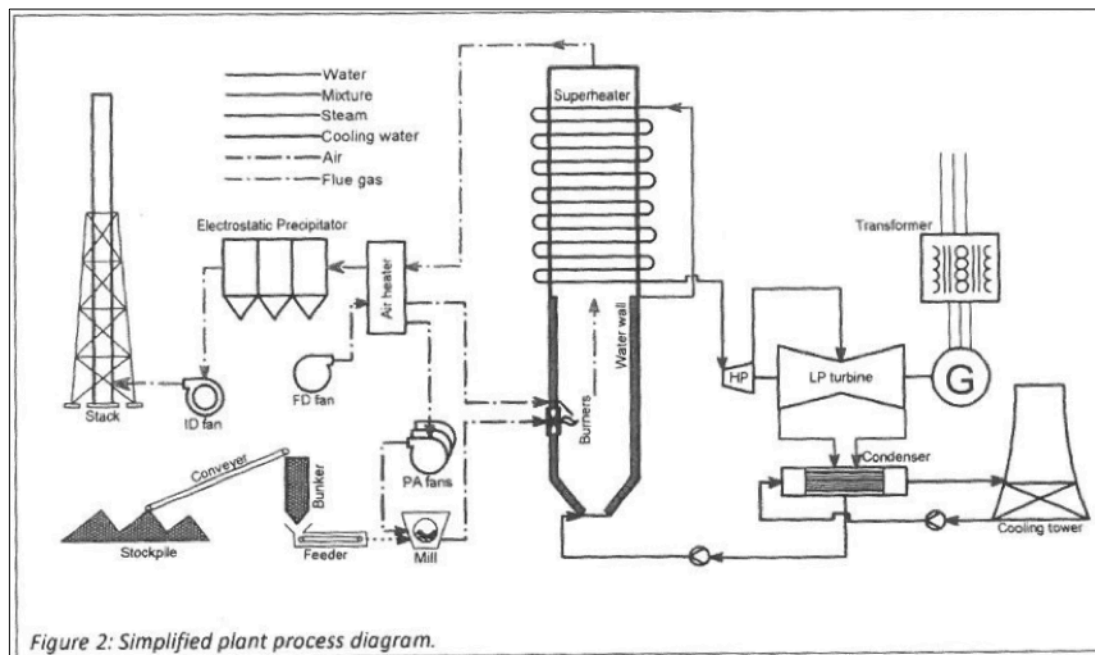
The chapter begins with a description of the two design projects followed by the theoretical basis of this analysis. The analysis covers a comparison of the two design briefs followed by a comparison of representative solutions and the reasoning that led to the solutions. This study is not an analysis of the design process, although aspects of conceptual design (related to the prescription of an artefact type) and detailed design (the development of a specific artefact proposal) do align with what have been termed *context description* and *artefact prescription* in conceptual design, and *inference* and *solution specification* in detailed design.

### 5.1 Project descriptions: An overview of the courses and projects

#### 5.1.1 M8: Power plant specification

In mechanical engineering the final project (M8) was the development of specifications for a single unit coal-fired power plant based on a simplified Rankine cycle, shown in Figure 5.1. Student teams were assigned a specified output power of their plant and were required to determine the basic design parameters that would achieve this power output. The required specifications included flow rates of the main material streams (water/steam, coal and air); operating temperatures and pressures (along with various thermodynamic properties required to determine these values) at the inlet and outlet of the various components in the system; and

the dimensions of some of the main functional parts (for example cooling pipe lengths and diameters, tower and boiler heights; pump capacities). The design did not include the detailing and drawing of the comprehensive artefact, and excluded detailed component design of, for example, joints, shafts or bearing selections. A number of engineering design techniques for tracing interfaces, cost optimisation and critical failure analysis were introduced in the course and required in the design. Rather than a comprehensive design of a power plant, the project was structured around key design concepts and skills in the context of a limited number of tightly defined aspects of the power plant.



**Figure 5.1 Data M8: power plant process diagram**

The substantive submissions took the form of four group submissions relating to the overall system and four individual submissions relating to each subsystem design. Each submission followed a strict format and numbering system based on a hierarchical sequence between system and subsystems, typical of engineering practice. Marking was done against a precise memorandum set up for each report, including conforming to format and an acceptable level of accuracy of all calculations. Because the solutions were convergent in most instances, teaching assistants under the supervision of the lecturer were able to mark assignments. The grade was based on the successful implementation of the prescribed design tools and the accuracy of the performance predictions based on prescribed engineering models.

The project was developed over 12 weeks within a 12-credit semester course (notionally 120 hours of work). Each week students were introduced to systems design concepts in a 45-minute lecture and it was intended that they use the concepts to develop their designs during a 3-hour tutorial session, and an additional 6-7 hours unsupervised time each week. Students completed the project in teams of seven through a combination of individual and team assignments. The lecturer had prescribed seven subsystems. The individual work related to the subsystem that was assigned to each student, while the integration into the full system was a team assignment. The sequence of work on the project was explicitly controlled

through interim tasks and reports prescribed each week, linked clearly to lecture input in a Gantt chart representing the flow of lecture content and design tasks and their interrelationships. This chart formed part of the course documentation handed out at the beginning of the course.

### 5.1.2 C5: Future foreshore

The civil engineering final project (C5) was a precinct development. Each year a different local precinct is identified for development. In this project the precinct was the Cape Town foreshore area, a piece of land between the centre of Cape Town, the harbour, and a large tourist centre, as shown in figure 5.2. Students were required to propose an overall development plan to improve the precinct, including detailing the design of a number of key infrastructural elements.



**Figure 5.2 Data C5: Future foreshore precinct**

The precinct plan was developed by a group of five students, and each member of the group selected an individual infrastructure element within the precinct to develop in technical detail in relation to the precinct plan. Typical infrastructural elements selected by students included among others multi-storey buildings, on/off-ramps to link the incomplete elevated freeway system with the existing road network, integrated public transport systems, water/sewage/stormwater reticulation systems, basement and retaining structures. The submissions included plan and detailed technical drawings, very limited narrative of the key design decisions and an appendix detailing the design calculations. The final assessment was based on an individual oral presentation and defence of the design to a panel of experts. An internal and external examiner considered expert in the main civil engineering sub-discipline associated with each student's detailed design were included in the assessment oral. Because the solutions were diverse, the designs were assessed based on a professional judgement of adequacy, rather than a rigorous check for accuracy.

The civil engineering course was run in a full-time block-course format over five weeks. At 24 credits (240 hours) the course is allocated twice the time of the mechanical engineering course, with a notional expectation of 48 hours per week. Although there were no formal lectures, there were ad hoc meetings where course details were elaborated and guest speakers presented information on various topics. The project was divided into three phases, two weeks of planning done as a team, and two weeks of individual detailed design of an infrastructural element. The final week was intended for review and revision of both planning and detailing phases prior to the submission for evaluation.

Both design projects represent the endpoint of a design trajectory within different engineering degree programs. Both projects involve the design of extremely complex engineering artefacts, at both an overall system level (high level analysis in M8 and precinct development plan in C5) and a more detailed subsystem level (subsystem specification in M8 and technical design of an infrastructural element in C5), with an expectation of iterations between the two levels. But the way in which the two projects were run in the different courses represent vastly different recontextualising choices, as will be shown in this chapter.

## **5.2 Analytical tools: Models of design and professional reasoning**

As indicated in chapter 2, there is not agreement on any particular design process. Although drawing on some key components of design processes, this study does not attempt to define or develop these processes. This is rather a study of knowledge and the nature of reasoning, especially between concrete particulars and theoretical generalisations. The analysis of the capstone designs in this chapter is presented in relation to insights from models of professional reasoning (Abbott, 1988) and design (Schön, 1983; Simon, 1981), and to some extent informed by Winch's (2010) elaboration of inferential reasoning within professions and vocations. Abbott (1988) identified the importance of recognising different organisational structures of knowledge. Simon (1981) and Schön (1983) emphasise a distinction between the context (outer environment/problem context) and the artefact (inner environment/solution), but recognise that an artefact always evolves in response to a context. Winch's (2010) elaboration of inferential reasoning within professional and vocations, although more tacit in the analysis, helps to integrate and link ideas inadequate to describe the data.

Smeby and Vågan (2008) argued that the inability of recently graduated professionals to apply the theoretical knowledge learned in their studies to the practical problems that they face in practice is not because of inadequacies in the knowledge base, but rather because knowledge in the academy is not readily applicable in practice. Academic knowledge needs to be recontextualised for application in practice. Abbott's (1988) formal distinction between the organisation of knowledge in the academy, based on logically coherent conceptual relations, and the organisation of practical knowledge of cases, based on typologies of diagnostic problems and treatment solutions, provides insight into their observation.

Abbott (1988) identified three modes of professional action: diagnosis, treatment and inference. Diagnosis and treatment are based on case knowledge organised by prevalence and efficacy respectively. Although ordered differently, both represent reasoning about external ontological referents; case types defined within professions. Abbott's (1988) third mode of professional action, inference, is based on knowledge organised fundamentally differently:

A profession's formal knowledge system is ordered by abstractions alone. Like any knowledge it is organised into a classification system and an inferential system. The classification, however, is quite unlike the diagnostic and treatment classifications. It is not organised from common to esoteric or from treatable to recalcitrant. Rather it is organised along logically consistent, rationally conceptualized dimensions. ... While these resemble the dimensions of the diagnostic classification, they are in fact more formal and rationalised. ... The character of the abstract classification system is thus dictated by its custodians, the academics, whose criteria are not practical clarity and efficacy, but logical consistency and rationality. Professional knowledge exists, in academia, in a peculiarly disassembled state that prevents its use. (Abbott, 1988, p. 53)

For the purposes of the analysis in this chapter I have called diagnosis and treatment modes of reasoning about material relations, how we make sense of the material details of the world. I have referred to inference, the mode of reasoning founded on abstract concepts whose rules of combination are defined within a disciplinary specialisation, as symbolic relations. Material relations concern the way in which we make sense of an external object in response to the external, ontologically real object. Symbolic relations refer to the formal rational conceptual links between concepts defined within any intellectual field of disciplinary knowledge and concerns the way we make sense of disciplinary concepts defined within the field in relation to each other. In chapter 6 I will develop material relations into what Maton (2014) calls ontic relations (relations “between knowledge and its objects of study” (Maton, 2014, p. 175)) and symbolic relations into discursive relations (“between knowledge and other knowledges” (Maton, 2014, p. 175)). I have chosen not to introduce Maton's terminology in this chapter because I want to stay closer to Abbott's ideas, and because an alternative social realist terminology was available in Muller's (2009) distinction between contextual and conceptual coherence, which seems closer to the concerns of Schön (1983) and Simon (1981), also used in this chapter.

Where Abbott (1988) is interested in the distinction between different organisations of knowledge, Winch (2010) is more concerned with the coherence of reasoning within professions/vocations based on relations between knowledge, skills, procedures and case examples, all founded on professional norms. What became evident in the data was that diagnosis and treatment alone are inadequate to describe the nature of reasoning, and that a translation from contextual features into symbolic representations is required for theoretical inference, suggesting a co-mingling of Abbott's modes of reasoning, more consistent with Winch's (2010) account of reasoning. Nonetheless, for this study the distinctions that Abbott (1988) makes between his modes of reasoning, based on the organisation of knowledge, provide the basis of significant aspects to the nature of professional reasoning.

The distinction between context and artefact, a central tenet of both Schön (1983) and Simon's (1981) models of design, provides an additional analytical lens. Both attest to the importance of the artefact development in conjunction with the context, largely concerned

with material relations. Although Schön (1983, p. 273) does allude to designs cohering around 'overarching theories' informed by professional norms, Simon (1981) is far more explicit about the role of disciplinary knowledge in design. In order to simulate the performance of a proposed artefact, he distinguishes between the inner environment (the internal parts and functions of the artefact) and the outer environments (the context in which the artefact operates), both subject to natural laws. The generic natural laws applicable to engineering can usually be described in symbolic mathematical expressions.

The particular properties of the artifact lie on the thin interface between the natural laws within it and the natural laws without. ... The artificial world is centred precisely on this interface between the inner and outer environments; it is concerned with attaining goals by adapting the former to the latter. (Simon, 1981, pp. 131-132)

But because all ontologically real contexts and artefacts are inherently complex, in order to make sense of them so as to design, we need to simplify them, recognise what matters and eliminate what does not. This is the process of diagnosis (Abbott, 1988), colligation, the process of recognising relevant simplifications, and classification<sup>12</sup>, the identification of a problem type. Simon describes the same process of colligation as follows:

How complex or simple a structure is depends critically upon the way in which we describe it. Most of the complex structures found in the world are enormously redundant, and we can use this redundancy to simplify the system. But to use it, to achieve the simplification, *we must find the right simplification*. (Simon, 1981, p. 228 emphasis added)

Where Abbott (1988) restricts diagnosis to material relations, Simon (1981) is not as prescriptive. He recognises that both relevant material relations and appropriate symbolic relations are central to engineering judgement.

What follows is a comparison of the context description and the artefact prescription in the design brief, and the nature of the inferences required to develop a solution in the two capstone design projects. In addition, the narrative weaves Bernstein's (2000) insights into pedagogic control (framing) into the analysis of the different projects. The analysis shows that the way in which the design project is constructed, either with the lecturer retaining control over the content, the sequence and the required solution format and limitations (strong framing), or leaving it to the students (weak framing), substantially changes the nature of reasoning required to complete the design. Framing (Bernstein, 2000) was discussed in detail in section 3.2.1.

### 5.3 Comparison of the design briefs

The design brief is the description of the required design; it sets the goal of the design, but also often suggests (or even prescribes) potential artefact types as solutions and implies key contextual elements. In professional engineering practice, the design brief is typically developed in response to a contextually emergent need. In a design project embedded in an academic course, the lecturer constructs the design brief, usually intended to mimic

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<sup>12</sup> Abbott (1988) uses the term 'classification' to denote a form of categorisation, while Bernstein (2000) uses the term classification to indicate the strength of separation between categories.

professional practice. The construction of a design brief for a design project involves important recontextualising choices, and the comparison between the two capstone design project briefs presented below illustrates the effects of these different choices.

### ***M8: Power plant specification***

The M8 design brief provided to students was in the form of a User Requirement Specification (URS).

The Republic of Rainbows plans an extensive expansion of its electricity supply network. It has decided to construct a number of single unit coal fired power plants at locations close to where the power is required. The generation capacity of each unit depends on its location, but all of them will be supplied by the same coal mine, and will have similar site specifics. [M8:brief]

Each student team was provided a designated plant capacity and minimum load requirement:

The capacity is in terms of net electrical power sent out onto the network. Each plant must produce all electrical power needed to run internal loads. The electricity must be delivered to the network according to the national standard [1]. [M8:brief]

In terms of Abbott's (1988) modes of professional practice this suggests that the diagnosis has been made (there is a shortage of electrical power) and the treatment has been prescribed (increase the power generation capacity by building more coal fired power plants across the country). The manner of the treatment prescribed is based on a direct mapping of previous solutions to similar problems, what (Abbott, 1988, pp. 57-58) calls 'routine professional processing'. Schön (1983) refers to designers drawing on a repertoire of previous solutions. In design research this transfer of previous solutions to new situations is called analogical reasoning (see for example Visser, 1998). This mode of reasoning is based predominantly on material relations without necessarily requiring recourse to inferential reasoning founded on specialised disciplinary knowledge.

The results of diagnosis and treatment were presented in the M8 design brief, without students having to engage in this process of reasoning. The insignificance of the process of diagnosis and the context from which the problem emerged in this design project is further illustrated by the imaginary name given to the 'republic', and that the same set of coal and metrological data is given to each team, although the 'location' of the different power plants was notionally different.

### ***C5: Future foreshore***

The C5 design brief provided to the students was in the form of an open-ended question that emerged as part of a faculty-wide collaboration with the City of Cape Town (CoCT) in the context of Cape Town as the World Design Capital (WDC) in 2013:

What should we do with the Foreshore? [C5:brief]

The area of interest was defined as:

The Foreshore precinct - bounded by the Waterfront to the north west, the Port to the north east, Culemborg to the south east and the more fine-grained older fabric of the city to the south west – is an area of crucial importance to the City. [C5:brief]

The general question was elaborated over the next week, to include accompanying photographs, documents and presentations by significant experts from the CoCT. In addition, students visited the site to get a 'feel' for the context themselves.

A general background document to the project elaborated the precinct:

The north Foreshore precinct is a derelict part of the city characterised by neglected and unused open spaces and remnants of an older freeway-building era. Yet there is great potential to make use of this precinct to create a vibrant, mixed use area, open and attractive to all Capetonians, demonstrating principles of integration and sustainability, and possibly re-establishing the historical link between central Cape Town and the sea. Major new planned projects in this area and in relation to the Port make this task an urgent one. (C5: SN2)

Beyond prescribing the precinct boundaries (and even those were open to negotiation), the brief in C5 made no specific prescriptions on the possible solution artefacts. Rather than prescribing an artefact in the brief, a diagnosis-treatment couple was implied:

- (1) ... provide an analysis of the current status, followed by the development a comprehensive plan for the precinct.
- (2) ... select a particular element of infrastructure, and carry out a technical civil engineering design of that element. [C5:brief]

In C5 students were presented with a real and specific context, presented in rich detail, from which they were required to identify key problems and recommend a plan to upgrade the precinct including the introduction of infrastructural elements (artefact types). Students were required to engage in both diagnosis (simplifying the context in order to identify relevant aspects and significant 'problems' in the context) and treatment (selecting infrastructural elements to address the identified problems). Again the reasoning was dominated by making sense of the contextual detail (material relations) without much (explicit) recourse to disciplinary insights (symbolic relations).

The comparison between the two design briefs presented above showed significant differences in the level of detail provided between the context and the artefact. The design brief in M8 presented an imaginary context in which the artefact functions. It was stripped of material detail and specified in precise symbolic form. On the other hand, the artefact was prescribed as a particular type of power plant, with detailed information on its subsystems. In C5 the context was real and accessible to students. It was presented in rich detail and students were expected to engage with the context in order to propose a range of artefacts to potentially address the problems identified within the precinct. The artefacts were not prescribed in the brief beyond being 'infrastructural elements'.

Both Schön (1983) and Simon (1981) see design as fundamentally about reasoning between the context and artefact. A more detailed analysis of the different recontextualising choices made in the design brief in relation to the context (outer environment) and artefact (inner environment) and their effect on the nature of reasoning required, is presented in the following two sections. Parallels with what in the design literature is called conceptual design, bring together the context description and the artefact prescription in the third section.

### 5.3.1 Context description: Outer environment

The contexts presented in the two design briefs were fundamentally different. In M8, all the features required for the design tasks were presented in simplified symbolic form. Students did not have to engage with the context themselves. In contrast, the context in C5 was specific and detailed. Students needed to engage with the context and simplify it themselves.

#### ***M8: Power Plant Specification***

Although the context presented in the brief in M8 was imaginary, students did not need to engage with the imaginary context. All the aspects of the context deemed significant were presented in the brief. These include limited details of material contextual features,

The sites where the plants will be located will have limited water supply, but not sufficient to use as final heat sink, therefore the atmosphere must be used. The flue gas must be cleaned from ash to generally accepted norms, and any other gaseous pollutants must be discharged at a sufficient height to avoid local contamination. Coal with specifications described in [2] will be supplied to a local stockyard using trucks, trains or conveyer, from where it needs to be transported by the plant equipment for use. [M8:brief]

Generic descriptions of contextual features were translated into symbolic disciplinary representations. For example, the ambient conditions for *all* sites are given in symbolic form based in thermodynamics, stripped by the lecturer of (what s/he has judged) extraneous contextual detail. No account was taken of daily or seasonal variation in the conditions. These were provided as constant and certain.

#### **Site metrological data**

The following information is valid for the proposed sites where the power plant units will be constructed.

- Ambient air dry-bulb temperature  $T_{db}=25^{\circ}\text{C}$
  - Ambient average relative humidity  $\text{RH}=10\%$
  - Atmospheric pressure  $P_{atm}=101.3\text{kPa}$
- See the next page for Psychrometric information

The saturation enthalpy vs temperature of moist air can be approximated by the following relationship:

$$h_s(T)=C_3.T^3+C_2.T^2+C_1.T+C_0 \dots \text{ [M8:brief]}$$

In this example significant contextual features were identified (by the lecturer) for example that the site has limited water available. Thermodynamics was identified as a significant discipline (by the lecturer); details of the thermodynamic conditions at the imaginary site were defined (by the lecturer), precisely, in terms particular to the specialised symbolic discourse of thermodynamics; variation in the ambient conditions was judged (by the lecturer) as irrelevant to the design. The chemical composition and calorific values of coal were provided (judged as relevant by the lecturer), while other potential disciplinary discourses, such as perhaps the impact on surrounding communities and issues of human rights, or a detailed survey of the site, were judged (by the lecturer) as not relevant to this design. However, rather than using the symbolic detail to classify the problem type, the students were expected to use this information to model, and consequently predict, the performance of the designed artefact operating in these ambient conditions.

The information provided in the M8 brief is a good example of the output of abstraction. A complex concrete context was simplified and only those aspects of the site relevant to the

design were identified and extracted. This included both the identification of significant material features and the identification of relevant disciplinary knowledge. There was a shift from material to symbolic description in the presentation of the ambient conditions as a fixed dry-bulb temperature, average relative humidity and fixed atmospheric pressure. Rather than being a precursor to diagnosis, the simplification of the context and the translation of material relations into symbolic relations was a precursor to inference. The diagnosis and treatment modes had already played out in the brief, and resulted in the prescription of a coal fire power plant. However, detailing the power plant required simulating the system in order to predict 'adequate' performance. Hence, a shift to the mode of inference was required.

The representation of the simplified context (material relations) as a constellation of related thermodynamic parameters (symbolic relations) in M8 resembles the logic of diagnosis. But where Abbott (1988) restricted the diagnosis mode to material detail, and classification to the identification of a problem type, in this example the same reasoning includes insights into relevant symbolic relations. Making the *right simplifications* (Simon, 1981) includes identifying the right disciplinary knowledge and identifying the right material features and translating the material relations into symbolic relations. While Abbott (1988) does recognise the crucial distinction between knowledge organised on the basis of case types (a form of contextual logic) as opposed to knowledge organised by logical rational conceptual relations, he fails to address the process of translating between the two.

### ***C5: Future foreshore***

In the case of C5 the context was both accessible to the students in rich detail and central to the problem. A great deal of richly detailed contextual information accompanied the brief in C5. The information was incomplete: students were expected to source any information that they needed for their planning and design. However, because the context was real, this information could be sourced rather than imagined. The information included numerous documents from a range of disciplinary perspectives (including for example surveying, architecture and urban planning). Guest lecturers associated with planning in the CoCT, were invited to present details about the context, including the history of the precinct, plans for development in the broader region, and examples of other approaches to precinct development. Students were expected to identify and source additional technical information as needed in their designs, for example, local geotechnical conditions, technical drawings of relevant existing infrastructure in the precinct, traffic data, and rainfall patterns.

In the case of C5, the diagnosis was not provided in the brief. The context was elaborated in far more detail than required for the design, and students were expected to investigate the context further. Although information about the context was available in both disciplinary and unspecialised forms, the lecturer did not prescribe specific disciplinary requirements. From a general need to 'improve' the precinct, students needed to strip the context of its material complexity, identify what was relevant and discard what was not, determine relevant disciplinary knowledge, and transform the material details into precise symbolic form

relevant to the identified disciplines. Diagnosis was in control of the students themselves (very weak framing).

### 5.3.2 Artefact prescription: Inner environment

The way in which the artefact was prescribed (or not) in the brief also had important implications for the nature of reasoning required of students. The artefact type and overall layout were prescribed in M8, while in C5 students needed to select and locate infrastructural elements (buildings, roads, services etc) in such a way as to improve the precinct.

#### ***M8: Power Plant Specification***

In addition to constraining the context (outer environment), the lecturer prescribed the required artefact type (inner environment) including the relevant subsystems and their relation to each other. By prescribing the form of the power plant cycle to be used and to explicitly require comparison to similar solutions found elsewhere in 'the republic' the lecturer was able to constrain the potential for divergent or creative alternative solutions and eliminate the need for students to consider the imaginary context themselves in order to develop the artefact.

All power plants must be based on a simple Rankine water-steam cycle, using coal as fuel. The maximum pressure and temperature must be comparable to typical subcritical steam plants. Other equipment such as coal mills, boilers, steam parts etc. must be of similar technology as employed elsewhere in the republic. [M8:brief]

This allowed the assessment to be potentially rigorous and consistent (matched to a strict marking rubric with predetermined analytical answers). But it also meant that the students were not required to match the diagnosis to a treatment, or to consider possible alternative treatments.

The diagrammatic representation of the power plant required in M8 was shown in figure 5.1 with accompanying text:

... a typical process diagram of a convectional coal fired power plant, as well as the simplified one to be used for this exercise. The boiler is called a subcritical, once through, tower-type steam generator.

The major differences are:

- No economizer, water needs to be heated to boiling point and evaporated in the water wall.
- No feedwater heaters, thus only one pump.
- No reheater, thus no Intermediate Pressure (IP) turbine.
- The superheater will be much larger than normal to extract maximum heat from the flue gas. [M8:SNHL,p3]

The process diagram provided to the students represents three significant recontextualising moves, all controlled by the lecturer. The first was to identify the plant as based on a Rankine cycle, which defines the thermodynamic assumptions in terms of a theoretical model of a typical power plant. The lecturer controlled the selection of disciplinary knowledge. The second was the simplification of a typical coal fired power plant by removing a number of

components in order to simplify the required analysis of the system, and to organise the relationship between the various components. By defining both the relevant components, and the subsystems into which they fall, the conceptual design was fully determined by the lecturer (the lecturer controlled selection of the material relations). Thirdly, the lecturer retained control over the sequence of calculations by referring to the process sequence (the lecturer controlled the sequence of symbolic relations by controlling the sequence of material relations):

... one can calculate the primary fluid properties before and after each component. This is done by systematically "walking" along with the fluid from a known point, and calculating the energy and mass balance for each component. ... [M8:SNHL,p4]

Even though the power plant represented in the process diagram is a simplification of a real power plant, it is nonetheless an extremely complex artefact, with multiple subsystems each comprised of multiple parts, processing multiple input materials in synchronised streams. There are complex interdependencies both as a result of interactions between the geometric parts and the input materials and as a result of the complex causal mechanisms to which the artefact, if constructed, would be subject. The diagram is simultaneously a symbolic representation of a power plant, and although the symbolic language is reasonably simple and straightforward to read, it is a formal representation defined by disciplinary conventions. Thus, in terms of prescribing the artefact, there are two related but analytically distinct parts to the artefact. The first relates to the complexity of the artefact itself, the number of parts and the way that the parts interact at a material level (material relations). The second relates to the complexity of the representation, in this case the process diagram (symbolic relations).

Material relations in this sense include the causal mechanisms that we understand to underpin the way in which things operate. Symbolic relations on the other hand refer to how we represent these material relations, in diagrams, equations, and labels; how we model these relations in mathematically formulated expressions that link theoretical concepts. The material relations are defined by the external ontological referent/s, while the symbolic relations are determined by the rules of conceptual coherence defined within any discipline. The artefact in the form of the process diagram is an example of extremely complex material relations represented in relatively simple symbolic terms. By way of a contrasting example, a thermodynamic analysis of one of the sub-systems, say the boiler, is a simplification of the material relations (although the geometric, material and thermal relations are still complex), and an increase in the complexity of the symbolic relations in order to perform complex, interrelated, thermodynamic calculations.

### ***C5: Future foreshore***

Although the C5 brief also alluded to complex artefacts (in both the precinct plan and the individual infrastructural elements), in contrast to M8, the complexity in C5 was left to the students to manage. The weak framing over the artefact prescription introduced ambiguity in the complexity of the material relations, because the students could choose to manage the complexity in different ways. For example they might consider the relationship between transportation and structures, consider a plan to accommodate both private and public

transport and locate structures accordingly, or they might sever the relations between infrastructural elements by, for example, simply locating structures haphazardly within the precinct with no consideration of their influence on the greater environment. They could deal with the elements discretely, sequentially, or could attempt to account for simultaneous interdependencies. By shifting control of the selection and organisation of the specific infrastructural elements entirely to the students, the lecturer potentially lost control of the level of complexity of the artefact/s.

A comparison of recontextualised contexts and a comparison between recontextualised artefacts was presented above. The stark differences highlight the subjective nature of the construction of design projects; design briefs can be constructed vastly differently. However, because of the interdependent relationship between context and artefact (Schön, 1983; Simon, 1981) the recontextualising choices do influence each other.

In M8 the lecturer prescribed a particular power plant type in order to address the local electricity shortage, and defined certain subsystem types in response to local conditions (for example air cooling towers because of the water-scarce environment). Although information about the outer environment (Simon, 1981) or context was presented in the brief in M8, it was stripped of material detail and replaced with symbolic representations defined by disciplinary norms. The uncertainty and variation inherent in any real context was replaced with precisely defined, invariable symbolic representations. The approximation and judgement required to make this shift was neither required of, nor evident to, the students. Nor was sufficient detail available to develop an artefact in relation to an understanding of the specific context. Because of the minimal detail provided on the context the artefact had to be prescribed in significant detail. The recontextualised context in M8 significantly modified the interdependent relationship between context and artefact, central to design (Schön, 1983; Simon, 1981), and all but eliminated the need for students to make informed engineering judgements based on contextually emergent needs informed by disciplinary insights. On the other hand the strong framing (Bernstein, 2000) of the task as a result of the precise prescriptions eliminated ambiguity in expectations of a solution.

In contrast, the artefact was not prescribed in the C5 brief beyond recognising the need for 'infrastructural elements' as part of the precinct improvement plan. The brief in C5 therefore forced students to engage meaningfully with a specific, real and complex context in order to prescribe a range of infrastructural elements to address the upgrading of the precinct. This required a far more detailed context in order to inform artefact choices. In this case the context was presented with rich and detailed material descriptions. The students were required to identify what was relevant in the context and discard what was not. They were required to translate the material reality into symbolic representation. Which meant that they were required to identify which theoretical disciplines were relevant to the design and which were not. The students were required to make the judgements and approximations to abstract the context themselves.

The context and artefact recontextualisation choices influence each other in the following ways. When the context was simplified and presented in limited symbolic detail, the artefact had to be prescribed in sufficient detail that it did not need to be developed in relation to specific contextual detail, eliminating the need to work reflectively between context and artefact, a central concern for Schön (1983). On the other hand, when the artefact was not prescribed in detail, it needed to be developed in relation to the context in which it operates, and consequently students needed access to a far more detailed context, whether that detail was prescribed in the brief, or students were referred to a real external context.

### 5.3.3 Conceptual design: Relation between context and artefact

Drawing on design literature in reference to the myriad of design processes available, conceptual design can be associated with the generation of an artefact type in sufficient detail to suggest an acceptable response to the design problem. It still requires refinement in order to predict its performance in context – what will be referred to as detailed design, covered in the next section.

The detail of artefact prescribed in M8 suggests the output of the conceptual design, even though students did not engage in conceptual design. In contrast the C5 students were required to engage in conceptual design. They had to propose an overall precinct layout and identify infrastructural elements to contribute to the improvement plan. The following two C5 examples (both considered exceptional designs based on the grades achieved) illustrate that, when the task is weakly framed (the students are required to make most judgements themselves), even in well-executed projects students can take vastly different approaches to the conceptual design.

The first team classified the problem as:

Ultimately, the Foreshore is a zone of transit, not a destination. [C5:Soln05,p1]

from which they developed 5 conceptual principles which guided the planning:

The guiding principles are Integration, Linkage, Liveability, Sustainability, and Employment. [C5:Soln05,p5]

This team proposed the following as part of their conceptual plan:

The canal aims to provide better linkage between the Foreshore, V&A Waterfront, and Cape Town train station, as well as providing employment opportunities with the provision of a water taxi service. The mixed-used developments will create employment opportunities, better link and integrate the Foreshore precinct, and provide a more liveable environment for all...

... a Park & Ride facility in Culemborg that is directly accessible from the N1 and the N2 via a system of on-ramps, off-ramps, and connecting surface roads.

The five-storey parking garage is capable of housing an estimated 6500 vehicles. The proposed parking garage will be a one-way aisle system with parking bays at 30 degrees to the direction of travel, thereby improving manoeuvrability and reducing the space requirement per parking bay. To facilitate integration of private transport with public transport,... [C5:Soln05,pp 1-3]

The diagnosis involved abstracting generic principles from the concrete particulars. Although the guiding principles may appear unspecialised, and the solution seems fairly

straightforward and common sense, underpinning it are principles and concepts from transportation planning. This field of engineering may be seen as a 'softer' discipline than thermodynamics in that it incorporates social and technical aspects, and from the outside may appear less theoretical. Nonetheless, the relation between the contextual problem and the precinct plan was coherently underpinned by the discipline of transportation planning, which is associated with urban planning principles.

The second example comes from a team that remained far closer to the context in the diagnosis mode, and identified a wider range of relevant material issues, associated with different disciplinary lenses (emphasis added).

The Foreshore is a region on the fringe of City of Cape Town (CoCT) which is famous for the fact that it exists entirely on *land that has been reclaimed* from the ocean. This area has a *rich history* but in recent decades ... is often described as an area that is empty and *lacking constructive interventions and human presence*. The area is bounded by the Port ... the railways and container handling depots ... incorporates the end of N1 National Freeway and contains the elevated N2 freeway ... has resulted in the area becoming an unattractive feature of the city with the area only being able to serve the purpose of offering free parking and being a barrier to expansion of the city.... one of the biggest obstacles to any future redevelopment is the elevated sections of the N2 freeway. ... the freeways were built in the early 1970's in order to allow improved flow of traffic in and out of city. However, now in the early 21st century, cities around the world have reached their saturation points and have turned to *public transport in order to provide a solution to the increasing need for transport*. Successful Bus Rapid Transit (BRT) systems ... a shift in focus from cities servicing cars to ones that focus on servicing pedestrians and non-motorised transport (NMT). This combined with current trends in city planning such as mixed-use land usage and the ideas of New Urbanism has pushed the City of Cape Town to rethink the current use or lack of use of land in the Foreshore area and made them consider options that will *reintegrate the area back into the city while fitting in with plans of their overall Spatial Development Framework*. [C5:Soln13,p1]

While their understanding of the problem was also heavily influenced by transportation planning, they included significant attention to the geotechnical challenges of the site. Their diagnosis mode was also far less abstract than the former team. They remained closer to the particulars of the context as they identified concrete examples of problems in the precinct. A comparison of the two different levels of abstraction in the same task suggests that conceptual design can be based on both more concrete material considerations as well as more abstract symbolic considerations. Although the first team provided a conceptually very coherent precinct plan, by retaining a closer connection with the specifics of the context, the second team identified an extremely important, not necessarily obvious aspect to the problem. The recognition of the significance of geotechnical challenges required some insight of geotechnical engineering. Their plan perhaps lacks the same level of abstracted conceptual coherence but covers more contextual detail. Both concepts were informed by disciplinary insights (symbolic relations).

These conceptual designs illustrate that handing control of the contextual problem (diagnosis) to the students results not only in the potential for a wider range of conceptual types (treatment), but also a range of prioritisation between conceptual elegance and coherence (symbolic relations) and contextual adequacy (material relations); a focus on contextually specific detail or more abstract and generalizable concepts. Both solutions were judged as

meeting the design objectives; even though the first team did not identify the challenging geotechnical conditions in the precinct, their attention to the transportation aspects and the coherence of their solution was considered convincing.

In both the prescription of the coal-fired power plant in M8 and the prescription of an arrangement of infrastructural elements in C5 there is a dominance of the material relations. The contextual details inform the artefact choice. Abbott's (1988) diagnosis-treatment couple provides a useful model of conceptual design. Diagnosis requires stripping the context of detail extraneous to the problem, and treatment requires the identification of an artefact type to potentially address the problem within the context. Both require a considerable understanding the material details of the context and artefact. Abbott's (1988) modes of diagnosis and treatment are established on an organisation of knowledge based on practical examples, a repertoire of cases associated with any profession (material relations).

Abbott (1988) suggests that professionals only engage in the mode of inference for novel or difficult problems. He called the direct match between a diagnostic case with a treatment type 'routine professional processing' (Abbott, 1988, pp. 57-58) not requiring inference based on disciplinary knowledge. But the representation of the context in M8 in precise symbolic thermodynamic terms although not required to prescribe the artefact (treatment) does indicate that even when an artefact has been prescribed, it needs to be specialised to perform a particular function in a specific context. The symbolic thermodynamic parameters are a precursor to the specialisation of the artefact on the basis of inference. Data pertaining to the contours, geotechnical soil classifications, rainfall parameters and transportation reports in the precinct, all presented in symbolic format, attest to the same requirement in C5. But more significantly, the more detailed evidence provided in the conceptual designs investigated in C5 showed that disciplinary insights informed contextual interpretations. This suggests that even in relatively routine engineering designs, there is an implicit disciplinary backdrop.

Schön (1983) argued that all designs are unique because each design specialises an artefact to a specific context and each context is unique. In order to do this, the contexts and artefacts need to be simplified. Making the *right* simplifications (Simon, 1981) is not necessarily straightforward, especially as contexts and artefacts become more complex. Identifying significant contextual features, identifying relevant disciplines, and translating material details into equivalent symbolic representation are all important skills needed to design. When, as in M8, the design brief fully prescribes the artefact, and the context has already been abstracted into symbolic format, students do not need to engage in the difficult task of simplifying and abstracting. On the other hand, when artefacts are un-prescribed and function in real, detailed contexts, as in C5, it is unlikely that all students will make the *right* (appropriate) simplifications and abstractions without some prior introduction to the process of simplifying and abstracting. The level of simplification of the context and prescription of the artefact is an important recontextualising choice in terms of extending or limiting the need for reasoning between material considerations and translation into symbolic representation, both central to developing professional judgement.

## 5.4 Detailed design: Specialising the solution

It was suggested that the output of conceptual design was the prescription of an artefact type, provided in more or less detail. The process of specialising the artefact in detail such that it will perform as intended in context can be associated with detailed design. While the conceptual phase of design resembles Abbott's (1988) diagnosis and treatment modes, in these examples, the detailing of the solution artefact so that it performs its intended purpose in the context requires recourse to inferential reasoning founded on disciplinary knowledge. Abbott's treatment mode, based solely on material reasoning, is inadequate to describe the level of symbolic reasoning involved. This is where Schon's (1983) very important critique of any notion of routine design solutions becomes important, and Abbott's idea of routine professional processing breaks down. Once the artefact type has been identified, and because each context is unique, the solution artefact has to be specialised to the unique context. And rather than merely prescribing a solution, disciplinary knowledge is invoked in order to specialise the solution.

Two parts to the process of specialising the artefact were distinguished for the purpose of this study: firstly the inferential reasoning involved in modelling the artefact's performance in context in order to adequately predict the performance the required function; and secondly the presentation of the final solution, stripped of the detail of the inferences, but in precise terms amenable to manufacture or construction. The following section presents both the inferential reasoning evident and the nature of the solution presented.

### ***M8: Power Plant Specification***

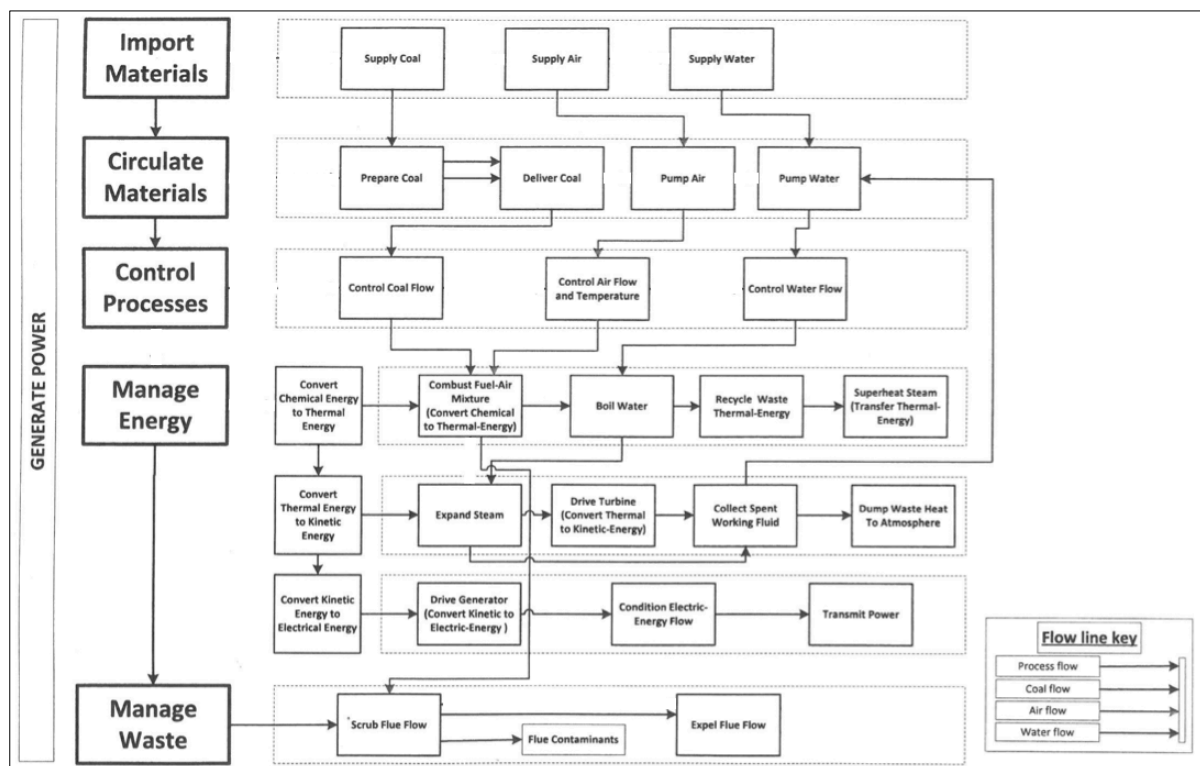
Because the context provided in M8 was reduced and presented in simple idealised form, the significance of the interplay between the inner and outer environments, central to both Schon's (1983) and Simon's (1981) models of professional practice, was reduced, but not eliminated entirely. The provision of the atmospheric conditions in thermodynamic representations indicates the need to specialise the artefact to the context. Even though the artefact was significantly simplified, the inherent complexity of the parts and their interrelations required recourse to complex disciplinary knowledge.

In M8, the lecturer managed this complexity with very strong framing over selection of knowledge, sequence of activities and pacing of submissions. The strong framing carried over into explicit evaluative criteria, prescribed in strict format and checked for accuracy. The design project was broken into eight submissions, each of which was graded and contributed to the final course grade. Each submission focused on a specific aspect of the design, which was defined precisely by the lecturer. The tasks informed each other and each step contributed to the final two submissions, indicating the inherent interdependence between subsystems. However, the very strong framing of the tasks functioned to separate aspects of the material and/or symbolic relations into smaller, more constrained problems. The prescribed sequence of tasks is presented below.

**Step 1 M8: Functional analysis**

The first submission required students to do a functional analysis of the system. It involved representing the system described in the process diagram in a flow diagram, an alternative symbolic representation. Figure 5.3 shows an example of the type of solution required.

This represents a reorganisation of the plant from physical logic represented in the process diagram to functional logic represented in the flow diagram. Although the two diagrams represent different perspectives of the plant, they both represent a simplified understanding of particular material relations the plant itself, while retaining simultaneous interdependencies between parts and functions respectively. Where the process diagram represented the physical relations between subsystems and showed the material flow paths, the functional flow diagram developed the relations between functions and their interdependencies, but the details of the subsystems, their geometric locations and the interaction with the material flow paths were removed. Both diagrams represent complex material relations, and provide indications of some of the simultaneous interdependencies between functions, materials or components. They are also both substantial simplifications of the 'real' material artefact that they represent. The nature of the simplifications was to identify significant material aspects of the plant and extract them from the full complexity of the plant. Both diagrams crucially retain interdependencies between the aspects identified. The functional flow diagram is a shift in representational type rather than a change in the complexity of either the symbolic or the material relations.



**Figure 5.3 Data M8: representative functional flow diagram**

It also represents a slight shift in control to the students, who had to decide which functions to represent and how to show their functional relations, which required them to familiarise themselves with the material relations in order to produce this representation.

### ***Step 2 M8: High level plant analysis***

The high level analysis required students to approximate the mass flow rate of the material streams and various thermodynamic characteristics of the plant at the inlet and exit of the components defined in the original process diagram, based on a simple Rankine cycle. The Rankine cycle defined the idealised relationships between the various thermodynamic properties as the water/steam flows through the power plant components at steady flow conditions. For example the cycle defines the pump and turbine as isentropic processes, meaning that although the pressure and temperature of the water/steam changes as it flows through each device, the entropy can be assumed to remain constant. This allowed unknown pressures and temperatures at the inlet and outlet of the device to be calculated using established symbolic relations. The Rankine cycle linked the material relations (for example: the work done by the pump increased the pressure and temperature of the water) to the symbolic relations (for example, the work done by the pump can be expressed as  $w_p = h_2 - h_1 = v(P_2 - P_1)$ ), which quantitatively relates the enthalpy change to the pressure change).

Recognising and understanding the relevant material relations in the contextual problem, and knowing what symbolic quantities were required, allowed chains of relevant symbolic relations to be constructed to approximate the thermodynamic properties of the fluid at various points around the cycle. In this design task, the lecturer identified thermodynamics as the primary field of disciplinary knowledge, and the Rankine cycle as the defining link between the material and symbolic relations.

The student is advised to refresh himself (sic) with the thermodynamic phase diagram of water in the liquid, mixed and vapour states. Much of the design and operation of a power plant is driven by the phase change and thermodynamic properties of water/steam in its various states.

The primary properties that will be used in subsequent analyses are:

- Temperature, **T**, in [K]
- Pressure, **P** in [Pa]
- Specific Enthalpy, **h** in [J/kg]
- Specific Entropy, **s** in [J/kg\*K] [M8:SNHL,p1]

Much like with the simplified context in M8, the lecturer provided all the key input parameters for students to begin their analysis. They were thermodynamically relevant parameters, approximated based on material relations of the system. This is a translation from material to symbolic relations, but in a dialectical relationship. Understanding the material relations and identifying which are significant is the basis of identification of significant symbolic relations, and understanding the symbolic relations informs what are significant material relations. This is not a case of 'applying theory' to a 'real problem'. However, as recontextualised in M8, the students were not required to engage with this dialectical relation.

The transition from material to symbolic format took three forms:

Comparison to existing plants:

Minimum temperature. This is the temperature of the water leaving the condenser and entering the boiler. A common type for inland plants is wet cooling towers. They usually produce a minimum cycle temperature of about 35°C. [M8:SNHL,p3]

Critical known material limits:

Max temperature. This is limited by the creep life characteristic of affordable steel... It is seldom higher than 560°C [M8:SNHL,p3]

Or some combination of both:

Max pressure. ... This is normally some level lower than the critical pressure of water. Many steam plants operate at a max pressure of 16.5MPa. [M8:SNHL,p3]

Importantly, in this project the lecturer made the transitions. The lecturer also defined the symbolic quantities that the students needed to calculate.

Summary of key outputs

The following results must be reported and documented in order for the subsystem analysis to be done. Most of this data can be displayed on top of the cycle diagram ...

- Mass flow of each material stream [kg/s]
  - Steam
  - Fresh Air
  - Coal
  - Flue gas
- Temperature between components for each flow stream [°C]
- Pressure between components of the Rankine cycle [kPa]
- Power or heat values for each component in the Rankine cycle [MW] [M8:SNHL,p10]

The values were determined based on mathematical models that integrate the chemistry of coal with mass flow and thermodynamic theories. The thermodynamic values were based on highly complex theoretical models made up of multiple coherent disciplinary concepts. The numerical results represent the output of very complex symbolic relations that model very complex material relations. By placing the symbolic outputs onto the process diagram, their link to the material relations was retained, and the generalisable theory was specialised to this contextual case. The output was not a theoretical generalisation, but rather a material specialisation, though in symbolic form.

Having defined the relevant disciplinary specialisation, identified the significant material relations relevant to the discipline, and translated them into symbolic format, the lecturer also controlled the sequence of reasoning, even within this step. However, multiple significant material relations exist and they interact in interdependent ways. The symbolic relations cannot capture these interdependencies directly, and consequently multiple iterations were required.

For the first round, the auxiliary loads will be an assumption, as it is an output of the lower level developments. Hence it is necessary to re-run the primary plant analysis once the subsystem results become available. This in turn will affect the subsystem analyses. At least two iterations will be needed to reach suitable convergence.

Another item that will require readjustment after the first subsystem analysis is the pressure drop through the various piping. Fortunately, only the superheater causes a significant pressure drop, which results in a slightly lower turbine inlet pressure than at the outlet of the boiler. The pump

also needs to produce a higher pressure than at the outlet of the boiler because of the hydrodynamic pressure caused by the water column in the boiler. This can only be taken into account once the boiler height is known.

Whenever any of the above inputs or losses changes, the total required steam flow will change, which in turn will affect virtually all other subsystem results. [M8:SNHL,p4]

It is important to recognise that this very strong control over selection and sequencing of knowledge enabled explicit evaluative criteria. In professional engineering practice, the ultimate evaluative criterion is whether or not the implemented solution works as it was intended to work. The artefact becomes a real artefact operating in a specific context and subject to the real causal mechanisms of the world. The evaluative criteria lie in the embedding of the material relations in the world. In an academic context, the evaluative criteria change. In this case the accuracy of the answers (output of symbolic relations) were evaluated. But the complexity of possible contexts and the artefact itself opens the potential for diverse solution possibilities. In order to manage a rigorous evaluation of the symbolic relations, the design was tightly constrained.

### ***Step 3 M8: Subsystem Analysis***

The logic of the third step, the subsystem analysis, was the same as the second step. Where the high level analysis involved a group effort to analyse the full system, the third step was an individual task in which each student analysed a subsystem in more detail. The lecturer defined 7 subsystems in the power plant, and each student in the group was individually responsible for the detailed analysis of a single subsystem, using the values approximated in the high level analysis as inputs, and returning refined values into the high level analysis after iterations. As with the high level analysis, the lecturer provided about 10 pages of notes for each subsystem, identifying appropriate theory and specialising it for use in that particular subsystem. The supplementary notes are all prefaced with a note that they are a simplification of what is used 'in industry'.

For example:

Steam generators are designed with a huge amount of experience. The sizing is based on several factors which are often conflicting, and cost or manufacturability is used to decide on certain values... have developed techniques and guidelines by which new steam generators are designed. Sometimes these guidelines have little physical foundation, but are rather a common characteristic observed from numerous similar designs...

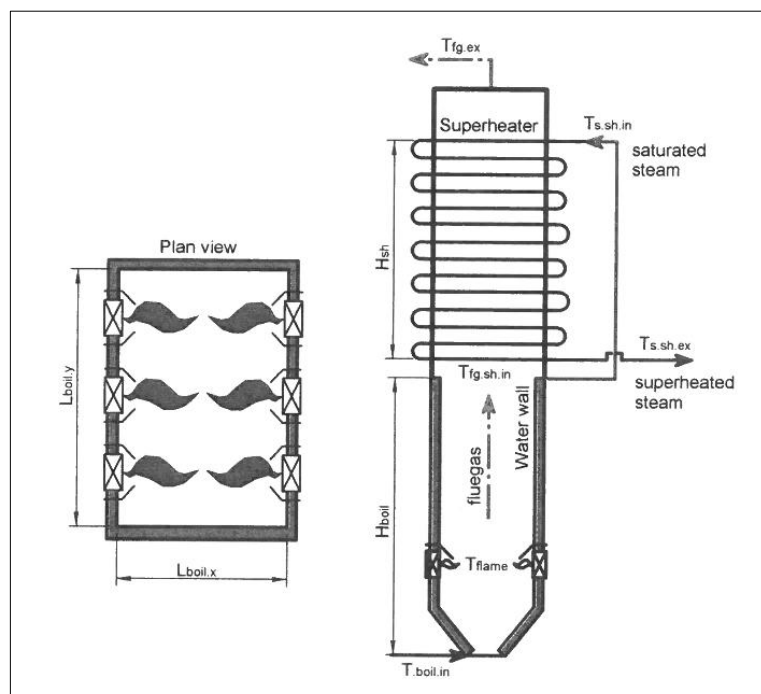
For this exercise, we will design the steam generator from more basic principles, with limited use of practical guidelines. To do this, a number of assumptions will be made that could be different to what is seen in actual power plants, however the assumptions are not completely invalid. Therefore, the methodology to arrive at the overall size of the equipment will be slightly different to the actual way steam generators are designed at present. [M8:SNBS,p20]

The above quote illustrates the significance of analogical transfer and limitations of science in practice when a system may be too complex to model accurately. When outsiders don't have access to the competitive wisdom, or when experience is limited, it forces inferences based on abstraction to 'first principles'. It is interesting to note that alone 'first principles' are considered inadequate in practice.

But even when working from 'first principles', there are a number of very significant contextual inferences that lead the theoretical reasoning. In M8, the lecturer generally provided the basic contextual reasoning behind the identification and specialisation of disciplinary knowledge. The following quotes from the supplementary notes provided for the basic sizing of the steam generation systems illustrate the dialectical relation between the material and symbolic relations.

The theory required was identified from a conceptually principled understanding of the context, which was supported by simplified diagrams of the steam generator (figure 5.4):

Cold water enters the boiler from the bottom, and flows vertically upwards through the water wall. The water wall is rectangular in cross section and contains burners on two opposing walls at a certain height. *The water is heated through radiation from the hot burner flame, and exits the water wall as saturated steam.* [M8:SNBS,p21]



**Figure 5.4 Data M8: boiler and superheater schematic**

The lecturer identified and described only those contextual details that were deemed necessary to the analysis. In other words, although the first two sentences described material relations, the significant material relations were identified with implicit reference to symbolic relations. It was the disciplinary knowledge of heat transfer that provided the rules of relevance in terms of material relations. This simplified context was then translated into disciplinary terms, which simultaneously identified theoretical ideas deemed significant to this context. For example, theoretically, heat transfer occurs by three mechanisms (conduction, convection and radiation) which all occur simultaneously. In the above paragraph the lecturer judged that, in the boiler, convection and conduction were negligible and consequently not worth calculating, while radiation was the principal heat transfer mechanism to consider. Here knowledge of similar artefacts likely provided the experience that convection and conduction contribute far smaller quantities of heat to the water in the

boiler. The specific material relations determined which general symbolic relations were relevant. The short paragraph above condensed the tight dialectical relationship between material relations and symbolic relations, which challenges the notion of design as the application of theory to a context. Material detail simultaneously informed the relevant theory.

The paragraph that followed in the notes repeated the same inferential process, this time identifying convection as the only significant heat transfer mechanism in the superheater.

From the water wall the steam is fed through the superheater where it flows in cross flow counter position inside pipes. The inlet of the superheater is the outlet of the flue gas. And the pipes make a number of horizontal passes through the flue gas cavity until it exits at the point where the water wall ends. *Water is superheated here through convection transfer of the flue gas heat.* [M8:SNBS,p20]

In the third paragraph the lecturer returned to the material relations and put the discursive simplifications back into context.

In practice the water wall extends up to the top, past the superheaters, but for this example we will assume it stops where the superheater starts. Also we will ignore any radiation heat transfer from the flame into the first rows of the superheater. [M8:SNBS,p21]

The first two paragraphs identified two theoretical heat transfer mechanisms, convection and radiation. Although the third paragraph implied that in reality both mechanisms operate simultaneously, this complex material relation was simplified, and based implicitly on the geometry of the boiler, each mechanism was assigned separately in different parts of the boiler.

Having identified relevant material elements and disciplinary concepts within this dialectical relationship the material relations were converted into symbolic formulations, drawing in a range of disciplinary traditions in order to 'model' the specific physical system. Figure 5.5 shows the idealisation of the material relations in relation to symbolic insights, which defined the symbolic formulations recruited to size the various components:

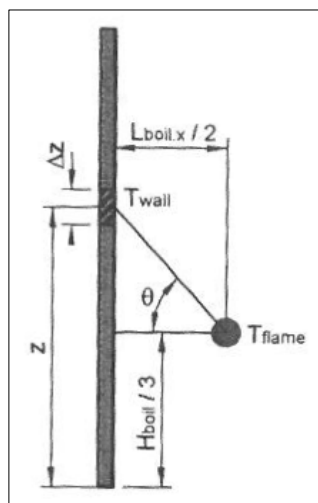


Figure 5.5 Data M8: boiler water wall geometric approximation

Principles from multiple disciplines were integrated to develop specific symbolic representations:

Mathematics (geometry, trigonometry and limits):

Consider a finite height segment  $\Delta z$  running along the perimeter of the water wall as shown in the figure above [figure 5.5].

Heat transfer

The radiation **heat transfer** from the fireball to the segment is:

$$\Delta Q_r = \varepsilon_{steel} \cdot F_{ash} \cdot F_z \cdot \Delta A \cdot \sigma_{SB} \cdot (T_{flame}^4 - T_{wall}^4)$$

... The flame temperature  $T_{flame}$  can be calculated by solving the **energy balance** at the combustion.

numerical modelling:

... incrementally calculate the heat absorption by the water, starting from the bottom.

Thermodynamics:

The inlet temperature and mass flow to the boiler is known from the high level analysis. [M8:SNBS,p24]

The disciplinary discourse was also specialised from its most general theoretical form, to a more particular form relevant to this case:

The general relation for radiation:

$$Q = cT^4$$

can be expressed as the radiation between 2 bodies:

$$Q = \varepsilon \sigma (T_a^4 - T_b^4)$$

which was further specialised for the simplified idealisation of the artefact, including approximations of relevant quantitative information:

Consider a finite height segment  $\Delta z$  running along the perimeter of the water wall as shown in the figure above [figure 5.5]. The radiation heat transfer from the fireball to the segment is:

$$\Delta Q_r = \varepsilon_{steel} \cdot F_{ash} \cdot F_z \cdot \Delta A \cdot \sigma_{SB} \cdot (T_{flame}^4 - T_{wall}^4)$$

The thermal emissivity  $\varepsilon_{steel}$  is typically about 0.8.  $F_{ash} \approx 0.6$  is an opacity factor that accounts for the obstruction of radiation heat by the ash particles. The view factor  $F_z$  ... determined from the geometry shown in the figure. ... For simplification, the conical shape of the boiler bottom can be ignored, so one can assume the segment area  $\Delta A$  stays constant for the full height and at the same distance all around the fireball. [M8:SNBS,p24]

Decisions were made about what to simplify and what required more accurate modelling. These decisions are made based on contextual inferences, and in the case of M8, the lecturer controlled them:

The wall temperature  $T_{wall}$  can be *assumed* to be the same as the water temperature inside the wall. However, it changes with height as it is heated up to the boiling point. In order to obtain the wall temperature it is necessary to *incrementally calculate the heat absorption by the water, starting from the bottom*. The inlet temperature and mass flow to the boiler is known from the high level analysis. [M8:SNBS,p24 emphasis added]

The temperature differential between the water and the water wall was judged insignificant, but the differential with height was judged to be significant. These insights derive from the material relations, but interpreted through disciplinary lenses and the decisions have consequences for the modelling procedure that resulted. The results of the analyses, which

were fed back into the high level analysis for another iteration using improved inputs, were symbolic condensations of both the complex theoretical insights and the material judgements made. These symbolic condensations allowed transfer between the high level analysis and the subsystem analyses.

The supplementary notes provided rich insight into the nature of the reasoning as a dialectical relationship between material and symbolic relations. However, the bulk of the student work was done in symbolic form, manipulating equations and iterating between results. The symbolic models derive from established conceptual models independent of specific contexts or artefacts and rely on consistent relations between ideas. But the material relations defined the inputs for the symbolic models, and the complexity of the material relations determined what symbolic relations were needed, and how they were combined. It is the complexity of the material relations that drove the need for multiple iterations. Before the symbolic modelling could be done, the material relations needed to be understood, in order to construct the symbolic relations. *The symbolic relations define all possible ways in which the concepts can go together, but the material relations define how, in this specific case, they must go together.*

However in this step there was little required from the students in terms of reading the artefact and interpreting the material relations. Although neither inevitable, nor the intention, there is the potential for students to operate almost exclusively in the symbolic realm, severing the primacy of the material relations as a result of the very explicit control over the knowledge selection and sequence in the notes.

#### **Step 4 M8: Interface control**

One of the challenges with multiple interdependent subsystems is transferring compatibility between the subsystems. The fourth step required students to identify 5 requirements that are shared between their subsystem and another subsystem. For example, the air supply subsystem supplies heated air to the steam generation system and the mass flow rate of air between the subsystems must be consistent.

The task required that these interfaces cover a range of material flow requirements (flow rates/capacity/states of the various material streams), energy flow requirements (thermodynamic parameters, forces/electric currents) and physical or geometric requirements. The task did not require the identification of the comprehensive list of interfaces, but addressed the nature of interface control. This was yet another recontextualising move, where the comprehensive material relations were secondary to the full range of conceptually different interfaces, as defined by the lecturer. Although an understanding of the material relations defined the reasoning, the measures of compatibility were theoretically calculated and symbolically represented, in relation to each power plant capacity. These symbolic representations enabled the material properties of the system to be transferred precisely between subsystems.

There was a slight shift in control over the selection of knowledge to the student. Although the lecturer prescribed the symbolic form of the interfaces, the student needed to read the context him/herself in this task. Although s/he needed to draw on the symbolic modelling of the various parameters, s/he also needed to identify significant parameters in terms of interface relations. But unlike a 'real' design, the recontextualised design did not require a comprehensive list of material relations.

### ***Step 5 M8: Life cycle cost optimisation***

Minimising cost is one of the major material relations driving design. In the fifth design task students are required to use a particular optimisation technique (a two factorial experiment) using only two parameters in the design, identified by the lecturer. This is a disciplinary technique developed to model the material relations of cost. But the outcome of the symbolic model depends on the material choices made. Not all parameters were optimised, only those defined as significant by the lecturer. For example, in the case of the generation system the factors prescribed were the stator current density and the transformer window frame aspect ratio. Students were given the upper and lower limits for these factors, and all the costing input data required for the optimisation. Once again the lecturer read the artefact in order to distinguish the significant from the insignificant and provided the symbolic quantification of the artefact in theoretical form. Students conducted the optimisation, and the convergent solution was marked for accuracy. Again, the task was based on the correct application of a symbolic technique for a single material relation, rather than on the material implications.

### ***Step 6 M8: Failure mode effect and critical analysis (FEMCA) and risk***

Students were introduced to a risk analysis technique (FEMCA). Students were provided a tabular format with an example in the format shown in table 5.1. For each subsystem the lecturer identified a component and one potential failure mode (shown in italics above and marked \*). Students were required to identify the affected functions, effects, and actions required for each failure or risk identified by the lecturer. The numbering system was prescribed by the lecturer and intended to trace statements back to their origins in previous analyses (either material or symbolic in nature).

**Table 5.1 Data M8: representative completed FEMCA template**

Subsystem	Component	Failure	Affected functions	Immediate effect	End effect
SS04 Fluegas subsystem*	SS04-02*	Motor bearing seizes*	FN1.7.4 Control pressure in combustion chamber FN1.7.2 Extract flue gas from furnace	Pressure in furnace will increase	Hot fluegas/flames can escape outside and burn instrumentation or set boiler alight.
Probability	Severity	Risk level	Failure detection	Mitigation	Corrective action
Occasional	Serious	HIGH	Pressure sensor in the furnace will indicate the rise.	-Shut down boiler -Have 2x50% fans - Implement condition monitoring on the bearings. - increase bearing design life	Replace the bearings. This may require that the bearings are replaceable, otherwise the whole motor must be replaced.

Once again the lecturer read the context and identified the significant features, in this case potential failure risks. The students' role was to assess the potential consequences of the failure and identify ways to mitigate and correct the potential failure. The whole task was located in material relations, and knowledge of the material practicalities would be required to complete the task competently. This is a good illustration of the coherence of a system of reasoning within a profession, encompassing theoretical knowledge, procedures and a repertoire of practical experience (Winch, 2010).

### ***Steps 7 and 8 M8: Subsystem and system specification***

The submission deadlines for steps 7 and 8 were on the same day at the end of the course. This indicates that the relations between overall system and individual subsystems were completely interdependent, more of a dialectical relation between system and subsystems than a hierarchical one.

Both submissions required the synthesis of decisions and inferences made in the previous steps and followed the same rigidly prescribed format.

- The system/subsystem definition - a concise description of basic functionality.
- Prime item diagram - identified (some) interfaces between system/subsystems internal and external to the system.
- Functional allocation - identified main functions of the system/subsystems and assigned them to a subsystem.
- Interface - identified some interfaces and referenced the documentation of the relevant metric and quantity.
- Requirements - a list of functional requirements with values and traces back to analytical documents where they were calculated.

A central focus of these final steps was to provide referenced traces to previously documented analyses or decisions. However, no new disciplinary processes were introduced. Rather these steps represented a return to the significant material relations, even though in many cases they were represented in symbolic form.

For example, the turbine system was 'defined' in terms of what it is and how it operates:

Work is extracted via blades in the single HP and multiple LP turbines mounted on the shaft, which rotate due to the steam mass flow. The associated efficiency of this action has been taken into account in order to determine the energy for electrical distribution from the plant as well as to run the plant. [M8:RepSoln7<sup>13</sup>]

In terms of the primary equipment requirements, students were given a tabular format to follow. A representation, constructed from multiple possibilities, is shown in table 5.2.

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<sup>13</sup> The solution has been reconstructed into generic format to meet the ethical requirements of the study.

**Table 5.2 Data M8: representative equipment requirement specification**

Metric	Value	Rationale/design parameter	Trace	Priority	Status	MoC	MoC description
HP steam pressure outlet	742±37kPa	... ensure adequate distribution of work extraction between LP and HP turbine to achieve adequate efficiency...	URS4108 Rev 1.2 par 4.1	Medium	Verify	Test	Pressure gauges shall indicate the pressure between the HP and LP

***C5: Future foreshore***

As with M8, the bulk of the inferential reasoning using disciplinary knowledge was done in detailed design. But in the case of C5, the recontextualising decisions were completely different. By leaving the control for the choice of artefact types (infrastructural elements) within the broader precinct plan to the students, the solution possibilities were unconstrained and divergent. This left students in control of reading the context/artefact in order to identify significant material relations, the identification of relevant fields of disciplinary knowledge, the translation of material relations into symbolic relations and the form of the final presentation of the solution. Where in M8, what counted as correct material and symbolic relations was explicit and rigorously checked against a rubric, the diversity of solutions in C5 precluded that, and the evaluative criteria were consequently more tacit, based on a professional judgement of adequacy rather than a rigorous check for accuracy.

The following is an analysis of one representative solution. Although prepared by a student, it is presented as a proxy for a typical solution. This was only one of the infrastructural elements designed, and no 'correct' solution existed against which the design could be checked. Based on the grade assigned to this solution, it was judged as exceptionally good, and therefore considered representative of the sort of reasoning and judgement expected of an 'adequate' solution.

The example involved the detailing of the geometric design of the links between the N2 and N1 intended to bring the incomplete freeways down to grade, and thereby free up space in the precinct for other developments, and to provide access to parking in order to address the integrated transport plan proposed for the precinct. The solution, shown in figure 5.6, was presented as a technical drawing of the new links between the N2 and N1 freeways, including plan view and horizontal alignment details, elevations and vertical alignment details.

In relation to the context presented in the brief, the solution represents a level of abstraction above the embedded concreteness of the problem. It still relates directly to the specific context of the precinct, constrained by the spatial limitations and directed by the need for accessibility. But it is represented in the abstracted language of technical drawings and notation. The solution presentation is symbolically dense in terms of the data and the terminology. Reference is made to beginning and ending points of vertical and horizontal curves, vertical and horizontal points of intersection and tangents. All are precise technical

CHAPTER 5

terms used in geometric road design, and all are presented in co-ordinate systems with radii, bearings, lengths and deviation angles, defined by surveying.

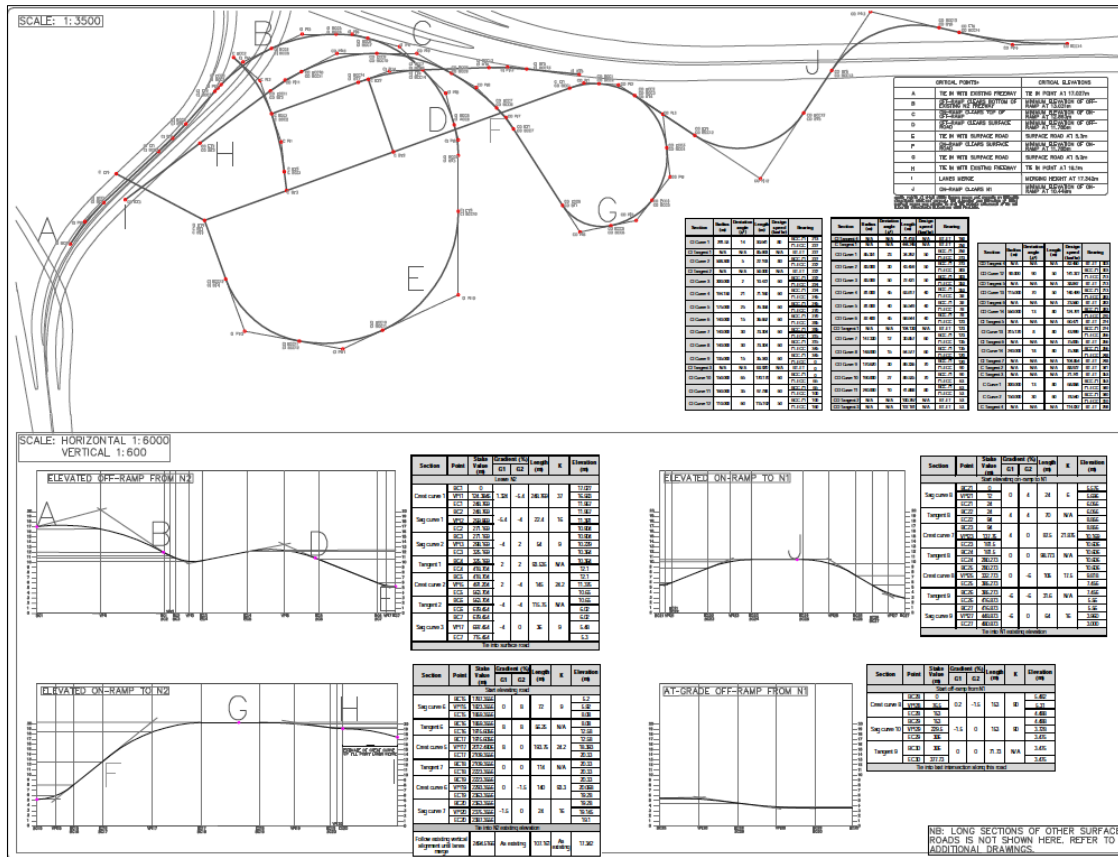


Figure 5.6 Data C5: geometric design solution

Behind the solution lies a complex set of material relations, including the existing geometric layout of the roads, vehicle dynamics, legislated policies and laws; driver behaviour; material strength (not covered in this project). In addition, the real context constrained the solution in very material ways:

The horizontal alignment proved to be a challenge with regards to obtaining a reasonable ramp speed profile while fitting the system into a restricted space. [C5:Soln05.14,p4]

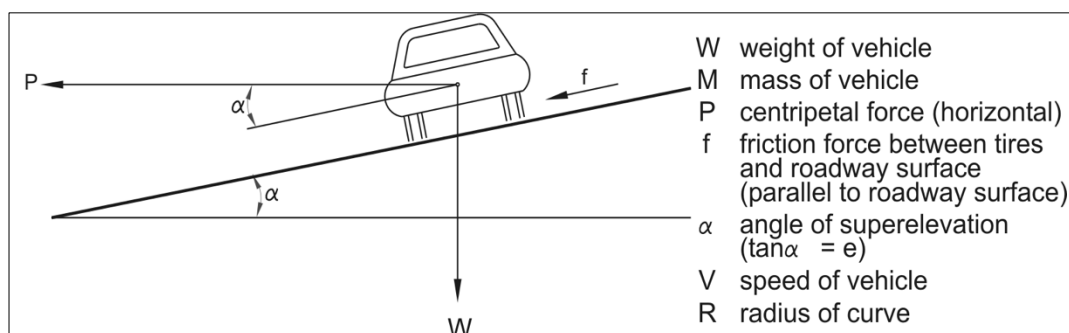
with interdependent consequences:

Due to the horizontal alignment of the system, there are a number of critical heights where the minimum clearance had to be obtained. These critical points were influential in shaping the vertical alignment. [C5:Soln05.14,p4]

As with M8, these material relations were captured symbolically in order to model the performance of the proposed artefact, and the complexity of the material interdependencies forced iterative cycles through symbolic chains of calculations. But unlike M8, the students were left to identify the significant material relations and translate them into symbolic form, and manage the iterations. Above are two of the significant material relations identified in this solution, the tendency of a vehicle to slide out of a curve at speed, and the space between the road surface and the base of the viaduct above the road through which the vehicles must pass. If identified, both can be addressed using disciplinary knowledge, including dynamics, geometry and surveying. However before they can be modelled symbolically their

significance needs to be identified and isolated from the rest of the complex material relations.

As with M8, the symbolic relations needed to be specialised to the case. Elaborating the process of determining the ramp speed profile in the horizontal curves, the student used “the standards set out in SANRAL’s *Geometric Design Guidelines*” and *TRH 17*”, two different sources that guide geometric road design. From the student's perspective these standards perform the same function in the design as the comprehensive notes provided by the lecturer in M8, except that in C5 the student needed to determine the sources him/herself, and in this case drew on two sources. Below is an extract from *Geometric Design Guidelines* compiled by the CSIR on behalf of SANRAL.



**Figure 5.7 Data C5: geometric design guidelines for design speed N1-N2 links (SANRAL, p. 4)**

The relationship between speed, radius, lateral friction and superelevation is expressed by the relationship:

$$e + f = V^2 / 127 R$$

The side friction factor is a function of the condition of the vehicle tyres and the road surface and varies also with speed. For the purposes of design, it is desirable to select a value lower than the limit at which skidding is likely to occur and the international general practice is to select values related to the onset of feelings of discomfort.... taken as  $f = 0,21 - 0,001xV$  or  $f = 0,19 - V/1600$  (incl a safety factor of  $\approx 3$ ) (C5) (SANRAL, pp. 4-7)

The guidelines present a type of contextual scenario, a vehicle, any vehicle, moving on a tar road in a curve with an inward slope. It is an illustrative example of a conceptual principle based in vehicle dynamics, and transferable across similar contexts rather than a conceptualisation emergent from a concrete scenario. Its origins are conceptual rather than contextual.

In terms of complexity, the symbolic formulation is a simple elaboration of a number of variables that can be defined sequentially and calculated simply; but it is also the condensation of principles of circular motion and centripetal acceleration; vector mechanics; friction; safety factors; and a sense of driver comfort. However, the centripetal acceleration for example is not in its familiar discursive form, condensing a unit conversion and gravitational constant into the number 127. 'f' is in fact not a frictional force, although it relates to friction, rather it is an empirical relation that attempts to quantify driver comfort.

Although the relation can be used to determine a minimum ‘safe’ curve radius, recognising that setting the lateral frictional factor to zero defines the ideal curve radius, which would require no steering input to follow the curve. This adds a level of insight that allows more variation in possible design decisions. The complexities of this scenario originate in the material relations, not in the symbolic relations. These in turn drive the complexity of the symbolic relations that are hidden behind the simple formulation. Figure 5.8 indicates this reasoning.

Horizontal Alignment Example  
Calculations:

① Determining range of radii for a given curve:

Relationship applies:

$$e + f = \frac{V^2}{gR}$$

where  $e \rightarrow$  superelevation  
 $f \rightarrow$  side friction factor  
 $V \rightarrow$  design speed (m/s)  
 $g \rightarrow$  m/s<sup>2</sup>  
 $R \rightarrow$  radius (m)

Procedure followed:

- Choose desirable design speed
- calculate  $f_{max}$  with  $f_{max} = 0.14 - \sqrt{1/1600}$
- choose superelevation for curve
- solve for  $R$ 
  - $\rightarrow$  when  $f = f_{max}$
  - $\rightarrow$  when  $f = 0$
- for  $f = f_{max}$   $\rightarrow$  least desirable radius
- for  $f = 0$   $\rightarrow$  most desirable radii

**Figure 5.8 Data C5: student example of reasoning between material and symbolic relations**

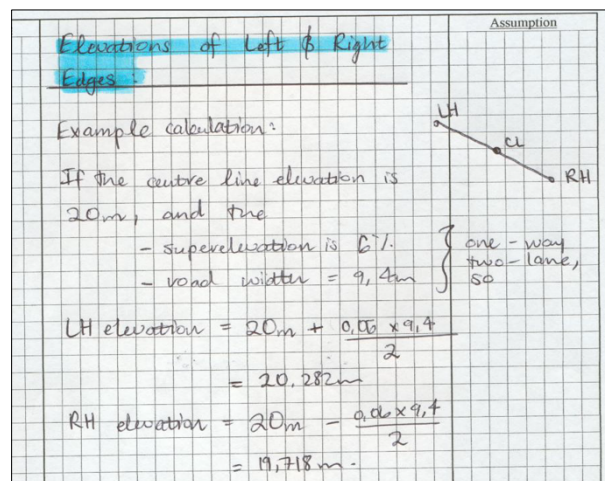
If a problem is presented in the idealised format with enough variables defined, calculating any missing variables is a very simple operation. But to use the simple symbolic formulation in a design requires an understanding of the underlying material relations, condensed into symbolic form. A fundamental difference between M8 and C5 lies in who interprets the relationship between the material and symbolic relations, the lecturer or the student. When the lecturer prescribes interpretation, the condensation of complex symbolic and material relations can be reduced to a simple formula. But the complexity lies in the meaning that condenses the material and symbolic relations, not in the simple symbolic expression. Hence, when the lecturer condenses the relations, the complexity of the material relations is reduced to a simple symbolic relation.

The second element referred to above, the clearance heights between lower road surface and the base of the viaduct of the overpass, used relatively simple geometric relations. But in order to minimise the number of calculations, and to tie into the existing specific context,

critical points were identified, and the geometric relations needed to be constructed for only these critical points, based on variable and uncertain operations.

The following assumptions are applicable to the design process:

- Drawings were not available for certain portions of the N1; hence, where required, road elevations were assumed from a geo-referenced ArcGIS map,
- The minimum clearance between the finished surfaces of two roadways is comprised of the section thickness of the upper viaduct and the maximum vehicle height as per regulations in South Africa. Hence, it was assumed that there are no vehicles with a height greater than that specified in the regulations. It is also assumed that the proposed elevated system will have section thicknesses similar to that of the elevated viaducts of Culemborg. This is, in all likelihood, an overestimate of the required section thickness, ... [C5:Soln05.14,p3]



**Figure 5.9 Data C5: student example of identification of critical material positions**

Once again the complexity lay in the material relations rather than the symbolic relations, and once again, the student was left to identify and manage these relations in C5.

### 5.4.1 Inferential reasoning: specialising the artefact

The nature of the reasoning involved in the specialisation of a prescribed artefact type to perform a particular function in a specific context was illustrated in the narratives above. Abbott's (1988) mode of inference recognises the role of disciplinary knowledge in professional action, but tends to imply its separation from reasoning based on contextual factors (of both the context and artefact). In both M8 and C5, the chains of inference shifted between material and symbolic relations in a dialectical relationship. Making sense of the contextual features both simplified and organised them, and suggested relevant disciplinary knowledge. Disciplinary knowledge provided principled insight into the contextual details and further functioned to simplify and organise the contextual features. Generalised theoretical concepts were related to other generalised theoretical concepts in ways determined by the specifics of the material detail. Inferences in design require reference to the material details of the context and artefact; they are not separate from the concerns of the world, nor are they imposed on the world.

Although this dialectical relationship was the basis of the reasoning in both M8 and C5, the recontextualisation of the designs significantly modified the nature of the required reasoning of students. Contexts simplified to precise symbolic representations, intended as symbolic inputs for analysis, artefacts prescribed in idealised form, and generalised conceptual relations condensed into defined mathematical form specific to a particular context or artefact, all functioned to reduce the significance of the material relations in favour of isolated symbolic relations. Understanding the material relations in order to identify what matters, and what does not, becomes unnecessary. Using insights into the material necessities to identify relevant disciplines and associated knowledge becomes unnecessary. Using insights from whole networks of conceptual relations to simplify and organise complex material relations becomes unnecessary. The profoundly dialectical relationship shown both in the supplementary notes provided by the lecturer in M8, and required of the students in C5, is potentially severed. Design becomes merely the application of (procedural) theoretical models. I would argue that it is making sense of the complex material relations that drives the demands for insights into the complex networks of the symbolic relations defined by theoretical disciplines. Once identified, the symbolic relations help to further simplify and organise the complex material relations.

Most of the recontextualising choices were evident in the brief in terms of how the context was presented and the artefact prescribed, (although the supplementary notes provided in M8 provided rich insight into the nature of inference behind a very complex design artefact). In Bernsteinian terms, M8 was a very strongly framed project (the artefact was prescribed in detail, the knowledge was identified and specialised to the context, the tasks were sequenced into discrete steps, the evaluative criteria were precise and explicit). By comparison, C5 was a very weakly framed project (students were required to select, sequence, pace and determine the adequacy of their own solutions). The problem with very strong framing of design projects is the potential to sever the relations between material relations and symbolic relations, favouring symbolic relations and putting the 'word' (conceptual relations) before the 'world' (material relations). When framing is weakened, the material relations are allowed in, as Wheelahan suggests from a critical realist perspective, since “knowledge arises from our practices in the world and not the structures of knowledge. World before word” (Wheelahan, 2010, p. 75). But the problem of very weak framing is that, in addition to allowing the material relations in, our fallible and limited knowledge of the complexity of the 'real' world opens multiple interpretations and prioritisations, some more or less relevant than others. Students having differential access to different interpretations will approach the project in more or less adequate, integrated and insightful ways. Ambiguous solution requirements make evaluative criteria more tacit and evaluation less consistent. Rather than being based on rigorous symbolic relations, the double complexity of material and symbolic relations requires evaluation based on a judgement of adequacy.

### 5.4.2 Artefacts specification: Solution presentation

In professional practice, any solution to a problem is evaluated on its efficacy (Abbott, 1988), or how well it addresses the problem in the 'real' world. This is regardless of how well we understand the problem or the theory that helps to inform the solution. However, before a solution is implemented, it does need to be finalised into specific descriptions for manufacture or construction. This usually takes the form of prescribed documentation including performance criteria and technical drawings. The solutions in the recontextualised design problems investigated in this study were all based on 'paper designs', symbolic representations of proposed solution artefacts in various forms. And as with the other elements of the two capstone design projects, the solutions took different forms.

The multiple submissions required in M8 tended to fragment the designed artefact. Each submission contained lists of material or symbolic items, simplifications of chains of inferences, but not necessarily retaining any sense of the whole system. Although the final submissions essentially integrated the outputs of each of the previous steps, and the prescribed numbering system did provide some sense of the whole system, overall, the solution appeared as a list of discrete symbolic elements or material elements. What these lists did allow was very explicit (strongly framed) evaluative criteria, with associated rigorous checking of the symbolic relations.

The solutions required in C5 took the form of 4-5 A3 technical drawings. The drawings included the overall precinct to indicate the general concept and the location of the various infrastructural elements within the precinct. Individual drawings included technical detailing of the infrastructural elements. The drawings were accompanied by (limited) text intended to justify the various design decisions taken. Students were allowed to submit appendixes that might comprise more detailed elaboration of their designs and design calculations.

Although the evaluation took account of the accompanying text, the bulk of the assessment was judged on evidence in the technical drawings, see for example the geometric design of the freeway off-ramps down to grade shown in figure 5.6. Although symbolic in nature, the technical drawings simplified and organised the material relations, by providing only those aspects relevant to the design (for example dimensions/slopes). Other material complexity (for example how drivers behave and might experience the roads, spacing and relations to the adjacent infrastructure, cost, the integration with the overall precinct plan) was stripped. Although the technical drawing is the output of chains of theoretical inferences, the nature of the solution presentation was to condense the complex material and symbolic relations into far simpler material and symbolic relations. But the drawings also held the design together, retaining the connectedness between parts and whole in a way that lists of discrete calculated values fail to do.

While the technical drawings give a strong sense of the material relations, the diversity of solutions meant that the evaluation was open to a great deal of professional subjectivity.

In both cases the design solutions presented were a simplification of both the material and symbolic relations on which the inferential reasoning was based. In both cases the solution was a shift from the general theoretical basis of many of the inferences, towards the detailing of a specific instantiation of an artefact type. The inclusion of technical drawing might help to hold the material relations together, while lists of discrete criteria tend to be more fragmented.

## **5.5 Summary of the analysis of the capstone design projects**

The narratives presented above were constructed against three theoretical contributions to knowledge relations. Models of professional action (Abbott, 1988; Schön, 1983; Simon, 1981) drew attention to the significance of contextual detail and movements between case-based reasoning and rules of conceptual coherence within theoretical disciplines. It drew on concepts that relate knowledge to the object of knowledge (Maton, 2014; Muller, 2009; Wheelahan, 2010). And it showed the effect of the locus of control (lecturer or student), or framing (Bernstein, 2000) on the demands made of students. The analysis set out to explore the nature of reasoning required in recontextualised design projects, and the demands placed on students to make sense of the material and symbolic relations that underpin these inferences.

While Abbott's (1988) three modes of professional action (diagnosis, treatment, and inference) are very useful, the analysis also showed the limitations of these modes, especially for novice professionals. His identification of the fundamentally different organisation of knowledge, a library of cases organised by prevalence and efficacy as opposed to networks of conceptual ideas based on conceptual coherence, is important for understanding the nature of professional reasoning. The distinction between material and symbolic relations went some way to capture the differences in the organisation of the knowledge. However, Abbott's recourse to medical metaphor in his modes of diagnosis and treatment appears to limit the applicability of his model in relation to engineering design. His modes do not consider the translation between the differently organised knowledge systems. Even when the conceptual design resonates with the diagnosis-treatment couple that (Abbott, 1988) calls 'routine professional processing', once the artefact has been conceptualised, it needs to be specialised to function in a particular context. Detailed design requires recourse to disciplinary knowledge. And during the conceptual design, insights from theoretical disciplines were evident in diagnosis.

However, if one sees an extension to diagnosis as a process of simplifying a context by removing extraneous detail (colligation in his terms) and abstracting the significant aspects into symbolic form for the purpose of inference rather than retaining the contextual aspects for classification, it has more applicability in engineering design. Similarly for treatment, if one recognises the brokering process as not limited to contextualising the treatment for the purpose of 'selling' the treatment to the patient, but more a process of specialising the

treatment to a specific context with the aid of disciplinary knowledge (inference), then treatment has more applicability in engineering design. I am proposing that for engineering design (at least as students experience it in a curriculum) it is important to see diagnosis as the stripping of extraneous detail for the purpose of both classifying a contextual case, and for the purpose of translating relevant contextual features into symbolic form based on disciplinary insights. Similarly treatment becomes a process of specialising a general solution to a particular context with or without recourse to inference. Design then can be seen as an intermingling of modes of diagnosis, treatment and inference, more in the spirit of Winch (2010).

The relationship between contextual detail and artefact solution highlighted by Schön (1983), or as Simon (1981) suggests, the reasoning at the interface between the outer environment and the inner environment, is also central to professional reasoning. This critical interaction is masked when recontextualisation strips the details of the context from the problem, resulting in the potential severing of the material relations with their innate complexity and the prioritising of symbolic or conceptual relations over making sense of the world.

Regardless of the nature of the inferences required to develop the solution, the solutions were both significant simplifications of the material and symbolic relations evident during inference. When a solution ends in a technical drawing, that drawing simultaneously simplifies the material and symbolic relations, but retains a level of integration or 'wholeness', that holds together the material and symbolic relations. When the solution requirement is a list of elements or criteria, there is a sense of fragmentation in the solution, and even when material relations might be the object of the list, symbolic answers seemed to dominate the output.

An extremely important aspect of professional knowledge in action lies in the relation between the contextual specifics of problem contexts and solution artefacts, and the conceptual generalities of disciplinary knowledge used to address them. When a context or an artefact is complex, as was the case in both examples, the number of relevant material relations and the simultaneous interdependence between them is huge. The significant relations need to be identified and the insignificant neglected. Systems of disciplinary knowledge (conceptual ideas and legitimate relations between them) can help to identify significant material relations, but only if the material artefact or context are understood on their own terms.

In the examples presented above, the inferences were all conceptual in nature. But when the conceptualisations related to contextual factors (either the context or the artefact), I termed them material relations. And when the conceptualisations constructed relations between concepts as defined by any theoretical discipline, I called them symbolic relations. The main argument presented above is that using disciplinary knowledge to solve 'real problems' requires a dialectical relationship between material and symbolic relations, rather than any notion of imposing symbolic relations onto material relations. But the nature of the inferential

knowledge chains showed shifting patterns of contextual and conceptual details, relative simplification and elaboration or complex interdependencies and symbolic condensations.

The final point to make is that although the knowledge relations evident in the two projects were remarkably similar, the control over the shifting knowledge relations was fundamentally different. In Bernstein's terms, all aspects of the design tasks in M8 were very strongly framed (controlled explicitly by the lecturer), while in C5 they were very weakly framed (either tacit or controlled by the students). In many respects the strong framing of M8 potentially reduced the project to symbolic manipulations, where students worked with idealised material relations and never had to face the uncertainty of reading complex material detail (context/artefact). The challenge that C5 posed was that because the framing is so exceptionally weak, the expectations of the students were ambiguous. Further, the assessment was based on a judgement of adequacy, whatever that may mean. The differences between M8 and C5 are central to the idea of curriculum recontextualisation; this is what changes (recontextualises) the discourse. Even though the content of the design projects and the knowledge relations involved in designing might be notionally the same, how the complexity of the project is controlled in order to fit into a course, who selects what counts and when, is central to learning and assessment.

The narrative comparison between M8 and C5 presented in this chapter gives a sense of the issues that are significant for understanding the nature of reasoning in design, and the effects of recontextualising choices on the reasoning. The following chapter develops the ideas presented in this chapter in terms of an LCT (Semantics) analysis (Maton, 2014). However, the narrative presented in this chapter shows that complexity of meaning takes two distinct forms, one based on systems of meaning in relation to material relations and the other based on systems of meaning in relation to symbolic relations. In order to specialise LCT (Semantics) so that it is able to distinguish between these distinct forms of complexity, the next chapter shows how I operationalise the concepts available in LCT using principles from social realism drawing on Sayer (2010). Where in this chapter the two capstone projects were analysed in detail, the significant aspects of the design projects identified here are developed in the following chapter across all 17 design projects. Because the 17 projects are located in three trajectories of sequential projects, the following analysis includes considerations of progression.

## Chapter 6 LCT (Semantics) analysis and discussion

In the previous chapter a distinction was made between material relations (referring to the concepts used to make sense of the object of design and the context in which it operates) and symbolic relations (the disciplinary concepts and the legitimate relations between those concepts defined within any disciplinary field). The detailed analysis of the two capstone design projects showed similarities in reasoning that underpinned both; a dialectical relation shifting between material and symbolic relations with continuous translations required between the two. However the analysis also illustrated the effect of different recontextualising choices on the nature of the reasoning *required of the students*. In this chapter an LCT (Semantics) analysis is extended to all 17 projects. However, the significance of the recontextualisation of contextual detail evident in the previous chapter required an adaptation to LCT (Semantics) in order to compare and contrast the effects of various recontextualising choices on the nature of reasoning required of students in each project.

### 6.1 Overview of the Semantics analysis

As discussed in chapter 4, this study is based on documentation gathered for each of the 17 engineering design projects, including the design brief and a solution memorandum. When a solution memorandum was not available, students' solutions assessed as 'excellent'<sup>14</sup> were used as a proxy for solution memoranda (not as a measure of learning). The 17 projects represent three design trajectories located in two different engineering programs. The mechanical engineering program includes four sequential design courses. The civil engineering program does not include a trajectory of design courses; instead design projects were selected from within disciplinary courses. Two trajectories of four design projects were identified, capped by the integrated design project presented in chapter 5. For convenience, Table 4.1 is repeated here (as Table 6.1) showing the 17 projects in the sequenced in which they are located in the curricula.

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<sup>14</sup> Solution examples to act as proxy solutions were selected from those student submissions judged by their grades to represent examples of the best solutions.

**Table 6.1 Data: design projects and trajectories**

	Civil Engineering		Mechanical Engineering
	Structures	Urban	
<b>YR2</b> S1			<b>M1</b> Bearing selection and mounting <b>M2</b> PRS for domestic appliances
<b>YR2</b> S2	<b>S1</b> Parking structure (Structures I)	<b>U1</b> Bikeshare scheme (Engineering Camp)	<b>M3</b> Gearbox design (Design I)
<b>YR3</b> S1	<b>S2</b> Steel shed (Structures II)	<b>U2</b> Flood attenuation culvert (Hydrology)	<b>M4</b> Wheel support assembly <b>M5</b> Multi-tool
<b>YR3</b> S2	<b>S3</b> Concrete slab (Structures III)	<b>U3</b> Sewage reticulation (Urban Water Services)	<b>M6</b> CCTV tower (Design II)
<b>YR4</b> S1	<b>S4</b> Parking garage (Structures IV)	<b>U4</b> Emmarentia Dam road (Urban Design and Management)	<b>M7</b> Multitask micro-machine (Product Design)
<b>YR4</b> S2	<b>C5</b> Future foreshore (Design Project)		<b>M8</b> Power plant specification (Systems Design)

The analysis in the previous chapter suggested four of units of analysis, outer environment or context; inner environment or artefact; solution specification; and inferences. Each of these units of analysis is defined in table 6.2 below.

**Table 6.2 Data: units of analysis**

Unit of analysis	Identifying the boundaries of analysis
<b>Context</b> <i>description</i>	The context was coded on the basis of the description of the environment in which the artefact was expected to function, as indicated in the design brief.
<b>Artefact</b> <i>prescription</i>	The artefact was coded on the basis of the level of detail and complexity indicated in the brief, and required to make sense of the artefact in order to complete the design project. The semantic code of the artefact as prescribed in the brief may differ from the semantic code of the artefact specified in the solution.
<b>Solution</b> <i>specification</i>	The solution was coded on the basis of the artefact specified as the final design solution, independently of the reasoning required to develop the solution.
<b>Inferences</b> <i>(specialising the solution)</i>	The inferences were coded based on the reasoning entailed in establishing relations between the context, artefact and solution in the process of specialising the artefact to its purpose and context in order to specify a solution.

The 17 design projects were each analysed in respect of the requirements for reasoning between theoretical concepts and contextual detail, in relation to each of the four units of analysis. The LCT (Semantics) code assigned to each unit of analysis for each project was based on an interpretation of the minimum requirements for making sense of each unit of analysis in order to complete the project. The coding is therefore not an inevitable outcome of the project; some students may be more inclined to engage with the project in ways that seek

a deeper, more integrated understanding of the project. The full analysis of each unit for each project is presented in appendix 2.

Because of the significance of contextual detail (of the context and artefact) demonstrated in the previous chapter, LCT (Semantics) was adapted in order to capture the distinction between material and symbolic relations. This adaptation and its theoretical basis is presented in section 6.2, followed by a presentation of the analysis in section 6.3.

## 6.2 Developing the Semantics analysis

As discussed in chapter 3, there are several concepts within the social realist school within the sociology of education that could be used to analyse the relationship between concepts and contexts. Most obvious would be to draw on what Muller (2009) called the logic of curriculum coherence, either a conceptual logic or a contextual logic. But the attraction of the semantics dimension of LCT is that all LCT dimensions recognise that both aspects of the dimension are always present. Rather than categorising something as one or the other, it is the relative significance of each aspect that is considered (Maton, 2014). This is particularly important for professional education, where both the contextual aspects of a problem and the conceptual tools used to solve the problem can be simultaneously significant.

LCT (Semantics) consists of two concepts, semantic gravity (SG) and semantic density (SD), which can be used to capture two aspects of shifts between contexts and concepts, without setting them up in opposition to each other. Semantic gravity explicitly retains a link between abstract, generalisable concepts and the objects to which they refer. Semantic gravity uses a relative scale from strong semantic gravity (where meaning is completely dependent on a context) to weak semantic gravity (where meaning transcends context).

All meanings relate to a context of some kind; semantic gravity conceptualizes how much they depend on that context to make sense. (Maton, 2013, p. 11)

Semantic density on the other hand refers to the relative complexity of meaning. Strong semantic density refers to more complex meanings constructed from multiple parts compounded and integrated, or condensed, into a coherent, complex whole. Weak semantic density refers to simpler meanings, the separation and elaboration of each of the parts into simpler parts from the whole.

Semantic density (SD) refers to the degree of condensation of meaning within socio-cultural practices, whether these comprise symbols, terms, concepts, phrases, expressions, gestures, clothing, etc. Semantic density may be relatively stronger (+) or weaker (–) along a continuum of strengths. The stronger the semantic density (SD+), the more meanings are condensed within practices; the weaker the semantic density (SD–), the less meanings are condensed. (Maton, 2013, p. 11)

However, as with many of the contributions from the social realist perspective in the sociology of education, LCT (Semantics) has tended to foreground the complexity of symbolic relations (the relations between conceptual ideas within a discipline) with less attention given to the complexity of the context from which they emerge or to which they are

applied. We see for example in work with semantic waves that the movement between the abstract ideas and concrete examples is characterised as a movement:

... from highly condensed and decontextualized ideas (SG-, SD+) towards *simpler*, more concrete understandings, often including examples from everyday life (SG+, SD-). (Maton, 2013, p. 14, emphasis added)

Although not the intention behind the semantic wave, there is a tendency for simplicity to *become* associated with elaborated or simplified (SD-) concrete (SG+) examples, and complexity to *become* associated with condensed or complex (SD+) abstracted (SG-) symbols. We see LCT (semantics) presented as a tool that:

... provides me with two distinct kinds of 'simplification' (Blackie, 2014, p. 462)

But the examples presented in chapter 5 make it clear that there is nothing necessarily simple about concrete problems. For example, in the civil engineering capstone design C5 (Future foreshore), students were posed the following real, contextually embedded problem:

What should we do with the Foreshore?

As posed, the problem was completely concrete, real and specific without symbolic language or theoretical concepts explicitly presented. The material provided to supplement the project added to its complexity by providing additional contextual details of the precinct. This problem could be coded as having very strong semantic gravity (SG+) and very weak semantic density (SD-) because the constellations of concepts required to make sense of the context do not lie in the formal relations between specialised disciplinary concepts. Rather, the complexity lies in coherence around the concepts needed to understand the material details of the context. The logic of the interdependent relations lies in contextual detail rather than in the logic of formal theoretical relations defined within disciplinary specialisation. Making sense of the context, deciding what to include and what to exclude, in terms of systems boundaries, deciding on where to draw the boundaries, is the basis of both understanding the context and simplifying it without simplifying it to the point of dislocating it from its reality. The complexity at this stage of the problem lies in the contextual detail rather than the theoretical reasoning.

In order to develop a means to capture this contextual complexity, the social realist distinctions between epistemology and ontology, and abstract and concrete, provide a useful starting point.

Firstly, by recognising that although the world exists independently of our knowledge of it, we can come to know about it through interaction between our concepts of the world and our action in the world.

The world can only be understood in terms of available conceptual resources, but the latter do not determine the nature of the world itself. ...Observation is neither theory-neutral nor theory-determined, but theory laden... Theory does not order given observations or data but negotiates their conceptualization, even as observation. (Sayer, 2010, pp. 83-84)

We therefore have to separate analytically 'what *is*' (ontology) from our 'understanding' of what is (epistemology). And even though our understanding of the world is theory-laden, our

concepts of the world do not determine the world or how it works. When we are wrong, the world acts back regardless of our conceptualisation.

The first step in the resolution of the complexity problem, while acknowledging the limits of our access to the fullness of 'what is', was to draw on Maton's distinction between ontic and discursive relations:

One can thereby analytically distinguish ontic relations (OR) between practices and that part of the world towards which they are orientated, and discursive relations (DR) between practices and other practices ... for knowledge claims these become: ontic relations between knowledge and its objects of study; and discursive relations between knowledge and other knowledges. (Maton, 2014, p. 175)

Prior to this introduction of ontic and discursive relations, a necessary adaptation to LCT (Semantics) for this study, I used the term material relations to refer to the concepts that we use to make sense of the artefact and the context in which it operates. Material relations correspond to what Maton calls ontic relations. Similarly, discursive relations correspond to what were called symbolic relations in the previous chapter (disciplinary concepts and their legitimate combinations defined within a body of disciplinary<sup>15</sup> knowledge). Note that both are conceptual in nature, but the ontic relations refer to how we make sense of things in the world (what they are and how they work), and discursive relations refer to how we make sense of disciplinary concepts in relation to each other.

The second part of the development to LCT (Semantics) in this study draws on the social realist distinction between 'concrete' and 'abstract':

The concrete object is concrete not simply because it exists, but because it is a combination of many diverse forces or processes. In contrast an abstract concept represents a one-sided or partial aspect of an object. (Sayer, 2010, p. 123)

This suggests that rather than being a simplification of concepts, their concrete realisations are in fact complex, and the abstraction out of the concrete is a process of simplification by stripping away detail. In order to distinguish the particular-general cline from the simple-complex cline for the purposes of this project, I have specialised LCT (semantics) in the following way:

The definition of semantic gravity as the dependence of meaning on context is restricted to a cline from the particular to the general:

- SG+: meaning is specialised to a particular instantiation
- SG-: meaning is generalised across contexts

*This is intended to eliminate any association of strong semantic gravity with the familiar or the simple.*

The definition of semantic density refers to the relative complexity of meaning, but in order to distinguish between the complexity of a concrete context or a concrete artefact and the

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<sup>15</sup> Note that disciplinary knowledge tends to be called 'specialised' knowledge within the Social Realist tradition of Sociology of Education. I have chosen to use 'disciplinary' knowledge to distinguish it from the process of specialising an artefact to function in a particular context.

complexity of a constellation<sup>16</sup> of concepts, I refer to the relative complexity of the ontic relations ( $SD^0$ ) and the relative complexity of the discursive relations ( $SD^d$ ) respectively.

In this discussion, the use of the term 'complexity' needs to be elaborated. The way in which I use it draws on Simon's (1981) pragmatic use of the term:

I shall not undertake a formal definition of "complex systems". Roughly, by a complex system I mean one made up of a large number of parts that interact in a nonsimple way. In such systems the whole is more than the sum of its parts, not in an ultimate, metaphysical sense but in the important pragmatic sense that, given the properties of the parts and the laws of their interaction, it is not a trivial matter to infer the properties of the whole. (Simon, 1981, p. 195)

Therefore simple ontic relations ( $SD^0-$ ) shall be used to refer to contexts or artefacts that can be adequately understood with reference to a small number of parts interacting in straightforward ways. Complex ontic relations ( $SD^0+$ ) shall refer to contexts or artefacts where the number of parts interacting and the ways in which they interact depend on simultaneously understanding multiple interactions and multiple potential outcomes. Likewise, simple discursive relations ( $SD^d-$ ) shall refer to disciplinary concepts that can be understood in relation to few other disciplinary concepts, in straightforward and intuitive ways. Complex discursive relations ( $SD^d+$ ) shall refer to disciplinary concepts that need to be understood in relation to far more disciplinary concepts, sometimes in embedded and very non-intuitive ways, requiring a more coherent mastery of the discipline/s.

The process of abstraction from the concrete can now be described as a process of weakening the semantic gravity from particular instantiations to generalisations that can be made across contexts ( $SG+\downarrow$ <sup>17</sup>  $SG-$ ). The semantic density of the ontic relations is weakened simultaneously by identifying and extracting significant aspects from the complexity of the context ( $SD^0+\downarrow SD^0-$ ). The semantic density of the discursive relations is potentially strengthened if disciplinary concepts are drawn into relations with other concepts ( $SD^d-\uparrow SD^d+$ ).

### 6.2.1 Developing the external language of description

Each of the units of analysis identified in each of the projects was coded on a scale of relative specificity (SG) and relative complexity (SD) based on the principles described above. The external language of description, or translation device, was developed through working dialectically with the theoretical principles of LCT (Semantics) and the empirical data. This process was described in detail in chapter 4.

The external language of description used to analyse semantic gravity is presented in table 6.3. Table 6.4 shows the external languages of description used to analysis semantic density.

<sup>16</sup> Maton (2014) uses the term constellation to refer to the way in which concepts, within a discipline, relate to each other in a coherent network of ideas defined by the discipline.

<sup>17</sup> (Maton, 2013) uses up and down arrows to indicate strengthening or weakening of LCT dimensions, where  $\downarrow$  indicates weakening and  $\uparrow$  indicates strengthening.

The symmetry between the categories for the ontic and discursive relations was a key element in the process of developing these languages of description.

**Table 6.3 Semantic gravity: relation of meaning (conceptualisation) to its external referent (material context or artefact)**

Specific and detailed, described in terms emergent from the context	SG++	Meaning relates directly to a <b>specific instantiation</b> of an object, described in <b>rich detail</b> specific to a <b>unique</b> case/situation. [Tends to be associated with $SD^{o++}$ & $SD^{d--}$ ; ontic condensation <sup>18</sup> & discursive rarefaction. <sup>19</sup> ]
	SG+	Meaning relates to (originates in) a <b>type of object</b> or <b>system</b> , it refers to real objects, but abstracted from a specific, unique instance to a <b>class/type</b> of object. [It is a form of <b>inductive</b> reasoning in that meaning is generalised from sets of particulars.]
Generic or idealised, described in terms imposed from a body of disciplinary knowledge.	SG-	Meaning is <b>imposed</b> from a disciplinary body of conceptually coherent knowledge, but the general law/s or concept/s are <b>specialised</b> for application to an object or class of object. [It is a form of <b>deductive</b> reasoning where an object is read through the lens of disciplinary knowledge in order to make sense of it.]
	SG--	Meaning resides in <b>general</b> laws or concepts that <b>transcend</b> contexts; it does not require a concrete reference to make sense. [Tends to be associated with $SD^{o--}$ & $SD^{d++}$ ; ontic rarefaction & discursive condensation.]

**Table 6.4 Semantic density: relative complexity of relations between concepts (discursive relations) or components (ontic relations)**

		<b>SD<sup>o</sup></b> Semantic density (ontic relations)	<b>SD<sup>d</sup></b> Semantic density (discursive relations)
Integrated in a coherent whole	SD++	Multiple <b>interdependent</b> components are <b>integrated</b> into a <b>contextually coherent</b> whole. The causal interdependencies are <b>embedded</b> and there is minimal attention to identification of significant aspects or exclusion of superfluous aspects.	Multiple <b>conceptually coherent</b> bodies of disciplinary knowledge are <b>integrated</b> in order to model or predict performance. Although the theoretical antecedents may be <b>embedded</b> , a coherent understanding of them is central to meaning. Theoretical constellations are used in relation to each other.
	SD+	Multiple <b>interdependent</b> components parts are <b>identified</b> and <b>separated</b> into constituent parts, while retaining necessary <b>simultaneous interdependencies</b> .	Multiple <b>interdependent</b> concepts within a conceptually <b>coherent</b> body of <b>disciplinary</b> knowledge are <b>identified</b> and <b>separated</b> into constituent concepts, but meaning is developed through <b>simultaneous interdependent</b> relations between concepts.
Separated into constituent parts	SD-	Multiple <b>interdependent</b> components parts are <b>separated</b> into constituent parts, and the interdependencies can be treated <b>sequentially</b> .	Multiple <b>interdependent</b> disciplinary concepts are <b>identified</b> and <b>separated</b> into <b>discrete</b> concepts that can be considered <b>sequentially</b> . Often expressed as procedural sequences.
	SD--	A component part is <b>dislocated</b> from its <b>relations</b> to other parts, losing the significance of the interdependencies within the system from which it was extracted, or it may be <b>imaginary</b> , effectively <b>severing</b> the real causal mechanisms that underpin real artefacts/contexts.	A concept is <b>disconnected</b> from its <b>relations</b> to other concepts, losing the significance of the interdependencies within the disciplinary body from which it was extracted, or an <b>unspecialised</b> common sense understanding is adequate. The concept can be treated in <b>isolation</b> from its related system of disciplinary concepts.

<sup>18</sup> Maton (2014, p. 130) refers to stronger semantic density as condensation of meaning, suggesting the integration of multiple elements into a unit or constellation that make up more complex meanings.

<sup>19</sup> Similarly, rarefaction refers to the weakening semantic density by the dislocation of parts of a constellation in order to 'unpack' or flesh them out. It is a form of simplification.

## CHAPTER 6

In order to illustrate some of the nuances in the coding of the data, the four tables that follow each compare two examples from the data, selected to clarify particular analytical distinctions. Each pair presented in each table has the same level of relative semantic gravity (specificity) but differs in the semantic density (complexity) of the ontic and/or discursive relations. These data were selected to illustrate significant comparisons between the coding principles. Many examples are selected from the capstone projects, but data from other projects will also be introduced. There are instances where data has been extracted from within a full unit of analysis for the purpose of this example, and differs from the coding of the full unit of analysis presented in appendix 2. These deviations are noted in a footnote.

Table 6.5 shows a comparison between an extract of data from the design brief in C5 (Future foreshore) and data from a single inferential step in the development of a solution to the same project. Both are coded SG++ because they refer to a specific instantiation of the context and the development of a fully specified solution artefact respectively. They were both presented in rich detail, which defined each example as unique. However, the complexity of their ontic and discursive relations was completely different. In the first example the complexity lay in the contextual detail (ontic relations), in the second the complexity lay in both the ontic and the discursive relations.

**Table 6.5 Complexity in relation to specific, unique instances (SG++)**

Ex 1: C5 (Future foreshore) – context presented in the design brief <sup>20</sup>	Ex 2: C5 (Future foreshore) – inferences behind the solution <sup>21</sup>
 <p>“The north Foreshore precinct is a derelict part of the city characterized by neglected and unused open spaces and remnants of an older freeway-building era. Yet there is great potential to make use of this precinct to create a vibrant, mixed use area, open and attractive to all Capetonians, demonstrating principles of integration and sustainability, and possibly re-establishing the historical link between central Cape Town and the sea. Major new planned projects in this area and in relation to the Port make this task an urgent one.”</p>	<p>“The horizontal alignment proved to be a challenge with regards to obtaining a reasonable ramp speed profile while fitting the system into a restricted space. Due to the horizontal alignment of the system, there are a number of critical heights where the minimum clearance had to be obtained. These critical points were influential in shaping the vertical alignment ... While it is conventional for freeway exits to be placed on the left-hand side of the road, this was not feasible for two reasons: firstly, the required horizontal alignment would cause the off-ramp to impose on the ... development. Secondly, the horizontal alignment would not allow the off-ramp to pass under the existing viaducts; instead, it would have to go up and over the existing viaducts.” (C5)</p> 
SG++: The descriptions relate to this <b>specific</b> precinct articulating or illustrating the unique combination of features in <b>rich detail</b> that defines this <b>unique case</b> .	SG++: The inferences refer to a <b>specific</b> road section that ties into existing roads and fits into a specific and constrained space. It related to a <b>unique case</b> .
SD <sup>o++</sup> : The <b>real</b> , the causal mechanisms that underlie the precinct (physical, social and economic), are <b>condensed</b> in the overall descriptions. The supporting documents cover a <b>wide range of considerations</b> (engineering, planning, historic, environmental) <b>adding to the complexity of the concrete context</b> . Although they have the potential to weaken the ontic density by implicitly suggesting aspects of the context that might be considered as significant, they <b>do not separate and organise</b> the various aspects of the precinct.	SD <sup>o+</sup> : The discussion shows that <b>significant</b> constituent parts of the context and artefact were individually identified, while retaining the <b>simultaneous interdependency</b> between the parts. The horizontal and vertical alignments combine into a three-dimensional description influenced by each other and the existing network into which it ties, the space constraints imposed by the rest of the precinct, vehicles using the road, the rules of the road and driver choices.
SD <sup>d--</sup> : The photographs, descriptions and site visits are initially meaningful <b>without</b> recourse to <b>disciplinary</b> knowledge. The process of diagnosis required student to use disciplinary insights to develop a more theorised view of the context in the process of diagnosis.	SD <sup>d+</sup> : The solution, communicated in condensed symbolic form, was based on mathematical models of vehicle dynamics, horizontal and vertical alignment, three-dimensional geometric curve descriptions and GIS survey norms and the relations between them. The solution required modelling these multiple concepts in relation to each other as defined by the <b>discursive rules of transportation engineering</b> .

<sup>20</sup> The initial presentation of the context shown in this example is prior to the introduction of supplementary texts, which decreased the SD<sup>o</sup> and increased the SD<sup>d</sup> presented in appendix 2.

<sup>21</sup> This example represents a single inferential step in the development of the solution, it does not represent the overall network of inferences required in the design.

Table 6.6 illustrates a comparison between types of artefacts (both coded SG+) prescribed in design brief of M8 (Power plant specification) and M1 (Bearing mounting). The examples are selected to illustrate differences in the complexity of the ontic relations even though the discursive relations have the same coding (SD<sup>d</sup>-). The technical representations require familiarity with technical drawing conventions, but each symbolic representation can be read sequentially and has meaning without reference to other symbolic representations.

**Table 6.6 Complexity in relation to object types (SG+)**

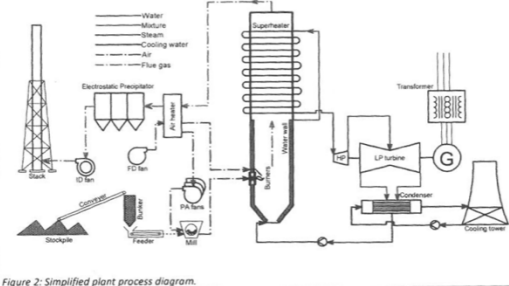
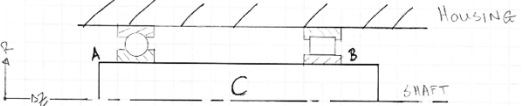
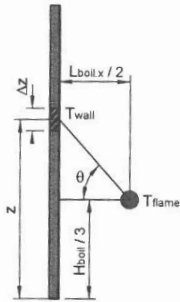
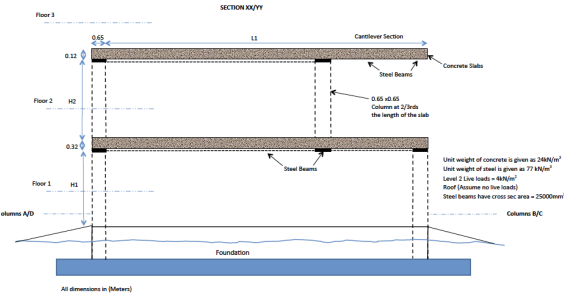
<p>Ex 3: M8 (Power plant specification) – artefact prescribed in the design brief</p>	<p>Ex 4: M1 (Bearing mounting) – artefact prescribed in the design brief</p>
 <p>Figure 2: Simplified plant process diagram.</p> <p>“All power plants must be based on a simple Rankine water-steam cycle, using coal as fuel” (M8)</p>	 <p>“A shaft supported by two bearings is shown. The shaft is subjected to radial loads and axial loads at C. The axial loads may act in either direction. ... Bearings A and B are separated by 100mm. A proposed modification to the shaft results in the load application point C being 25mm from B. The applied loads are radial force <math>P_R = 16\text{kN}</math> and axial force <math>P_A = 4\text{kN}</math>. ...” (M1)</p>
<p>SG+: The diagram and text describe a <b>type</b> of power plant (simple Rankine water-steam cycle, using coal as fuel) rather than any specific power plant. It relates to a potentially concrete object, but abstracted from a specific instantiation.</p>	<p>SG+: The diagram and text describe a <b>typical</b> bearing arrangement on a generic shaft, it relates to potentially concrete objects, but abstracted from a specific instantiation.</p>
<p>SD<sup>o</sup>+: The process drawing <b>separates</b> the power plant into constituent components (boiler, turbine, cooling tower etc.) and three material streams (fuel, air and water), while retaining the <b>simultaneous interdependency</b> between the parts and the material flow streams. Coal is delivered to the boiler and burned, the amount determines the heat in the boiler, which in turn, in conjunction with the amount of air, determines the air temperature. Cold water entering the water wall is being heated by the fireball, which is simultaneously heating the air passing through the furnace. Once the air and water enter the superheater at particular temperatures, the heated air further heats the water, depending on their relative temperatures. This describes only a part of the extremely complex system, in which multiple real processes interact <b>interdependently</b>, but the process diagram functions to <b>identify</b> significant parts and eliminate others.</p>	<p>SD<sup>o</sup>--: The complexity of a system has been completely <b>stripped</b> and <b>simplified</b>. A very small part of a machine has been <b>isolated</b> from the rest of the machine, effectively removing the complexity of any real effects of the system. The variable and indeterminate relation between a motor and the load it drives has been reduced to fixed axial and radial forces; the geometric constraints of the power transmission mountings and concerns relating to assembly of bearings in relation to those elements have been stripped and ignored. The artefact has been simplified by <b>dislocating</b> it from the real influences of the world, and reduced to merely the operating characteristics of two kinds of roller bearing.</p>
<p>SD<sup>d</sup>-: Although the analysis required in the inferences have a stronger SD<sup>d</sup> the artefact presented in this process diagram <b>identifies</b> and <b>separates</b> each part, process and material stream so that it can be read <b>sequentially</b>. The technical representation requires familiarity with technical drawing conventions, but each symbolic representation can be read sequentially and has meaning without reference to other symbolic representations.</p>	<p>SD<sup>d</sup>-: Although a symbolic representation of a system, each component can be identified and read <b>independently</b> and does not require the others to make sense. Meaning can be constructed <b>sequentially</b>. The selection of the bearings follows a defined step-by-step procedure, which although it embeds concepts from tribology, probability and mechanics, only requires <b>sequential</b> predefined calculations (SD<sup>d</sup>-).</p>

Table 6.7 illustrates examples of disciplinary knowledge imposed on artefacts in order to construct idealisations, which simplify the artefacts for the purpose of analysis. Discursive relations were imposed on ontic relations in order to weaken the semantic density of the ontic relations. These idealisations are a significant part of design, but in both examples the idealisation was constructed in the recontextualisation, eliminating the need for students to work between theory and context.

**Table 6.7 Complexity defined by disciplinary knowledge (SG-)**

<p>Ex 5: M8 (Power plant specification) – supplementary notes provided.</p>	<p>Ex 6: S1 (Parking structure) – artefact prescribed in the design brief.</p>
<div style="display: flex; align-items: flex-start;">  <div style="margin-left: 20px;"> <p>“Consider a finite height segment <math>\Delta z</math> running along the perimeter of the water wall as shown in the figure above. The radiation heat transfer from the fireball to the segment is:</p> </div> </div> $\Delta Q_r = \epsilon_{steel} \cdot F_{ash} \cdot F_z \cdot \Delta A \cdot \sigma_{SB} \cdot (T_{flame}^4 - T_{wall}^4)$ <p>The thermal emissivity <math>\epsilon_{steel}</math> is typically about 0.8. <math>F_{ash} \approx 0.6</math> is an opacity factor that accounts for the obstruction of radiation heat by the ash particles. The view factor <math>F_z</math> ... determined from the geometry shown in the figure. ... For simplification, the conical shape of the boiler bottom can be ignored, so one can assume the segment area <math>\Delta A</math> stays constant for the full height and at the same distance all around the fireball.” (SNBS:24)</p>	 <p>The parking garage is relatively unrealistic (with the level two columns mounted on the span between the level one columns), constructed primarily with a view to providing analytical challenges than a functional building. The function of the building is incidental to the design; loads are given as symbolic terms with limited justification. The focus is on calculation procedures rather than on the design of a functional structure. The sketches provided are substantially simplified with all detail not pertaining to the specific calculations stripped. They are neither conceptual layout sketches, nor proper technical drawings.</p>
<p>SG-: The mechanism of radiation (<b>a theoretical concept</b> that describes a particular form of heat transfer) was identified as significant. The geometric idealisation with quantitative approximations as proxies for the material behaviour represents an idealisation determined by disciplinary principles.</p>	<p>SG-: Although the parking structure resembles a generic structure (SG+), the limited detail and selected simplifications were determined by the conceptual requirements of a loading analysis rather than emerging from functional requirements of a real structure, which weakens the semantic gravity to SG-.</p>
<p>SD<sup>0</sup>-: The mechanism of radiation was separated from convection and treated independently. The effect of changing distance, ash in the air and the various material properties are imposed individually to capture the combined effect. But the mathematical expression provided meant that an understanding of the ontic relations that gave rise to the expression was unnecessary, and instead symbolic proxies can be applied sequentially.</p>	<p>SD<sup>0</sup>--: The structure consists of slabs and columns (structural elements) idealised to a point of being unrealistic by the disregard of key structural features, including access ramps, stairwells or shear walls. The unrealistic position of a column without regard for load bearing implications indicates the importance of analytical variant. The dislocation is further emphasised by the diagrammatic rather than technical nature of the sketches provided.</p>
<p>SD<sup>d</sup>-: The mathematical equation provided drew on theories of radiation heat transfer, geometry, and numerical methods. Although the equation integrated these concepts into a coherent whole (SD<sup>d++</sup>), by presenting it already constructed, each term can be <b>read independently</b> and <b>applied sequentially</b> in order to approximate the heat transferred in each part of the water wall, without understanding the integrated theoretical foundations.</p>	<p>SD<sup>d</sup>+: The configuration of the structure was defined in order to introduce as wide a range of conceptual complications as possible within the limited scope of the analysis.</p>

The difference in the semantic gravity of M1 (SG+) in table 6.6 and S1 (SG-) in table 6.7 lies in the nature of the idealisation. The ontic relations in M1 were stripped to highlight the simultaneous but contradictory need to both locate and assemble the bearing, while the ontic relations in S1 were stripped to highlight analytical (discursive relations) variations. In M1 the simplifications emerged from contextual concerns, in S1 from conceptual concerns. It is this distinction that emerged in the different coding of the semantic gravity.

Table 6.8 illustrates generalised concepts that transcend contexts (SG--). The two examples illustrate the difference between generalised disciplinary knowledge and generalised everyday forms of knowledge.

**Table 6.8 Complexity in relation to generalised concepts (SG--)**

Ex 7: generalised theory of radiation heat transfer <sup>22</sup>	Ex 8: C5 (Future foreshore) - interim student solution to planning phase <sup>23</sup>
Radiation heat transfer from a black body: $Q = cT^4$ or the radiation between 2 bodies: $Q = \epsilon\sigma(T_a^4 - T_b^4)$	“Ultimately, the Foreshore is a zone of transit, not a destination ... The guiding principles are Integration, Linkage, Liveability, Sustainability, and Employment.”
SG--: Radiation is one form of heat transfer that <b>occurs in any system</b> , regardless of whether or not it is a significant factor. For radiation, the <b>general relation</b> that describes the amount of heat (Q) released by a body is a function of its temperature (T): $Q = cT^4$ , which can be expressed in terms of radiation between two bodies as a function of the emissivity ( $\epsilon$ : a material property), Area (A: a spatial property), a constant ( $\sigma$ : Stefan-Boltzmann constant) and the difference in temperature between the bodies: $Q = \epsilon\sigma A(T_a^4 - T_b^4)$ .	SG--: The problem is <b>abstracted</b> from the concrete details in <b>generic</b> terms that <b>transcend</b> the context completely. They seem to be imposed on the context (as suggested by some of the supporting materials), rather than emergent from the context in any particular way.
SD <sup>o</sup> --: Radiation heat transfer has been <b>dislocated</b> from all the other possible ontic relations that occur in any context.	SD <sup>o</sup> --: Read outside of its relation to the full solution, this extract appears completely dislocated from the complexity of the precinct (SD <sup>o</sup> --).
SD <sup>d++</sup> : Radiation is a disciplinary concept that describes a real mechanism; it draws on fundamental concepts of energy, rather than describing the transfer of heat through particle collisions, as is the case for other forms of heat transfer. Radiation describes the transfer of heat in the form of electromagnetic waves. In its discursive form, meaning draws on multiple <b>embedded</b> concepts within physics.	SD <sup>d</sup> --: The principles listed are entirely discursive, but neither condense discursive meaning, nor elaborate relations between the ideas. They are so generic as to be dislocated from each other and any substantive bodies of knowledge. An alternative coding suggests that these are highly condensed principles founded on transportation engineering and urban planning disciplines (SD <sup>d++</sup> ).

In addition to identifying the significance of the ontic relations in the analysis, the data above showed that stronger semantic gravity is not necessarily associated with simpler meanings. The examples showed that each dimension of semantics varies independently of the other dimensions. By illustrating how a concrete example can simultaneously represent strong semantic density particularly when the complexity lies in the ontic relations, the data

<sup>22</sup> This example was not taken from the data directly, but was rather implicit in the heat transfer calculations presented in M8.

<sup>23</sup> This example is presented outside of the context of the full solution, which suggests stronger SD<sup>o</sup> and SD<sup>d</sup> than coded in this extracted example.

highlighted how the typical use of the semantic wave can obscure an important aspect of complexity.

While theorists in the social realist tradition in sociology of education have typically focused on the complexity (or condensation of meaning) of the discursive relations, the nature of the ontic relations has tended to be left unexamined. The tendency to miss the significance of the semantic density of the ontic relations is particularly problematic for the professions, which Bernstein (2000) recognised as regions, lying at the interface between strongly classified bodies of disciplinary knowledge and their respective fields of application. For professional education, this double trajectory of complexity is an important and complicating factor. *The challenge for curriculum design lies in sequencing an increase in complexity when we recognise that complexity can occur in necessary ontic relations or discursive relations, or both.*

### 6.3 Presentation of the Semantics analysis

The results of the LCT (Semantics) analysis are presented in the following four sections. The 17 projects were compared and contrasted in relation to each of the units of analysis (context, artefact, solution and inferences). What follows is a discussion of the key features that emerged in the analysis of each unit of analysis, along with graphical representations to show comparative relations between each project. To aid interpretation, a description of the graphical representation of the semantic density analyses is presented in appendix 3.

#### 6.3.1 Reading the context

The presentation and role of the context in a design project is a very important recontextualising choice. The comparison between the two capstone projects presented in the previous chapter showed how very differently design contexts can be recontextualised. In the case of M8 (Power plant specification), the context was superfluous to the project. The relevant information about the context was provided in a constellation of thermodynamic terms, which students needed to understand in relation to one another ( $SD^{d+}$ ). Students did not need to make sense of the context in terms of the ontic relations at all ( $SD^{o--}$ ). The context that was presented was a relatively generic context defined by the thermodynamic knowledge requirements of the task (SG-). By comparison, students needed to make sense of the context presented in C5 (Future foreshore); a real and specific context (SG++), presented in everyday terms ( $SD^{d--}$ ), and associated with rich contextual detail ( $SD^{o++}$ ). Whereas in M8, the context was presented in precise thermodynamic terms that signalled the importance of thermodynamics and related knowledge to the design, in C5, students were left to identify relevant disciplines and to abstract the relevant details of the context into theoretical forms themselves. Although the supplementary documentation provided to students might have suggested the significance of the field of transportation planning ( $SD^{d+}$ ) as one way to read and simplify the context, this was implicit in the data, and some students recognised additional disciplines (geotechnical details for example).

Generally there are three distinct ways in which the context was presented in the briefs, labelled *simplified*, *imaginary* and *real* contexts. These three context types tend to be associated with particular semantic codes, summarised in table 6.9 below. The semantic codes presented are explained in the text that follows.

**Table 6.9 Context types**

Context type	<i>Simplified</i>	<i>Real</i>	<i>Imaginary</i>
SG	SG-	SG++ or SG+	SG+↓↓SG--
SD <sup>o</sup>	SD <sup>o</sup> --	SD <sup>o</sup> ++↓SD <sup>o</sup> + or SD <sup>o</sup> -	SD <sup>o</sup> ++↓↓SD <sup>o</sup> --
SD <sup>d</sup>	SD <sup>d</sup> - or SD <sup>d</sup> +	SD <sup>d</sup> --↑ SD <sup>d</sup> - or SD <sup>d</sup> +	SD <sup>d</sup> -- or SD <sup>d</sup> -

***Simplified contexts (SG-/SD<sup>o</sup>--/SD<sup>d</sup>-)***

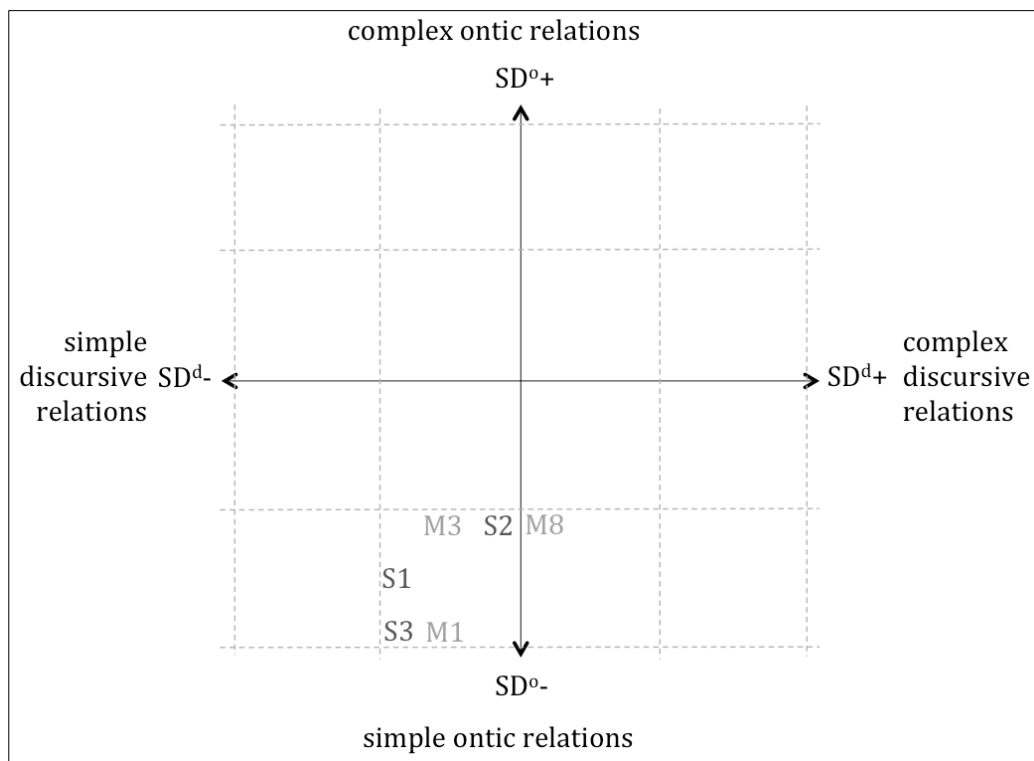
In many cases, as in M8 (Power plant specification), the context was *simplified* and presented as a list of relevant but discrete disciplinary technical descriptors. In M1 (Bearing mounting) and M3 (Gearbox design), the influence of the context was defined by the rotational speeds and power or loads imposed. In S1 (Parking structure), S2 (Steel shed) and S3 (Concrete slab) the contextual aspects from which live loads would normally be developed were irrelevant because they were defined in the brief as uniformly distributed loads with a prescribed magnitude. In all of these projects there was no need for students to read the context and make sense of it. The process of recontextualising the context reduced the complexity of the ontic relations and expressed them as discrete technical specifications.

These simplified types of descriptions transcend any particular context, and were either completely superfluous to the project (SG--) or were described in symbolic terms imposed on a generic context from a particular disciplinary tradition (SG-). The ontic relations involved in these contexts can be seen as irrelevant and coded as dislocated from real causal mechanisms (SD<sup>o</sup>--), replaced usually by a discrete list of discursive descriptors (SD<sup>d</sup>-). Sometimes, as in the case of M8 (Power plant specification), the thermodynamic descriptors represented a constellation signalling the importance of the conceptual relations inherent in the discipline (SD<sup>d</sup>+). But more often the discursive descriptors were merely a list of discrete input variables (SD<sup>d</sup>-) needed for procedural calculations. For example, in M3 (Gearbox design), the context was replaced with an input and output rotational speed and associated power, which was used to size the various mechanical elements that make up the gearbox.

*Simplified* contexts have the advantage of minimising ambiguity by being very explicit about input values for inferential modelling, making it easier to check the accuracy of discursive relations in the inferential chains. But they also present contexts as precise and certain, and tend to disguise the uncertainty inherent in real contexts and the judgement required to read a real context. For example, in M3 (Gearbox design), any real load-motor interface would be variable and dynamic, but through simplifying the context, that variability was replaced with a precise and stable known load. In M8 (Power plant specification), the ambient conditions would experience daily and seasonal variation. Through the recontextualisation process that

constructs simplified contexts, these real uncertainties are eliminated, usually without explicit justification or explanation.

Figure 6.1 shows the semantic density of each of the projects with simplified contexts in relation to each other<sup>24</sup>. The figure shows that all the projects were categorised as very weak semantic density of the ontic relations (irrelevant of dislocated contexts) with weak semantic density of the discursive relations (sequential technical descriptors). The constellation of thermodynamic descriptors strengthened the semantic density of the discursive relations of M8.



**Figure 6.1 Semantic density for *simplified* contexts**

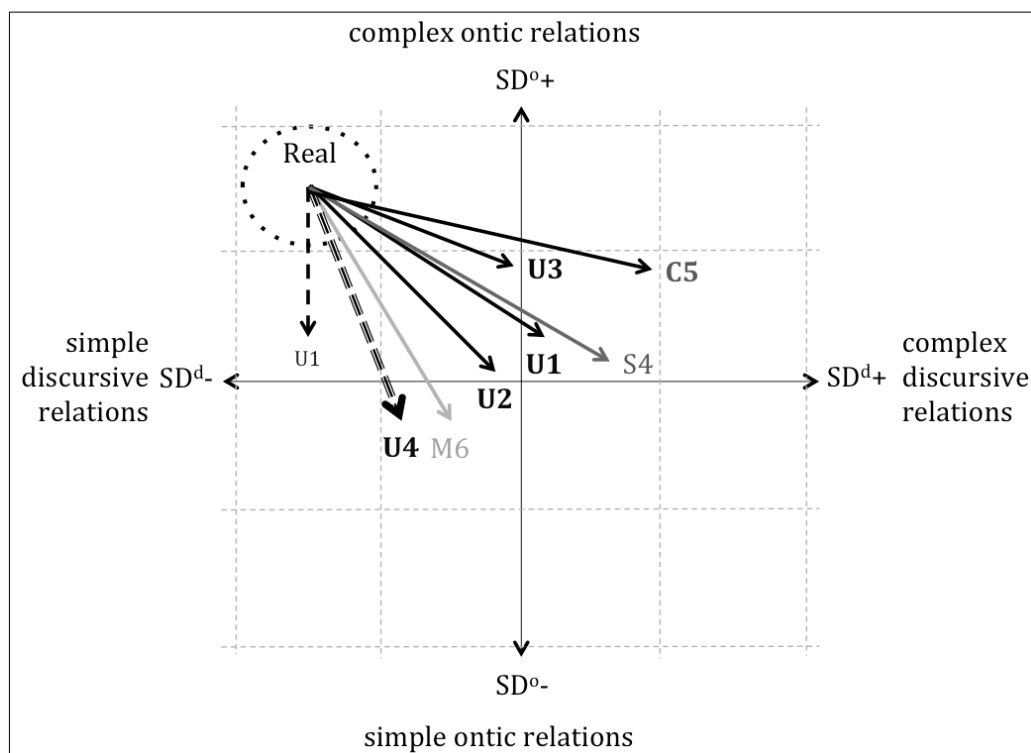
### ***Real Contexts (SG++/SD°+/SD^d-)***

Whereas simplified technical contextual descriptions transcend contexts (SG-), *real* contexts refer to specific and particular contexts (SG++). All four civil engineering urban stream projects (U1 (Bikeshare scheme); U2 (Flood attenuation culvert); U3 (Sewage reticulation); and U4 (Emmarentia Dam road)) and the final civil engineering project C5 (Future foreshore) referred to specific physical contexts. In mechanical engineering, the only project where a real context was provided was M6 (CCTV tower), and in this case the context was a regional context (SG+) rather than a particular context. In structural engineering the only project with a real context was S4 (Parking garage), probably because the conceptual layout of the structure was not given and the specific context (the UCT campus) provided input for

<sup>24</sup> Details for interpreting the semantic density graphics is provided in appendix 3. Within each category (e.g. SD°-) the context was coded high (h) on the SD°- boundary, medium (m) or low (l), and plotted relative to each other within the category.

conceptual design decisions (overall capacity and layout; access points; key structural features). Taking the social realist position of ontological realism means that if there is a particular ontological referent, the ontic relations must be grounded in that reality and its inferred causal mechanisms. While acknowledging variation and fallibility in how we make sense of that reality, we cannot simply impose our preferences on it. Reading the significant ontic relations in a specific real context and representing them in discursive terms becomes central to these design tasks. But on an individual level, the fallibility of knowledge also means that each student can read the context differently.

In the projects with real and specific contexts (SG++) the context holds the potential for multiple embedded ontic relations ( $SD^{o++}$ ). Initially they tended to be untheorised ( $SD^{d--}$ ) in the project brief. For students, the first stage in these design projects required identification and separation of the significant ontic relations ( $SD^{o\downarrow}$ ) and translation into disciplinary forms ( $SD^{d\uparrow}$ ). This semantic shift required of the students is shown in figure 6.2. The '*real*' bubble located in  $SD^{o++}/SD^{d--}$  represents the real ontological contextual referent. The arrows show the semantic shifts required of the students in order to define the context in discursive terms. The reason that there are two representations of U1 (Bikeshare scheme) is that the two elements of the project required such diverse disciplinary knowledge requirements. Describing the terrain and terrain requirements was rooted in surveying knowledge and procedures ( $SD^{d+}$ ), while describing the associated details of the bikeshare scheme was based largely on a common-sense, unspecialised understanding of the context ( $SD^{d--}$ ).



**Figure 6.2 Semantic density for *real* contexts**

U1 (Bikeshare Scheme) and C5 (Future foreshore) provide the closest association with the real contexts, drawing on personal experience and interpretation presented in unspecialised

language ( $SD^{d--}$ ) in contexts that included multiple embedded interdependent ontic relations ( $SD^{o++}$ ). The project in U1 required students to investigate the feasibility of introducing a bikeshare scheme onto an existing university campus. The project involved surveying a single potential route and endpoint for the scheme, conceptually designing the bikeshare station and proposing terrain changes needed to make the route safe and manageable to cyclists and other route users including pedestrians, cars and busses, based on the surveyed terrain. The context for U1 was the UCT campus in its current form, including the terrain and usage: a congested campus with limited parking, narrow pathways shared by motor vehicles, busses and pedestrians. The campus is built on the slope of a mountain, and has many staircases and steep inclines. The climate consists of dry hot summers with strong winds and cool wet winters. But these details were not specified in the brief and students were expected to draw on their own experiences of the campus in their designs. Although the design brief specifically identified the campus, and made reference to aspects of the campus context that might be considered (for example noting the likely building usage to approximate capacity, pointing out the student bus service to be considered in relation to the bike share routes and stations, and implied the use of existing roads for access), much of the detail was left to students to identify from their own everyday and embedded experience of the particular campus ( $SG^{++}/SD^{o++}/SD^{d--}$ ). They were required to either identify these details as significant or discard them as irrelevant to the design ( $SD^{o\downarrow}$ ).

In U1, the project was located in a surveying course, and the brief referred to local trig beacons. For some students, both the course and the trig beacons potentially implied that those ontic relations that go beyond the procedures, knowledge and skills pertaining to the main discipline were in fact secondary to the design. Therefore surveying potentially functioned to privilege some salient contextual features, implicitly reducing the complexity of the context ( $SD^{o\downarrow}$ ) and implying discursive forms (in this case by the production of a digital elevation map in order to precisely describe slopes and spaces that impact on the design) ( $SD^{d\uparrow}$ ). In this example discursive relations drove the simplification of the ontic relations. This shift in the complexity of the context was a result of the location of the project in a disciplinary course, an example of pedagogic recontextualisation.

The other urban engineering projects located in disciplinary courses, U2 (Flood attenuation culvert), U3 (Sewage reticulation) and U4 (Emmentia Dam road), provided the same cues for selecting appropriate discursive relations to simplify the context (hydrology, hydraulics and geometric road design, respectively). Only those contextual features related to hydrology (watershed, water courses and drainage points); water services (annual average daily demand (AADD); existing servitudes and slopes); and horizontal alignment (slope inflections and sightlines) were of relevance ( $SD^{o+}/SD^{o-}$ ), depending on whether the interdependencies had to be considered simultaneously or could be treated sequentially. In most cases these were interpreted from available contour maps and other GIS data available for the real contexts ( $SD^{d-}$ ). While unspecialised contextual knowledge informed design decisions in U1; in U2, U3 and U4 the contexts were read in technical symbolic form, restricted to the discipline defined within the host courses.

S4 (Parking garage) was also located in a disciplinary course, but reference was made in the brief to the influence of other disciplines, most notably because of their influence on the context. For example transport planning influences access and exit points in terms of merging with existing traffic, parking arrangement affects capacity; geotechnical details influence foundation choices and construction science provides insight into options available for structural elements. Insights into these multiple disciplines ( $SD^d+$ ) help to identify the salient contextual features relevant to the design ( $SD^o+$ ); the context is simplified through the lenses of disciplinary knowledge. Again the recontextualisation into a design brief hints at which disciplinary lenses are appropriate ( $SD^d$  drives  $SD^o$ ), but in this example the ontic features of the context also suggest disciplinary specialisations. There is a shift toward a more dialectical relationship between the ontic and discursive relations.

C5 (Future foreshore) is the only civil engineering project not located in a disciplinary course; instead it is seen as the capstone design, integrating all the preceding disciplinary courses. Consequently it is the only civil engineering project with no cues provided to identify significant disciplinary knowledge from the course in which it was located. For the first time students were expected to read the real context themselves and determine appropriate disciplinary knowledge for themselves. They needed to engage fully in the mode of diagnosis (Abbott, 1988). They needed to identify significant ontic relations and discard others ( $SD^o\downarrow$ ). They needed to identify relevant theoretical disciplines and discard others, and transform everyday experiences of the context into precise technical descriptors to use in their design models ( $SD^d\uparrow$ ). In the solutions investigated, code shifts were driven by both recognition of significant disciplines (the importance of transportation planning to the problem), and emergent from the details of the context (recognising that because much of the precinct is built on reclaimed land, geotechnical aspects are an important consideration). In the absence of disciplinary cues, the ability to read both ontic and discursive relations in relation to each other was important for this design project.

While *real* contexts required students to engage in the process of diagnosis (Abbott, 1988), the more complex and embedded the ontic relations are the more scope there is for a diversity of interpretations. When students are required to make the semantic shifts themselves, the complexity of the ontic relations potentially introduces variation in the way that students might read the context, which in turn introduces divergence in the potential design solutions, and learning experiences across the class. This scope makes it difficult to provide detailed and explicit evaluative criteria, and poses a challenge to assessment. Deliberately locating the design projects in disciplinary subjects goes some way to reducing the potential scope for interpretative diversity, but has its own problems in terms of how disciplinary lenses are selected by students as a result of disciplinary privilege rather than in dialectic relation with the context itself.

By contrast, although *simplified* contexts are potentially rooted in real contexts, because students are presented with the already simplified ontic relations, usually in discursive terms, variation in reading the context is eliminated and solutions tend to be more constrained.

Although *simplified* contexts provide an important step in learning to design, unless the semantic shifts inherent in the simplifying of the context are made explicit, not all students will necessarily appreciate the *real* basis of simplified contexts. Consequently, when faced with the far stronger semantic density of the ontic relations in *real* contexts than in *simplified* contexts, it should not be surprising that many students are at a loss as to how to make the semantic shifts themselves.

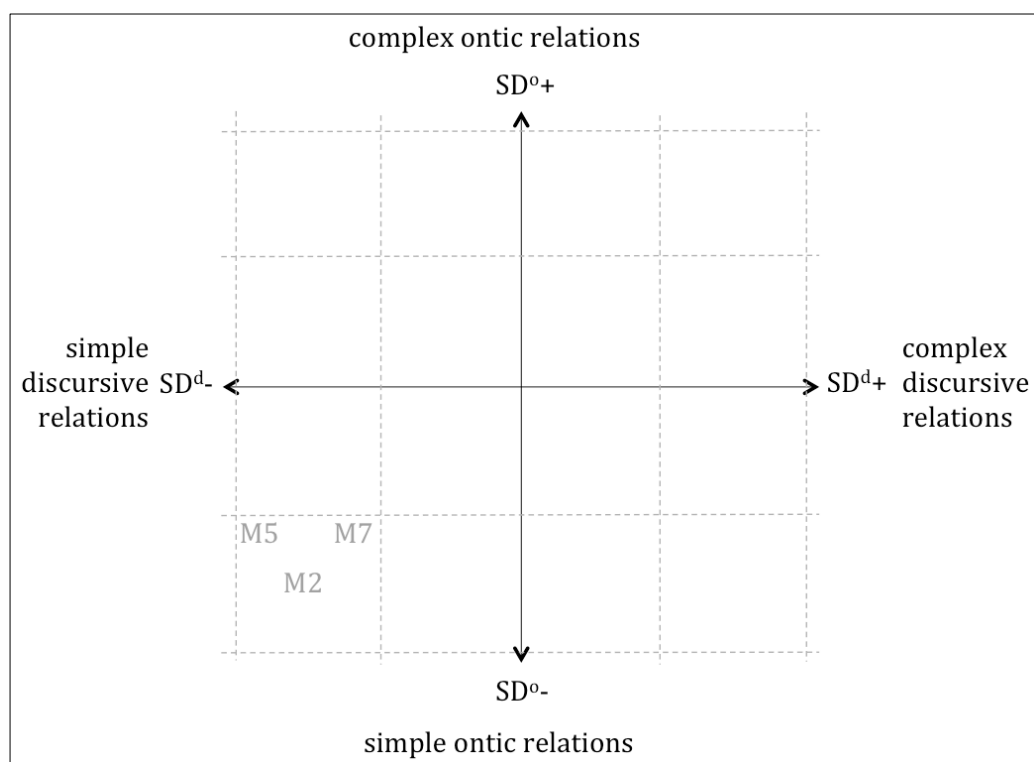
U4 (Emmarentia Dam road) has a dotted line between real context and the output of diagnosis in figure 6.2 above. This indicates that the diagnosis was largely presented within the brief. This approach offers an example of one way in which to navigate the boundary between *real* and *simplified* contexts. Students were given access to the specific detailed context, but the lecturer extracted the significant features and translated them into discursive terms in the brief. Although the context was real, the brief also functioned to simplify it, and the simplification was made explicit for students. However, this explicit transition from *real* to *simplified* contexts would be better positioned at the start of the design trajectory than at the end.

### ***Imaginary contexts***

*Imaginary* contexts attempt to mimic real contexts, but since they lack a direct link to an ontologically real referent, the ontic relations are potentially severed. The three projects that set up *imaginary* contexts, M2 (PRS for domestic appliances), M5 (Multi-tool) and M7 (Multitask micro-machine), are shown in figure 6.3. All three *imaginary* contexts referred to generic types of contexts, for example generic machine shops or generic markets, which could be coded SG+. But because they were imaginary rather than real, they required students to imagine significant ontic relations. From a social realist perspective, this means that the significant ontic relations were not necessarily grounded in ontologically real causal mechanisms that emerge as a result of real interactions. Instead they potentially sever these real connections and can result in dislocated ontic relations (SD<sup>0--</sup>) and associated disconnected discursive (SD<sup>d--</sup>) relations. This is not inevitable, but because students are likely to have differential familiarity with the generic context types, this disconnection is likely at least for some students. By comparison, even though students may read real contexts more or less effectively, at least all can get some access to the context (SD<sup>d--</sup>) if it has a real referent.

By way of example, in M5 (Multi-tool), students were required to design a multi-tool for an imaginary market of cycling enthusiasts. In a real context a design of this nature would require an understanding of competitive costing models, consumer choices based on a sound understanding of the proposed market, and knowledge of manufacturing resources available. These are just some of the factors making up the complex web of mechanisms at play in a real context (SD<sup>0++</sup>). One might identify costing as one of the more important ontic relations, but the brief states, “(a)lthough the cost does not need to be calculated the expense of the design needs to be kept to a minimum where possible.” Even though cost was identified as significant, it is not considered sufficiently significant to model theoretically. Another

important material relation is related to desirability in terms of functionality and aesthetics. But it is tricky to determine relevant functionality in an imaginary market, especially if, as in a market defined as cycling enthusiasts, some students may not know one end of a bicycle from another. And even though the brief states that “(e)xtreme marks will be considered for aesthetically pleasing and thought out designs” nothing indicates what ‘aesthetically pleasing’ might be. It is left unspecialised and ambiguous. By weakening the semantic gravity ( $SG+\downarrow\downarrow SG--$ ) the significance of the ontic relations were reduced to dislocated contextual features ( $SD^{\circ--}$ ) understood in common-sense ways ( $SD^d--$ ). Unless the design context is taken seriously, and the discursive relations required for modelling the significant material relations matter, it should not be surprising that, when students enter the workplace, they do not know how to read the significant details of the real contexts that confront them.



**Figure 6.3 Semantic density for *imaginary* contexts**

The challenge with *imaginary* contexts is their inherent ambiguity. What does one need to imagine and how imaginary can it be? Without the specifics of a real context ( $SG++/SG+$ ) to ground the significant aspects and their interdependencies, an imaginary context has the potential to lead towards unrealistic and disjointed understandings, which in turn potentially leads to disjointed and imaginary artefacts, at least for some students. For example in M7 (Multitask micro-machine), students were required to design a multi-tasking micro-machining device. The implication from the brief was that the artefact needed to improve the performance of an imaginary chain of micro-machining operations for an imaginary client. Students are instructed to “Choose a hypothetical client and application.” This imaginary client and process formed the basis of the ontic relations, including the discursive measures of performance, which were potentially equally imaginary for some students.

### 6.3.2 Prescribing the artefact

In all the projects except C5 (Future foreshore) students were instructed to design a particular artefact type, but the level of specificity (SG) and detail (related to SD) prescribed in the brief in relation to the required artefact differed. In this section the coding relates to the level of specificity and complexity indicated in the brief in relation to the artefact to be designed, at the beginning of the design process. In the following section the artefact is also coded, but as the end product of the design process, the solution specification.

#### ***Semantic gravity - the specificity of the artefact prescription in the brief***

The semantic gravity of the artefact prescribed in the brief refers to the level of specificity as detailed in the brief, and to an interpretation as to whether the detail originating in the material details of the artefact was based on the ontic relations (SG+/++) or was imposed on the artefact to illustrate analytical points based on discursive relations (SG-/--).

M4 (Wheel support assembly) is the artefact coded with the strongest semantic gravity. The artefact was prescribed in the brief in specific detail including the way in which the parts fit together, and their dimensions. The project required detailing of a very specific artefact, and only has meaning in direct relation to this artefact. The exploded assembly drawing provided prescribed all the relevant aspects of the artefact (SG++). On the other extreme the layout of both S1 (Parking structure) and S3 (Concrete slab) – although also prescribed in the brief – were intended to illustrate analytical points rather than being based on emergent contextual or functional needs. In both structures significant structural features such as ramps and stairwells for access to the different levels were omitted; instead many unrealistic features were introduced, such as inappropriately cantilevered slabs and arbitrarily located beams. These structures were prescribed based on a need to illustrate analytical points imposed by a disciplinary body of knowledge represented as a structural object without regard for material reality or functional necessity (SG-). The structures can be seen as generic objects with features transferable across different structures. Meaning is located in the conceptual ideas and analytical procedures rather than in the specifics of the artefact.

C5 (Future foreshore) was also coded SG-, because the prescription of an infrastructural element was judged to be more generic than an artefact type. Even though C5 has the same semantic gravity coding as S1 (Parking structure) and S3 (Concrete slab), the logic of the artefact prescription is fundamentally different. These differences will be shown in the coding of the semantic density of the ontic relations presented in the next section. Where C5 was embedded in the material functionality of the artefact (SD<sup>0</sup>++), most of the material details of the artefact in S1 and S3 were stripped (SD<sup>0</sup>--/-).

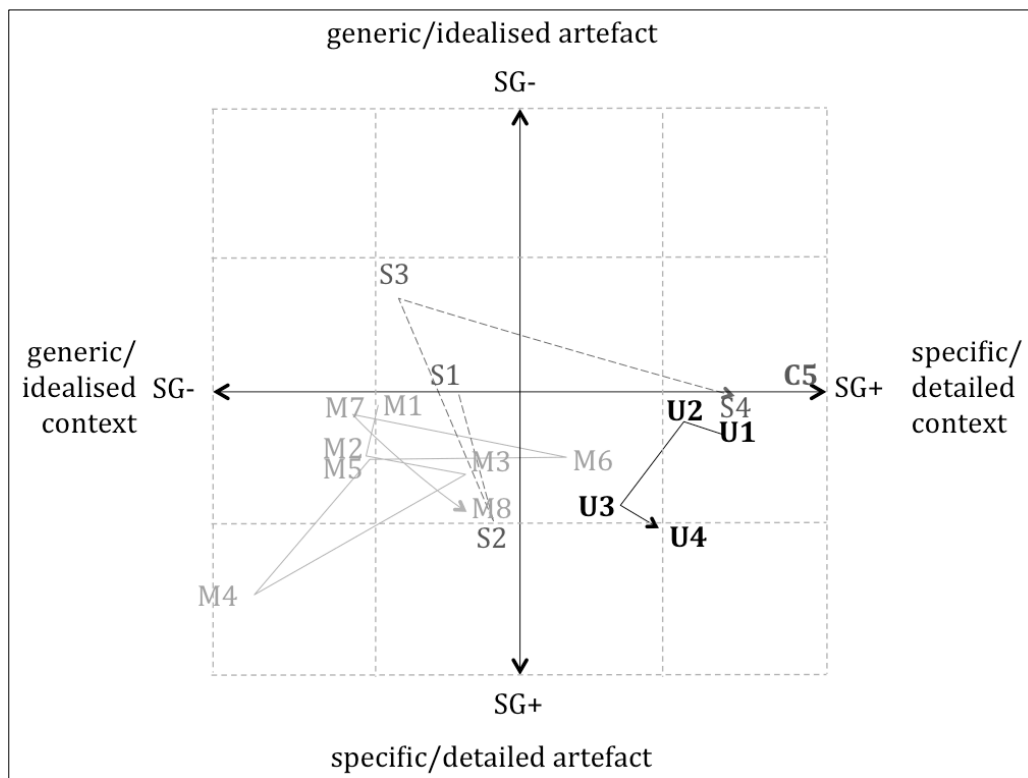
In most of the design projects the artefact was prescribed in the design brief as a type of artefact (SG+); students were instructed to design a gearbox (M3), a band saw (M2), a flood attenuation culvert (U2), a parking garage (S4) and so forth. However, within the SG+

category the specificity of the detailing covered a range, coded high (h), medium (m) or low (l).

Artefacts coded high in the category (SG+(h)), on the boundary with SG++) were typically prescribed in the brief in terms of layout and subsystem specification, which constrained the solution. The artefact type was prescribed relatively precisely. These projects included M8 (Power plant specification), where the process diagram defined the components of the artefact in relation to each other and U3 (Sewage reticulation) where the type of reticulation system prescribed in the brief meant that the layout was limited by the existing streets and erven defined in the context. On the other hand, S2 (Steel shed) and U4 (Emmentia Dam road) were coded SG++(l), on the boundary with SG+. The level of prescribed detail given in the conceptual sketch provided in the brief in S2, and the prescribed points of the road and the site contours in U4, both restricted the artefact to a particular solution.

Artefacts coded low in the category SG+(l), on the boundary with SG-, tended to be stripped of significant detail much like S1 (Parking structure), but to make ontic rather than discursive points. For example M1 (Bearing mounting) was stripped of power transmission elements to focus on the tension between mounting a bearing against a shoulder while considering the implications of the position of the shoulder for assembly. U2 (Flood attenuation culvert) was reduced to the implications of the channel cross-section to realise the need to attenuate the flow rate of water during a flood and spread the flow over a longer time. Both of these refer to the functional requirements (ontic relations) of the artefact rather than to analytical points. Artefacts prescribed without general layout drawings or sketches were also coded low (SG+(l)) because the artefact type was not constrained by a prescribed layout, and the prescription in the brief was more generic. The artefact prescription in the brief of S4 (Parking garage) was limited to a location and function of the structure. M7 (Multitask micro-machine) listed a range of possible machining processes students might consider for inclusion.

Figure 6.4 shows a comparison between the specificity (semantic gravity) of the context and the artefact as presented in each design brief. Projects located below the horizontal axis indicate more specific artefact prescriptions, and those to the right of the vertical axis indicate more specific context descriptions. The arrows in the diagram indicate the sequential trajectory of the projects through the three curriculum streams.



**Figure 6.4 Specificity: comparison between context and artefact** <sup>25</sup>

Figure 6.4 illustrates how much more variation there is in the context description than in the artefact prescription. While the artefact was generally specified at the level of type, the context in the structures and mechanical streams tended to be far more generic, described in ways imposed by the analytical requirements of the design rather than emerging from real contexts. The urban stream was different; the context tended to be more central to the design than in the other streams, and consequently more specific. However, none of the streams show any apparent progression between projects in terms of specificity of either the context or the artefact.

### ***Semantic density - the complexity of the artefact prescription in the brief***

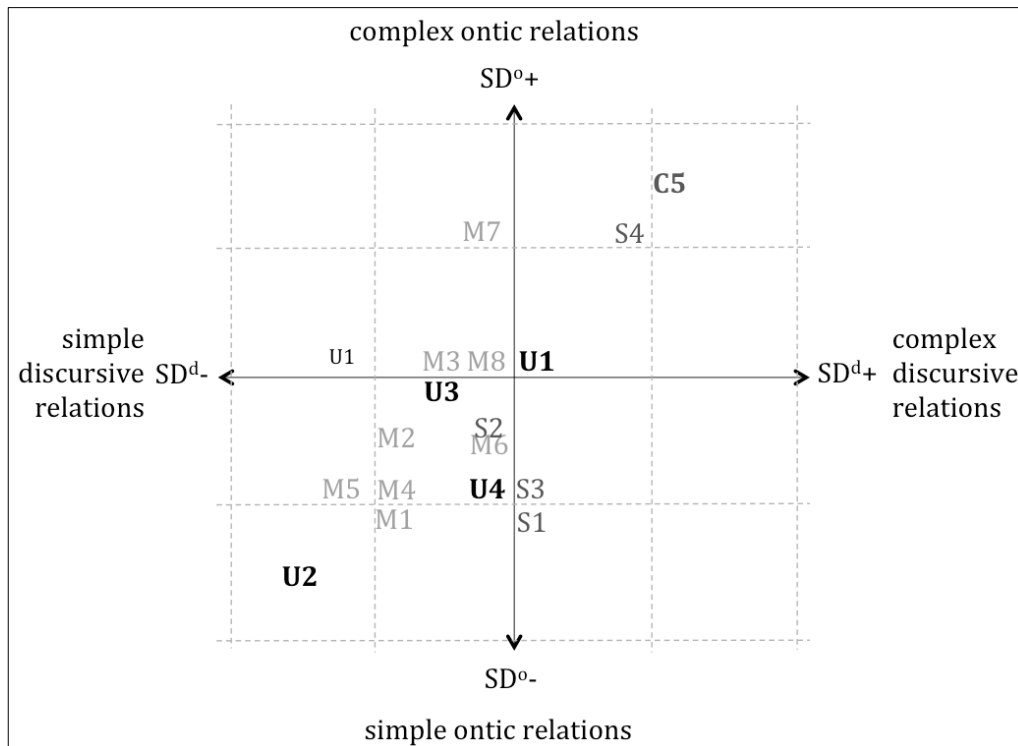
Since all artefacts can be described in complex or simple ways depending on the purpose of the description, the complexity of the artefact was coded in terms of the complexity of the understanding required to complete the project. Finding ways to simplify an artefact so that it is reasonably manageable both in terms of the time allocated to complete the project and in terms of the level of progression within the curriculum is a central recontextualising decision.

Coding the complexity of the artefact prescribed in the brief was based on a judgement of the knowledge about the artefact required to complete the task. For example, M2 (PRS for domestic appliances) required students to develop a product requirement specification for either a band saw or a drill press. Both are complex artefacts, both in terms of understanding

<sup>25</sup> In order to retain consistency with Maton's (2014) inverted vertical axis for SG, the somewhat uncomfortable convention places a 'low' artefact categorisation as closer to the negative end of the axis, or above a 'high' categorisation.

the form and function of the artefact ( $SD^{0++}$ ), and in terms of the engineering science required to model, for example, the physics of machining, the complex of elements that interact in the drive train in relation to the dynamically varying cutting load, the strength and rigidity of the structure and so forth ( $SD^{d++}$ ). But in order to complete the task, only a basic appreciation of the main functions as discrete operations ( $SD^{0-}$ ) and a list of comparative technical performance characteristics ( $SD^{d-}$ ) were required.

Figure 6.5 summarises the coding of the semantic density for each of the artefacts prescribed in the briefs.



**Figure 6.5 Semantic density: complexity of the artefact prescription**

There are three artefacts coded in the very weak semantic density of the ontic relations category ( $SD^{0--}$ ): M1 (Bearing mounting), U2 (Flood attenuation culvert), and S1 (Parking structure). All three artefacts were substantially stripped of significant ontic features, resulting in dislocations to the point of being unrealistic, or *idealised*. What is important about these *idealised* artefacts is that they are simplified so as to focus on discrete aspects of the artefact: an ontic relation in the case of M1 (locating shoulders in relation to assembly issues) and U2 (flow restrictions through reduced flow area), and a discursive constellation in the case of S1 (load paths and associated analyses). S3 (Concrete slab), although just over the  $SD^{0--/-}$  boundary, is also *idealised*, but done so for the purpose of illustrating the relation between slab support categorisation (ontic relations) and associated procedural calculations (discursive relations).

These four artefacts (M1, S1, U2 and S3) were also coded SG- or on the SG- boundary. However the semantic density of the discursive relations for each is quite different,  $SD^{d--}$  for

U2,  $SD^d$ - for M1, and  $SD^d+$  for S1 and S3, indicating the focus of the idealisation, ontic or discursive. These *idealised* artefacts provide potentially useful starting points in design curricula, and in the case of M1 (Bearing mounting), was a logical precursor to the more complex gearbox design (M3). But as with the *simplified* contexts, at some point students need to learn to construct the idealisations from more realistic artefacts. Nor do these projects all represent a curriculum starting point, or a logical progression from simpler to more complex recontextualised artefacts (other than M1 to M3).

The other projects refer to more integrated or coherent artefacts, with stronger semantic density of the ontic relations. But in all cases the artefacts were recontextualised to reduce the semantic density of the ontic relations ( $SD^o\downarrow$ ). Four distinct recontextualisation techniques used to simplify the artefact ( $SD^{o++}\downarrow$ ) were evident in the data:

1. Detailing the artefact in a diagram identified and organised the relevant subsystems in relation to each other, enabling the artefact to be understood as a sequence of simpler parts.  **$SD^{o++}\downarrow SD^{o+}$  by prescribing simpler ontic relations:**

In cases where the artefacts were prescribed in *detail* in the brief, the artefact description functioned to identify relevant parts of the artefact, disregard others and prescribe the organisation between parts within the artefact. While it is not inevitable, it does hold the potential for the various elements in the artefact to be considered sequentially ( $SD^o-$ ) without consideration of the complex whole. M4 (Wheel support assembly) was the most extreme case in which the artefact is fully prescribed, but S2 (Steel shed), U4 (Emmarentia Dam road) and M8 (Power plant specification) all used this technique to constrain and consequently simplify the artefact. However, M8 did retain stronger semantic density of the ontic relations. In M8, the plant process diagram defined the significant subsystems and their relation to each other. In S2, the conceptual sketch identified all the structural elements and their configuration in relation to one another, reducing the design to sizing the various structural elements. In U4, the prescription of significant aspects of the road (for example the stake value and elevation of three points; box culvert sizes and deck thickness and cover) constrained and simplified the potential variation and consequently simplified the artefact. The detailed specification of significant aspects of the artefact simultaneously strengthened the semantic gravity and weakened the semantic density of the ontic relations by identifying what was significant and eliminating what was not.

2. Prescribing discursive relations presented in mathematical expressions identified and organised relevant ontic relations by imposing discursive relations on the artefact. However this simultaneously potentially weakened the discursive relations to procedural sequential calculations.  **$SD^o\downarrow$  and  $SD^d\downarrow$  by defining discursive relations:**

The recontextualisation of the artefact in M8 (Power plant specification) imposed condensed mathematical expressions on the artefact, which effectively weakened the semantic density of the ontic relations. Although the discursive relations that underpin the project requirements

were very strong ( $SD^{d++}$ ), the supplementary notes provided by the lecturer potentially weakened them significantly. For example, the mathematical expression for the radiation heat transfer shown in Table 6.4, presented previously, is an example of how the discursive relations can be used to impose both identification and organisation onto the ontic relations. If the students had been required to develop the mathematical expression themselves, they would have first had to make sense of the ontic relations in order to identify relevant discursive relations in the specific case. Although not inevitable, it is possible for students to apply the given mathematical expressions (into which the complex discursive relations are embedded) sequentially, in a procedural manner, and applied with minimal appreciation for the complex embedded discursive relations. But leaving students to develop the discursive relations from the ontic relations can realistically only be done for simpler artefacts.

In the case of well-established artefacts with associated codes of practice or design guidelines, the codes prescribe sequential procedures that define both what to consider and often the sequence in which to consider it. As with the supplementary notes in M8 (Power plant specification), these codes function to reduce the semantic density of the discursive relations ( $SD^d\downarrow$ ) by imposing sequential procedures, which although founded on constellations of disciplinary knowledge ( $SD^{d+}$ ) can be used without necessarily a full appreciation of the theoretical antecedents. The discursive procedures simultaneously function to identify and sequence significant ontic relations, which effectively also weakens the semantic density of the ontic relations ( $SD^o\downarrow$ ). For example, a different structural element was designed for each task in S2 (Steel shed), each defined by established procedures. The CCTV tower (M6) followed established design procedures for each of the mechanical elements identified in the brief. The sewage reticulation design (U3) was informed by design guidelines, but these guidelines are less prescriptive than codes of practice and consequently did not weaken the semantic density as much.

3. The brief prescribed the use of generic design techniques<sup>26</sup> to simplify the semantic density of the ontic relations by directing focus of particular aspects of the artefact. Rather than imposing meaning on the artefact from discursive expressions, the artefact is simplified directly from consideration of the ontic relations.  **$SD^o\downarrow$  by applying generic discursive techniques directed at ontic relations:**

Where design guidelines and mathematical expressions specialised for application in particular contexts all use discursive relations to identify and organise significant ontic relations, design research has developed techniques for simplifying the ontic relations of an artefact in a different way.

M2 (PRS for domestic appliances) and M7 (Multitask micro-machine) prescribe design techniques in the brief by which the semantic density of the ontic relations of complex artefacts can be simplified in their own right. For example, functional analysis is a technique

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<sup>26</sup> Generic design techniques or design methodology are the subject of design research (or design thinking research).

for stripping all ontic relations except those pertaining to the functional requirements of the artefact and listing them as discrete functions ( $SD^{0++\downarrow\downarrow}$ ,  $SD^0-$ ). Functional flow block diagrams start with the discrete functions and build links between the functions slightly increasing the semantic density of the ontic relations (potentially  $SD^0\uparrow SD^0+$ )<sup>27</sup>. In M8 (Power plan specification) design techniques included functional analysis, interface control and failure mode effect and critical analysis (FEMCA), described in chapter 5. None of these techniques were evident in the civil engineering projects.

4. The brief prescribes a sequence of tasks, each of which draws attention to particular parts of the artefact in a prescribed sequence. Embedded within the prescribed sequence of tasks is an imposed identification and organisation of the key elements in the artefact, ontic or discursive.  **$SD^0\downarrow$  and  $SD^d\downarrow$  by strong framing of the selection and sequence of tasks:**

Although the artefact layouts in U1 (Bikeshare scheme), M3 (Gearbox design) and M6 (CCTV tower) were not prescribed in the brief, the task instructions operated to weaken the semantic density of the ontic relations. In M6 the very limited range of possibilities for the CCTV tower, and the focus on standard bolt, weld and bending considerations in the brief did much of the work of constraining the layout of the tower. U1 and M3 were both located early in the curriculum trajectory, and the prescribed sequencing in the brief constrained M3, while the focus on the surveying in U1 implicitly reduced the artefact itself to secondary importance in the design. In all three briefs, the complex interdependencies between the artefact components and functions were reduced by the recontextualisation.

M7 (Multitask micro-machine), S4 (Parking garage) and C5 (Future foreshore) are coded  $SD^{0++}$  because students were required to make sense of the artefact type themselves. All these artefacts could be configured in multiple ways, and without conceptual layout sketches, students had to decide what elements to include and why. Although S4 is in a structures course, the brief explicitly required students to consider multiple other disciplines. Therefore, unlike the other civil engineering projects located in a disciplinary course, the discipline did not function to completely constrain the disciplinary perspective on the ontic relations. The main difference between the three is that in S4 and C5 a specific context was prescribed from which to develop an artefact, whereas M7 relied on an imaginary context with no real ontic referent to ground it.

### 6.3.3 Specifying the solution artefact

For the purpose of this study, distinctions have been made between the artefact *prescribed* in the brief, the artefact *specified* in the final solution proposal and the inferential reasoning required to *specialise* the artefact such that it functions as required within a specific context.

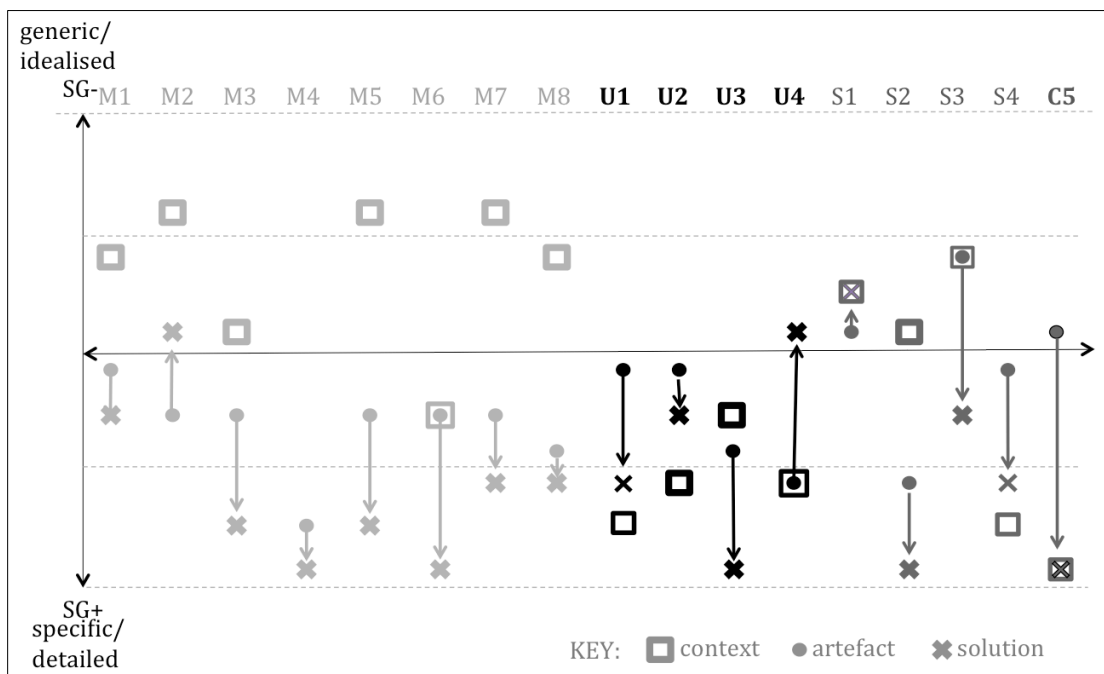
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<sup>27</sup> In the case of M2, the way in which students dealt with the functional interdependencies was limited and it was deemed inadequate to shift the artefact into the  $SD^{0+}$  category. Later in the trajectory of projects these interdependencies might be more manageable for students, and consequently more complex.

The analysis of the artefact prescription was presented in the previous section, the solution specification is presented in this section and the inferential reasoning required to specialise the artefact will be presented in the section that follows. In many cases the solution included both fully dimensioned technical drawings, including manufacturing or construction instructions, and a technical report detailing procedural calculations and design decisions. The report was coded as part of the inferential reasoning, while the nature of the artefact presented in the technical drawings or technical specifications as a result of the inferential reasoning, was coded as the solution specification.

***Semantic gravity - the specificity of the solution specification***

Figure 6.6 shows the relationships between the specificity of the context (□), the artefact prescribed in the brief (●), and the requirements for the solution specification (✕) plotted on a semantic gravity cline. The arrows highlight the direction of the shift in semantic gravity from the artefact as prescribed in the brief (●) to the artefact specified in the solution (✕). It does *not* show the path of all the inferences made between the brief and the solution. In those projects where the context (□) played a significant role in the designs it tended to have a stronger semantic gravity, usually similar to the artefact prescription and solution specification. The weaker semantic gravity of the context in most mechanical engineering projects shows the disconnection of the context from the designs. As discussed previously the context was largely incidental to these designs. Projects in which all elements of the design had a weaker semantic density correspond to those projects in which the discursive relations dominated the ontic relations.



**Figure 6.6 Comparing semantic gravity shifts between context, artefact and solution**

As mentioned previously, the artefacts prescribed in the briefs tended to be at the level of type (SG+). In contrast, the solutions usually detailed the specifics of a particular instantiation of the artefact (SG++) to meet some purpose in some context. Typically the inferential reasoning required to develop an artefact solution involved an overall process of strengthening the semantic gravity (SG+↓SG++), shown in figure 6.6 as a downward arrow.

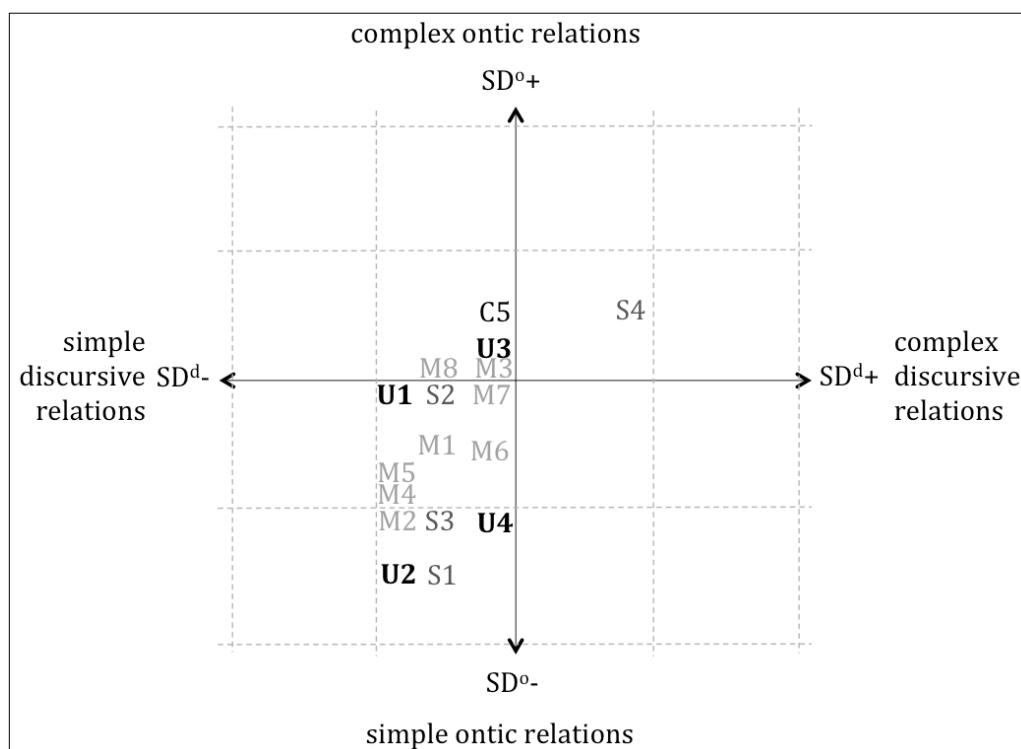
There were three exceptions to the overall strengthening of the semantic gravity between artefact prescription and the solution specification. M2 (PRS for domestic appliances), U4 (Emmarentia Dam road), and S1 (Parking structure) show a weakening of the semantic gravity indicated by an upward arrow. These exceptions reveal interesting points about the nature of design.

S1 resembled an extended tutorial or test question rather than a design project. It tended to be dominated by structural mechanics knowledge. The ontic relations appeared incidental, used simply as a vehicle to illustrate analytical points. The weakening rather than strengthening of the semantic gravity of the solution supports this interpretation. U4 takes this to the extreme in that it is a test; disciplinary knowledge is the basis for evaluation. This is suggestive of the challenge of moving from engineering science courses focused on the discursive relations to design where the ontic relations become more significant.

M2 on the other hand shows something else. M2 only covers the first phase of a design, the phase most closely aligned to Abbott's (1988) mode of diagnosis where the weakening of the semantic gravity is a necessary move in diagnosis, the stripping of specific detail into a more general form. This case suggests that the process of inference required to specialise the artefact may involve movements up and down the semantic gravity scale, even though the result is an overall strengthening of semantic gravity.

### ***Semantic density - the complexity of the solution specification***

In most projects the solution specification took the form of a technical drawing of the solution and/or a list of technical specifications. The semantic density coding of each of the projects solutions is shown figure 6.7. The semantic density of the ontic relations shows far more variation than that of the discursive relations. The strength of the semantic density of the ontic relations tended to lie in the complexity of detail provided in the technical details, either including multiple interacting parts (SD<sup>o+</sup>), or only extracted parts of the whole artefact (SD<sup>o-</sup>), while lists of performance characteristics tended to dislocate each part from the others (SD<sup>o--</sup>). The complexity of the artefact is reduced in the presentation of the solution. The technical and symbolic representations in drawings and technical characteristics can usually be read sequentially, suggesting relatively simple sequential discursive relations (SD<sup>d-</sup>). The coding of the semantic density of the discursive relations in the solution specification indicates simplification of the disciplinary knowledge used to design the artefact. The complexity of the knowledge used to design becomes invisible in the solution.



**Figure 6.7 Semantic density: complexity of the solution specification**

Those projects located on the boundary with  $SD^{d-}$ , and coded  $SD^{d-}(l)$ , although presented in symbolic form, tended to be informed largely by unspecialised or everyday knowledge. Those projects on the boundary with  $SD^{d+}$ , coded  $SD^{d-}(h)$ , required insights into coherent bodies of disciplinary knowledge in order to develop the solutions. Projects in the middle of the category coded  $SD^{d-}(m)$  drew on substantial disciplinary knowledge, but under precise and explicit instructions provided in the brief. This strong framing potentially reduced the reasoning to sequential procedural calculations rather than requiring insights into the discursive relations defined by a body of disciplinary knowledge.

The only project with a solution specification that fell outside of the category ( $SD^{d-}$ ) was S4 (Parking garage). The reason for coding S4 at a stronger semantic density of the discursive relations ( $SD^{d+}$ ) was that the project did not require students to produce a coherent technical drawing of the structure. There were illustrative drawings in the report, but the solution suggested that evaluation was based on structures knowledge ( $SD^{d+}$ ) informed by other disciplinary traditions placing it on the boundary of the  $SD^{d++}$  category. The solution was not simplified into precise technical specifications that can be read sequentially for the purpose of manufacture or construction. In terms of design and in relation to the other projects, by retaining the stronger semantic density of the discursive relations, the coding suggests that the solution was actually incomplete.

The difference between the projects coded  $SD^{o+}$  and  $SD^{o-}$  lies in a judgement about the extent to which the interdependencies were carried through into the solution specifications. For example, M3 (Gearbox design), the drawing condensed all the considerations of strength, deflection and fatigue, which take into account support of the various load paths, geometric

compatibility in terms of packing and issues related to assembly. These simultaneous ( $SD^{0+}$ ), often contradictory ontic relations were the basis of assessment. By contrast, in M6 (CCTV tower) each element of the design was fully represented and could be evaluated sequentially ( $SD^{0-}$ ): the tower section must be resistant to bending and buckling failure; the weld specifications must support the wind load, as must the bolted connections. Yet in terms of curriculum sequence, the more complex artefact (M3) comes before the simpler artefact (M6).

The solutions coded ( $SD^{0--}$ ) consisted of lists of dislocated technical specifications. None of these projects included a technical drawing to hold the artefact together as a whole. For example, U2 (Flood attenuation culvert) required only the channel cross-section dimensions as the solution; S1 (Parking structure) required the compressive axial load on the columns as the solution; S3 (Concrete slab) required a table of slab types and nominal dimensions; and M2 (PRS for domestic appliances) required technical specifications listed as discrete criteria. Although M8 (Power plant specification) also required listed technical parameters, various techniques are used to retain links between ontic relations.

The weaker semantic density of the ontic relations for solutions presented as discrete lists of performance criteria or outputs from procedural calculations stands in contrast with the standard engineering practice of specifying the precise details of the solution artefact in the form of technical drawings. This flags the significance of using technical drawings as a means of simplifying the results of the dialectal relation between the complex discursive and ontic relations that underpin the design. The technical drawings capture the resulting detailed specification of the necessary dimensions and arrangement of parts in relation to each other, but strip the discursive relations on which the detailing was based, strip the ontic relations pertaining to context, and weaken the semantic density of the ontic relations pertaining to artefact function.

#### 6.3.4 Inferential reasoning - specialising the solution

Inferential reasoning refers to the constellations of concepts (ontic or discursive) and the chains of reasoning between them required to specialise an artefact to perform a particular function in a specific context. These inferential chains showed shifting semantic relations. The first of these shifts was discussed in relation to projects with real contexts. Specific contexts ( $SG^{++}$ ) hold the potential for a range of embedded ontic relations ( $SD^{0++}$ ), and are often initially perceived through intuitive unspecialised meanings ( $SD^{d--}$ ). Reading a context in order to identify significant issues involves identifying significant ontic features ( $SD^{0\downarrow}$ ) and translating them into discursive representations ( $SD^{d\uparrow}$ ), which simultaneously weakens the semantic gravity ( $SG\downarrow$ ).

M2 (PRS for domestic appliances) covered only the first part of the design process. The semantic gravity of the prescribed artefact type ( $SG^{+}$ ) was weakened to list generic performance characteristics ( $SG^{-}$ ). Completing the design would result in a fully specified

artefact (SG<sup>++</sup>), strengthening the semantic gravity again. The process of identifying salient ontic features (SD<sup>o+</sup>) and organising them into sequential lists (SD<sup>o-</sup>), was often driven by reading both the context and artefact type through coherent bodies of disciplinary knowledge (SD<sup>d+</sup>), as was described in M8 (Power plant specification), or in routine designs, driven by simple concepts or procedures (SD<sup>d-</sup>) in M1 (Bearing mounting).

Although the previous section showed that there is a general strengthening of the semantic gravity (SG<sup>↑</sup>) from artefact prescription to solution specification, this section will show that the path is not direct. However, given the complex nature of inferential reasoning, the analysis of only a few projects is shown in detail to illustrate the nature of these inferential chains of reasoning in terms of their shifting semantic codes. The first two examples compare the effect of the semantic density of the ontic relations (SD<sup>o</sup>) on the inferential network, and the second two the effect of the semantic density of the discursive relations (SD<sup>d</sup>) on the inferential network.

### ***Effect of semantic density of ontic relations***

In the first example, M1 (Bearing mounting) is compared to M3 (Gearbox design). These projects were selected for two reasons. Firstly there was a natural progression from M1 to M3 in terms of increasing complexity of the ontic relations. Secondly, both provided detailed step-by-step instructions in the brief, which were used as the basis of this analysis. The details of each inferential step are provided in the text for M1. Because of the complexity of M3, and the two projects in the second comparison, each step of the inferential reasoning is presented in detail in appendix 4. However the graphical representations follow the same logic as presented in M1.

The inferences for M1 (Bearing mounting) are shown in figure 6.8 and those for M3 (Gearbox design) are shown in figure 6.9. The shade of the markers indicates the strength of the semantic gravity. Each marker represents the semantic code of the context (□), artefact (○) or solution (✕). The inferential steps are represented by solid dots with a number indicating the order of the inferences. The arrows show the directions of the inferential chains and the prior prescriptions or inferences that they draw on.

The inferential reasoning required to design the bearing seats and select appropriate bearings is shown in figure 6.8. The figure illustrates the following:

1. The first step (○→1→✕) required students to consider the addition of shoulders on the shaft to locate the bearings and transfer the axial load.

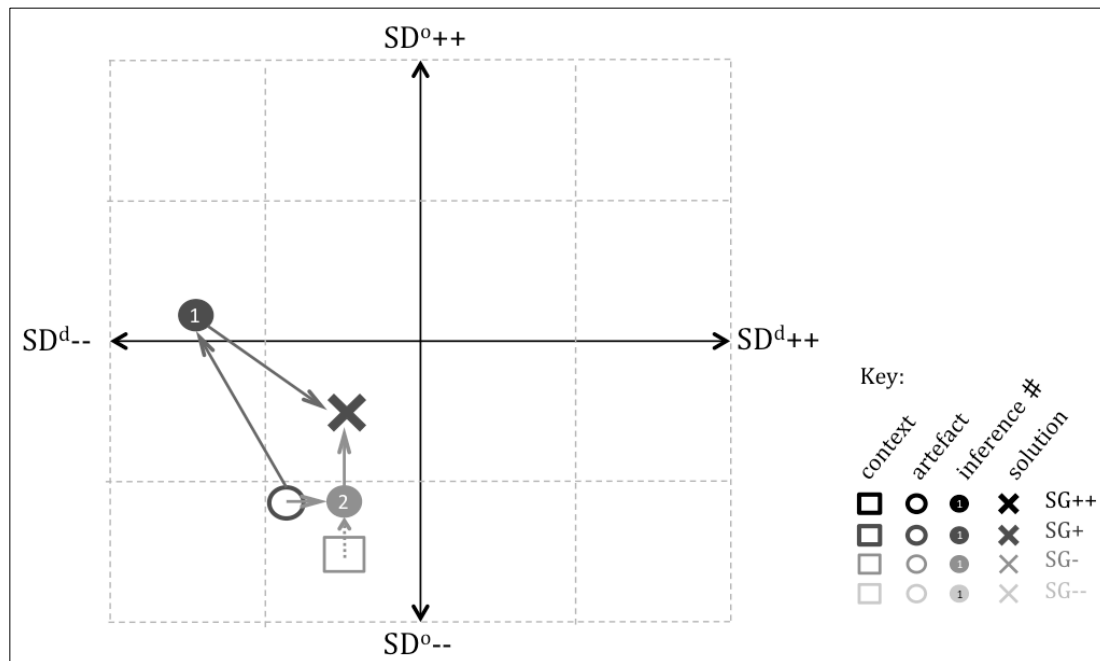
The shift (○→1) shows that no reference to the context was required. The reasoning was based on reading the symbolic representation of the prescribed artefact (SD<sup>o--</sup>/ SD<sup>d-</sup>). The movement from ○→1 shows the semantic density of the ontic relations was strengthened (SD<sup>o--</sup>→SD<sup>o+</sup>) as the two-dimensional representation was visualised in three dimensions, both as drawn and in the process of assembly. The stripped, dislocated artefact was visualised in different configurations, introducing a more complex artefact with parts interacting simultaneously. The discursive relations were simultaneously weakened because the symbolic representation was translated into a visualisation of the artefact in three dimensions (SD<sup>d-</sup>→SD<sup>d--</sup>).

The shift (1→✕) required a return to the symbolic technical drawings but with the addition of symbolic detail by the introduction of additional symbols to represent thread detail and changes to the shaft diameter to create locating shoulders (SD<sup>d--</sup>→SD<sup>d-</sup>). The result is a more complex symbolic representation, but it can nonetheless be read sequentially. The presentation of this reasoning on the technical drawing simultaneously reduced the semantic density of the ontic relations by representing the inferences in a finalised artefact that can simply be read off the technical drawing (SD<sup>o+</sup>→SD<sup>o-</sup>).

- The second step (○+□→2→✕), sizing the bearing to support the applied load, required consideration of the artefact (shaft diameter) and the context which implicitly defined the simplified applied loads:

The solid arrow from the artefact (○→2) indicates that the artefact informed the reasoning. The dashed arrow from the context (□→2) indicates that although the loading would have been informed by the context, the simplified symbolic representation of the load provided in the brief severed the relation. The procedural calculations required to determine the bearing selection remained dislocated from the contextual ontic relations (SD<sup>o--</sup>), but stronger in the category because they also drew on the artefact prescription. Despite being based on probability theory, tribology, empirical testing and the sizing (SD<sup>d++</sup>), the calculations could be followed procedurally (SD<sup>d-</sup>) without reference to the theoretical antecedents.

The final specification of an appropriate bearing (2→✕) increased the semantic density of the ontic relations marginally, because the calculated load factor needed to be considered in relation to the maximum bearing load capacity of a standard catalogued bearing and matched to the calculated shaft dimensions (SD<sup>o--</sup>→SD<sup>o-</sup>). The symbolic answer was interpreted in material terms, but the solution specification was a bearing code in simple symbolic form.

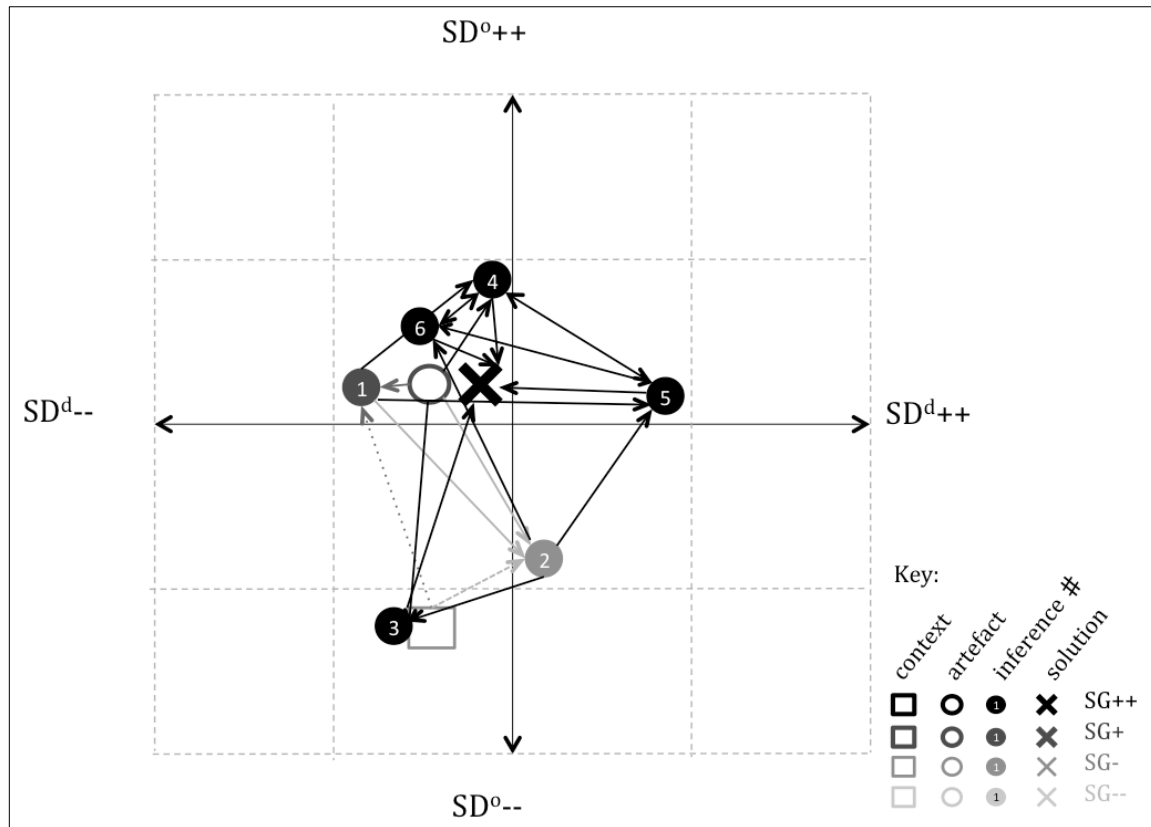


**Figure 6.8 Inferential chains: M1 (Bearing mounting)**

The two very simple inferential chains in M1 indicate a significant strengthening of the semantic density of the ontic relations, despite the relatively weaker coding for the context (□), artefact (○) and solution (✕).

M3 (Gearbox design) was a substantially more complex artefact than M1 (Bearing mounting). It consisted of multiple parts (gears, shafts, bearings and a housing) all interacting and functioning in interdependent ways. It required consideration of geometric compatibility

(for both operation and assembly), functional predictability (able to deliver the required load and power at the required speed) and reliability (strong enough to not break under load or fatigue). Consequently the reasoning required far more inferential steps and often needed input from multiple previous steps. Because of the complexity of the reasoning, the detailed analysis of each step along with a development of figure 6.9 is provided in appendix 4. However the basis of reading the diagram is the same as for M1. Figure 6.9 shows the network of inferences required to complete the gearbox design project.



**Figure 6.9 Inferential chains: M3 (Gearbox design)**

The semantic codes for the inferential chains of reasoning again show a far greater semantic range than was evident in the discrete coding of the context, artefact and solution. The main difference between M3 and M1 lies in the increased complexity and interdependence of inferences. The number of components considered in the design strengthens the semantic density of the ontic relations. This in turn drives up the number and complexity of both the required discursive procedures and their relations to each other. This suggests that the strength of the discursive relations is, at least partially, dependent on the strength of the ontic relations.

Once again the simplified context (from which the load, power and speed requirements would have been extracted) only implicitly informed the design (dashed arrows to steps 1 and 2). On the other hand an understanding of the prescribed artefact directly informed steps 1-4. Step 6 required the specification of an appropriate bearing; ostensibly the same task as step 2 in M1. However, in the case of M3, outputs from previous steps were required in order to

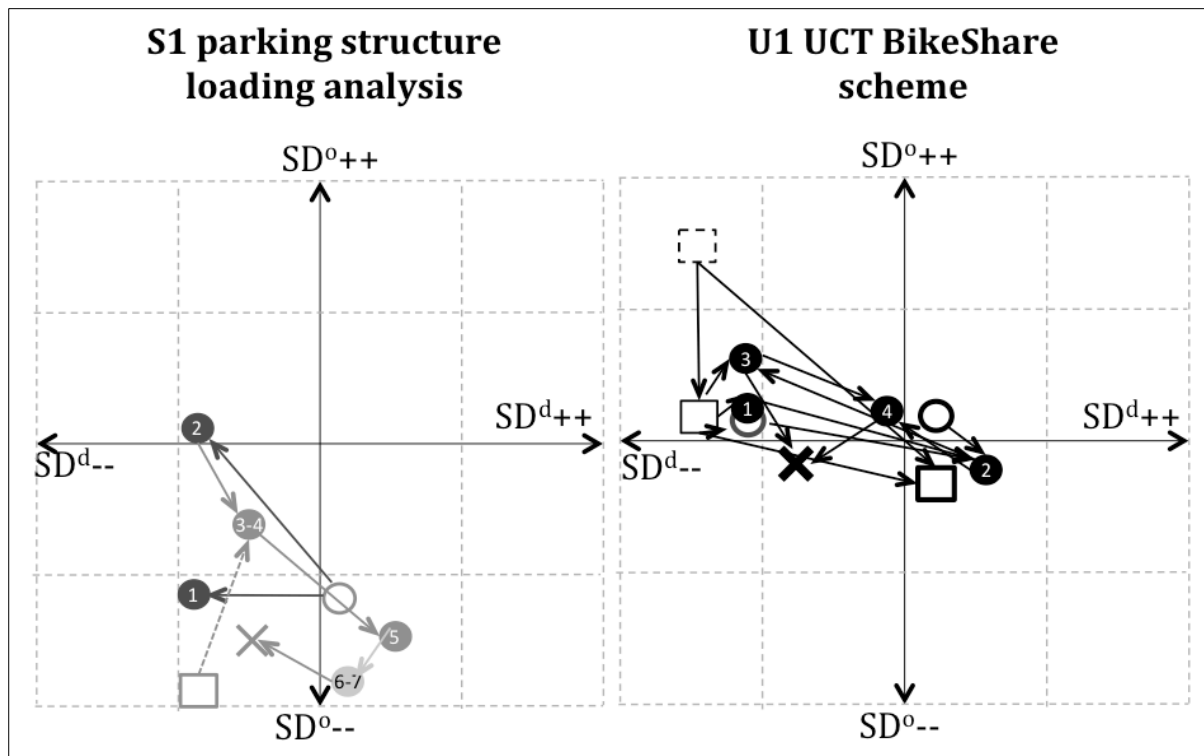
select appropriate bearings. The gear forces determined in step 2 introduced loading. These same loads (step 2), in conjunction with the shaft and housing layout (proposed in step 4) and the power requirement (provided implicitly from the context), determined the minimum shaft diameters required to support the loads (step 5). The bearing selection in step 6 required consideration of the load (step 2) and shaft diameters (step 5), which in turn defined minimum shoulder requirements, feeding back into step 5 (the shaft diameters) and step 4 (the layout).

The interdependence of design decisions, with shifts that show relative strengthening and weakening of the semantic density of the ontic and discursive relations, is illustrated in figure 6.9. The shifts indicate the reasoning was dominated by ontic relations in some steps and by discursive relations in others. This illustrates the dialectic relations between ontic and discursive considerations. The complex network of inferences shows simultaneous interdependencies, where earlier steps inform later steps, which potentially have consequences for the earlier steps, resulting in iterative calculations and interdependent decisions. Multiple interdependent decisions introduce variability and potential divergence of solutions because decisions made in some steps influence the requirements for later steps.

### ***Effect of semantic density of discursive relations***

Two additional projects are discussed in detail to illustrate the differences between reasoning dominated by disciplinary knowledge (S1 (Parking structure)) and reasoning founded on contextual detail (U1 (Bikeshare scheme)). Once again the detailed, step-by-step analysis of each inferential step in the projects is provided in appendix 4. The output of those analyses is shown in figure 6.10.

There are five significant observations to make in comparing the inferential chains of reasoning between S1 and U1 shown in figure 6.10. Firstly, the tone of the markers shows that the semantic gravity of U1 remains substantially stronger than S1. Secondly, in U1 the semantic density of the ontic relations remained strong throughout, while in S1 they tended to be far weaker. Thirdly, both projects reach the same strength of semantic density of the discursive relations – in the case of S1, in the structural mechanics modelling, and in U1 in the knowledge, skills and procedures of surveying. Fourthly, the inferential chains in S1 are more linear, while those in U1 show far more interconnections between steps, similar to M3 discussed above. Finally, the real context links to both an everyday understanding of the context and a disciplinary representation of the context, and most of the inferential steps draw on aspects of the context. By comparison in S1 there is no requirement to refer to the context other than implicitly in terms of the applied loads that would normally be approximated from a sense of the context.



**Figure 6.10 Comparison of inferential chains: S1 (Parking structure) and U1 (Bikeshare scheme)**

In S1 the context ( $\square$ ) was simplified ( $SG-/SD^{o--}/SD^{d--}$ ) and irrelevant to the reasoning as seen by the absence of connections to the context except the implicit link which represents the live loading provided in the brief. The artefact prescribed was idealised with significant structural details removed, and in an unrealistic configuration intended to introduce analytic variation ( $SG-/SD^{o--}/SD^{d++}$ ). Although many of the steps in S1 required relatively complex calculations founded in structural mechanics ( $SD^{d++}$ ), the chain of inferential steps was linear.

By comparison in U1 the real context ( $SG++/SD^{o++}/SD^{d--}$ ) – the UCT campus – first required simplification ( $SG++/SD^{o+}/SD^{d--}$ ). In addition, the context needed to be viewed through the lens of surveying and associated spatial reasoning. The simplified context directly informed the selection of an appropriate route (step 1) which was surveyed (step 2). An understanding of spatial data, and considerations of the functionality of the artefact would both have informed surveying choices made in step 2. The design of the details of the bikeshare scheme itself (step 3) drew on both the technical information developed in step 2, the specifics of the artefact and a familiarity with the context. Like the context, the artefact was prescribed without explicit disciplinary reference, but the location of the project in a disciplinary subject implied the significance of surveying. The introduction of the knowledge, skills and procedures required to survey a piece of land and to represent it symbolically in a map introduced strong semantic relations of the discursive relations ( $SD^{d++}$ ). Both the surveyed terrain and the details of the bikeshare scheme informed decisions about how to modify the route terrain to better accommodate the bikeshare scheme more effectively (step 4). This shows a far more dialectical relation between context and artefact, as well as the influence of contextual detail on the interdependence between inferential steps.

Although U1 did draw on disciplinary surveying knowledge, the integral role of the context, understood in both disciplinary and everyday terms, kept the inferences rooted in the context (SG++) and reduced the simplifying power of discursive relations over ontic relations. In contrast, the over specification of the discursive relations at the expense of coherent ontic relations in S1, kept the inferences at a more generic level, and never really tied them to the material realities of either context or artefact. Both of these projects represent starting points in design trajectories, but with very different logics. The challenge for both projects lies in that early in an engineering curriculum, students have limited mastery over coherent bodies of disciplinary knowledge. This appears to leave a choice between projects rooted in the context and reliant on unspecialised knowledge, or projects over-constrained by a limited insight into multiple coherent bodies of disciplinary knowledge, severed from contextual necessity.

## 6.4 Summary of the Semantics analysis

This chapter began with the argument that the social realist school of sociology of education tends to neglect the influence of the complexity inherent in contextual detail (of both context and artefact). LCT (Semantics) provides a tool with the potential to turn our attention to empirical cases where meaning coalesces around understanding material details. The examples selected from the data in this study showed that context-specific problems (SG++/+) are not necessarily simple (SD--/-). Rather, for problems located in particular contexts and specific artefacts, the complexity often lies in the concepts defined by the constellation of meanings associated with material details, rather than concepts defined by the constellation of meanings defined by rules of specialised disciplinary knowledge. In order to untangle this relationship between contextual complexity and conceptual complexity, the semantic density dimension was analytically separated into ontic and discursive relations respectively.

The analysis of the four units of analysis for each project (context, artefact, solution and inferences) revealed a far more dialectical relation between the concrete particulars of the design and the disciplinary knowledge recruited to develop a design solution than is indicated by the notion of 'applying theoretical knowledge to solve practical problems'. It showed how the recontextualising choices affect this relationship, prioritising either ontic or discursive relations, modifying the insights needed from disciplinary knowledge (discursive relations) or eliminating the significance of the material details (ontic relations). Analysis of the reasoning between context and artefact in relation to disciplinary knowledge in the process of developing a solution showed an overall strengthening of semantic gravity, somewhat at odds with the logic of the academy which is the development of generalisable and abstracted knowledge (a weakening of semantic gravity). But the analysis of the inferential networks involved in this process showed continual shifts up and down the scale of semantic gravity, usually with an overall trend of weakening followed by strengthening.

There was no clear trajectory of progression evident in the three design streams investigated (mechanical, structures and urban). Perhaps because of this 'double trajectory' of complexity (contextual and conceptual), and perhaps as suggested in the literature review, there are just too many learning objectives included in design courses (Dym, 2006; Dym et al., 2005). However, if we are serious about developing the skills that students need to work with disciplinary knowledge when faced with the contextually complex problems encountered in professional practice, we do need to develop curriculum sequences that are more intentional about progression in complexity of both ontic and discursive relations, and their interaction. This becomes a problem of recontextualising choices, and their effects.

Recontextualising design projects into a trajectory that progresses from simple to complex becomes the management of compromises. The analysis above suggests some challenges. For instance, the simpler design projects, appropriate for the beginning of the trajectory, might recontextualise contexts as simplified, artefacts as idealised, and then sequence the inferential steps. While a necessary first step, it does run the risk of severing the critical relation between ontic and discursive relations, and of reducing the discursive relations to mere procedures with no need for discursive insight. Progression through strengthening the semantic density of the discursive relations runs the risk of rendering the ontic relations superfluous. However, progressing through strengthening the semantic density of the ontic relations without the requisite insight into the discursive relations runs the risk of devaluing the power of disciplinary knowledge and resulting in naive and unrealistic solutions.

At the end of the sequence students need to face projects that require a truly dialectical relation between the ontic and discursive relations. However this requires students to have a solid grasp of multiple coherent bodies of disciplinary knowledge; it opens up a diversity of understanding, prioritising and discarding aspects of the context and artefact; and it requires experience of reading contexts in disciplinary terms, idealising complex artefacts and recognising significant disciplines. Two different approaches to building this competence were evident in some of the data. In the civil engineering streams, both the structures and urban stream located projects within disciplinary courses. This helped to constrain the range of disciplinary possibilities. In mechanical engineering, the introduction of generic design techniques introduced ways for students to identify and organise significant ontic relations in complex artefacts.

One final observation to reiterate was the importance of a context with a real basis. The data suggests that the significance of the context to the design is too often underestimated. A progression from simplified contexts, where the recontextualising agent extracts salient ontic features from the context and represents them in discursive terms, to real contexts where students are required to make these shifts themselves, is useful. But how does one progress from one to the other if the process of simplification in the earlier projects is not made explicit? Providing a real context, accessible to students, cannot be underestimated. The problem with imaginary contexts (such as imaginary clients, markets and workshops) is that there is no ontological referent to hold conceptualisations together.

## Chapter 7 Discussion: Weaving the empirical findings into the theoretical field

Although industry is generally satisfied with the current quality of graduate engineers it regards the ability to *apply theoretical knowledge to real industrial problems* as the single most desirable attribute in new recruits. But this ability has become rarer in recent years... (J. King, 2007, p. 7)

The empirical problem at the heart of this study was the persistent concern with engineering graduates' inability to apply their theoretical knowledge to solve the problems that they face in professional practice. This problem seems prevalent across time and countries (Grinter, 1955; J. King, 2007; C. R. Mann, 1918). Nor is it unique to the engineering profession; there is evidence of similar concerns in other professions (Smeby & Vågan, 2008). As discussed in chapter 2, much of the focus across general, professional and vocational education on graduate preparedness has been directed at the development of graduate attributes and generic skills, without consideration of the contribution of confident mastery of disciplinary knowledge (cf. Martin et al., 2005). This study took a knowledge perspective to investigate disciplinary knowledge in projects intended to mimic professional practice.

The empirical problem was recast in theoretical terms into two research questions informed by social realism within sociology of education and the nature of the case study:

1. What is the nature of the reasoning involved when specialised disciplinary knowledge is recruited to develop specific, often concrete, artefacts?
2. What is the logic of progression in a trajectory of engineering design tasks in terms of the relation between knowledge and artefact?

In response to the first question the study presents a challenge to the common sense notion of engineering as the application of scientific knowledge, instead suggesting a far more dialectical relationship between disciplinary knowledge and the complexity of 'real' contexts and artefacts. It also demonstrated the effect that recontextualising choices have on the nature of the reasoning required. A further aspect of recontextualising knowledge into a curriculum concerns the construction of a curriculum that progresses, shifting students through a process of developing knowledge and skills, in this case, to use disciplinary knowledge to solve contextually specific problems. This relates to the second question. In terms of the central themes in this study (complexity and specificity), no trajectory of progression was evident. However the findings do suggest potential for more intentional curriculum trajectories for developing the skills that students need to work between abstract theoretical knowledge and complex, situated contexts. The empirical findings are discussed in section 7.1.

LCT (Semantics) was developed in order to characterise shifts in specificity and complexity between projects and within projects. The significance of contextual detail, and the

complexity inherent in real contexts and artefacts, necessitated further development of semantic density within the Legitimation Code Theory framework. I address this development as a methodological issue in section 7.2. LCT offers a diverse toolbox of concepts for analysing curriculum and pedagogy (amongst other things) and the conceptual developments presented in this study contribute to a growing methodology for analysing curricula – in this case particularly the analysis of professional and vocational curricula.

This study also contributes to current debates within the theoretical field in which it is located, the social realist school of sociology of education. The findings offer useful insights that challenge some of the central tenets of the field, most notably the primacy given to singulars over regions and a blindness to the significance of the complexity of contextual detail. In most social realist accounts of professional knowledge in the sociology of education, the external ontological referent is seen as secondary to the internal disciplinary knowledge relations. Contextual problems are seen as 'little applications' of disciplinary knowledge. This study suggests that the way in which the contextual details (of both context and artefact) are recontextualised has very significant implications for the demands placed on the insights into the disciplinary knowledge recruited. Bringing design research together with social realism within sociology of education allows a conversation between the two intellectual fields that contributes to both. The theoretical contributions to knowledge that result are presented in section 7.3.

## **7.1 Empirical contributions: Learning to work with knowledge in context**

Although the data was drawn from engineering design projects, the problem addressed in this study is the more general problem of learning to work with disciplinary knowledge in relation to specific contextual problems. The research relates to understanding the nature of reasoning between concrete context and abstract theory, and structuring a curriculum that intentionally develops the skills needed to do this. Engineering design projects were analysed for two reasons. Firstly, engineering is considered to be a science-based profession founded on established bodies of coherent knowledge (singulars in Bernstein's (2000) terms). This makes the identification of *disciplinary knowledge* more apparent. It also recognises the role of separate disciplinary specialisations in the analysis. And secondly, within an engineering curriculum, design is the most likely place to find disciplinary knowledge *used in relation to specific concrete or practical problems*. But the design tasks analysed were not necessarily designed to develop the skills to use disciplinary knowledge in relation to contextual problems. In many cases they were developed to meet other objectives set up in each course, often in isolation from each other. So, although the design projects provided useful insights into the problem addressed in the study, the findings should not be read as a critique of specific design projects or recontextualising choices. Instead, this study provides insight into the nature of professional reasoning and provides potential for progressively structuring these skills in a curriculum, whether within design courses or not.

Sections 7.1.1 and 7.1.2 develop the discussion more generally in relation to the first research question: the nature of reasoning when specialised disciplinary knowledge is recruited to solve contextually specific problems. Section 7.1.3 elaborates on the second research question: developing potential curriculum trajectories for learning to use disciplinary knowledge in context.

### 7.1.1 Recontextualising context and artefact

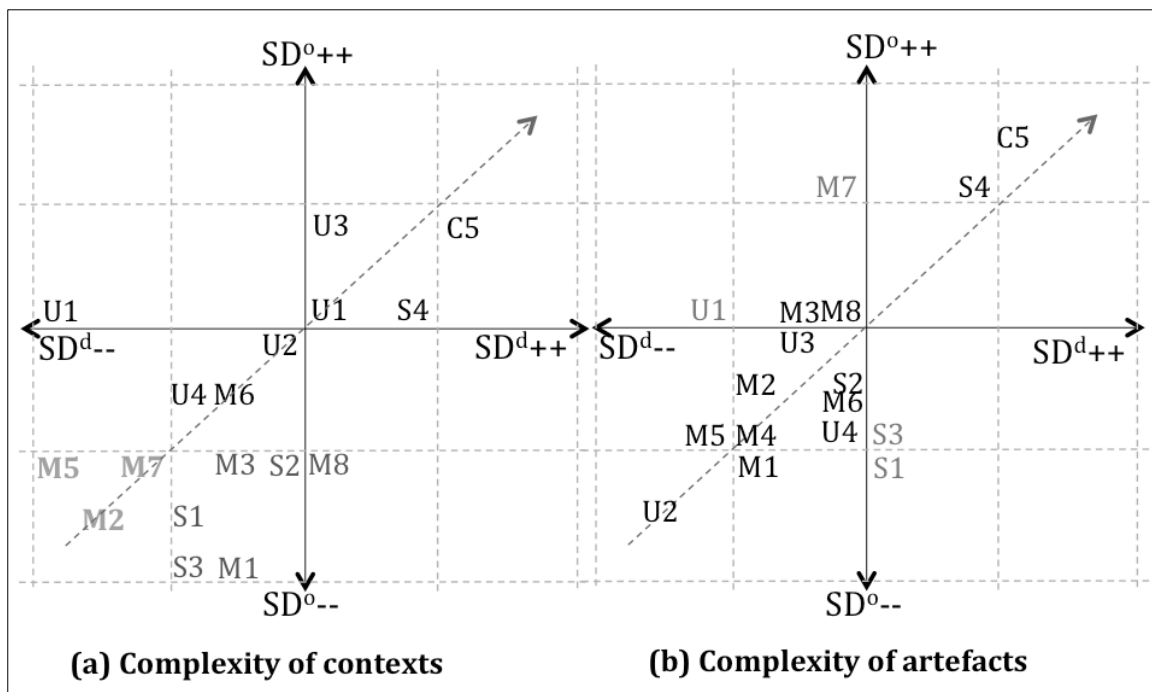
The relation between context and artefact was presented in detail in chapter 5. Simon (1981) describes design as adapting the properties of the artefact at the interface between the outer environment and the inner environment, both subject to natural laws. Schön (1983) describes design as a dialectically reflective process of progressive problem setting and solution proposals between the context and artefact. When a design problem is recontextualised into a curriculum task, both context and artefact are recontextualised, in most cases a process of simplifying them in order to fit into a course within the curriculum with consideration for the expected disciplinary mastery at that level in the curriculum. The LCT (Semantics) analysis in chapter 6 illustrated how recontextualising choices affect the relative specificity and the complexity of both the ontic and discursive relations associated with making sense of the task in terms of the artefact and context. I argue that it is the dialectic relation between the ontic and discursive relations that is at the heart of using specialised disciplinary knowledge to solve 'real' professional engineering problems. And when these relations are unintentionally distorted in the process of recontextualisation it has implications for learning to use disciplinary knowledge in practice.

Solving 'real' problems in this case study refers to the process of conceptualising an artefact intended to perform a specific function in a design project that is intended to simulate professional engineering practice. Real contexts and real artefacts all refer to specific, inherently complex externally real ontological referents. Using Abbott's (1988) mode of diagnosis, colligation (the identification of significant ontic features and the exclusion of those deemed irrelevant ( $SD^{\circ}\downarrow$ )), and classification (the association with other, more generic examples ( $SG\downarrow$ )), provides a useful starting point to describe the process of simplifying the complexity inherent in contexts and artefacts in order to design. But in engineering design, the data suggest that this process of simplification is also associated with the introduction of symbolic representations of the context and artefact, determined in relation to internally coherent conceptual bodies of disciplinary knowledge ( $SD^d\uparrow$ ). At the heart of the recontextualisation in design are choices about how to describe the context and prescribe the artefact in the brief; the extent to which contexts are simplified and artefacts are idealised. If students are to learn how to diagnose for themselves, they ultimately need to confront the complexity of specific contexts and artefacts.

Although only the urban engineering projects (U1-U4), one project in structures (S4 (Parking garage)), one project in mechanical engineering (M6 (CCTV tower)) and the civil engineering capstone project (C5 (Future foreshore)) were located in specific contexts

(SG+/+++), most of the artefacts were prescribed as artefact types (SG+) or specific artefacts (SG++) in the brief. This suggests that there is a far greater consideration of the impact of the ontic relations of the artefact than of the context in setting the design projects. Yet, as Schön (1983) argues, an artefact has to be designed to function effectively in a specific context. Students need to be given the chance to engage meaningfully with *real* contexts and artefacts. *Simplified* contexts and *idealised* artefacts are both the result of abstraction out of specific, inherently complex details of concrete examples into more generic (SG-) and simplified (SD<sup>o-</sup>) forms, usually as discrete symbolic representations (SD<sup>d-</sup>). Although *imaginary* contexts mimic real contexts, they have the weakest semantic gravity (SG--) because meaning is not subject to any external ontologically real context. They are not grounded by anything other than imagination.

The analysis of the relative complexity of the context and artefact as determined from the brief is reproduced in figure 7.1.



**Figure 7.1** <sup>28</sup>Comparison of semantic density across contexts (a) and artefacts (b)

The tone represents the relative strength of the semantic gravity. In figure 7.1a, those contexts associated with a real ontological referent, having a stronger semantic gravity (SG+/SG++), were labelled *real* contexts and are shown in a dark tone. *Imaginary* contexts, severed from any reference to a real context (SG--), are light. Contexts presented in *simplified*, usually symbolic form and notionally representative of generic contexts, are in an intermediate tone. Figure 7.1b shows that most artefacts were prescribed as a type, sometimes quite specifically (SG++), other times more generically (SG+). They are represented in a dark tone. *Idealised*

<sup>28</sup> U1 in figure 7.1a appears twice, SD<sup>d--</sup> for the bikeshare scheme based on unspecialised knowledge and SD<sup>d+</sup> in relation to the surveying component of the design project.

artefacts (SG-) are shown in a lighter tone. Although coded SG-, C5 (Future foreshore) is also shown as dark because of its link to an ontologically real external referent.

One obvious trajectory of design projects lies in a progressive increase in the complexity of the reasoning required. However none of the three trajectories of design projects show any progression in complexity, either of context description (figure 7.1a) or artefact prescription (figure 7.1b). In both diagrams it is evident that there is an approximate correlation between the semantic density (complexity) of the ontic relations and the semantic density (complexity) of the discursive relations. As the semantic density of the ontic relations increases, so the complexity of the discursive relations increases. I have argued that it is the complexity of the ontic relations that in most instances makes the demands on the discursive relations in these design projects. More complex artefacts/contexts require more insight into the discursive relations. Real contexts and artefacts that refer to real external artefacts show this dialectical relationship between ontic and discursive relations most closely.

On the other hand, because imaginary contexts sever the relation between meaning and an external ontologically real context, there is the potential to dislocate both necessary ontic relations and their associated discursive relations (M2, M5, M7). Contexts presented in *simplified* form reduce the complexity of the ontic relations ( $SD^{\circ\downarrow}$ ), but, depending on the nature of the symbolic representations, may increase the insights into discursive constellations of concepts required to make sense of the context ( $SD^{\circ\uparrow}$ ). This manifests in a shift down and right on figure 7.1a (S1, S2, S3, M1, M3, M8). *Idealised* artefacts (S1 and S3 shown in figure 7.1b) show the same pattern, severed or discrete ontic relations, cohering around more complex discursive descriptions. This latter recontextualisation, the dominance of discursive relations in relation to idealised artefacts, is a feature of most textbook questions designed to develop students' mastery of discursive relations. Discursive relations potentially dominate *simplified* contexts and *idealised* artefacts.

U1 (Bikeshare scheme) and M7 (Multitask micro-machine) show the opposite tendency: both shifted left in the figures ( $SD^{\circ\downarrow}$  in relation to  $SD^{\circ}$ ) indicating the dominated of ontic relations. U1 is both a complex artefact and is located in a complex context ( $SD^{\circ+}$ ), however it draws largely on unspecialised everyday knowledge ( $SD^{d--}$  or  $SD^{d-}$ ). In the early stages of the curriculum students probably have limited mastery of disciplinary knowledge with which to make sense of the project, and have to rely on everyday unspecialised knowledge. The ontic relations in M7 (Multitask micro-machine) also dominated the reasoning about the artefact, the selection and positioning of existing modular machining components, selected on the basis of an imaginary client and machining process. The imaginary context, severed from a specific external ontic referent, appeared to affect the artefact. Without a real context in this weakly framed project, the discursive reasoning appeared quite fragmented. The artefact was shifted to the left in the diagram, representing a weakening of the semantic density of the discursive relations – I would suggest in part due to the imaginary context and in part due to the very weak framing of the project.

U1 (Bikeshare scheme) required students to develop a solution in relation to the specifics of the context. Despite limited knowledge, the ontic relations dominated. Projects S1 (Parking structure) and S3 (Concrete slab) draw on whole bodies of internally coherent disciplinary knowledge ( $SD^{d+}$ ), despite being *idealised* artefacts located in *simplified* contexts ( $SD^0-$ ). Students were required to manipulate concepts in relation to each other with limited insight into the contextual detail. Here, the discursive relations dominated. I would suggest that the discursive representations of the context and artefact, coupled with the stronger framing of the tasks, forced the primacy of the discursive relations. I would go as far as to argue that S1 and S3 are not design problems, rather they are extended disciplinary problems, separated from the world and internal to a coherent body of disciplinary knowledge.

### 7.1.2 Specialising the solution

In the recontextualised design projects investigated in this study, all the projects remained what might be termed 'paper designs'. Each project ended with a solution described in symbolic form on paper, as a list of technical specifications, a detailed design report articulating the reasoning behind the design, and/or a set of technical drawings. In contrast, problem solving in professional practice ultimately stands or falls on its effective implementation in the world, even though a paper design might be a significant evaluative point in the design process. In professional engineering practice the solution becomes the artefact, an individual material instantiation of the solution artefact. It becomes part of the world and functions in the world as a result of real causal mechanisms despite expectations based on conceptual models of how it should function; effectively stripped of all discursive relations. In the curriculum, the design solutions were evaluated on the symbolic expression of the solution as interpreted by the assessor, without being tested 'in the world'.

Despite these differences, the development of a solution artefact showed a general trend of strengthening the semantic gravity from a more generic artefact prescription in the brief towards a particular detailed specification in the solution ( $SG+\uparrow SG++$ ). As presented in a list of discrete parameters (such as dimensions or performance criteria) or technical drawings (symbolic representations of the artefact which defines specific criteria), the far more complex reasoning involved in the inferences that underpinned the artefact development was not evident in the presentation of the final solution. The solutions therefore represent a weakening of both the discursive and ontic relations compared to those evident in the inferential reasoning behind the presentation of the solution ( $SD^{d+}\downarrow SD^d-/SD^0+\downarrow SD^0-$ ). The advantage of a comprehensive set of technical drawings detailing the solution is that they do retain some relation between components even if read sequentially ( $SD^0-$ ), while lists of discrete parameters tend to dislocate the ontic relations ( $SD^0--$ ).

The process of specialising the artefact to a particular purpose in a specific context involved a network of inferences between ontic and discursive considerations, set up in a dialectical relationship (see figures 6.8-6.10). When one considers only the semantic coding of the relation of context and artefact to the solution, one misses the vast network of reasoning, with

associated shifts between the general and the particular (SG- and SG+) (refer to figure 6.6) and the relative complexity of the discursive and ontic relations (SD- and SD+). Rather than just a general strengthening of the semantic gravity from *context description* and *artefact prescription* to *solution specification*, we see movements up and down the range of semantic gravity. Rather than static definitions of the semantic density of the discursive and ontic relations, we see continuous shifts between contextual (SD<sup>o</sup>) and conceptual (SD<sup>d</sup>) considerations, sometimes defined by discursive insights, sometimes by ontic imperatives. The analysis of the inferential chains of reasoning showed a far more dialectic relationship between discursive and ontic relations than is suggested by the idea that disciplinary knowledge is simply 'applied' to contextual problems.

The comparison of figures 6.8 and 6.9 shows a marked increase from M1 (Bearing mounting) to M3 (Gearbox design) in the number of inferential steps needed to develop a solution, but more significantly, a more interdependent network of inferences, each with multiple inputs. This indicates the influence of the complexity of the artefact (SD<sup>o</sup>) on both the scope of the inferential requirements and the complexity of the discursive relations (SD<sup>d</sup>). As the artefact becomes more complex, the number of inferences and the network of influences between them increases. A similar point was made in a study of three capstone design projects in a design-build-test evaluation (Wolmarans, 2016). This might indicate that, at least to some extent, the complexity of the ontic relations drives the requirements for stronger semantic density of the discursive relations (requiring more coherent and integrated insights into whole disciplines). When the significance of the semantic density of the ontic relations is not considered in the recontextualising choices, the relations between the ontic and discursive aspects of the tasks are left to chance.

The different coding of the nature of inferential reasoning between S1 (Parking structure) and U1 (Bikeshare scheme) shown in figure 6.10, shows the trade-off inherent in recontextualisation choices, especially early in the curriculum before students have adequately mastered a wide range of disciplinary specialisations in sufficient complexity. When the discursive relations are prioritised at the expense of ontic imperatives, it appears to result in a more linear chain of inferences, which does not require a continual return to ontic implications. When the ontic relations are prioritised, it can be at the expense of the power of discursive knowledge. This trade-off was evident throughout the trajectory of projects to some extent, with C5 (Future foreshore), capping the urban and structures trajectories in civil engineering, perhaps offering the best balance between the two.

The effect of framing (Bernstein, 2000) on the nature of inferential reasoning was illustrated in the detailed description of the capstone courses presented in chapter 5. The strength of the framing of the project relates to the level of control that the lecturer retains in the recontextualised design. The very strong framing in M8 (Power plant specification) compared to the very weak framing in C5 (Future foreshore) appeared to modify the insights into complex bodies of disciplinary knowledge (SD<sup>d</sup>) needed to develop the artefact.

Although the inherent dialectical relation between the ontic and discursive relations lay behind both projects, the different recontextualising choices raised the potential for severing this dialectic in both cases, in different ways. In M8, the very strong framing of the project, the explicit organisation of the contextual detail and the prescribed development of generic theory specialised for direct implementation in each sequential analytical step, had the potential to sever the ontic relations and reduce the discursive relations to mere procedural manipulations. This was not inevitable. The detailed elaboration of the reasoning in the supplementary notes provided a very explicit model of the nature of the reasoning required, but the assessment protocol could not evaluate the nature of the student engagement with the notes. In C5 the very weak framing of the project meant that any students who could not adequately make sense of the material (ontic) relations, potentially constructed fragmented models of the artefact/context and inadequate or inaccurate symbolic (discursive) models. Students may potentially resort to common sense notions of the context and artefact, and sever the discursive relations. Again, this was not inevitable. Those who could read the context and artefact would experience the full dialectical relation between the ontic and discursive relations, and the continual shifts between the two during the process of designing. Alternatively, careful work in the field of reproduction (teaching, coaching and mentoring actions in the classroom), could be used to assist students to hold the dialectical relations together. But the field of reproduction (Bernstein, 2000) was not considered in this study. Without intervention in the field of reproduction, the very weak framing would likely result in considerable variation of experience across the class with an associated challenge for reliable and consistent assessment.

Although Abbott (1988) suggests that inferences are based on knowledge organised academically, linked by rules of conceptual coherence defined internally to any particular body of disciplinary knowledge (discursive relations), what the data in this study showed was a far greater influence emergent from the concrete particulars of each case (ontic relations). And what Abbott's three modes of professional action fail to identify explicitly is the need to translate between ontic and discursive relations.

### **7.1.3 Implications for progression**

Sections 7.1.1 and 7.1.2 above have principally addressed the first research question, the nature of reasoning when abstract disciplinary knowledge is recruited to solve contextually specific problems. But the data in this study was drawn from recontextualised engineering design projects, and the discussion centred around the effect of different recontextualising choices on the nature of reasoning. The second research question related to the logic of progression in a curriculum. Although there was no logical progression evident in the design projects investigated, an understanding of the basic nature of reasoning in design, and the effect of recontextualising decisions on the inferences required, offers potential for the construction of more intentional progression in a curriculum.

The lack of a clear progression in any of the three trajectories investigated can be attributed to a number of reasons beyond the scope of this study. Firstly, design in a curriculum is required to meet a very wide range of objectives, not only those of learning to work between generalisable knowledge and particular contextual details. Dym et al. (2005) argued that far too many teaching and learning objectives have been assigned to engineering design projects. Secondly, the design projects investigated were not necessarily set up for the purpose of developing the skills needed to work with knowledge in context. Each project was recontextualised by a different lecturer for the purposes of developing particular objectives specific to that course. For example in M8 (Power plant specification), the project was intentionally designed to introduce students to discrete systems design tools. Much of the fragmentation that occurred in relation to the design was as a result of the intention to manage each task for different purposes. The details of specialising generalisable knowledge for use in the particular case was provided in the supplementary notes, so that students could work with the systems design tools without getting lost in the complexity of the artefact and associated disciplinary knowledge. Nonetheless the analysis does indicate the potential for designing a logical progression particularly in terms of complexity.

The investigation of progression in terms of specificity (semantic gravity) and complexity (semantic density) has its roots in the insights from the social realist perspective on sociology of education as well as the data investigated. Claims of the power of abstract disciplinary knowledge lie in its generalisability; that it is not constrained to any contextual instance, but rather is transferable across contexts. This is the logic of abstract theory. But the nature of design has a different logic, a logic of the particular. Design is about specialising general theory to a particular instantiation.

The justification for progression in terms of complexity is perhaps more intuitive. When cumulative knowledge building (Maton, 2013) is seen as an accumulation of ideas but more importantly of their relation to each other, this suggests a strengthening of the semantic density of the discursive relations. From this perspective, progression in a curriculum suggests the accumulation of concepts and their rules of combination, particular to the discipline. Essentially learning is the strengthening of the semantic density of the discursive relations. This study has shown that there is also complexity inherent in the ontic relations, and that the semantic density of the ontic relations influences the insights required of the discursive relations. A progression from weaker to stronger semantic density (complexity) in design can progress by strengthening semantic density of the discursive relations, the ontic relations or both. And as suggested in the analysis above, the ontic and discursive relations, while analytically separated, are inherently dependent on one another. Changes in the semantic density of one tend to affect the semantic density of the other, whether intended or not.

The contextual detail of both the context and artefact are very important for learning to use disciplinary knowledge in context. When either are highly idealised or simplified, students do not get the opportunity to abstract out of the specific complex material details. They have no

opportunity to engage in the process of translating ontic relations into the symbolic representations of discursive relations that are required for the inferential predictive modelling at the centre of engineering problem-solving. Insights gained from understanding the complex networks of conceptual relations defined within a body of disciplinary knowledge also help to identify and organise relevant material relations. But to land students in complex contexts, without access to whole bodies of knowledge, is equally unlikely to develop the skills for using knowledge in context. It can be overwhelming in the first instance, and potentially lead to the naive application of common sense knowledge in the second.

Developing a logical progression of projects from simple to complex (increasing semantic density) involves consideration of the complexity of the context and artefact, the location in the curriculum in relation to specialised disciplinary knowledge, and the relative framing (specification of selection and sequence of tasks within each project). But all recontextualising choices have consequences. Four techniques used to weaken the semantic density of the project were identified in the data. While recontextualising techniques are an important part of designing a trajectory that progresses from simpler to more complex projects, the techniques each affect the discursive relations, the ontic relations, and the relations between the two, in different ways:

- *Prescribing the artefact in detail* identifies and organises the significant ontic relations, removing the need to diagnose and reducing the complexity of the interplay between artefact and context.
- *Imposing discursive expressions on artefacts* (either by prescribing discursive expressions, or using codes of practice) forces a primacy of discursive relations, and uses them to identify and organise the ontic relations.
- *Prescribing generic design techniques* forces the primacy of the ontic relations, in some cases at the expense of disciplinary knowledge.
- *Prescribing a sequence of short tasks* can sever the relations between the ontic and discursive relations resulting in disjointed sequences of procedural steps.

The most direct way to manage the complexity of the reasoning requirements is to manage the complexity of the ontic relations of the context and artefact prescribed in the brief. In terms of progression this means using recontextualisation to simplify the ontic relations in earlier projects and progressively leaving the inherent complexity of contexts and artefacts with minimal simplification in the later projects. In terms of specificity this would suggest a trajectory from more precisely specified artefacts (SG++) in the earlier projects, where the given layout or descriptions help to both identify and organise the ontic relations that matter, and constrain the possibilities of variation. The semantic gravity of the prescribed artefacts can then be progressively weakened to prescribed artefact types (SG+) and finally to artefacts that are not prescribed at all (SG-), but rather emerge in response to the contextual requirements of the project as in C5 (Future foreshore). The weaker semantic gravity of underspecified artefacts should not be conflated with the weaker semantic gravity of idealised

artefacts defined by the conceptual requirements of the task, as was the case in S1 (Parking structure) and S3 (Concrete slab).

Recontextualising techniques available to simplify the earliest projects include the following ideas identified in the data:

- Provide *simplified contexts*, where the relevant ontic features have been identified, organised and translated into symbolic form. It would be useful to show this process explicitly rather than presenting the simplified context without justification. U4 (Emmarentia Dam road) was an example of making the simplifications more explicit.
- Simplify the artefact and specify it in detail, *specify the layout and some of the critical dimensions/performance criteria*. M8 (Power plant specification) managed the extremely complex artefact using a process diagram.

Both of these techniques require using the brief to strengthen the semantic gravity and weaken the semantic density of the ontic relations of the artefact and context. The symbolic representation of material contextual features (in diagrammatic or mathematical form) simultaneously introduces a weak form of semantic density of discursive relations, which in turn may function to imply relevant disciplinary knowledge for students to further manage their inferential chains.

In addition to providing slightly more complex contexts and artefacts, perhaps with less explicit translation of material detail into symbolic form, the following recontextualising choices might provide more intermediate projects:

- *Identify relevant bodies of disciplinary knowledge* that students can use to view the context and artefact, providing guidance as to the nature of translation from material detail to symbolic representation. But this requires the presentation of contexts and artefacts with sufficient complexity to require insights from disciplinary knowledge, and sufficiently accessible to all students to retain their ontic coherence. The surveying task and related decisions in U1 (Bikeshare scheme) was an example of this form of recontextualisation.
- *Specify a sequence of inferential steps* to be followed, which helps to organise the inferential networks that students need to reason through as they develop a solution. M3 (Gearbox design) was an example.
- Set up projects that only require *one mode of inferential reasoning*, for example get students to only simplify a context or artefact and represent it in symbolic form as was done in M2 (PRS for domestic appliances).

To prepare students for confronting real contexts and unspecified artefacts in professional practice, it is important that they are taught to simplify contexts and idealise artefacts from complex material details. They need to learn to identify relevant knowledge disciplines based on insights into their conceptual rules of combination. This can only realistically be achieved towards the end of an engineering program, once they have *mastered multiple disciplinary specialisations* in order to use them insightfully and in relation to each other. And they need

to have had some *experience with simplifying complex ontic relations and translating them into symbolic relations*. Imaginary contexts and idealised artefacts presented to students in the design brief, and design projects located in disciplinary courses, work against this objective. Recontextualising choices that can be considered:

- Provide students with *real contexts* which they are able to access and experience, contexts for which relevant technical data is available.
- *Leave the selection of artefact type to the students* – an artefact type that responds to the needs inherent in the real context.
- Require that *students identify relevant knowledge disciplines* from a range of possible disciplines.
- Include the need to *present a technical drawing* to some level of detail in order to retain the coherence of the ontic relations rather than only the presentation of fragmented discrete performance criteria.

However, these open-ended projects with multiple divergent solutions pose significant challenges to both the experience of students across a class and the validity and consistence of the evaluations. There is therefore also a need to intervene in the field of reproduction, in the classroom, to help direct the students as they struggle to make sense of contextual detail in relations to abstracted knowledge.

#### **7.1.4 The nature of professional reasoning**

The models of design and professional action used in this study all attend to the significance of contextual detail for design. From Schön (1983) we see the importance of working between context and artefact. From Abbott (1988) we get the very useful ideas of abstracting out of context (diagnosis) and relocating in context (treatment). Simon (1981) draws the distinction between external material relations (outer environment) and internal material relations (inner environment), both referring to making sense of the object, with or without recourse to disciplinary knowledge. All suggest the importance of concrete contextual considerations, emergent from the contextual detail of the design problem.

In contrast, theorists in the Bernsteinian tradition after Durkheim have tended to focus on the internal relations of knowledge and the coherence within a particular disciplinary specialisation at the expense of external relations to the object of knowledge (Wheelahan, 2010, pp. 40-42). These theorists have tended to see internally coherent knowledge structures as 'applied to' external objects. For example Young and Muller (2014a) critique Schön (1983) for stripping the disciplinary knowledge base on which professionals make judgements, and prioritising the specific (contextual) over the general (conceptual). Rather they see the rules of coherence of specialised disciplinary knowledge as structuring our understanding of the context.

Much of the current thinking in relation to the nature of reasoning in design – or more generally in relation to professional judgement – gives primacy to either context after Schön (1983) or concept after Bernstein (2000). Alternatively the work categorises the components

of context and concept (Hanrahan, 2014; Muller, 2009). This study has shown the limitations of both approaches by recognising the inherently dialectical relationship that involves complex chains of inferential reasoning between knowledge and context in engineering design.

Firstly, the contextual details make their own demands on disciplinary knowledge. It is the emergent properties of the real that determine which knowledge is relevant and which is not. Secondly, professional knowledge draws on multiple disciplines, each with its own internal disciplinary concepts, rules of legitimate combination based on conceptual coherence, and appropriate external referents. These rules help to simplify and organise external contextual details. However, the contextual details also go some way to organising the relations between disciplinary concepts, while conforming to the rules of conceptual coherence within each discipline. And thirdly there is a continuous shift between contextual considerations and conceptual considerations as the design progresses. The study suggests that the ontic relations drive the discursive relations, the simpler the artefact, the lower the demands on disciplinary knowledge. Insight into the conceptual inferential chains defined within whole bodies of specialised disciplinary knowledge also contributes to simplifying and organising complex artefacts and contexts. The relationship between the two is dialectical.

At the heart of these engineering design projects was the shift from context and artefact prescription in the brief towards the solution specification, a process of making reasoned inferences. In order for students to develop their inferential reasoning between context and knowledge, it is important that at some point students confront a complex context and artefact, without too much sequential procedural direction or disciplinary prompting. It is only in this sort of project that the true dialectical nature of the reasoning between knowledge and context is required. The heart of professional judgement becomes evident when the necessity of design emerges from the material demands, where the power of disciplinary insights can inform the simplification and organisation of the ontic relations, and in turn the ontic relations can make necessary analytic demands of the disciplinary knowledge. Until students are able to work with knowledge in conjunction with ontic necessity, it is trite to speak about the power of abstract generalisable knowledge. Unless the general can be specialised to the particular, it lacks purpose in the professions.

## **7.2 Methodological contributions: Developing LCT (Semantics) to analyse professional knowledge**

The analysis in chapter 6 required adaptations to LCT (Semantics). I have called these adaptations methodological because they emerged in response to the inadequacy of the current development of LCT (Semantics) to capture the significance of context in the data. It is not that any new concepts were added to LCT. Rather, existing concepts from different dimensions of LCT were reorganised in order to deal with the data. Essentially the development of an external language of description required the reorganisation of existing

relations within the internal language of description. In the language of this study, the ontic relations made new demands on the discursive relations.

Although a number of conceptual tools were available to analyse the relation between knowledge and object, LCT (Semantics) was selected because semantics recognises both the relation of knowledge to context (semantic gravity) and the relative condensation of meaning (semantic density) (Maton, 2013, 2014). Rather than categorising meaning as contextual or conceptual, semantic gravity in particular recognises all knowledge as being knowledge about something, and all concepts relate to some external, material aspect of the world. Semantic gravity offers an analysis of the extent to which knowledge depends on its ontological referent (context) to have meaning. Abstract theory, transferable across many contexts and referring to many objects, is then weak semantic gravity. Making sense of the specifics of a particular context and problem depends on understanding that specific context and problem. This is described as stronger semantic gravity. Semantic density suggests a relative accumulation of ideas; when the semantic density is weaker, it implies that fewer ideas need to be drawn on in relation to each other to hold relevant or legitimate meaning, while the stronger the semantic density, the more concepts – held in coherent relation to each other – are required to make sense of something. Semantic gravity then can be seen as a relative scale from particular (SG+) to general (SG-), and semantic density as a scale from simple (SD-) to complex (SD+). And when presented on a Cartesian plane, the two can be analysed in relation to each other.

The limitation of LCT (Semantics) for this study was that semantic density has usually been associated with symbolic knowledge or practices, and has become associated with the complexity of theoretical ideas, the condensation of concepts into more complex concepts (holding together a 'bigger', more complex idea). And in this way, complex ideas (SD+) have typically been associated with generalisable theory; transferable across multiple contexts (SG-). In contrast elaborating ideas, weakening the semantic density (SD-), has been associated with 'simple' concrete examples (SG+). What this study has shown is that when the context has not been idealised or simplified in pedagogic discourse, when the full specificity and detail of the context comes into view, it has its own strong semantic density, a complexity inherent in the multiple and interdependent relations between 'things' in the context. In order to make sense of the context, one has to make sense of all the interacting parts simultaneously (SD+). But the strength of the semantic density lies not in the internal relations between concepts defined by rules of conceptual coherence within a body of disciplinary knowledge. Instead it lies in the sense that we can make of a real context. The conceptual relations lie in the emergent properties of the context.

In order to distinguish between contextually emergent complexity and conceptually determined complexity, I turned to the distinction between ontic and discursive relations (Maton, 2014, pp. 175-177). Maton introduced ontic and discursive relations within LCT (Specialisation), which like LCT (Semantics) maps two legitimating principles in relation to each other – in the case of specialisation the social relations and epistemic relations. Ontic

and discursive relations were introduced as a subdivision of epistemic relations. The discursive relations refer to the internal relations between concepts within a particular disciplinary specialisation, while the ontic relations refer to the external relation of ideas to the object of meaning. In this study, discursive and ontic relations have been recruited as dimensions of LCT (Semantics). This development was required in order to investigate the relations between disciplinary concepts and between disciplines (discursive relations) as analytically distinct from relations between concepts about the object of knowledge (ontic relations).

The introduction of a distinction between the semantic density of the ontic relations ( $SD^o$ ) and discursive relations ( $SD^d$ ) enabled an analysis of the relative complexity of the conceptualisation of the contextual details ( $SD^o$ ) and conceptual constellations ( $SD^d$ ) and their intertwined influence on each other. Although both epistemic in nature, they differ in their focus. The former relates to making sense of the contextual details emergent from specific instantiations of the ontological referent, the latter on the imposition of meaning on the context from the perspective of disciplinary conceptual relations. Although somewhat akin to the distinction that Muller (2016) makes between internal and external relations, rather than subjecting the external relations to the internal relations, subjecting the world to the word, adaptation of semantic density introduced in this study enables a more balanced relation between the two.

What became very evident from the data as a result of the introduction of semantic density of the ontic relations as distinct from the semantic density of the discursive relations, was the dialectical relation between ontic relations and discursive relations in design. Rather than suggesting that meaning is imposed on contextual detail from within a body of disciplinary knowledge, it became evident that meaning also resides in making sense of the contextual detail *on its own terms*.

The distinction further illuminated the significance of recontextualising choices on the nature of reasoning in a curriculum task. Recontextualisations that weakened the semantic density of the ontic relations tended to also (sometimes inadvertently) weaken the semantic density of the discursive relations. Recontextualisation that retained the strength of the semantic density of the ontic relations tended to require more insights into constellations of disciplinary concepts (stronger semantic density of the discursive relations). Without the introduction of semantic density of the ontic relations, neither the significance of the complexity of contextual detail, nor the effects of recontextualising conceptual detail are evident. Rather than suggesting that professional reasoning is merely about shifts between context and concept, semantic density (of ontic and discursive relations) enables an analysis of the effect of the relative complexity of each. The introduction of the semantic density of ontic relations avoids the association of the concrete, the contextual and the particular with the simple and the familiar. It explicitly recognises that there can be complexity in the contextual, and opens a window onto the effects of the complexity of the world. Consequently, the semantic density analyses have gone some way to showing why so many students are unable to use the

powerful disciplinary knowledge they have accumulated in their studies when confronted with the complexity of real professional problems.

The introduction of the semantic density of the ontic relations allowed strong semantic gravity to be disassociated from any notions of simplicity or familiarity. Instead, semantic gravity was restricted to a cline from the particular to the general. What was evident in the data was that when the semantic gravity was strong (SG+), the complexity tended to lie in the contextual detail (SD<sup>o+</sup>). When the semantic gravity was weaker (SG-), the complexity tended to lie in the conceptual detail (SD<sup>d+</sup>).

I have called this a methodological contribution even though it is also a contribution to the theoretical field defined by LCT because all of the concepts drawn on here are already part of LCT. It is rather a reorganisation of some of the concepts and tools in order to deal with the significance of complex contextual detail evident in the data. This is an important methodological development for the analysis of professional knowledge – knowledge that has a somewhat different logic to general academic knowledge. The external language of description developed for this study may thus prove useful in the growing interest in professional knowledge and professional education (its construction into curricula).

### **7.3 Theoretical contributions: A conversation between design thinking and sociology of education**

Design research has become dominated by the importance of contextual detail after the model of reflective practice introduced by Schön (1983). Schön's model of professional reasoning has tended to leave the significance of specialised disciplinary knowledge tacit. Drawing on the social realism in the sociology of education has shown the role of disciplinary knowledge more explicitly.

On the other hand, consideration of models of design (Schön, 1983; Simon, 1981) and professional reasoning (Abbott, 1988) have shown the significance of contextual details (of the context and artefact) to the nature of reasoning in professions. While social realism within the sociology of education gives primacy to disciplinary knowledge without explicit consideration of the influence of contextual detail, and to the demands that the external world places on disciplinary knowledge, it is limited especially in terms of analysing professional knowledge. While the analytical concepts and tools associated with social realism in the sociology of education have provided rich insights into aspects of engineering design, the empirical case in this study has also raised questions in relation to some of the central tenets of the field. In a theoretical tradition dominated by a notion of separation and boundaries, this is a study of integration and crossing boundaries. It therefore offers a number of challenges to established ideas in the field, even though drawing productively on tools developed within the field.

This section will address the theoretical contributions to design thinking research in the first instance and to social realism within the sociology of education in the second.

### **7.3.1 Models of professional knowledge in action: A response to design thinking research**

The data in this study were collected from recontextualised design problems, located in a curriculum and not collected from professional engineering practice. It is therefore not possible to say anything definitive about how well Simon (1981) or Schön's (1983) processes are able to model 'real' design. But what can be said is that when the framing of a design project constructed in a curriculum is very strong and the problem is defined fully in the brief, there is no requirement for students to engage in a reflective process of reasoning between context and artefact, and between problem and solution in iterative cycles of problem setting and solution generation. When the framing is strong the process tends to resemble the linear 'technical rational' process described by Simon. When the framing is weaker, and when the brief refers to a real context, accessible to students, there is far more scope for the iterative and 'reflective' process described by Schön. However the reflective process was far more explicitly guided in the data by insights from well-understood bodies of disciplinary knowledge than implied by Schön.

Although Schön's (1983) treatise on the reflective practitioner has been embraced by design thinking theorists, he positioned his work as a model of professional knowledge in action. Likewise Simon (1981), who is also drawn on by the design thinking theorists, proposed that design was the basis of all professional reasoning. Therefore, Abbott's (1988) three modes of professional action, namely diagnosis, treatment and inference, are consistent with both Schön and Simon. All three scholars emphasise the significance of context. But in many projects investigated in this study, the significance of the context appears to have been largely overlooked, replaced instead by imaginary or simplified proxies. All three scholars recognise that developing a design solution or professional treatment requires specialising a general solution to a particular implementation in a specific context. This shift in reasoning as the design evolves was evident in the data, a general strengthening of the semantic gravity, except when projects required only part of the design, or were not in fact designs.

Simon (1981) has been critiqued by design thinking theorists for being too rigorously linear in his 'technical rational' design process (see for example Dorst & Dijkhuis, 1995), who have tended to prefer Schön's (1983) more 'reflective' approach to design. In the data investigated in this study, at least in the mechanical engineering trajectory of projects, and most obviously in M8 (Power plant specification), there was more evidence of the technical rational method of design after Simon (1981). The contexts, simplified to symbolic representations of certain, non-variable lists of theoretical parameters, both prevented any sort of reflective reasoning between context and function, and emphasised the rigour of precise technical reasoning. The strong framing of the analytical requirements particularly in M8 (Power plant specification) and M3 (Gearbox design) also tended towards the linearity of technical rational design

described by Simon. As illustrated in figure 6.9, although the reasoning required in M3 resembled an iterative network of inferences rather than a strictly linear process of reasoning, there was no direct link to the context. Since Schön's model of design is one of continual 'problem setting', identifying and conceptualising problems as the solution evolves *in relation to the context*, it is not surprising that we don't see evidence of his model of reasoning when the context is absent. In the projects that were very strongly framed, the problems had already been identified and described in the brief by the lecturer, and hence students do not engage in problem identification.

On the other hand, the weaker framing of especially C5 (Future foreshore) opened up the potential for 'reflective' reasoning between context and artefact, a repetitive cycle of problem solving and solution generation in that the proposed solution creates new problems as the design evolves. However, Schön (1983) has been critiqued by social realists in sociology of education for his apparent devaluing of the specialised disciplinary knowledge that underpins professional reasoning (Young & Muller, 2014a). The reasoning demonstrated in the solutions investigated (admittedly 'good' solutions) indicated that insights into specialised disciplinary knowledge certainly directed the design considerations. The role of disciplinary knowledge in the evolving design as Schön describes it, is largely tacit, but not as absent as Young and Muller (2014a) would have it. Schön describes overarching theories that inform design reasoning in professional practice, clearly evident in the recognition of the design problem in C5 (Future foreshore) as one of accessibility and liveability, informed by insights into urban planning and transportation planning.

Perhaps Abbott's (1988) three modes of professional reasoning, not generally referred to by design thinking theorists, provide a better model of the nature of reasoning between disciplinary knowledge and contextual problems. Diagnosis (the stripping of extraneous detail and categorisation of a problem) and treatment (the specialising of a solution for application back into a specific context) capture the essence of the features of design that Schön was addressing. Inference, with its attention to the rules of conceptual relations within bodies of disciplinary knowledge – knowledge organised differently than that of the case-based classification of knowledge used in diagnosis and treatment – provide the basis of Simon's technical rational method of design.

But, based as they are on a medical metaphor, Abbott's (1988) three modes of professional reasoning require some attention if they are to work for engineering design. What Abbott called routine professional action involves a diagnosis-treatment couple, the identification of a problem type (case-based reasoning) with a solution type. In what is typically called conceptual design, the proposal of an artefact type in response to the emergence of a problem, resembles this couple. But what Abbott fails to recognise is Schön's (1983) contention that each solution is unique because each context is unique. This means that even when an artefact type has been identified, it still needs to be specialised for a particular function, in a specific context. And this specialisation usually requires the mode of inference. Nor does Abbott (1988) address the shift from a case-based (contextually emergent) organisation of

knowledge (diagnosis and treatment) to disciplinary knowledge organised on the basis of internal rules of relevance and conceptual coherence. In LCT (Semantics) terms, how are ontic relations translated into discursive relations for the purpose of inference, and back into ontic relations in order to describe the specialised artefact solution?

LCT (Semantics) helped to develop the relation between diagnosis-treatment and inference. Diagnosis can be described as a process of weakening the semantic density of the ontic relations ( $SD^{\circ}\downarrow$ ) as relevant contextual details (or context or artefact) are identified and irrelevant detail is stripped (colligation). It is also a process of weakening the semantic gravity of a problem ( $SG\downarrow$ ) as the specific problem is generalised to a type of problem (classification). If the problem is a typical problem and can be classified as such, the reasoning may remain in terms of the ontic relations. The treatment partner may consist merely of identifying an existing solution and specifying it for this application. In this case a specific 'off the shelf' artefact/process can be prescribed. The solution already exists as a particular artefact/process ( $SG++$ ) with its complex internal components and functionality ( $SD^{\circ}++$ ). Although there was little evidence of this form of reasoning in the data investigated in this study, there were elements of it in M7 (Multitask micro-machine). Students were required to identify a hypothetical machining process and select a number of existing machining modules to combine into a multitask machine. But even in this project, the particular configuration of the existing machining modules and the interdependence of their interrelations required recourse to inferential reasoning, based on scientific predictions of performance, and mathematical relations in space and time.

Diagnosis is a useful metaphor, if we extend diagnosis to include not only the categorisation of a problem type, but also the translation of ontic relations into symbolic representations defined by discursive relations within relevant bodies of disciplinary knowledge. This still requires the generalisation of the problem out of the specifics of the particular scenario in which it emerged ( $SG\downarrow$ ) and the identification of material features relevant to the problem ( $SD^{\circ}\downarrow$ ), and also includes the introduction of relevant discursive concepts ( $SD^{\text{d}}\uparrow$ ). This in essence becomes what Schön (1983) describes as problem setting. And although the specifics of the discursive relations remain largely tacit in Schön, there are traces of the way in which disciplinary knowledge informs the reasoning. For example, as Quist (an expert architectural instructor) guides Petra (an architectural student) through her design he is repeatedly referring to ideas of geometric coherence and balance, central knowledge themes in architecture (Schön, 1983, pp. 79-104).

Treatment can be described as the opposite process. A generic solution type (artefact/process type) is identified and specialised to a particular function in a specific context ( $SG\uparrow$ ). This typically requires that the ontic relations are prescribed in detail, reintroducing the complex interdependence between parts ( $SD^{\circ}\uparrow$ ), while the discursive relations that may have informed the specialisation of the solution recede into the background ( $SD^{\text{d}}\downarrow$ ).

Abbott (1988) describes inference as chains of reasoning based in conceptual relations, where legitimate conceptual links are defined by the internal rules of any discipline. But this tends to foreground the discursive relations without recognising the significance of the ontic relations. If the discursive relations define the legitimate rules of relations between concepts, then the ontic relations define the specific relations relevant to the case. The supplementary notes provided in M8 (Power plant specification) illustrate the interdependence between the discursive and ontic relations. In the example discussed in section 5.5.1 (step 3) principles of heat transfer were specialised for application in the boiler and superheater. General principles of radiation and convection were modified by the specific geometry and air conditions in the boiler and superheater respectively. Without an appreciation for the ontic relations, the way in which a boiler operates, the details of the internal structure of the boiler, the generalisable heat transfer theories would have been of no use in the analysis.

Winch's (2010) elaboration of inference in professional and vocational work is based on an integrated and embodied understanding of conceptual networks of ideas relating legitimate ontic and discursive relations, suggesting a more integrated view of inference than Abbott (1988) suggests. Professional knowledge includes the disciplinary knowledge, procedures and skills along with repertoires of professional examples and experience of skilled work that cohere around a profession or vocation. Symbolic relations, internal to a disciplinary body of knowledge, separated from context, are inadequate to describe expert professional work.

Following Schön (1983) rather than Simon (1981), design becomes multiple cycles of diagnosis-inference-treatment (Abbott, 1988), informed by a coherence between knowledge, procedures and contextual specifics (Winch, 2010). In LCT terms, it involves continuous shifts between the particulars of the problem and the generalities of abstract knowledge ( $SG\downarrow\uparrow$ ); the ontic details and discursive details, drawing on a complex understanding of the whole ( $SD^o\uparrow/SD^d\uparrow$ ) and focussing on simplified aspects of the parts ( $SD^o\downarrow/SD^d\downarrow$ ).

### 7.3.2 The nature of professional reasoning: Singulars and regions

As was discussed in chapter 3, Bernstein was strongly influenced by Durkheim's (1995) insights into the parallels between abstract symbolic knowledge and sacred religious knowledge. This first boundary, between the *profane* concerns of the everyday world and the *sacred* knowledge of things unseen, has been discussed variously by for example Beck and Young (2005), Bernstein (2000, pp. 81-86) and Gamble (2014). The influence is evident in how Bernstein theorised knowledge structures and their relation to curriculum structures. What he called 'singulars', form the basis of sacred knowledge, separate from the world and controlled by those initiated into the secrets of symbolic knowledge, a symbolic system of meaning separated from the world but able to describe and explain what we observe and experience in the world. What Bernstein called 'regions' can be likened to the application of sacred knowledge to the profane concerns of the world.

Singulars are disciplinary specialisations, separated from both other disciplines and separated from the concerns of the world. Disciplinary knowledge is a system of concepts defined by internal rules of legitimate connections, or discursive relations. The separation of knowledge from external concerns and its strong classification is what enables the development of strong internal relations of coherence and the power to generalise (Bernstein, 2000). From this reasoning it follows that learning becomes gaining access to powerful ways of knowing, and requires immersion in a discipline in order to not only accumulate the concepts defined within the discipline, but more importantly to develop mastery over their rules of legitimate combination. This suggests a curriculum constructed of strongly classified disciplinary subjects.

'Regions' followed from singulars as Bernstein's way of theorising traditional professions. Bernstein defined regions as a consequence of the weakening of the classification of singulars, both in relation to other singulars and in relation to the world. Regions are therefore theorised as a collection of singulars with relations to each other (weakening the classification between each) and facing outwards to the world (which weakens the classification between knowledge and its external concerns). This establishes the 'word' as the basis for the 'world'" (Wheelahan, 2010, p. 40). Consequently Bernsteinian theorists argue from the primacy of singulars: first the singulars in which specialised disciplinary knowledge is produced by an inward focus on conceptual coherence; then the regions which are recontextualised singulars, looking both internally to related bodies of specialised disciplinary knowledge and externally to their fields of practice (Bernstein, 2000, p. 52).

Muller (in Muller, 2016; and Young & Muller, 2014a), arguing from a Bernsteinian perspective, developed the notion of regions as typified by traditional professions in terms of 'knowledgeable action'. The regionalisation of knowledge becomes the external application of the internal relations of specialised disciplinary knowledge to address something other than itself. Muller explicitly linked the internal, conceptually coherent, relations inherent to singulars to what Bernstein (2000) referred to as the *internal language of description*, which remains relatively 'invariant'. In order to make sense of an external object, in order to address an external problem, the contextual details of the external object<sup>29</sup> are read through the lens of a discipline. The internal rules of the discursive relations provide the rules for organising how we 'make sense' of the external object. The external object is defined by the application of disciplinary ways of seeing it. The way in which the disciplinary organises the external object is determined by the external links to that object, the rules by which 'internally coherent concepts' are linked to 'external objects' ('grammaticality') (Muller, 2007, 2016) or an *external language of description*. For Muller, since professional reasoning is based on the application of specialised disciplinary knowledge to solve the problems of the world, knowledgeable action is the skilful construction of a chain of reasoning between "the 'invariants' of the conceptual pile and the variability of the empirical instance" (Muller, 2016, p. 82).

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<sup>29</sup> By external object I mean something that is external to the concepts and relations defined within a particular knowledge specialisation.

Central to this account of professional reasoning is the positioning of specialised disciplinary knowledge necessarily prior to its external application, and the separation of disciplinary knowledge from the concerns of the world. It is only once the initiate has mastered the discipline (both concepts and relations) that s/he can start to build external relations to the world. The structure of traditional engineering curricula do tend to follow this logic, first the foundational sciences (strongly classified singulars), then the engineering sciences (weakening the classification between singulars), and finally the application of the sciences in design (weakening the classification between the sacred and the profane) towards the end of the curriculum.

What this account of professional reasoning fails to recognise, is the importance of the influence of the external object and the complexity of its internal relations. I will use two examples from the data to illustrate ways in which the external object announces itself. In M8 (Power plant specification), the analysis of the heat transfer in the furnace and superheater was based on thermodynamics, a disciplinary specialisation. From within this specialisation we know that heat transfer occurs by three mechanisms: convection, conduction and radiation. Knowledge of thermodynamics is necessary to recognise that all three mechanisms are present. However, it is knowledge of the *contextual* detail, experience with similar furnaces/superheaters, that allows the system to be simplified such that only radiation need be considered in the furnace, and convection in the superheater. The professional judgement demonstrated in the supplementary notes provided for M8 was based on a dialectical relationship between the generalities of the disciplinary knowledge and knowledge of the particularities of the context. By positioning internal (discursive) relations prior to external (ontic) relations, the insights based on the internal coherence of the object itself are overlooked. Muller's (2016) account of professional reasoning positions the discursive relations as internal to the reasoning (defining its logic or coherence) while the ontic relations are positioned externally. The alternative account proposed by Schön (1983), positions the ontic relations as internal to the reasoning (providing the logic or coherence) with disciplinary knowledge left tacit and external. The argument that I have presented is that the 'external' object has its own internal logic based on a different logic (ontic relations) *not* necessarily defined by any particular discipline (discursive relations). And the two logics (discursive and ontic) sit in dialectical relationship with each other. Undoubtedly mastery of the discursive relations, of disciplinary knowledge, provides insight into the 'external' object, but familiarity with and knowledge of the object itself determines which knowledge is relevant and the way in which the specific discursive concepts combine.

U1 (Bikeshare scheme) presents another interesting view on the logic of professional reasoning. By virtue of its position early in the curriculum, students would have limited expertise in different disciplines. As such, students were required to make sense of a complex contextual project with minimal recourse to multiple disciplinary insights. Only once they had made sense of the context, identified significant and discarded insignificant details, could they employ specialised surveying knowledge and procedures. Some familiarity with cycling

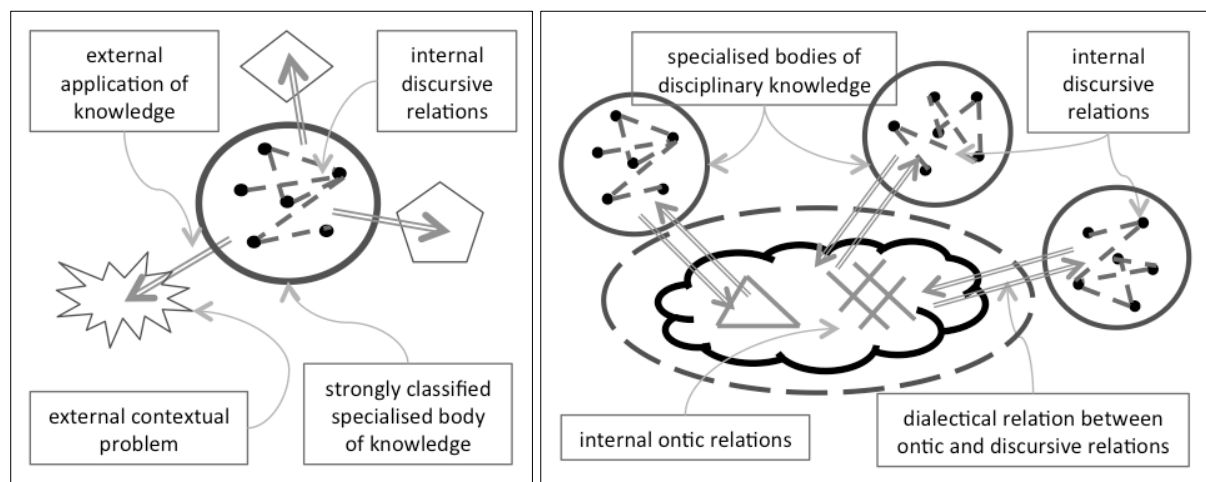
was needed to identify that steep inclines would be a problem and to recognise the challenges faced by sharing routes with pedestrian and/or motorised vehicles. Some familiarity with the concept of a bikeshare scheme was required to determine the space required for storage. Familiarity with the specific campus provided the internal logic of the design, and preceded the recruitment of surveying knowledge and skills. Surveying was used to map a route and, based on the insights provided by the mapping, to propose modifications to the existing terrain, all driven by the internal logic of a bikeshare scheme on a particular campus, but also informed by disciplinary knowledge and procedures internal to surveying.

The examples in the data where the logic of the project might be seen as defined by the internal relations of disciplinary specialisations were in S1 (Parking structure) and S3 (Concrete slab). In both cases the context was stripped away completely and the artefacts were presented as generic idealised structures. I would argue that it was the recontextualising strategies that modified the nature of the reasoning. By locating both projects within disciplinary courses, and by idealising both structures, influences of other disciplines were eliminated, and contextual detail was not required in order to recognise significant disciplines. The ontic relations were simplified to idealisations that were defined by the needs of the discursive relations. The recontextualisation shifted the logic of the projects to a logic defined by internal discursive relations, applied externally to a somewhat incidental example. This model is represented diagrammatically in Figure 7.2a.

S4 (Parking garage), C5 (Future foreshore) and to some extent M7 (Multitask micro-machine) all required that relevant knowledge specialisations be identified from the requirements of the context and artefacts. Certainly mastery of multiple disciplines would be required to identify relevant knowledge, but *which* knowledge was determined by the needs of the contextual detail (context and artefact). These projects might be characterised by a dialectical relationship between the internal logic of the context/artefact (ontic relations) and the different internal relations of the disciplinary knowledge (discursive relations). This dialectical model is represented diagrammatically in Figure 7.2b.

In most social realist accounts of professional knowledge in sociology of education, the external ontological referent is seen as incidental to the internal disciplinary knowledge relations. Contextual problems are seen as 'little applications' of disciplinary knowledge. Bernsteinian concerns lie with internal conceptual relations as imposed on external objects, at the expense of the manner in which the objects themselves 'act back' on our ideas about them, and announce themselves beyond the confines of any disciplinary specialisation. Wheelahan (2010, pp. 39-43) critiqued Bernstein's approach as relying too much on the structure of knowledge at the expense of the object of knowledge. In contrast, "[c]ritical realists argue that knowledge arises from our social practices in the world and not our structures of knowledge. World before word." (Wheelahan, 2010, p. 75). In those design projects where students were required to engage with real contexts and detailed rather than idealised artefacts, a model of reasoning based on the external application of internally coherent

knowledge was inadequate to describe the complex dialectical relationship between the 'word' and the 'world'.



**Figure 7.2 Application of specialised knowledge to an external object (a). Dialectical relation between knowledge and object (b).**

### 7.3.3 Recontextualisation: A tension between singulars and regions

Throughout this study the point has been made that design projects in the curriculum are not the same as problems faced by engineers in professional practice. In Bernsteinian terms, they are recontextualised. Although often inspired by professional practice, they are dislocated from it and reconstructed for a curriculum. Recontextualisation from the field of production (and in the case of professional knowledge, also from the field of practice) into a curriculum is a process of selecting what to include and exclude from the vast store of possible knowledge and skills. It includes ordering this knowledge into a sequence, imposed by the structure of the curriculum and its time and space constraints. In the case of design projects, they need to be set up in such a way that they can be completed within the time allocated in the curriculum amidst other curriculum choices. And finally, where in practice a successful design solution is implemented in the world, and stands or falls on its emergent properties, the evaluative criteria for most design projects in a curriculum are based on a 'paper design' judged on the basis of very different assessment criteria. Bernstein's pedagogic device draws attention to the critical, but often overlooked insight that the structure of knowledge in a curriculum is different to the structure of knowledge in its parent discourse partly as a result of the ideological influences on recontextualisation.

Much of the literature on engineering design in the curriculum presented in chapter 2 centres around the need to increase the design content and to introduce design earlier in the curriculum. This call is premised on the assumption that design mimics professional practice, and more design will better prepare students to perform in practice. And it is in response to the persistent concern over the inability of graduate engineers to use the knowledge they have accumulated in their studies in the workplace. However, taking the pedagogic device

seriously raises a warning that this is unlikely to address the concerns it is intended to address, because recontextualisation modifies the primary discourse.

The empirical findings illustrated the range of recontextualising choices evident in the data investigated in this study, and the effects that these choices have on the nature of the reasoning required. Most significantly, this study suggests that the way in which the contextual details (of both context and artefact) are recontextualised has very significant implications for the demands placed on the students' insights into the disciplinary knowledge that they use, depending on whether the object of design is positioned internal to the task, external to the knowledge or in dialectical relationship with knowledge. Unless at some point students are required to confront the complexity of the ontic relations in dialectical relation with multiple disciplines in complex discursive relations, the reasoning required will be inadequate to model professional reasoning.

I would suggest that underpinning the different recontextualising choices evident in the data is a tension between the logic of singulars and the logic of regions. As discussed in Chapter 3, Bernstein (2000) described singulars as inward facing, concerned with the production of abstract theoretical knowledge. Regions face outwards towards the field of practice. A professional curriculum needs to take both aspects into account, both the internal logic of the disciplines it is founded upon (singulars), and the outward application of that knowledge in the field of practice (regions). The difference in the logic of singulars and the logic of regions can be described by drawing on the principles developed in the LCT (Semantics) analysis presented in chapter 6. Singulars are concerned with the production of abstract, generalisable knowledge, founded on principles of internal conceptual coherence and idealised contextual details. The work of singulars can be described as a weakening of semantic gravity and strengthening the semantic density of the discursive relations while simultaneously weakening the semantic density of the ontic relations ( $SG \downarrow SD^d \uparrow SD^o \downarrow$ ). On the other hand, regions are concerned with the specialisation of abstract knowledge to particular, increasingly complex contextual instantiations. The process can be described as a strengthening of both the semantic gravity and the semantic density of the ontic relations while simultaneously weakening the semantic density of the discursive relations to a particular formulation ( $SG \uparrow SD^o \uparrow SD^d \downarrow$ ). There is a contrast between specialisation for the purpose of generalising, or specialising to the particular, associated with inverse semantic codes.

Research-intensive universities, concerned principally with the production of knowledge and the transmission of symbolic meaning, tend to be aligned with the logic of singulars ( $SG \downarrow SD^d \uparrow SD^o \downarrow$ ). Engineering and other traditional<sup>30</sup> professions, principally concerned with modifying the world to meet particular goals, are aligned with the logic of regions ( $SG \uparrow SD^o \uparrow SD^d \downarrow$ ). When the ontic relations are left unconsidered, as they have been by most sociology of education theorists in the social realist tradition, the development of singulars is assumed to be one of increasingly complex reasoning, while regions are assumed to require

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<sup>30</sup> Social realist discussions of the newer professions, labelled 4th generation professions, suggest different semantic relations, and have not been considered in this study.

less complex reasoning. On the other hand, when the discursive relations are left unconsidered, as they have been in some of the more 'progressive' commentaries, singulars are viewed as pointless because of their distance from the concerns of the world, and regions become paramount without regard for the power of the knowledge that informs judgement (Bernstein, 2000; Muller, 2016).

In terms of the data presented in this study, the role of contextual detail (of both the context and artefact) is central to recontextualising decisions. Based on the argument presented above, when contexts are simplified and presented in symbolic form, and when artefacts are idealised, the recontextualising principle is based primarily on the logic of singulars as defined by the discursive relations. When students are confronted with complex contextual detail (in relation to both real contexts and detailed artefacts) the principle of recontextualisation is based on the logic of regions, which includes consideration of the ontic relations. I would argue that this tension between the logic of singulars and the logic of regions, contributes to the uneven trajectory evident in the data.

What this theoretical perspective offers the social realist school within the sociology of education is an additional lens on both the nature of reasoning in regions, and the tension between different recontextualising logics. While social realists in sociology of education remain blind to context, and particularly the influence of the complexity of contextual detail on the nature of reasoning, they also have a limited capacity to deal with the nature of regions.

#### **7.3.4 Pedagogic code modalities**

Reference was made to the classification and framing of the projects in the capstone courses presented in chapter 5, and although not discussed in the thesis, appendix 2 includes a classification and framing categorisation of each unit of analysis for each project. Since classification (the power of separation) and framing (control) are central to Bernstein's (2000) concern over the role of education in reproducing social inequality, I include some discussion on how this study was informed by these concepts and how the LCT (Semantics) coding links to classification and framing.

Bernstein's principle argument for the way in which schooling reproduces social inequality is that some children are predisposed by virtue of their upbringing to the form of reasoning and meaning-making that is valued in school, while others are not. School is (by definition, social realists would argue) based on an elaborating code, which focuses on making explicit logical chains of inferential reasoning, the rules of which are defined by particular disciplinary knowledge specialisations. In order to learn the concepts and rules of combination, the subject needs to be separated out from other subjects (strongly classified) with the rules explicitly defined (strongly framed). This enables students to be immersed in the discipline. Bernsteinian scholars, (see for example Hoadley, 2008; Straehler-Pohl & Gellert, 2013), conducting work in schools, have argued that when subjects are integrated with other subjects

(weakening the classification), the internal rules of each subject become blurred or at best tacit (weakening the framing), and unless students have already been schooled in the legitimate meaning-making and elaborating rules (usually at home), they are disadvantaged by the tacit evaluative criteria. Those students from homes aligned with a different code to that valued in school are subject to what has come to be called a 'code clash' (different rules of legitimacy, often contradictory) (Maton, 2014) between the pedagogic code of formal education and the pedagogic code enacted at home.

The weak classification and framing of regions evident in some of the design projects analysed poses a challenge to the advantages of strong classification and framing for learning. This challenge should not be overlooked in terms of its relation to equitable distribution of access to knowledge across diverse social experience and background. When the framing is weak (implicit expectations) and the classification is weakened (disciplines are integrated and aimed at application to the world), students are thrown back onto the symbolic and cultural capital that they bring to the task. Because 'what matter' in design is different to 'what matters' in strongly classified and framed disciplinary courses, unless the expectations of the weak classification and framing of design projects is made explicit, there is likely to be differential access to the forms of meaning that matter across the class.

As has been shown in the data, the logic of design coheres around a specific context and problem arising from the context, not necessarily from a disciplinary specialisation. In order to define a solution and specialise it to a context and purpose requires the integration of insights from multiple disciplinary specialisations (weak classification of the discursive relations). Engineering judgement is founded on learning to read the contextual details and being able to translate them into symbolic form. When the symbolic relations are defined and sequenced for students (strengthening the framing of selection and sequencing), as was the case in M8 (Power plant specification), engineering judgement is not necessarily required of the students. I am arguing that very strong classification and framing (of disciplinary knowledge) tends to work against learning professional judgement. On the other hand, very weak classification and framing, as was seen in C5 (Future foreshore), is a very different pedagogic code than students experience in disciplinary subjects in the curriculum. Without intentionally schooling students in the transition from strong classification and framing to weak classification and framing, those students who can read the tacit signals (usually as a result of symbolic and cultural capital acquired in the home) have a significant advantage over those who have not had opportunities to acquire such.

The point being made here is that if there is an expectation that professionals will be able to draw on disciplinary knowledge to solve contextually specific problems in practice, they should be taken through a trajectory of progressively weakening the strong classification and framing experienced in disciplinary courses to the weak classification and framing that develops professional judgement. This is not an argument for an integrated curriculum. If disciplinary knowledge is to drive professional judgement, then students need to be schooled and become proficient in the internal, conceptually coherent, rules of the disciplines. In order

## CHAPTER 7

to draw on the power of specialised disciplinary knowledge, students need to be sufficiently proficient in various disciplines to recognise what will be relevant, and confident with rules of combination in order to specialise selected disciplinary concepts to specific contextual problems. But students need to learn how to read contextual detail as the basis for identifying and organising disciplinary knowledge. If knowledge remains separate from the world (strongly classified), organised by its own logic and not ready for direct application in professional problems as Abbott (1988) and Smeby and Vågan (2008) point out, then many students are likely to struggle to reorganise that knowledge as defined by the contextually specific problems they will face in practice.

## Chapter 8 Conclusions

This study set out to investigate why graduate professionals struggle to 'apply' the theoretical knowledge that they learn in their studies to solve the problems that they face in professional practice. What is it about the nature of professional reasoning between abstract, generalisable theory and the concrete particulars of contextual problems that students are generally not prepared for when they graduate with professional degrees? And how might curricula be structured in order to develop this skill?

The case study selected was engineering design. As a science-based profession, engineering explicitly draws on well-established disciplinary knowledge specialisations, and engineering design is characterised as a process of using scientific knowledge to design artefacts or processes that address contextually emergent needs. The data was selected from design projects located in two engineering curricula, representing three sequential trajectories of design. This introduces a limitation of the study, because recontextualised design projects are not the same as the problems faced in professional practice even though they may mimic them. What this study can contribute to 'real' engineering practice is therefore limited. On the other hand, it has much to contribute in terms of understanding how the choices we make when we construct design projects affect the nature of reasoning between knowledge and contextual detail (of the context and artefact). Consequently it provides useful insights into how one might design a logical progression of projects with the explicit intention of developing the skills needed to 'apply' theory to solve 'real' problems.

The research was positioned within the field of sociology of education from a social realist perspective, drawing on the models and concepts established by Basil Bernstein (2000) and in this study extended by particularly Johan Muller (2009, 2016) and Karl Maton (2013, 2014). The research design is consistent with the intellectual field and the findings have been located within current conversations within the field. The most notable theoretical insight that this study shows is the blind spot in the field regarding contextual detail and the influence of the object of knowledge on reasoning. From a Bernsteinian perspective, professional reasoning is rooted in what Bernstein (2000) labelled 'regions'. This positions disciplinary knowledge necessarily prior to the application of knowledge to address external concerns and consequently suggests that all meaning is imposed on the context and artefact from the perspective of relevant disciplinary knowledge. It fails to recognise that the external object imposes its own requirements on knowledge and that meaning also resides in knowledge of the details of an artefact and how it works. In order to address the blindness to contextual detail, adaptations were proposed to LCT (Semantics) (Maton, 2013, 2014), the primary analytical tool used to analyse the data required significant adaptations.

## 8.1 The nature of professional reasoning

The first research question related to the nature of professional reasoning:

What is the nature of the reasoning involved when specialised disciplinary knowledge is recruited to develop specific, often concrete, artefacts?

Although the data was located in the curriculum, theories of professional knowledge and design were drawn on in the first stage of analysis. Design thinking theorists have been making the point that design is the co-development of problem and solution space through iterative contextually emergent problems after Schön's (1983) model of professional reasoning as reflective practice, and Simon's (1981) characterisation of design at the interface of the internal and external environment. What became evident in the analysis is the centrality of contextual detail; the relative complexity of both the context from which the design need arises, and the complexity of the proposed artefact intended to address the contextual need.

However, insights into the contextual detail gained from disciplinary insights were shown to be equally important. These are the external relations of knowledge to the object of knowledge gained from a mastery of the complex internal conceptual relations of specialised disciplinary knowledge (Muller, 2016; Young & Muller, 2014a). This does not refer as much to the procedural application of mathematical expressions, but rather to the insights that impose meaning and organisation on contexts and artefacts, especially complex contexts and artefacts. Where the design thinking theorists have tended to prioritise the contextual aspects of design, knowledge theorists have tended to prioritise the internal conceptual relations inherent to any disciplinary specialisation. *What this study has shown is that there is a far more dialectical relation between the design context and artefact, and the specialised knowledge recruited to develop a solution, than either knowledge theorists or design thinking theorists have typically recognised.*

Abbott's (1988) three modes of professional action – diagnosis, treatment and inference – provided useful insights into the nature of reasoning evident in the data. The differentiation between knowledge organised by a typology of cases (diagnosis and treatment) and knowledge organised by rational conceptual relations (inference) informed the LCT (Semantics) analysis. Semantic density was adapted to include a distinction between ontic relations (relations between knowledge and its object – corresponding to some extent with case typologies) and discursive relations (formal rational relations between concepts – the basis of the rules of inference). But what Abbott (1988) failed to address explicitly was the translation between the two knowledge forms. Inference appears located in the discursive relations and organised by the rules of the discipline; diagnosis and treatment appear restricted to ontic relations, rooted in contextual details of the context and artefact. The data showed that diagnosis and treatment were also informed by disciplinary insights and inference was defined by the contextual specifics, not only the internal rules of conceptual coherence. Diagnosis defined as colligation (simplification of the contextual detail by a process of identifying significant features) for the purpose of classification (identifying a

typical problem) *or* inference (requiring the translation of contextual features into symbolic representations) is a more adequate description for engineering design.

There are also a number of things evident in the data that have not yet been adequately accounted for in the sociology of education. Firstly, professional knowledge draws on multiple disciplines, each with its own rules of internal coherence, relevance and evidence. When a contextual problem is addressed, these multiple disciplines need to be considered in relation to each other, weakening the classification of each. What has not been addressed is how different disciplines influence each other, when for example heat transfer theories are specialised in terms of geometry, using rules of numerical modelling. Secondly, the contextual details make their own demands on which disciplinary knowledge is relevant and how it needs to be specialised to the specific case. When is thermodynamics relevant (or not), and when are geotechnical insights significant (or not)? How do professionals account for those inconvenient little practical issues not defined by the theory, like the ash in the air, or the driver in the vehicle? Thirdly, conceptual insights help to simplify and organise contextual details, making them more manageable, for example the simplification of which heat transfer mechanisms to consider in which parts of the artefact, even though in reality all are always in action. These points all speak to a continuous shift between contextual considerations and conceptual considerations in a dialectical relation as the design progresses.

### **8.1.1 Recontextualisation: The effect on the dialectical relation between theory and context**

All the design projects analysed were located in the curriculum. They are not the same as the contextually emergent problems faced by professional engineers; they are recontextualised (Bernstein, 2000). Although the projects often mimicked aspects of real engineering problems, important choices about the presentation of the context and artefact, the prescription of disciplinary knowledge, design thinking concepts, or sequential steps were all seen to have an effect on the nature of reasoning required in each project.

It was evident that the nature of the required reasoning was modified by how the context was presented (simplified, real or imaginary); how much detail was prescribed in relation to the artefact (an artefact type or generic, contextually detailed or idealised); what disciplinary knowledge was prescribed (or not); the level of specialisation of discursive relations to the specific context (explicit mathematical expressions found in codes of practice); and the prescription of a sequence of tasks, or not. These recontextualising choices can be used to manage the complexity of the project, but they also tend to shift the dialectical relation between theory and context, usually unintentionally.

Simplified contexts, where the contextual detail was stripped and only those aspects relevant to the design were presented as (usually) discrete symbolic representations, simplified the task and clarified expectations, but potentially severed the ontic relations, as did idealised

artefacts. Real contexts and complex artefacts without prescribed limits to constrain them simultaneously required familiarity with the context or artefact, and multiple disciplinary specialisations with greater insight into the knowledge. If students lack familiarity with the context or artefact, or mastery of the relevant disciplines, there is the potential to slip into fragmented and unspecialised understandings. Imaginary contexts (and potentially imaginary artefacts, although there were none identified in this data) are extreme cases, in that they have no external ontological referent on which to base meaning. They are severed from their ontological base and depend on each student's own imagined context or artefact.

The location of a design project in a disciplinary course certainly helps students to identify what knowledge might be useful to understand the problem, potentially using the discursive relations to structure the ontic relations. But it also prioritises one discipline over others, and discursive relations over ontic relations. It reduces the significance of understanding the context and artefact in its own right. When this was taken to the extreme, and specific discursive relations are defined, usually as mathematical expressions constructed for direct application to the artefact or context, neither insight into the discursive relations nor the ontic relations are required. Instead, the task potentially becomes a procedural manipulation of symbolic equations. Unless the development of the symbolic expression is made explicit, both ontic and discursive relations are potentially severed. The construction of the symbolic expression is the specialisation of all the possible discursive relations to the specific contextually defined instantiation, a dialectical relation between contextual detail and theoretical generalisation. But it requires significant insight into both multiple bodies of disciplinary knowledge and familiarity with the context and potential artefact.

Prescribing generic design thinking tools, or sequential inferential steps, can simplify the project by reducing each step to a more manageable task; it helps to clarify expectations, and can be used to draw attention to various ontic and discursive relations. But it also risks reducing the project to procedural manipulations.

Although the complexity of a project can be managed by using a number of distinct techniques, each one risks modifying the truly dialectical relation between specific contextual detail and generalisable knowledge.

### **8.1.2 Progression: Learning to work with knowledge in context**

The second research question related to progression in the curriculum. In this study progression was considered in terms of specificity and complexity, neither of which provided the basis of progression in the data investigated. While there may be a different logic of progression, I have argued that the basis of cumulative learning is the accumulation of knowledge (and skills), but more importantly, mastering the legitimate relations between concepts (and procedures). Mastery of a disciplinary specialisation comes of mastering the concepts and relations between concepts determined by the rules of legitimate combination defined within that discipline. This is accomplished through increasing the semantic density

of the discursive relations, necessitating increasingly complex insights into the whole body of knowledge. Mastery of the skills to work with knowledge in context therefore means mastering specialised disciplinary discourses, but also mastering increasingly complex contexts (and artefacts), managing more interacting parts and processes interacting in multiple interdependent ways. From this perspective, progression in design involves increasing semantic density of both the ontic and the discursive relations.

I have argued that the more complex the artefact, the more parts and processes interacting in interdependent ways ( $SD^{o+}$ ), the more demands are made of specialised disciplinary knowledge ( $SD^d+$ ). It becomes more challenging to recognise appropriate disciplinary knowledge as the context/artefact becomes more complex. A more integrated view of the relevant disciplines helps to simplify and organise the contextual detail in principled ways. And complex contextual detail requires the construction of more complex symbolic representations of the specific contextual detail. This suggests that complexity of the design projects can be managed by controlling the complexity of the context and artefact presented in the design brief. Which in turn suggests a logical progression from simple contexts and artefacts to more complex artefacts in real contexts.

A progression from simple designs to complex designs can in the first instance be managed by simplifying the ontic relations of the context/artefact, which in turn simplifies the demands on the discursive relations. The ways in which contexts and artefacts can be simplified was discussed above. Interim projects exposing students to more complex contexts and artefacts can be managed through the prescription of generic tools or disciplines to get students to do the simplifications themselves. But if the purpose is to develop the skills required to use knowledge in the solution of contextually emergent problems, then it is critical that students are at some point confronted with real contexts and detailed artefacts, and are required to both identify and specialise appropriate discursive relations. But to avoid the complexity of the task exceeding the experience of most students, it is important to constrain the complexity of at least the artefact to something manageable.

Design tasks that leave the interpretation of the ontic relations of context and artefact to students, that leave students to decide which knowledge is relevant and which is not, that require students to work dialectically between knowledge and contextual detail, are weakly classified and weakly framed. That means that the requirements of an adequate solution are ambiguous and subjective. One of the most profound insights that Bernstein (2000) left us with is that when classification and framing are weakened, when evaluative criteria are tacit, those who do not come well prepared from their prior experiences to recognise what matters and what does not are distinctly disadvantaged. If prior experience is left to chance, only those students with appropriate social and professional experiences are likely to succeed. Before students are confronted with these weakly classified and weakly framed professional projects, it is therefore critical that they are well prepared to tackle them. Beyond designing an *intentional* progression of projects in a curriculum, careful attention should be given to structured support in the field of reproduction (interventions in the classroom). Although

beyond the scope of this study, interventions in the classroom are crucial for broadening access to the knowledge and skills required to make professional judgements.

## **8.2 LCT (Semantics): A methodological adaptation**

The adaptation made to LCT (Semantics) (Maton, 2013, 2014) is both a theoretical contribution and a methodological one. The significance of contextual detail in the data exposed a blind spot in the social realist perspective on sociology of education. The introduction of the semantic density of the ontic relations as distinct from the semantic density of the discursive relations provided a method for recognising the effect of contextual detail, and especially contextual complexity, on the demands placed on disciplinary knowledge. It also led to a critique of the conceptualisation of 'singulars' and 'regions', which positions the internal relations of conceptual coherence necessarily prior to the external application of these relations to the world. But, as Wheelahan (2010) has argued, the world makes its own demand on knowledge. This study presents evidence in support of Wheelahan's position. But more than that, it offers a more adequate description of regions than currently suggested. It is on this basis that the findings in this study are applicable beyond engineering design, more generally to professional and vocational education.

Methodologically, the adapted LCT (Semantics) provides an external language of description useful for the study of other professions. In fact, in any situation where disciplinary knowledge is brought in contact with ontologically real objects, this adaptation makes the object itself visible in the analysis. It illuminates the effect of simplifying and idealising objects for the purposes of learning to work with specialised disciplinary knowledge. It provides a tool for thinking about curriculum progression when there is a double complexity (in both the discursive and ontic relations) to consider.

## **8.3 Considering the nature of regions: A theoretical conversation**

Chapter 7 concluded with a discussion on the implications of the empirical findings in this study, more generally for the intellectual field in which the study was located. The social realist perspective on the sociology of education has tended to neglect the significance of contextual detail on the nature of reasoning. While this allows for an adequate understanding of singulars or specialised disciplinary knowledge separate from the specifics of any context, it does become a problem when regions are defined as mere applications of this specialised knowledge externally to some other purpose (see for example Bernstein, 2000, p. 9). This study has shown that there is a far more dialectical relationship between knowledge and context than suggested by the external application of specialised disciplinary knowledge internal rules. The adaptations introduced to LCT (Semantics), informed by consideration of social realism after Sayer (2010), enabled a more adequate description of the nature of regions.

Considering the distinctive characteristics of singulars and regions, it also became evident that there is a tension between the logic of singulars and the logic of regions. Perhaps this is more evident in research-intensive universities, where power lies in creating knowledge, a logic of weakening the semantic gravity in search of theories that are ever more abstract and generalisable, and increasing the semantic density of the discursive relations in search of fewer concepts to condense existing discursive relations into ever more elegant symbolic representations. What this study has shown is that without careful consideration of the dialectical relation between theory and context, both discursive and ontic relations can be severed, leaving curricula founded on imaginary relations, with neither the power to generalise across contexts nor the power to specialise to particular context. It is not just the knowledge that is stripped.

## **8.4 A final word**

There are a number of limitations to this study, notably that it is located in the curriculum and not in professional practice, and that it focuses on the scientific disciplines with very limited attention to the multiple other disciplines that inform professional engineering reasoning. Despite these limitations this study does have significant implications for any notions of using professional education as a means towards social transformation. Linda Kotta's PhD thesis (2011) showed that when the pedagogic relations in engineering design courses break down, it is the most vulnerable students who suffer the most (see also Kotta, Case, & Luckett, 2014).

This study has shown the inherent challenges beyond pedagogy that face both students and teachers of design as a result of the knowledge itself. There is a shift in the nature of the knowledge relations when students shift from disciplinary subjects to those grounded in contextual detail and imitating the world of professional practice. This study makes these challenges and contradictions more explicit, and in doing so offers ways in which the shift to professional reasoning can be more intentionally structured for all students. Where much of the attention on engineering design education has been directed towards 'soft skills', enabling skills or graduate attributes, for example communication and teamwork, what this study has shown is that there is also an important knowledge component to design. When assumptions are made about students' prior knowledge, or design projects are constructed around unspecialised knowledge, then the important dialectical relation between disciplinary knowledge and specific contextual details and the implications they have for recontextualising disciplinary knowledge are likely to remain hidden.

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## Appendix 1 Informed consent forms

### PHD DATA COLLECTION

NS Wolmarans (MRSNIC008)

#### PHD SUPERVISORS:

A/Prof Kathy Lockett & Prof Jenni Case

#### WORKING TITLE

Engineering design in the curriculum: articulating the recontextualising rules and implications for progression

#### RESEARCH QUESTIONS

With regard to engineering design in the curriculum:

- What are the structuring and organising principles of engineering design?
- What is the logic of progression in sequential engineering design tasks?

I am in the process of completing a PhD in the sociology of knowledge looking at engineering design. I am studying the logic and structure of engineering design as a curriculum subject, and the logic of progression through the curriculum. I am coming to you as the convenor of one of the design subjects that I would like to include in my study.

Involvement in the study would entail the following (please tick each aspect in which you are able to participate):

- Provide access to the design brief (project requirements handed to the students) for either the major design project in the course, or a sequence of three significant design projects, depending on the structure of the course.
- Provide copies of 1 or 2 examples of 'good' student work, as would be presented to ECSA for accreditation purposes. I will collect and copy the work myself.
- Participate in a recorded discussion on what you consider to be fundamental to engineering design and how you attempt to incorporate that into your course ( $\pm$  1 hour).

I know that you are busy and will keep your involvement to a minimum

I am also aware that having someone else scrutinise your teaching practice on any level can be uncomfortable. I would like to assure you that my project is not about teaching practice or an evaluative judgement of your style. I am focused on the knowledge and knowledge structures required to 'do design'. Your participation will be kept anonymous, and I will also present anything that I intend to publish or present that draws on your data to you before publication and I offer you the option to withdraw your data from the analysis should you prefer me to do so. No reason needs to be provided. I will share my findings with you should you be interested.

For reasons of complying with ethical clearance I am required to keep evidence that you have granted me informed consent to use the data from your course.

Course: \_\_\_\_\_

Convenor: \_\_\_\_\_

Signature: \_\_\_\_\_ Date: \_\_\_\_\_

INFORMED CONSENT

MRSNIC008

## PHD DATA COLLECTION

NS Wolmarans

### PHD SUPERVISORS:

A/Prof Kathy Luckett & Prof Jenni Case

### WORKING TITLE

Engineering design in the curriculum: articulating the recontextualising rules and implications for progression

### RESEARCH QUESTIONS

With regard to engineering design in the curriculum:

- What are the structuring and organising principles of engineering design?
- What is the logic of progression in sequential engineering design tasks?

I am in the process of completing a PhD in the sociology of knowledge looking at engineering design. I am studying the logic and structure of engineering design as a curriculum subject, and the logic of progression through the curriculum. I am coming to you because one of the design course convenors has identified your project as an example of a good solution and I would like to ask your permission to use it as part of my data set.

Your involvement in the project will be kept anonymous. My analysis will be done at a reasonably abstract level, meaning that any identifying characteristics of your solution are unlikely to lead to your identity being known outside of myself and your convenor. Although I would request that you grant me permission to reproduce elements of your work as examples of potential solutions in my thesis and in subsequent publications. I should also mention that my analysis is not an evaluation of your or your lecturer's performance, but is rather intended to identify the features and characteristics of the knowledge required to do design as a curriculum subject. I may present aspects of your solution in my thesis and in subsequent publications.

Your involvement is limited to providing me with your marked project which I will copy and return the original to you, and the signing of this form. Since the intellectual property for your project lies with you, I am required to keep evidence that you have granted me permission to use your work.

Course: \_\_\_\_\_

Design Project Title: \_\_\_\_\_

Please indicate if you grant me consent to

[ Y/N ] use your project as data      [ Y/N ] present your solution or parts thereof.

Name: \_\_\_\_\_

Signature: \_\_\_\_\_ Date: \_\_\_\_\_

## Appendix 2 Description and coding of individual projects

### M1: Bearing selection and mounting

<p><b>M1: Project description</b> The first design project in the first mechanical engineering design course involves the sizing and mounting of two roller bearings on a generic shaft.</p>		
<p><b>M1: Context (outer environment)</b> The brief functions to strip the outer environment completely: no indication is given of the context or purpose. The only mention of any context is that the shaft will operate at 1200rpm, and is expected to last for 6 months. No indication is given for why, or what sort of period 6 months of operation might represent. The context is <i>simplified</i> to list of discrete precise technical specifications; the ontic relations are replaced with very simple discrete discursive relations.</p>		
<p>SG-(l): By not referring to any context, the technical specifications given in the brief appear to be <b>imposed</b> from the theoretical requirements rather than emergent for any context. No attempt to link them to a context is made (l).</p>	<p>SD<sup>o</sup>--(l): No engagement with or understanding of any context is required. Aspects that would emerge from the context have been defined as discursive relations (shaft speed and bearing life).</p>	<p>SD<sup>d</sup>-(m): The relevant contextual aspects have been given as a list of discrete technical specifications (shaft speed and bearing life), which provide sequential input into procedural calculations.</p>
<p><b>M1: Artefact (inner environment)</b> The brief functions to strip the complexity of the artefact of which this is an interdependent part. Instead a small part of the inner environment is dislocated from the rest of a machine and presented as a generic shaft mounted on two different types of roller bearings. The brief functions to define what aspects the students need to consider and excludes everything else. It simplifies the geometric considerations in terms of eliminating the geometric relations with power transmitting components and consequently any consideration of space and assembly. It replaces what would be a variable and uncertain load with a fixed load applied at a point, and provides all input variables that would otherwise be selected based on a judgement of the outer environment, without providing any justification for the selections. The design brief is presented in technical and symbolic language, distinct from everyday interpretations and requiring a limited understanding of the material relations represented. The artefact is a simplified <i>idealisation</i> of a bearing arrangement.</p>		
<p>SG+(l)<sup>31</sup>: the artefact is a <b>typical</b> bearing arrangement on a generic shaft. The load specification for bearing selection can be applied to any bearing selection. However, the unrealistic simplifications tend to weaken the SG of the artefact as it could be interpreted as an artefact constructed to illustrate a conceptual idea (SG-) rather than representing a material configuration.</p>	<p>SD<sup>o</sup>--(h): The complexity of a system has been completely <b>stripped</b> and <b>simplified</b>. A very small part of a machine has been <b>isolated</b> from the rest of the machine, effectively removing the complexity of any real effects of the system. The variable and indeterminate relation between a motor and the load it drives has been reduced to fixed axial and radial forces; the geometric constraints of the power transmission mountings and concerns relating to assembly have been ignored. The context has been simplified by <b>dislocating</b> it from the real influences of the world, and reduced to merely the operating characteristics of two kinds of roller bearing. However, the significance of locating the bearings against shoulders while simultaneously considering the implications for assembly does place it high in the category</p>	<p>SD<sup>d</sup>-(l): the artefact is presented in technical language (drawing conventions and performance characteristics), which needs to be understood to make sense of the problem. But because the complexities of the machine and its function have been stripped, the technical terms can be read separately and treated sequentially.</p>
<p><b>M1: Solution:</b> The solution consists of a technical sketch of the mounting adaptation and a bearing designation. The mounting solution consists of a slightly more complex and detailed technical drawing of the generic artefact, including shoulders for mounting provided by either endcaps or shoulders. The solution is read in terms of both assembly and the interaction between bearings and shoulders to control the load paths. The bearing selection, involves the designation of a particular bearing with associated dimensions and loading capacity.</p>		
<p>SG+(m): Although the mounting solution adds significant detail to the solution, and the bearing selection designates a</p>	<p>SD<sup>o</sup>-(m): The detailing of the solution adds complexity and needs to show consideration of both assembly and the</p>	<p>SD<sup>d</sup>-(m): although the semantic density of the ontic relations increases, the technical drawing and bearing</p>

<sup>31</sup> In order to retain consistency with Maton's (2014) inverted vertical axis for SG, the somewhat uncomfortable convention places a 'low' artefact categorisation as closer to the negative end of the axis, or above a 'high' categorisation.

<p>specific bearing with associated dimensions and load capacity, the imaginary nature of the artefact, and the dislocation from real interactions means the solution retains a sense of a typical bearing arrangement.</p>	<p>interaction between bearings and shoulders to control the load paths. The bearing designation needs to be understood in relation to applied and rated loads, and needs to be geometrically compatible with the shaft and shoulder solution. But the simplified artefact allows these to be considered sequentially.</p>	<p>designation does not show any shift in discursive relations, the language is specialised, but can be read sequentially. The solution is informed by procedural specialised knowledge, under explicit direction in the brief.</p>
<p><b>M1: inferences (detailing the solution):</b>  The reasoning in relation to the mounting solution requires visualising the material interactions between the elements in relation to assembly and load paths, involving reasonably complex three-dimensional geometric visualisations represented in two dimensions.  The bearing selection calculations are procedural requiring minimal insight into their basis in probability theory and tribology, these foundations are not required to complete the task. Students do need to appreciate that the value calculated refers to the maximum predicted load factor that the bearing is likely to experience, and consequently they need to find a bearing with a diameter that matches the shaft diameter, and has a load bearing capacity <i>larger</i> than that calculated. Insight into the operation of the machine would be required to determine the input variables for the calculations, but these are provided in the brief, without reference to how they were determined.</p>		
<p>SG+: Although the reasoning requires consideration of the hypothetical artefact, the dislocated nature of the artefact precludes specific detail, restricting the task to the level of a class of artefact.</p>	<p>SD<sup>o</sup>-(h): Although the solution remains stripped of complex interdependencies, the reasoning does require the visualisation of load paths, and the recognition that the bearing has to be assembled onto the shaft imposing geometric constraints. The simplicity of the artefact allows these to be considered sequentially, even though they are interdependent.  The bearing selected also includes consideration that it needs to fit the shaft diameter and have a load factor greater than that calculated. This requires the discursive relations to be considered in terms of the ontic relations, increasing interdependence.</p>	<p>SD<sup>d</sup>-(l): The solution to the mounting part of the design involves a slightly more complex representation of the system, more details are added, but it does not shift beyond the sequential representation of components.  Although the calculations are based on probability theory and tribology, these foundations are not required to complete the task. Rather the calculations are sequential procedural mathematical manipulations.</p>
<p><b>M1: Recontextualisation</b></p>		
<p><b>Classification:</b>  This task is a basic introduction to machine element design, restricted to procedural calculations and typical generic assemblies relevant only to bearing mounting and selection. Although it appears informed by the world, it is in fact bounded from the world and restricted to generic concepts about bearings. The design brief functions to locate the problem as a generic machine element design (roller bearings) problem. By stripping the context the brief effectively separates it from the real influences of the world. And the solution is convergent and restricted to considerations of what is named in the brief.</p>	<p><b>Framing:</b>  The knowledge and sequence of reasoning are explicitly prescribed in the brief, although there are two aspects of reasoning required that are not explicitly named in the brief or prescribed in the catalogues, but are required for a successful solution:</p> <ul style="list-style-type: none"> <li>• the need to consider the bearing assembly and disassembly (in isolation from the rest of the assembly)</li> <li>• recognition that the value calculated in the bearing selection procedure refers to the maximum predicted load factor that the bearing is likely to experience, and consequently that a bearing with a diameter that matches the geometric requirements, and has a load bearing capacity <i>larger</i> than that calculated is needed.</li> </ul> <p>But by removing any need to interpret the context, and not positioning the students in any way as professionals, the ambiguity of the evaluative criteria and social relations are removed.</p>	
<p>++ C: The knowledge is specialised mechanical engineering design knowledge, dealing only with bearings and separated from the need to interpret contextual everyday influences. The solution is also convergent. All aspects are strongly classified.</p>	<p>++ F: Selection sequence and social relations are all strongly framed, which helps to strengthen the framing of the evaluative criteria despite the two interpretive aspects required of students.</p>	

## M2: Product requirement Specification (PRS) for domestic appliances

**M2: Project description**

The second project in the first design course involves the development of a product requirement specification for either a drill press or band saw for an imaginary toolmaking company entering the DIY market.

**M2: Context (outer environment):**

The context is an imaginary company entering the established DIY tool market. The context has the potential to provide complex real input into the design, including real economic limitations on the design in competition with other manufacturers and importers, real manufacturing opportunities and constraints in terms of the resources available to the 'imaginary' company, and potentially labour and marketing aspects. However, there are in fact only three aspects derived from the context that have any relevance to the task:

The DIY market implies a small, relatively portable and affordable artefact in comparison with industrial machinery.

The products selected for the competition analysis must be comparable in terms of cost or performance criteria:

Three competitors products should be compared in tabular form. The three products chosen should either be in a similar price range (max 25% difference) or in a similar performance range.

And the legislative documents referenced must be South African.

If students are listing standards/documents for work place machinery or foreign standards, these are not the most appropriate standards and should be penalised.

All other aspects of the context are stripped for the purposes of the evaluation, but against a backdrop where each aspect of the required task is explicitly specified, this potentially sets up an ambiguous context, where it is not entirely clear which aspects of the imaginary scenario are relevant for the students to consider, and which are not.

The context is *imaginary* because although also simplified, students need to imagine some relations and what these are is not clear.

SG--(h): the context is a generic tool manufacturer entering the DIY market. Although meaning is derived from association with equivalent types of potentially real scenarios (SG+), because it is imaginary and based on an unspecialised understanding of a professional context, there is a potential dislocation from real causal mechanisms, effectively disconnecting meaning from any real referent (SG--).

SD<sup>o</sup>--(m): The context plays a potentially ambiguous role in this task. In terms of the task there are three issues that need to be read from the context (a sense of 'cheapness'; a sense of comparative tools; and reference to national standards). Other than the list of standards, these issues are superficial and dislocated from their real effects. The potential exists for a richly complex and embedded context (SD<sup>o</sup>++), but the recontextualisation disconnects from real mechanisms<sup>32</sup>.

SD<sup>d</sup>--(m): the imagined context is presented in everyday common sense terms, and meaning resides in a common sense understanding of the context rather than drawing on a theoretical principles or symbolic language.

**M2: Artefact (inner environment)**

Students are assigned either a drill press or band saw as the product. These artefacts are both inherently complex, but the level of detail expected of the student engagement with the artefact is unclear. In the brief students are instructed to research and develop familiarity with real examples of their assigned artefact, but which aspects and which examples are left to their discretion. This expectation is largely in terms of what the machines look like (general layout, size and shape), what bits and pieces they are made up from (material clamping, safety features, cutting/drilling parts) how they function (relation between cutting tool and material part, and additional functional features), rather than in terms of the science behind their design. There is no requirement to understand cutting theory (beyond perhaps the provision of coolant) or strength and power transmission (beyond a contextual comparison with comparable machines in terms of power, speed and general dimensions).

SG+(m): students are instructed to develop the PRS for a type of DIY tool (either a band saw or drill press). The PRS relates to a class of tool, in sufficient detail to specify the performance requirements but without detailing the specifics of the artefact itself. But the brief does refer the students to investigate any three examples of the tool for comparative purposes, which places it in the middle of the category.

SD<sup>o</sup>-(m): the tool prescribed is an intrinsically complex artefact comprised multiple interacting parts that respond to cutting loads in complex and dynamic ways (SD<sup>o</sup>++). But for the purposes of this task only a basic understanding of the basic functions and parts is required, generally at the level of sequential considerations.

SD<sup>d</sup>-(l): there is very limited requirement for specialised knowledge of the artefact, but there is reference to discrete performance criteria presented in precise technical language. This places the instructions low in the weak category

**M2: Solution:**

The solution consists of a list of discrete technical performance requirements.

The final solution (the PRS) is supposed to be an integration of the three prior tasks (FAD;FFBD;CA), but the format is a disjointed list of discrete requirements, organised in sections defined by the discourse of a PRS rather than the material artefacts general layout or function. The use of precise technical characteristics does introduce limited symbolic language,

<sup>32</sup> Ontic relations are founded on the critical/social realist position on ontological realism. When a context is imaginary, the link to emergent causal mechanisms at the level of the real is potentially severed.

"The PRS must include a list of functional performance requirements and constraints. These should be clearly stated, with appropriate numerical values where pertinent."

but is interspersed with simple everyday language, for example

"have an easy to reach emergency button and control switches"

The primary relation in a real design is between performance criteria and cost, but none of the discursive tools introduced capture this relation, and consequently even though the FFBD capture some of the functional interdependencies, the task remains imaginary and dislocated from the primary real relations.

SG-(h): the PRS lists specific performance requirements, ostensibly relevant to a specific tool, but the severed inter relations between items, and the lack of detail about the solution organisational logic of the PRS suggest a conceptually organised solution rather than a contextually emergent product.

SD<sup>o</sup>-(h): although the tool prescribed is an intrinsically complex artefact, the PRS is merely an itemised list of key features with no reference to the interdependencies. And since the primary relation in a real design is between performance criteria and cost, but none of the discursive tools introduced capture this relation, the solution remains imaginary and dislocated from the primary real relations. The reference to potentially real functions and parts places it high in the very low category.

SD<sup>d</sup>-(l): The use of functional analysis tools and comparative performance characteristics introduces symbolic language, but each analytic tool is relatively simple and is used sequentially, although the solution does integrate the items from the three prior analyses, it does not introduce relations between them. This places the solution low in the weak category. In addition, the technical specifications draw on unspecialised understanding of the reference artefacts.

### M2: inferences:

Prior to collating the PRS, students are required to complete three systems design tasks. The functional architecture diagram (FAD) requires students to identify all the discrete functions performed by their assigned artefact, and cluster them based on functional logic. There is an expectation that students will examine existing examples of the artefact and use that as a basis for understanding the complex interacting functions inherent in the artefact. It is a shift from geometric logic of interacting parts to functional logic represented symbolically, a shift from complex ontic relations to simplified discrete discursive relations. The functional flow block diagrams (FFBD) develops the identified functions. It draws on the FAD, but reintroduces the ontic relations to some extent and increases the complexity of the symbolic representation slightly. The competitor analysis is a separate task, and explicitly refers students to three existing 'similar' artefacts. Students need to identify and list the key performance characteristics. Although real artefacts are the external referents, minimal understanding of the ontic relations is needed, rather the students merely catalogue the technical specifications in simple symbolic language. All the inferences involve simplifying the ontic relations and replacing them with simple, discrete symbolic representations.

SG+: All the inferences are based on translating specific parts and functions from example artefacts into a new more generic form, weakening the semantic gravity from a specific example to a typical performance specification.

SD<sup>o</sup>-(m): Although the result is a list of discrete performance requirements, the process of inference requires a limited understanding of the interdependencies of in a real artefact, but sequential consideration is probably adequate.

SD<sup>d</sup>-(l): The process of inference introduces simple system design tools (FFBD and FAD), which use formal symbolic forms to simplify and represent the ontic relations.

### M2: Recontextualisation

#### Classification:

The task is a mechanical design task intended to introduce students to the formal process of developing design requirements at the beginning of any design using systems design conceptual tools. But the scenario draws on everyday meanings in an imagined context, weakening the boundaries between the disciplinary knowledge recruited and everyday meanings.

Although the solution is reasonably convergent there is some limited scope for variation in the actual list of requirements "The ordering does not have to be sequential but the grouping of items must be logical,... If a student includes a requirement that doesn't come from the functional analysis, this should be queried".

#### Framing:

Although the disciplinary knowledge is explicitly selected and sequenced, the level of detail required of the artefact is unclear. The brief positions students as employees in an imaginary company, but this context sets up significant ambiguities, both in the social positioning of the students as both professionals and students, and in terms of what really matters from the context in terms of the solution. This suggests that the framing over the discursive relations is quite strong, while framing over the ontic relations is substantially weaker and consequently introduces ambiguity. The positioning the students as employees of a company, yet subject to pedagogic evaluation compounds this ambiguity.

+C: the disciplinary knowledge and solution are strongly classified, but the introduction of an everyday understanding of a professional context weakens the classification between specialised and everyday knowledge.

-F: The project initially appears to be very strongly framed because of the explicit prescription and sequence of the tasks. However, the imaginary context and potentially superficial reference to the artefact introduces a number of ambiguities, which are compounded by the ambiguous social relations. Both tend to weaken the framing of the task substantially.

**M3: Gearbox design**

**M3: Project description:**

The third project in the first design course requires students to design a two-stage gearbox to match particular input and output specifications. The gearbox includes three shafts, each mounted on two roller bearings and two pairs of helical cut spur gears, all housed in a casing. Students need to select the gear ratios, determine the loading in the system and design the gear teeth and shafts and select the bearings based on these loads. They need to consider assembly, precision location and load paths in the housing design.

**M3: Context (outer environment)**

The context is implicit and generic; a motor (specified by power and speed) drives a load (at a specified speed, and as potentially inducing 'moderate shock') that will operate indoors, from which the gearbox must have a "low noise output". The design brief thus reduces the outer environment to characteristics that have a direct bearing on the gearbox performance, rather than describing an environment or context. Rather than being emergent from contextual details, the context is reduced to discursively defined quantities that take the place of a real (material) context and provide the input variables for the design. Although conceptually imposed, they relate to and consequently define the context in precise (if discursive) terms.

The context is *simplified* to a list of discrete 4 technical specifications

SG-(h): No context is referenced, and like M1, the performance specifications are **imposed** on the task to meet the theoretical requirements of the problem rather than emerging from any context. But the additional implicit contextual reference to "low noise" and moderate shock, does strengthen the SG in this category (h).

SD<sup>o</sup>--(h): the context from which problem emerged, and the purpose to which the gearbox will be put has been stripped and replaced with discrete, apparently disconnected performance criteria.

There are only two pieces of contextual data provided that have material implications for the gearbox design - the ambient temperature means that the gearbox will heat up in operation and the bearing mounting will need to accommodate differential thermal expansion, and the "low noise output" suggests that the gears are helical cut gears. Both details are dislocated from relations to any real context, but do shift the task high in the very weak category

SD<sup>d</sup>-(m): The limited contextual detail provided is in simple but technical terminology, with precise conceptual meanings associated (the motor speed and power, the load characterisation). But each piece of information maps to a separate unrelated technical implication, and the terminology is quite basic, thus placing the context low in the weak category.

**M3: Artefact (inner environment)**

The requirements of the artefact are described in considerably more detail than the context, and the details take the form of both material and symbolic descriptors. The bulk of the details are listed sequentially, with little reference to relations between the various parts or concepts. There are however two exceptions that relate ideas and parts. The justification for designing the shafts on the basis of a deflection limit is given on the basis of conceptual relations: "As fatigue analysis is not covered [in this course], the shaft sizing must be such that the lateral deflection of any shaft at any gear may not exceed 0.08 mm. Stress calculations must be performed to verify that the assumptions for the deflection analysis are still valid" which refers to the theoretically defined relationship between fatigue, strength and deflection predictions. And more subtly, with reference to the way the material parts interact "The output shaft of the gearbox does not necessarily need to be co-axial with the input shaft, but the axes of the input and output shaft must lie in the same horizontal plane with as small a separation as possible" which suggest implications of the gear ratios and assembly requirements.

SG+(m): The brief prescribes the type of power transmission device (gearbox, with helical cut gears) that must be designed. Some variation is allowed in the layout of the gearbox, which positions in the middle of the category

SD<sup>o</sup>+(l): as described in the brief the interdependencies between the various components are organised sequentially, but there is an indication of important simultaneous interdependencies for example in the layout of the shafts, which has implications for the gear ratio choices and simultaneously has assembly implications. Although the links are not explicitly made, the descriptions carry the potential for a more complex understanding of the interactions, and hence the coding is low in the strong category.

SD<sup>d</sup>-(m): the technical terminology used in relation to detailing the artefact requirements carries more detail and more specialised symbolic meaning that that used to describe the context. However, even the links made between fatigue, stress and strain, the specifications can be read separately and used sequentially. Understanding the relations between the various specifications is not required.

**M3: Solution**

The solution consists of a number of fully dimensioned technical drawings and assembly instructions.

The outputs of the task are three technical drawings, a general assembly that lists all the parts and shows how they go together, detailed drawings of all manufactured parts and an elaboration of the process of assembly, together with a report that documents justifications for decisions made, and procedural calculations for sizing the various components.

SG++(m): The solution is the precise

SD<sup>o</sup>+(l): Because the layout is not

SD<sup>d</sup>-(h): the drawings are all in symbolic

<p>description of a gearbox designed to deliver a particular speed and transmit a particular power. The technical drawings provide precise and specific manufacturing and assembly instructions. Although the detailing results in a specific and precisely detailed gearbox, it is not an entirely unique solution, and one would expect similar solutions to emerge from this problem.</p>	<p>prescribed in the brief students need to show a solution that integrates geometric considerations (how the parts go together to perform the required function including speed regulation, gear meshing and load support, in conjunction with considerations of manufacturing and assembly), with the dimensions calculated simultaneously. However, the gearbox is never built and tested, and consequently the solution remains predictive based on only those aspects of the material relations that were identified as significant, it is never tested in the world. So it does not move into the very strong category.</p>	<p>language, but can be read as sequential representations. The detailing of the artefact draws on many procedural calculations that influence each other, with some guidance in the brief, but students need to draw on a deeper appreciation of the multiple procedures to hold the interdependencies together.</p>
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**M3: inferences (detailing the solution) - see also appendix 4:**

In order to get to the solution, multiple steps need to be taken, and some iteration between steps may prove necessary.

Firstly the **number of teeth** on each gear needs to be determined: in order for the input and output shafts to rotate in the same direction, a two stage gearbox is needed, because a gear pair reverses the direction of rotation of the shafts. To ease the assembly the input and output shafts need to be on the same horizontal plane, but if the gear pairs do not have the same number of teeth they will not be coaxial, using gear pairs with the same module (tooth size) and similar ratios will minimise the distance between the shaft axes. The ratio of gear teeth is the same as the ratio of shaft speeds, but because all gears have whole teeth, there are not infinite possibility gear ratios and consequently the shaft speed may not be the exactly required speed.

The second step is to determine the **gear forces** and size the width of the gear required to carry the forces developed. From the selected gear ratios and gear type (helical gears are effectively prescribed by the "low noise" requirement ostensibly emergent from the context of operation) in conjunction with the power transmitted and the rotational speeds, the forces acting on the gears and transmitted through the elements to the shaft and bearings can be calculated. Although prescribed in the brief, it results in a reasonably complex vector analysis that can then be used to determine the width of the gears needed to support the power transmitted. The calculations, although procedural, embed fatigue, stress analysis and strain limitations simultaneously. The only material consideration is that the direction of the helix chosen determines the direction of the axial load induced and has consequences for the selection of the position of the locating and floating bearing.

The **calculation of the gear width** is based on conceptual models of material performance. All the relevant material relations are defined in the brief, or condensed into the force calculations. The calculations used to determine the width of the gears needed to support the power transmitted, are procedural and sequential. Although they do embed fatigue, stress analysis and strain limitations simultaneously, no conceptual understanding of these interrelations are actually required to perform the calculations.

The **layout** of the bearings and gears on shafts depends on the direction of the gear forces as well as assembly and manufacturing considerations. Each shaft requires one locating and one floating bearing. The direction of the axial load determines which bearing should be locating (locate the shaft in place axially) and floating (allow the shaft some axial movement to accommodate any thermal expansion). Raised shoulders on the shaft function to locate the bearings on the shaft, but the position of the shoulders may be restricted by assembly considerations. The width of the seats is determined by the width of each component seated on the shafts.

The design of the **housing** is a geometric puzzle that includes a casing that can house all the gearbox parts, locate them precisely as intended for operation, and allow assembly (and disassembly) of the component parts into an assembled whole.

The **diameters** of the various shaft sections are determined from the interaction between the forces transmitted from the gears, the location of the forces which depend on the lengths of the various shaft sections and the material used for the shaft. The process of designing the shafts involves in iterative process of checking shaft sizes in a complex three dimensional vector system, selection of appropriate two dimensional systems in which to do the deflection and strength calculations, the use of principle of superposition to determine the resultant three dimensional stress and deflections, and a check on the tested shaft size.

The **selection of appropriate bearings** depends on the resultant gear forces and the shaft geometry. The principles of selection are the same as for M1, but this time the forces are as a result of real material interactions rather than just prescribed, and the geometric interactions are more complex, because the shaft size needs to first be determined from strength and deflection calculations, and the assembly considerations are real and therefore more complex.

There are multiple simultaneous interdependencies that are likely to result in iterative calculations and interdependent decisions. These in turn are likely to result in divergent solution possibilities.

<p>1 SG+: although this is a movement towards specifying the gears, it is still at the level of a generic type.</p>	<p>SD<sup>o</sup>+(I): the determination of the gear teeth requires the simultaneous consideration of the way that gears operate to control shaft speeds, the relation between gear diameter, tooth size (module) and shaft layout, considerations of assembly, and judgement of an</p>	<p>SD<sup>d</sup>-(I): the determination of the gear teeth requires a simple multiplication of two ratios, in order to achieve a particular shaft speed output. It is the operationalizing of a single simple ratio calculation very low in the weak category).</p>
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<p>2 SG-: the determination of the gear forces is a shift away from contextual particulars into a representational form that can transcend contexts, even though it represents the context from which it was developed. This general representation is used to specify the width of the gears required to transmit the load without breaking, and is also used to specify the shaft and bearing sizes.</p>	<p>adequate speed match. SD<sup>o</sup>-(l): The type of gear required for "low noise" introduces an axial load in the system as a result of the helical angle, but this is define along with the pressure angle for the gear teeth prescribed. Although the geometry of the gear (diameter, module, tooth shape and number) are what determine the forces, the actual calculations are conceptually defined and the only material consideration is that the direction of the helix chosen determines the direction of the axial load induced and has consequences for the selection of the position of the locating and floating bearing. This positions it very low on the weak category.</p>	<p>SD<sup>d</sup>+(l): The determination of the gear forces depends on the gear ratios chosen in the previous step, along with the power and speed involved, and the gear geometry. Although this is prescribed in the brief, it results in a reasonably complex vector analysis and representation</p>
<p>3 SG++: the sizing of the gear width to carry the required load is a process of specifying a particular dimension of the gears to be used.</p>	<p>SD<sup>o</sup>-(h): Although based on models and tests of gear strength and failure, in order to determine the width of the gear required to transmit the required load, a procedural calculation can be used without understanding the material relations. The specified safety factor, and no need for standard sizes means that no conceptualisation of the material relations is needed for this step, although 'sensible' precision and tolerancing on the dimension might be considered a limited material consideration.</p>	<p>SD<sup>d</sup>-(m): The calculations used to determine the width of the gears needed to support the power transmitted, are procedural and sequential. Although they do embed fatigue, stress analysis and strain limitations simultaneously, no conceptual understanding of these interrelations are actually required to perform the calculations.</p>
<p>4 SG++: the layout of the gears, shafts and bearings within the housing is also a step in defining the specific layout for this gearbox.</p>	<p>SD<sup>o</sup>+(h): Planning the layout of the gears, bearings and shafts within a housing that needs to both support the elements under load and allow for assembly of the individual components is an exercise in visualising the various components and the load paths. The bearing and shaft layout and geometry depends on the gear forces and assembly considerations. Each shaft requires one locating and one floating (to allow differential thermal expansion) bearing. The interaction between the direction of the axial load can lead to modifications in the direction of the gear loading. This is very high in the strong category.</p>	<p>SD<sup>d</sup>-(h): the layout is represented in technical drawing conventions, which assists with the visualisation. While each element has a symbolic representation, and the linework carries geometric meaning, the symbolic representations can be read sequentially. And because of the complexity of the visualisation, and the number of components required, it is relatively high in the weak category.</p>
<p>5 SG++: The shaft design involves defining the specific dimensions of each of the shafts</p>	<p>SD<sup>o</sup>+(l): The shaft design does require some consideration of the geometric relations with the various elements including consideration of assembly and axial location. Students also need to manage the relations between the various theoretical calculations and interpret the results in relation to each other and the material consequences. That places this in the strong category, but the relations are relatively straightforward, and consequently low in the category.</p>	<p>SD<sup>o</sup>+(l): The shaft design involves complex theoretical calculations based on the loading to predict deflection and strength. The calculations draw on vector representations, complex stress and strain analysis, and require a relatively high level of conceptual understanding to complete competently. This is very high in the strong category.</p>
<p>6 SG++: bearing selection is a process of specifying a particular bearing to carry the required load and fit the shaft and space available in the housing</p>	<p>SD<sup>o</sup>+(m): Consideration of the space available and the directions of the loading is required in the specification of the bearings, and it is dependent on the</p>	<p>SD<sup>d</sup>-(m): The calculations used to determine the appropriate bearings are procedural and sequential. Although they do embed tribology, probability and</p>

	forces transmitted from the gears. Locating and assembling the bearings requires far more consideration than in M1 because of the additional interacting components.	strength principles simultaneously, no conceptual understanding of these interrelations are actually required to perform the calculations.
<b>M3: Recontextualisation</b>		
<b>Classification:</b> The task is a standard gearbox design task typical of an intermediate mechanical engineering design. Although it integrates knowledge from other disciplines, these can be considered standard design calculations. The integration of a large number of parts allows for some divergence in the details of the solution.		<b>Framing:</b> The brief provides clear instruction on what knowledge and procedures to use and indicates a sequence. But within this sequence, are minor sequencing choices that the students need to make. The exclusion of any context or role play as professionals avoids potential ambiguity.
+C: the project is couched in specialised technical terms, without reference to everyday meanings. Even the less technical aspects need to be read in specialised discourse. The project includes many routine design calculations, but the integration of different element selection procedures strict technical drawing requirements and technical reporting requirements weaken the classification of the project somewhat. Because of the number of elements integrated into the solution, and the slight weakening of the framing on the sequence of the design, there is some scope for divergent solutions, although quite minimal.		+F: Selection and sequence of knowledge are defined although the minor sequencing decisions that students can make weakens the framing very slightly. The requirements for the solution are explicit. The lack of context, with its associated ambiguous social positioning is avoided in this task.

#### **M4: Wheel support assembly**

<b>M4: Project description:</b> In the first project in the second design course students are provided an exploded assembly drawing of a wheel and support assembly in imperial units. They are required to convert the units to SI units, scale the various components and then modify the dimensions to meet standard sizes, and produce CAD drawings of the modified assembly and parts including tolerancing and manufacturing instructions on the drawings.		
<b>M4: Context (outer environment)</b> No context is provided nor are any contextual details required.		
SG--(v1): The project completely <b>transcends</b> any contextual reference.	SD <sup>o</sup> --(v1): No engagement with or understanding of any context is required.	SD <sup>d</sup> --(v1): No description of any context is required or provided.
<b>M4: Artefact (inner environment)</b> The artefact is fully detailed in an exploded assembly drawing, with dimensions provided in imperial units. Although it has a number of geometrically interacting parts, it is a relatively simple artefact with no consideration of function or strength required. Reading the drawing requires familiarity with manufacturing processes, materials selection and tolerancing principles.		
SG++(m): A specific configuration of a wheel assembly is provided in detail	SD <sup>o</sup> -(l): The wheel assembly is composed of a small number of interacting parts performing a very simple function. Some familiarity with manufacturing processes, materials selection and tolerancing principles is needed to understand the drawing.	SD <sup>d</sup> -(l): The wheel assembly is presented in formal technical language with reference to manufacturing processes. But the references can be treated as simple sequences.
<b>M4: solution:</b> The solution is presented as fully dimensioned assembly and parts drawings. The solution includes additional detail based on scaling and then selection of standard sizes and details of machining and tolerancing details in specialised symbolic language. The solutions therefore adds detail and presents it in symbolic form. The machining and tolerancing instructions are far more complex than those provided in the initial drawing. The result is a very precise technical specification in symbolic form of standard manufacturing instructions. Although the solution is the result of integrating scaling, standardisation and manufacturing process knowledge, this is not necessarily evident in the solution.		
SG++(h): The solution details a specific configuration of the wheel assembly in more detail than presented in the brief	SD <sup>o</sup> -(l): Although there are changes in the various sizes of the components, the solution is essentially at the same level of detail and complexity as the artefact presented in the brief.	SD <sup>d</sup> -(l): The wheel assembly is presented in formal technical language with reference to manufacturing processes and associated tolerancing. But since it is merely a modification to the drawing provided in the brief it is low in the category.
<b>M4: inferences (detailing the solution):</b> The task is largely dependent on geometric compatibility and visualisation. Limited consideration of the potential function is required to specify the fits between parts (whether there is a tight friction fit or the need for relative slippage). This also requires		

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familiarity with standard fits and the simple calculations required to specify the consequent dimensional tolerance. Simultaneously manufacturing processes need to be considered as there are links between tolerancing and manufacturing techniques. Technical drawing is a very precise symbolic language that integrates dimensional and manufacturing instructions with precision.		
SG+: The inferences tend to require consideration of more general processes and options beyond the particular, so indicate a weakening of the semantic gravity.	SD <sup>0+</sup> (v1): in order to finalise dimensions, simultaneous consideration of geometric compatibility in relation to standard sizes is required. Tolerance specification requires simultaneous consideration of geometric compatibility, function and manufacturing process.	SD <sup>d-</sup> (l): Finalising the dimensions involves a simple sequence of unit conversion, scaling and a consideration of the ontic relations.
<b>M4: Recontextualisation</b>		
<b>Classification:</b> This is a standard machine design task that integrates technical drawing skills and conventions with insight in manufacturing processes and dimensional tolerancing. There is not expectation of everyday knowledge and the solution is relatively convergent, although judgement about standard sizing imposed on the scaling opens up room for some variation in solutions.		<b>Framing:</b> The instructions are clear about the use of standard drawing conventions, the use scaling and conversion from imperial to standard metric sizes. The tolerancing decisions and their relation to manufacturing processes are more implicit, and are potentially problematic for the evaluative criteria. There are no ambiguities in the positioning of students and they are given precise formatting instruction.
++C: The specialised knowledge is defined by mechanical design, no recourse to everyday understandings is expected and the solution is mostly convergent		++F: The knowledge requirements are explicit, the sequence of operations is short and straightforward, the evaluative criteria are explicit and there are no ambiguities in the social relations.

**M5: Multi-tool**

<b>M5: Project description:</b> The second project in the second design course is the conceptual design and drawing of a multi-tool for an imaginary market.		
<b>M5: Context (outer environment)</b> No explicit context is given, however the multi-tool is implicitly positioned as a product competing in an existing market. It seems that students are expected to imagine a competitive product, possibly aimed at the cyclist market. In reality this would suggest that pricing (and associated material and manufacturing costs) is the primary material relation, and that aesthetics is a very significant aspect. However costing is not actually a formal part of the assessment "Although the cost does not need to be calculated the expense of the design needs to be kept to a minimum where possible." And even though the brief states that " Extra marks will be considered for aesthetically pleasing and thought out designs" nothing indicates what aesthetically pleasing may be. The context is <i>imaginary</i> .		
SG--(h): The context is imaginary and generic, although there was the potential to refer to a type of market and producer (SG+), the dislocation from any need to understand a real context dislocates meaning from real mechanisms, resulting the the potential to <b>transcend</b> the real mechanisms operating in any context. However, students do need to imagine multiple ideas about the imaginary context, which places it high in the category	SD <sup>0--</sup> (h): The imaginary context, although potentially a complex interaction of market forces, consumer choices, manufacturing opportunities (SD <sup>0++</sup> ), is instead simplified to a dislocated set of imaginary ideas, severed from relation to any real context. The expectation to make multiple assumptions does place it high in the category.	SD <sup>d--</sup> (l): The imaginary market is understood in unspecialised ways, there are no criteria referred to for aesthetic judgements.
<b>M5: Artefact (inner environment)</b> The prescribed artefact is a generic 'multi-tool'. It consists of a number of specified 'tools' that fold away into a portable penknife type device. It is described in terms of convenience and portability, both relatively common sense ideas.		
SG+(m): The prescribed device is a type of portable tool. The prescription of some tools that must be included is balanced with some discretion around tool selection, and layout	SD <sup>0-</sup> (l): The prescribed artefact is a set of small tools that fold away into a portable penknife type device. Only the geometric requirements for folding and unfolding have any real impact on the design.	SD <sup>d--</sup> (h): The required tools are named and carry very limited specialisation, but most concepts are introduced as unspecialised conceptualisations.
<b>M5: solution:</b> The solution consists of three parts, a sales pitch description of the tool, without recourse to any specialised knowledge, two pages of CAD drawings of the tool in various views and configurations, including Bill of Materials, and a page of pencil sketches illustrating the initial development of the concept. The CAD drawing seems to focus on CAD skills and drawing conventions. The design aspect seems to be limited to the geometric configurations and 'packing' visualisation. However, implicit in the Bill of Materials is some consideration of manufacturing processes in terms of materials selection.		
SG++(m): The drawings describe the conceived tool in specific dimensional	SD <sup>0-</sup> (l): The significant ontic relations are restricted to visualising the geometric	SD <sup>d-</sup> (l): The formal presentation of the solution in technical drawings is

and material detail. But the detail is mostly conceptual, even in the drawings.	packing, a list of material choices with loose links to manufacturing processes. The other ontic relations, cost, aesthetics and convenience are imaginary and dislocated, weakening the SD in the category.	specialised, but the associated sales pitch and reference to aesthetics is unspecialised and weakens the semantic density of the discursive relations significantly. The solution is developed from imaginary and unspecialised knowledge in relation to a potential client.
<p><b>M5: inferences (detailing the solution):</b> It seems students need to imagine a marketable product with no formal marketing or costing tools, leaving the inferences as intuitive rather than specialised. In terms of the concept development there is no evidence of formal idea generation techniques nor formal comparisons with existing tools, again the inferences are intuitive and unspecialised. Rather we see an implicit association with cyclists' needs from the brief (which puts non-cyclist students at some sort of disadvantage). The only significant inferential reasoning required relates to the visualisation of the geometric compatibility between parts, assisted by the CAD modelling required. The only specialised knowledge relates to technical drawing conventions and the skills to operate the CAD program.</p>		
SG++: The inferential process does take the generic tool to specific detail.	<p>SD<sup>o</sup>-(1): Although the visualisation and geometric compatibility requirements require simultaneous geometric visualisation, the dislocated ontic relations in relation to cost and aesthetics weakens the semantic density considerably.</p> <p>As prescribed the tool supposed to take into account common sense conceptualisations of cost, convenience, and aesthetics, but the imaginary nature of the artefact dislocates these ideas from each other.</p>	SD <sup>d</sup> -(1): Technical drawing skills and knowledge are required, but beyond that most of the inferences are unspecialised imaginary and intuitive. There are also no formal ideation techniques introduced.
<p><b>M5: Recontextualisation</b></p>		
<p><b>Classification:</b> The project draws strongly on common sense understandings of a potential tool in terms of costing and market potential. Other than formal drawing conventions, there seems to be little requirement for specialised disciplines. The solution is reasonably divergent, although the brief does seem to hint at aspects that would be desired.</p>	<p><b>Framing:</b> The written text positions students in an ambiguous position, there is a mixture of 'pitching to investors', and illustration the concept to "bosses / prospective buyers". It seems to be a marketing rather than technical piece. The CAD modelling and drawing requirements are clear and explicit, and appear to be the focus of evaluation. However, the ambiguity of the external context, the implicit and common sense way in which students recruit marketing, costing and aesthetic elements and the positioning of students expected to draw on other expertise potentially confuses the task by bringing in imaginary and extraneous elements that appear not to be formally evaluated despite the reference in the brief.</p>	
<p>--C: The limited recourse to specialised knowledge, relatively divergent solutions make this project very weakly classified</p>	<p>-F: The CAD modelling and drawing requirements are strongly framed, but the centrality of the ambiguous context and the common sense elements opens up the use of unspecified, unspecialised knowledge. Social positioning further weakens the framing of the evaluative criteria</p>	

### M6 CCTV tower

<p><b>M6: Project description:</b> The third project in the design second course is the conceptual design and partial detailing of a 10m tower to mount a 50kg CCTV camera. The design involves conceptualising the tower configuration and detailing the bolt and weld strengths and checking the tower for bending and buckling strength under wind loading and the static payload.</p>
<p><b>M6: Context (outer environment)</b> 50 CCTV camera towers are to be erected in Cape Town, and wind loading is defined as an important consideration along with the given payload on top of the tower. But the specific location in Cape Town and the actual wind conditions in that area are not specified. The solution indicates a number of further contextual factors that students are expected to extract independently. Security for the cameras is important; manufacturing should take into account that the coastal region has aggressive environmental conditions; and aspects of construction need to take into account transporting the structure and on-site assembly. These contextual aspects need to be identified by the students.</p>

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The context is <i>real</i> , although also has characteristics of a simplified context.		
SG+(m): The context is specified broadly as Cape Town, but specific locations within Cape Town with their associated ambient conditions and security are generalised across the whole region, but by referencing a <b>regional</b> context, students can potentially access real contextual details.	SD <sup>o</sup> -(m): From the context students need to recognise security as an issue, dealt with in unspecialised ways; and the influence of the coastal environment for material choices and the influence of wind on the loading specialised for structural analysis. These contextual factors can be treated sequentially.	SD <sup>d</sup> -(m): Most contextual factors are in unspecialised form, except the reference to the importance of wind loading and the need to source technical data on wind loading which signals specialisation, and affects all the strength calculations, which raises it in the category.
<b>M6: Artefact (inner environment)</b> The artefact is a 10 tower (without external supports) with a 250mm platform to support a 50kg payload, bolted to a 1m <sup>2</sup> base. But the specific form of the tower is left to the students to design. Although a relatively simple artefact, the design requires consideration of strength and fatigue in the sizing bolted joints and welds, and buckling and bending of the tower. These details increase the relevant ontic density and associated discursive density.		
SG+(m): As prescribed in the brief the artefact is a 10 m tower required to support a 50kg payload under wind conditions. Although the specific configuration and dimensions of the tower are not specified, there is considerable constraint to the concept, placing it in the middle of the category.	SD <sup>o</sup> -(h): The material relation between the wind loading and the conceptual structure of the tower influences the bolt, weld and tower dimensions interdependently, although they can be dealt with sequentially.	SD <sup>d</sup> -(h): The reference to weld, bolt and tower design, and the need to consider both static loading and fatigue life signal discrete specialised procedures, which can be dealt with sequentially.
<b>M6: solution</b> The solution consists of conceptual sketches of three concepts, CAD drawings detailing the selected concept including dimensions and bolt and weld detailing, and a report documenting the main strength calculations (buckling, bending, weld and bolt). The solution is presented in symbolic format (drawings and calculations) laced with common sense or everyday interpretations. Although the input values for the strength calculations are read from the interaction between the context and the artefact, that the artefact is never built and inserted back into the context, the approximations are only evaluated discursively and are never tested in the world.		
SG++(h): The solution involved adding specificity to the generic tower. The configuration, bolt and weld sizes as well as cross sectional dimensions are given in the solution. Each solution has scope for some individuality, coding high in the category	SD <sup>o</sup> -(m): The solution is a drawing of a simple structure with details of the dimensions of the various connections bolt and welds which can be read sequentially.	SD <sup>d</sup> -(h): The solution represents the output of the multiple procedural calculations under limited guidance in the brief. The solution simplifies these into precise sequential technical details.
<b>M6: inferences (detailing the solution):</b> Significant and complex inferences between the context and the artefact to approximate the form and magnitude of the loading on the proposed artefact which provides the basis of the detailing in the form of strength calculations. Once the loads have been determined, students conduct procedural calculations in order to determine minimum part dimensions required to sustain the loads. The various element dimensions have minimal effect on the other dimensions. There is also an expectation that once sized, the closest appropriate standard size would be selected, this is a shift from discursive to ontic relations.		
SG++: The inferences specialise the generic type of tower to a particular version, strengthening the semantic gravity.	SD <sup>o</sup> -(l): The various mechanical elements do not impact one another and the ontic relations can be treated sequentially.	SD <sup>d</sup> -(h): The contextual details of wind loading need to be quantified to provide discursive input for the procedural design calculations, but the impact of each of the designed elements does not impact the others, so the discursive relations can be treated sequentially.
<b>M6: Recontextualisation</b>		
<b>Classification:</b> Although different CCTV tower configurations are possible, the solution is relatively constrained because the considerations are restricted to designing the machine elements only. The specialised knowledge required tends to be procedural sizing calculations, along with some material stress analysis. There is some expectation of integrating specialised knowledge with an everyday understanding of the context.	<b>Framing:</b> By defining what aspects of the tower need to be analysed, the task frames the specialised knowledge strongly. Although the sequence of calculations is not defined, there is limited interdependence between the various structural elements once the loading has been quantified and so it does not matter. But the weakly classified context forces some ambiguity into the evaluative criteria.	
+C: The relatively strong framing of the knowledge tends to strengthen the classification by restricting the solution options and defining the specialised knowledge required, but the everyday understanding of the solution and the ambiguity of how to work with it, simultaneously weakens the classification.	+F: Although the knowledge selection is strongly framed, and the social relations retain reasonably strong framing, the weak classification of the context weakens the framing somewhat, especially in relation to the evaluative criteria	

**M7: Multitask micro machine****M7: Project description:**

The third design course encompasses a single large design of a micro machining device that incorporates multiple micro machining operations. The device is designed in relation to imaginary clients with imaginary machining processes. It is essentially a product design project.

**M7: Context (outer environment)**

Students are required to design a multitasking micro machining device.

"... Choose a hypothetical client and application."

"it is important to minimise the handling from machine to machine, process to process, and therefore the need has arisen to develop a multi tasking micro machine that integrates the various micro-machining processes and evolve a unique machine that meets the major requirements."

The implication is that the artefact needs to improve the performance an imaginary chain of micro machining operations for an imaginary client. The context therefore refers to an everyday, unspecialised understanding of a professional machine shop. The context also implies the introduction of an artefact competitive to similar artefacts available in the market.

Although intended to refer to real machine shops, the imaginary client and processes introduce many *imaginary* aspects of the context.

SG--(h): The context is intended to reference generic ideas about typical precision machining shops (SG+), but the hypothetical client and imaginary machining processes on which the design is based have no necessary relation to a real context and leave the imaginary context potentially **unrelated** to reality.

SD<sup>0</sup>--(h): The hypothetical client and imaginary chain of micromachining operations process forms the basis of the ontic relations of the context. Although the intension is to draw on generic understandings of a professional machine shop (SG+) and a specific manufacturing process (SG++), the imaginary nature of the context potentially dislocates the ideas from any real reference.

SD<sup>d</sup>--(h): The imaginary context sets up contradictory discursive relations. The intension to draw on specialised knowledge of manufacturing terms (SD<sup>d</sup>-) contradicts with generic understandings in unspecialised terms of professional workplaces (SD<sup>d</sup>--). Although the reference to technical manufacturing process does raise the semantic density in the very weak category.

**M7: Artefact (inner environment)**

The prescribed artefact is an inherently complex artefact, integrating mechanical and electrical components to perform complex precision tasks.:

"most of the miniature engineering components require multiple features which are to be processed using different processing mechanisms like Micro-Electro Discharge Machining (mEDM) Micro-turning, Micro-Electro Discharge grinding (mEDG) and Micro-milling. As the micro component as well as the micro-feature size are small (0.05~0.5mm), it is important to minimise the handling from machine to machine, process to process, and therefore the need has arisen to develop a multi tasking micro machine that integrates the various micro-machining processes ... featured with several micro-machining modules, including: a drive unit for different processes, indexing head, online imaging system (optional) CNC control and ultrasonic actuations (optional). ... mounted on the table. A coupling with precision indexing ... on the indexing head that houses six different stations.... ." [M7b1]

Students are expected to refer to examples of similar actual machines as a basis for their design, and the solution is the specification of a potentially real machine.

SG+(l): The brief prescribes a type of machine and lists the sorts of operations that could be considered, which does allow some discretion in the selection of processes. There is reference made to examples of similar machines supplementary to the brief, but as with M2, students are potentially left to reference only their conceptions of such a machine. The difference is that students need to engage in far more detail than in M2, but those details offer a range of divergent options, which places it low the category.

SD<sup>0</sup>++(l): The artefact is extremely complex, requiring the integration of multiple manufacturing processes into a single unit, including mounting miniature components to a very high level of precision, controlling the various processes, and taking into consideration responses to processing such as cutting depth and speed. The significant aspects of the machine are not identified. But the listed potential processing components weaken the SD<sup>0</sup> in the category. However the imaginary nature of the sequence of processes that the machine is required to perform for an imaginary client potentially undermines the ontic basis of the machine, and consequently potentially severs the ontic relations from any real referent (SD<sup>0</sup>--)

SD<sup>0</sup>-(h): The artefact is inherently complex, and the very open specification in the brief, which does not provide much guidance, suggest that students will need to draw on insights from multiple disciplines to develop the artefact (SD<sup>d</sup>++). However there is some ambiguity and when reviewed in relation to the solution; there are indication that in fact quite limited specialised insights were needed (SD<sup>0</sup>-). This consequence for the requirements of understanding arises from the conflicting framing, a complex artefact with weak framing over most aspects and not enough time allocated in the course to manage the complexity without stronger framing.

**M7: solution**

The solution consists of a collection of technical drawing of the whole system and various subsystems and parts and a list of procured items using technical descriptions.

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<p>The project is done in teams and each student submits their contribution to the project. Although the solution includes an assembly and bill of materials for the full machine, each student details different parts of the machine and consequently the solution appears somewhat fragmented. Further, the complexity of the machine and the limitations of student time result is somewhat fragmented justification based on apparently arbitrarily selected analyses, often selected to show proficiency with a particular conceptual tool or technique rather than a proof of the product. It appears that the impact of the significant but imaginary context dislocates the project from real influences and fragments the solution.</p>		
<p>SG++(l): The solution is intended to specify particular aspects of the final configuration of the machine, but the magnitude and complexity of the design appear beyond the scope of time available and consequently many aspects are left under/unspecified, so while each student produces a specific solution, it is coded low in the category.</p>	<p>SD<sup>o</sup>-(h): Although the drawings present a complete assembly of the product, designed fully from conceptualisation by the students and so potentially SD<sup>o</sup>+ the fragmented nature of the analyses that precede the drawings (sequential and partial) raise doubt over the adequacy of the material product, and the compatibility of the pieces that make up the whole.</p>	<p>SD<sup>d</sup>-(h): The drawings are complex and represent a very complex machine, based on a sequence of symbolic analyses, integrated into the final drawing.</p>
<p><b>M7: inferences (detailing the solution):</b>                  The design task is broken into 4 assignments, followed by a review and integrated submission of the four preceding tasks. The first task involves developing the imaginary context,                    "State the hypothetical problem that your customer is experiencing and identify their needs to resolve the same. Illustrate the customer's problem using sketches and indicate the present status in terms of: production cycle time or cost or any other tangible output." [M7:A1].                    Based on this context students develop an understanding of their product requirement using system design tools. The second task involved developing diverse concepts and using design tools to modify combine and evaluate aspects of the concepts, along with project planning tools. The third task focuses on the analytical modelling of performance of the parts of the system/subsystems of the artefact. This includes integrating existing subsystems as units identified in external websites into the machine, reducing some of the analytic demand of the project. The fourth task includes a cost analysis and technical drawings of the artefact. It appears that the impact of the significant but imaginary context dislocates the project from real influences and fragments the inferential chains resulting in a fragmented solution.</p>		
<p>SG-: The inferences cover a range of semantic gravity, but the imaginary nature of the context and the huge complexity of the artefact seem to result in a dominance of weak semantic gravity, where students apply theoretical constructs to aspects of the artefact, or organise their design and develop concepts using design and systems conceptual tools, to demonstrate proficiency with conceptual tools, rather than allowing the artefact requirements to drive the inferences.</p>	<p>SD<sup>o</sup>--(h): Although it is clearly intended that students use design techniques to identify significant material relations, extract them from the complexity of the artefact/context in order to model performance discursively, a number of aspects militate against rooting the inferences in the real artefact (imaginary context, extremely complex artefact beyond the scope of a course) and leave the reasoning quite dislocated from the real material relations and interdependencies.</p>	<p>SD<sup>d</sup>-(h): The inferences appear to be driven by the need to show proficiency in a sequence of design techniques imposed on the design problem. Although the intension is clearly to develop interdependencies integral to design of complex artefacts, a number of aspects militate against simultaneous interdependency (imaginary context, extremely complex artefact beyond the scope of a course) and leave the reasoning sequential and in some cases even disconnected.</p>
<p><b>M7: Recontextualisation</b></p>		
<p><b>Classification:</b>                  The project introduces product design concepts applied to the design of an extremely complex artefact. It draws on multiple disciplines (design, mechanics, costing) and relates to an imaginary machine process for an imaginary client, which results in a huge diversity of potential solutions</p>	<p><b>Framing:</b>                  The sequence of tasks do to some extent define some of the conceptual knowledge required, but the analytical tools depend on the part/s each student selects to detail and their reading of what knowledge is relevant to that part. The magnitude of the artefact results in students selecting parts to design and neglecting other parts with no clear criteria for what to focus on and what to ignore. This comes in part from positioning students are professionals, responsible for both reading the material details and deciding what to prioritise, and partly from the ambiguous evaluative criteria.</p>	
<p>--C: The knowledge is multidisciplinary and draws on the everyday, and the solutions are divergent, all features of weak classification</p>	<p>--F: Although the sequence of defined tasks would suggest some strength in framing, The very ambiguous social relations and evaluative criteria weaken the framing over selection and sequencing resulting in a very weakly framed task</p>	

**M8 Power plant specification**

**M8: Project description:**

The final design course requires the development of a user requirement specification for a single unit coal fired power plant based on the simplified Rankine cycle. The design includes sizing the main components and material flow rates and specifying aspects of risk assessment, interface control and documentation. It is essentially a systems design project

**M8: Context (outer environment)**

The context is imaginary and lacks any contextual detail. What detail is provided is done so to justify limitations on the artefact, but are explicitly prescribed in the brief.

"The Republic of Rainbows plans an extensive expansion of its electricity supply network. It has decided to construct a number of single unit coal fired power plants at locations close to where the power is required. The generation capacity of each unit depends on its location, but all of them will be supplied by the same coal mine, and will have similar site specifics.... The sites where the plants will be located will have limited water supply, but not sufficient to use as final heat sink, therefore the atmosphere must be used. "

But the technical specifications deemed relevant to the design (thermodynamic properties of the ambient conditions) are provided in precise and certain discursive form without contextual justification

"Site metrological data

The following information is valid for the proposed sites where the power plant units will be constructed.

- Ambient air dry-bulb temperature  $T_{db}=25^{\circ}C$
- Ambient average relative humidity  $RH=10\%$
- Atmospheric pressure  $P_{atm}=101.3kPa$

See the next page for Psychometric information

The saturation enthalpy vs temperature of moist air can be approximated by the following relationship:

$$h_s(T)=C_3.T^3+C_2.T^2+C_1.T +C_0 \dots "$$

The limited contextual descriptions do not require interpretation or abstraction for the design.

Although the context is imaginary, the significant contextual issues are provided in a constellation of technical specifications, mimicking a *simplified* context.

SG-(h): Although the context appears imaginary, there is no necessity to consider the context, instead all necessary contextual details are given in theoretical terms which **impose** the necessary information on a relatively generic context.

SD<sup>o</sup>--(h): No engagement with or understanding of the context is required. The material relations of the context have been simplified to the ambient conditions and the restricted water supply, two elements, independent of each other and presented as certain, absolute and as isolated facts without relations to any other aspects.

SD<sup>d</sup>+(l): The ambient conditions are provided in symbolic form, and within the specialised field of thermodynamics relate to a range of implications for the power plant performance. The information also functions to signal the relevant specialised discipline, which in turn implies rules of relevance and evidence. The contextual specification signals a far more complex set of relations that might first be assumed.

**M8: Artefact (inner environment):**

The prescribed artefact is extremely complex with multiple subsystems and parts all interacting simultaneously and interdependently. But in the brief and accompanying documentation the significant material relations and theoretical concerns are identified.

"All power plants must be based on a simple Rankine water-steam cycle, using coal as fuel. The maximum pressure and temperature must be comparable to typical subcritical steam plants. Other equipment such as coal mills, boilers, steam parts etc. must be of similar technology as employed elsewhere in the republic."

"... a typical process diagram of a convectional coal fired power plant, as well as the simplified one to be used for this exercise. The boiler is called a subcritical, once through, tower-type steam generator.

The major differences are:

- No economizer, water needs to be heated to boiling point and evaporated in the water wall.
- No feedwater heaters, thus only one pump.
- No reheater, thus no Intermediate Pressure (IP) turbine.
- The superheater will be much larger than normal to extract maximum heat from the flue gas." (SNHL:3)

The process of recontextualising a coal fired power plant substantially simplifies the plant. The process diagram above helps to identify and separate significant interdependencies. Coal is delivered to the boiler and burned, the amount determines the heat in the boiler, which in turn, in conjunction with the amount of air, determines the air temperature. Cold water entering the water wall is being heated by the fireball, which is simultaneously heating the air passing through the furnace. Once the air and water enter the superheater at particular temperatures and the heated air further heats the water, depending on their relative temperatures.

But the supplementary notes provide procedural descriptions, in discursive form that reduces the complexity to a sequence of procedural calculations.

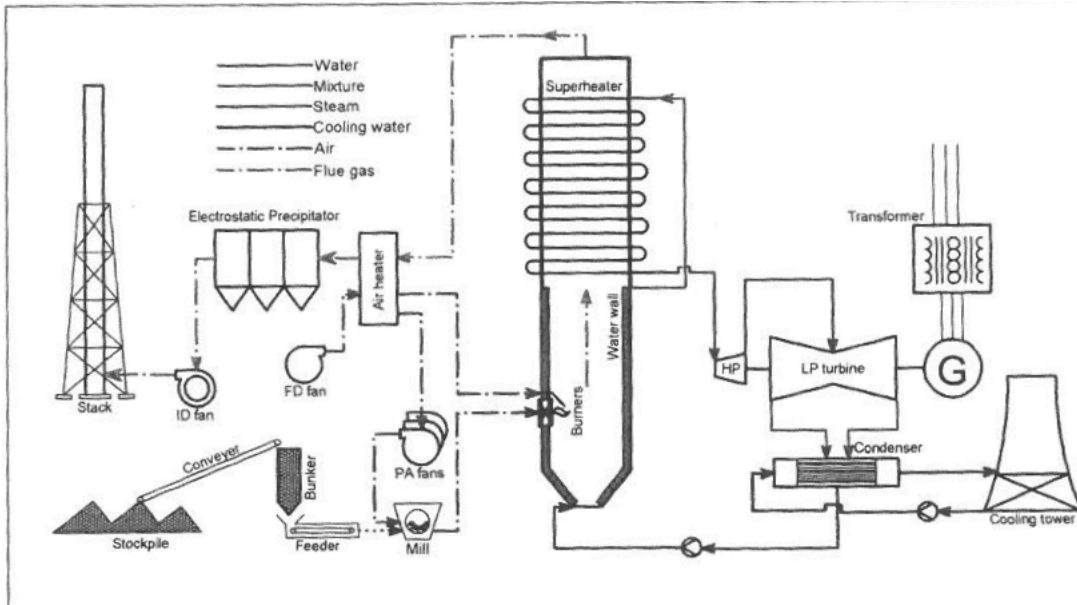


Figure 2: Simplified plant process diagram.

SG+(h): The diagram and text describe a **type** of power plant (simple Rankine water-steam cycle, using coal as fuel) rather than any specific power plant. However there is no discretion in the subsystem types, only the operating parameters and dimensions required to achieve those conditions are left to be determined, placing it high in the category

SD<sup>0</sup>+(l): the process drawing **separates** the power plant into constituent components (boiler, turbine, cooling tower etc.) and three material streams (fuel, air and water), while retaining the **simultaneous interdependency** between the parts and the material flow streams. Coal is delivered to the boiler and burned, the amount determines the heat in the boiler, which in turn, in conjunction with the amount of air, determines the air temperature. Cold water entering the water wall is being heated by the fireball, which is simultaneously heating the air passing through the furnace. Once the air and water enter the superheater at particular temperatures and the heated air further heats the water, depending on their relative temperatures. This describes only a part of the extremely complex system, in which multiple real processes interact **interdependently**, but the process diagram functions to **identify** significant parts and eliminate others.

SD<sup>d</sup>-(h): very complex specialised knowledge is drawn from multiple disciplinary specialisations (electromagnetism, thermodynamics, heat transfer and mass balances) is required to develop the operating parameters and detail the solution of this plant (SD<sup>d++</sup>). But the recontextualisation presented in the accompanying supplementary notes **identifies** and **separates** these interdependencies to the point where each symbol can be read **sequentially** and the analysis can be followed in a step-by-step procedure without necessarily appreciating the complex disciplinary antecedents. The recontextualisation substantially reduces the SD<sup>d</sup>. The technical representation requires familiarity with technical drawing conventions, but each symbolic representation can be read sequentially and has meaning without reference to other symbolic representations

**M8: solution (details of artefact - inner environment):**

The solution is defined as the final two reports, one a group report on the whole system and the other an individual report on each of the seven subsystems defined by the lecturer. Both reports draw on previous tasks, but without necessarily elaborating the inferences in the previous tasks. Both reports include the same content and layout prescribed to a strict format, that represents the layout of a design specification.

- The system definition - concise description of basic functionality of the system/subsystem [this focuses on describing the ontic relations of the system/subsystem in quite material terms, for example " The turbine extracts work from the pressurised steam mass flow via the HP and LP turbines. These turbines are mounted onto a shaft which drives the generation system." A7:6]
- Prime item diagram - identifies main parts of the system/subsystem and the interfaces between subsystems internal and external to the system [the prime item diagram is a symbolic representation of simplified material relations]
- Functional allocation - identifies main functions of the system and assigns them to a subsystem [an alternative symbolic representation of the material relations, this time in matrix format]

- Interface - identifies some interfaces and references the documentation of the relevant metric and quantity [this is another material relation, for example the relation between "SS05-SS06: Steam flow and physical connection interface with cooling system" [A7:8]]
- Requirements - lists functional requirements with values and traces analytical documents, and means of confirmation etc; operational requirements and reliability etc [although some of the parameters are defined in symbolic form and depend on prior discursive analyses, the output describes precise material relations for example the steam pressure at the outlet of the HP turbine is quantified, with an acceptable tolerance; the reason for this value is provided, in this case in terms of efficiency and distribution of energy, and a physical means of checking the value is determined, a requirement to measure the pressure at this point.]

A very significant part of the final document is the numbering system used to trace design parameters back to their analytical origins in prior reports.

<p>SG++(l): The solution shows the beginnings of specialisation with certain aspects are specified precisely. The solution specifies the main performance parameters of the power plant, and does indicate some of the key dimensions, a number of specific details would be required to complete the manufacturing details and final dimensions to fully specify a particular power plant. However, the magnitude and complexity of the referent artefact is far too great to complete within the course, so coded low in the category.</p>	<p>SD<sup>o</sup>(l): the solution documents represent a significant simplification of the material relations in that layers of interdependencies are separated and presented sequentially. So for example, the prime item diagram illustrates the physical links between subsystems, but not the thermodynamic interdependencies, the interfaces identified are limited and although they indicate the significant material parameters like geometry or material quantities, the interfaces are not linked to each other. While there are simultaneous interdependencies, the solution did not require comprehensive recognition of significant ontic relations, rather an illustrative range of examples. However, the reference back to the previous documents does retain the roots in simultaneous interdependence.</p>	<p>SD<sup>d</sup>-(m): Although the solution is in many respects dependent on the outcomes of prior specialised analyses, and those interdependencies are retained in the tracing numbering system, in the solution the discursive relations are presented as independent items, sometimes in symbolic form, sometimes in more material form. The solution represents a simplified output of extremely complex inferential relations based on specialised knowledge and analytical numerical models SD<sup>d</sup>-(h). The convergence of the solution, and the consequent checking of the correct symbolic answer means that the assessor is able to check the discursive results. Even though the interdependencies lie behind the solution, the purpose of the solution is to separate them. It does however require specialised knowledge to understand each item. The very precise instructions in the brief shift the code into the middle of the category.</p>
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**M8: inferences (detailing the solution):**

The solution consists of a pack of eight submissions, each with content and format very explicitly defined and constrained. The reports include group submissions relating to the overall system and individual reports relating to each of the seven prescribed subsystems. The inferences do increase the specificity of the artefact, but do not detail the full artefact, nor detail the specifics of most of the subsystems, although strengthening the SG, not to the level of the particular. The supplementary notes provide detailed inferential chains between the ontic and discursive relations, illustrating the high level of complexity inherent in the relations between the ontic and discursive inferences, but students can use these in far more procedural ways, at a far weaker semantic density than inherent in the artefact design.

**Step 1: Functional analysis**

The first submission required students to do a functional analysis of the system, which involved representing the system described in the process diagram in an alternative symbolic representation of a flow diagram. It is a reorganisation of the plant from physical logic of the process diagram to functional logic of the flow diagram.

**Step 2: High level analysis; and Step 3: Subsystem basic sizing analysis**

The second and third submissions involve the symbolic output of numerical models founded on discursive theories used to predict the performance of the system/subsystems, using initial performance parameters defined in symbolic form.

"With the above inputs known, one can calculate the primary fluid properties before and after each component. This is done by systematically "walking" along with the fluid from a known point, and calculating the energy and mass balance for each component. ...

For the first round, the auxiliary loads will be an assumption, as it is an output of the lower level developments. Hence it is necessary to re-run the primary plant analysis once the subsystem results become available. This in turn will affect the subsystem analyses. At least two iterations will be needed to reach suitable convergence. " [SNHL:4]

The above statement indicates both the complex interdependence of the material relations, which in turn require complex

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discursive modelling. Although this section elaborates the relationship between the ontic and discursive relations in detail, which indicates the level of complexity of the task, students are able to apply the mathematical condensations procedurally with very limited appreciation of either the material or discursive relations from which they were developed.

### Step 4: Interface control

"Develop interface control document between two systems" [CI:6] (individual)

The fourth step requires students to identify 5 requirements that are shared between their subsystem and another subsystem. For example, the air supply subsystem supplies heated air to the steam generation system and the mass flow rate of air between the subsystems must be consistent.

The form the requirements should take is prescribed by the lecturer and must include at least one requirement form each of the following three categories:

- material flow requirements (flow rates/capacity/states of the various material streams),
- energy flow requirements (thermodynamic parameters, forces/electric currents) and
- physical or geometric requirements.

Although the requirements are expressed in symbolic form, the basis of their significance lies in the material relations. This step highlights the simultaneous interdependencies of the physical system. However, that a comprehensive list of interface requirements is not expected, suggests that while the logic of the step lies in the material relations, the logic of the assessment lies in the discursive relations, can students recognise a range of conceptually different forms of interfaces? It is the idea of interfaces rather than all the actual interfaces that matter for assessment.

### Step 5: Life cycle cost optimisation

Students apply a particular costing model based on a two variable Design of Experiments method. The lecturer defines the procedure, the variables and the limits within which the variables should be optimised. Consequently students neither need to interpret the material relations, nor translate them into discursive relations, they can merely apply the formula procedurally.

### Step 6: Failure mode effect and critical analysis (FEMCA) and risk

"FEMCA: Compile FEMCA document and risk matrix" [CI:6] (group)

Example provided:

Subsystem	Component	Failure	Affected functions	Immediate effect	End effect
SS04 Fluegas subsystem	SS04-02	Motor bearing seizes	FN1.7.4 Control pressure in combustion chamber FN1.7.2 Extract flue gas from furnace	Pressure in furnace will increase	Hot fluegas/flames can escape outside and burn instrumentation or set boiler alight.
Probability	Severity	Risk level	Failure detection	Mitigation	Corrective action
Occasional	Serious	HIGH	Pressure sensor in the furnace will indicate the rise.	-Shut down boiler -Have 2x50% fans - Implement condition monitoring on the bearings. - increase bearing design life	Replace the bearings. This may require that the bearings are replaceable, otherwise the whole motor must be replaced.

For each subsystem the lecturer identifies a component and an associated failure. The students complete the rest of the table, incorporating a single failure identified for each subsystem.

### Step 7: Subsystem functional specification and Step 8: System specification (same submission deadline)

This document consolidates and integrates the outputs of steps 3-6 (subsystem model, interface control; life cycle cost optimisation and FEMCA) and 1-6 respectively. Again it follows a very strict layout and format.

The system specification follows the same format as the subsystem specification, only that it integrates the effects of each subsystem:

- The system definition - concise description of basic functionality
- Prime item diagram - identifies main parts of the system/subsystem and the interfaces between subsystems internal and external to the system
- Functional allocation - identifies main functions of the system and assigns them to a subsystem
- Interface - identifies some interfaces and references the documentation of the relevant metric and quantity
- Requirements - lists functional requirements with values and traces analytical documents, and means of confirmation etc; operational requirements and reliability etc

<p>SG+: Although the project results in increasing detail and specificity of the artefact, it does not take the design to completion, and leaves many details generic.</p>	<p>SD<sup>o</sup>-(h): The supplementary notes and tightly prescribed steps in the project define the material relations as sequential, although the notes to explain the significant complex relations. Many of the steps force the students to conceptualise the symbolic results in relation to the interdependencies in the artefact, but the simplification allows them to be considered sequentially.</p>	<p>SD<sup>d</sup>-(h): Although not the intension, the presentation of theory specialised to the specific case of the power plant mean that students can use the mathematical expressions procedurally and sequentially without necessarily understanding either the theoretical antecedents or the significant ontic relations that specialised the theory.</p>
<p><b>M8: Recontextualisation</b></p>		
<p><b>Classification:</b> As is typical of a design task, multiple disciplinary traditions are integrated and related to a concrete artefact, which suggests weak classification. But in this task the solution is so constrained and the framing is so strong that the classification of the task is strengthened considerably.</p>	<p><b>Framing:</b> The specialised knowledge required is laid out in elaborate detail, providing extremely strong framing over selection. The eight tasks are discretely sequences and the evaluation of each task is precise and detailed checking for accuracy, sequence and evaluative criteria are very strongly framed. There is no ambiguity about the social positioning; the students are positioned as students, even when the format demanded is influenced strongly by professional documentation norms.</p>	
<p>+C: The integration of multiple disciplines and the relation to a concrete artefact suggest strong classification, but the specialised information provided relating to the conceptual details is so specialised, and the framing constrains the solution to a convergent 'correct' answer, that in fact the classification becomes strong</p>	<p>++F: Selection, sequencing and the evaluative criteria are precise and explicit, students are taken through the design process clearly positioned as students subject to following the instructions, which avoids any ambiguity in the social relations or evaluative criteria. All aspects of the project are very strongly framed.</p>	

### **UCT Bikeshare scheme**

<p><b>U1: Project description</b> The first project in the Urban Engineering stream is located in a surveying and GIS course. Students were required to investigate the feasibility of introducing a bikeshare scheme onto the existing university campus. The project involved surveying a single potential route and endpoint for the scheme, conceptually designing the bikeshare station and proposing terrain changes needed to make the route safe and manageable to cyclists and other route users including pedestrians, cars and busses based on the surveyed terrain. The context is <i>real</i>.</p>
<p><b>U1: Context (outer environment)</b> The context is the UCT campus in its current form, including the terrain and usage: a congested campus with limited parking, narrow pathways shared by motor vehicles, busses and pedestrians, and the climate, dry hot summers with strong winds and cool wet winters. The campus is built on the slope of a mountain, and has many staircases and steep inclines. But these details are not specified in the brief and it is expected that the students will draw on their own experiences of the campus in the design. Although the design brief specifically identifies the campus, and makes reference to aspects of the campus context that might be considered (for example noting the likely building usage to determine capacity, points out the student bus service to be considered in relation to the bike share routes and stations, and implies relation to existing roads for access) much of the detail is left to students to elaborate from their own everyday and embedded experience of the campus, and to either identify as significant or discard as irrelevant to the design.</p> <p>However, as the brief progresses there is a shift to specialised knowledge of surveying, with the provision of the real survey beacons from which students will survey their site.</p> <p>"Students are expected to run a traverse, do detailed surveying, and levelling in their working site. From the data gathered, students should be able to create 3D scenes in ArcGIS and perform several tasks using this data.</p> <p>Traversing - you are going to run a traverse on your working site to bring control.</p> <p>Tacheometry - you are going to carry out a detailed survey to capture detail necessary for your map.</p> <p>Levelling - level over your traverse points to determine the gradient of your site.</p> <p>GIS - you are going to use GIS to plot the map and contours, and to create a Digital Elevation Model (DEM)"</p> <p>The real project requires student teams to survey a proposed route and make proposals for a bikeshare scheme in respect of how the terrain can be made to accommodate the route, as well as the infrastructure required to store and service the bikes. The coding therefore relates to the terrain survey and associated route modifications based on specialised knowledge but informed by everyday insights.</p>

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<p>SG++(m): the context, the UCT campus, is a <b>particular and unique</b> context. It is central to the task, and students use the context to develop a solution.</p>	<p>SD<sup>o++</sup>↓SD<sup>o+(l)</sup>: The context (the UCT campus) provides the input for the design task;. In the brief it is presented as a condensed whole, where all the interdependencies are embedded (SD<sup>o++</sup>). Students need to identify what is relevant to the project, and discard what is not. Because the context is based on a real context, students are able to retain the simultaneous interdependencies between significant elements identified (SD<sup>o+</sup>).</p>	<p>SD<sup>d--</sup>↑SD<sup>d+(l)</sup>: Initially the context of the campus was introduced in everyday terminology, relating to student and staff movement and use of venues SD<sup>d--(m)</sup>. However, part of familiarising themselves with the context involved surveying the route in order to describe it in technical terms. The survey increased the SD<sup>d</sup> to SD<sup>d+(l)</sup> requiring specialised surveying knowledge with its associated constellation of concepts and procedures.</p>
<p><b>U1: Artefact (inner environment)</b>          The brief provides instructions for the requirements of the "bikeshare" scheme in terms of familiar everyday terms, and students are referred to Wikipedia for information on the general idea of bike share schemes. In the brief the requirements of the artefact are described in unspecialised terms, but there appears to be an expectation of simultaneous consideration of a number of factors:</p> <p style="padding-left: 40px;">"Each group will be assigned a site, for which they will need to analyse and come up with a proposal. Some key issues will involve accessibility, parking for X-number of bicycles, routes to other bikeshare stations, location of Jammie Shuttle stops. You will need to bear in mind that you will also have to provide vehicular access as the bicycles may require being moved from one station to another should the demand arise. Your team will need to provide a method for this to take place. Your design should also have as little impact as possible on existing infrastructure."</p>		
<p>SG+(l): The bikeshare scheme is prescribed in generic terms as a generic solution in the brief. But within the type, there is a large amount of discretion left to the students, placing it low in the category. The ambiguity between the specifics of the route and the generic unrealistic nature of the scheme make the coding somewhat uncertain.</p>	<p>SD<sup>o+(l)</sup>: the brief suggests that a number of aspects emergent from the context and inherent in the artefact need to be considered simultaneously in the "bikeshare" and there is an expectation that students will draw on their experience of the context to elaborate those mentioned. But there is a sense in which a very superficial appreciation of the ontic relations is adequate for much of the project, which weakens the SD in the category.</p>	<p>SD<sup>d+(l)</sup>: if the modifications to the cycle terrain, based on the formal survey are considered the artefact, then the artefact is coded SD<sup>d+</sup>, but with insights from unspecialised everyday knowledge which places it low in the category. However if the bikeshare scheme itself is considered the artefact then the SD<sup>d</sup> is reduced to SD<sup>d--(h)</sup> because the 'bikeshare' scheme is introduced in everyday terms, and students are referred to Wikipedia for more information on the concept. It is used in an unspecialised way to provide input for consideration in the specialised design. The legal requirements for spacing place it higher in the very weak category.</p>
<p><b>U1: Solution:</b>          The solution takes the form of a report that details the proposed solution, including details such as bicycle selection, accessory recommendations to meet safety and convenience requirements, the logistics of bicycle exchange, a concept design of the bicycle station structure and a Digital Elevation Map (DEM) of the surveyed route including modifications to the route required to make the scheme feasible.</p> <p>The substance of the design lies in the realities of the accurately surveyed terrain, and judgements of changes required making the bikeshare scheme feasible, such as the introduction of widened roads or paths, changing slopes and accessible locations for the bikeshare stations. But these judgements are made against the unspecialised details of the bikeshare scheme itself. There is an inherent tension between the imaginary and generic bikeshare scheme understood in unspecialised and intuitive ways and the real and specific details of the terrain, presented and analysed in specialised surveying symbols and procedures. The two parts have therefore been coded separately to illustrate the inherent tension.</p>		
<p>SG++(l): The dual nature of the solution (bikeshare and terrain) makes the coding somewhat ambiguous. The surveying of a route and station, and the modifications presented in the solution are unique to the context and in considerable detail (SG++h), but the details of the bikeshare scheme itself, are relatively generic, reducing the SG to low in the category.</p>	<p>SD<sup>o-(h)</sup>: The DEM of the surveyed route with proposed modifications to make the bikeshare scheme feasible on the campus is a simplified representation of the many inferences based on the interactions between the needs of a safe cycle route and the existing terrain and usage (legislated spacing, reduced cycling gradients, shared access, etc). But because many of the details of the bikeshare scheme itself are imaginary and superfluous, it weakens the SD<sup>o</sup></p>	<p>SD<sup>d-(l)</sup>: The DEM is a technical representation of surveying component, represented in a technical drawing, however technical drawing principles do not appear to have been strictly required (l).          SD<sup>d--(h)</sup>: The bikeshare scheme itself remains intuitive and everyday without disciplinary insights other than those related to the survey and route, which locates it high in the category.</p>

significantly.

**U1: inferences (detailing the solution) - see appendix 4**

The first part of the project involved familiarising themselves with the concept of a bikeshare scheme (done at a relatively superficial, unspecialised level) and the context (identifying the route that will be use, and consequently recognising the parts of the site that need to be surveyed in detail). It is essentially a process of recognising what is significant to the design and developing that in more detail, and stripping what is irrelevant. Initially it occurs in relation to the ontic relations rather than the discursive relations; tudents need more information than provided in the brief, they draw on their own experience of the campus, and find out about what a bikeshare scheme entails.

This was then used to develop the first step in the design, deciding on a route that joins the two prescribed endpoints. The basis of the decision appears to be a sense of the most direct and accessible route available, bringing together a sense of what it would mean to cycle on the campus, and the general 'feel' of the landscape. The first step remains in the ontic relations, but weakens the ontic relations by identifying and separating the relevant from the irrelevant relations.

The second step was to survey the route, a process of converting the 'experience' of the real route into a symbolic representation of the route against which performance criteria can be measured, compared and predicted. The surveying process further strips the context of extraneous detail and simultaneous represents it in complex symbolic form - as a digital elevation model. The DEM is an integration of measurement skills and techniques, complex calculation procedures (including three dimensional geometry and error corrections), and interfacing with specialist software able to represent the results graphically as a topographical map. It is a process of abstracting the outer environment, simplifying the ontic relations and translating them into a symbolic representation that integrates multiple complex specialised disciplinary skills, procedures and conceptual relations, or strengthening the discursive relations. To some extent this involves a simplification of the ontic relations because only the terrain is considered, human interaction and choices about cycling are removed, cost implications are irrelevant to this part of the problem.

From the survey output, read in conjunction with practical implications of cycling, challenges to the implementation of the bikeshare scheme were identified:

"There are a number of problems that the current landscape will cause if it is left as it is. To make the route viable, some changes need to be made.

The first issue is that the Ring Road is a very busy road, already used all the time by motorists and pedestrians and Jammie Shuttles as well as trucks. Adding cyclists into the same road will be an inconvenience to all other road users as well as to the cyclists themselves. The design of the bicycle lane would have to be so as to have the least effect on traffic; ideally the cyclists should not come into contact with the motorists.

The second issue with the current, unaltered route is the slope of the North lane. It has a gradient of 1:5.6. Cyclists that cycle at competition level have commented that a gradient of 1:8 is about as steep as a cycle route can be. The design will have to account for this.

The next problem that the current route has is the walkway that starts at the bottom of North Lane is a busy pedestrian walkway ordinarily. If it is taken away, to make space for the cyclists, then the pedestrians will not have a place to walk and this will result in a traffic jam. Also without a proper system to separate cyclists and pedestrians, accidents could happen.

Another problem is that at the end of the walkway there are steps that the cyclists have to go up and down, it is impractical to get them to get off their bicycles and walk when they reach the stairs therefore the design has to account for this."

These problems emerged as a result of reading the details provided by specialised topographical map in relation to cycling on the campus. It brings together specialised and unspecialised knowledge.

Finalising the design involved decisions about spacing the bicycle lane, and modifications to gradients to facilitate cycling, and vehicular access to the stations can be made. Once again the ontic relations are brought back into conjunction with the discursive relations in order to make decisions.

Although the report is padded with some somewhat extraneous details relating to the development of the "bikeshare" scheme, there are also pertinent aspects that emerge and influence the design decisions. The extraneous details tend to relate to aspects of the world that the students do not have the theoretical tools to address (costing, structural detailing) or lack exposure to alternatives (space saving stacking systems), and common sense assumptions around safety and security issues. However, there are also a number of spatial issues that emerge including legal requirements and guidelines for bicycle path dimensions and position relative to other road users, critical slope limits for cycling, experience of the campus in terms of the practicalities of cycling the proposed route amongst other vehicles and pedestrians, challenges imposed by existing infrastructure such as stairways and road crossings.

There are a number of other aspects to the project that contribute to the complexity of producing the finished product, including team interactions, the physical nature of the surveying task, and issues of time management.

SG++→ SG++→ SG++ →SG++

SD<sup>o</sup>+(l)↓ SD<sup>o</sup>-(h)↑ SD<sup>o</sup>+(m)↓ SD<sup>o</sup>+(l)SD<sup>d</sup>--(h)↑↑SD<sup>d</sup>+(m)↓↓SD<sup>d</sup>--(h)↑SD<sup>d</sup>-(h)

<b>U1: Recontextualisation</b>	
<b>Classification:</b> The project brings together specialised knowledge of surveying and unspecialised knowledge of a generic bikeshare concept and familiarity with the campus. But the specialised knowledge is restricted to surveying. The solution is influenced strongly by the context, and although the survey itself, if correct, should represent the actual terrain surveyed, the influence of the common sense decisions relating to the bikeshare scheme introduce both ambiguity and divergence in the solution.	<b>Framing:</b> The interplay between the imaginary and unspecialised requirements of the bikeshare scheme, and the specialised surveying requirements of the project, set up significant ambiguity. It is unclear what is expected of the knowledge and detail pertaining to the former, while the later is explicitly selected and sequenced. It seems that the positioning of the students as 'consultants' rather than students is what drives the extraneous details in the report, and the ambiguous positioning the students as professionals, conducting a feasibility study or tender (contradictory) and then requiring academic signoffs on the specialised tasks adds further ambiguity
-C: The integration of specialised and unspecialised knowledge and the influence of the unspecialised knowledge on the potential divergence of the solution indicate a weakly classified task, but the restriction to a single disciplinary discourse (surveying) does strengthen the classification somewhat	-F: There is a significant tension between the bikeshare solution and the surveying aspects of the task, the former has weak framing over selection and sequencing, while the later has strong framing over selection and sequencing. Although the surveying component of the task is the main assessed component, suggestive of stronger framing, this is not entirely clear and there was the potential to spend much effort on detailing the bikeshare scheme itself. The contradictory positioning of students and the ambiguous evaluative criteria further weakens the framing for those students who do not realise that the design is fundamentally a surveying task.

**U2: Flood attenuation culvert**

<b>U2: Project description</b> The second project in the Urban Engineering stream is located in a hydrology course. Students each identify a catchment area in South Africa, use a range of hydrological methods to predict flood discharge over a range of return periods, and design a culvert at an appropriate point in their catchment area to attenuate a 1 in 50 year flood peak by 30%		
<b>U2: Context (outer environment)</b> The context is any real area in South Africa represented on a contour map and the limits of the area identified by the relationship between watercourses, watersheds and drainage points. Students need to be able to access and read GIS data and to understand the idea of a catchment area in order to identify an appropriate context for their design. The context is <i>real</i> .		
SG++(l): The context, although chosen by students is real and <b>specific</b> . Although limited detail about the context is required	SD <sup>o</sup> -(h): Located in a hydrology course and under the influence of explicit step by step details, only the features pertaining to the technical definition of a catchment area are relevant to the context, which include contours and rainfall data. The limits of the catchment require students to interpret what the contours represent in terms of the real terrain, and appreciate the interaction between the terrain and the watersheds, watercourses and drainage point. The interactions are simple enough to be considered sequential.	SD <sup>d</sup> -(h): The context needs to be read in terms of specialised knowledge of a contour map and rainfall conditions, although they influence each other, the relation is simple enough to treat sequentially in this project.
<b>U2 Artefact (inner environment)</b> The artefact, a culvert, is a generic flood attenuation structure, but only general details of the type of culvert and global dimensions are required. The task stipulates that unrealistic culverts may be needed in some contexts, suggesting that the flood modelling is more relevant to the task than the artefact itself.		
SG+(l): The artefact is understood at the level of type, and it remains in a generic unspecialised form. But since very limited understanding of culverts themselves is required for this task, almost more of an idealisation than a type, it is coded very low in the category.	SD <sup>o</sup> --(m): The understanding of the artefact is limited to the size of the channel through which the floodwater is intended to flow. It is dislocated from the material realities of the structure itself, but does define the notion of flood attenuation, as a single dislocated ontic concept.	SD <sup>d</sup> --(m): The details of the culvert are reduced to the area of the channel relating to hydrological calculations with no requirement for structural detailing or geotechnical integration is required. Although the channel cross section could be considered a 'technical' specification, it is understood in fairly everyday ways.
<b>U2: solution (details of artefact - inner environment):</b>		

The culverts are defined in terms of number and shape of channels and the width and height dimensions. The dimensions are based on reducing the peak estimated flood discharge by 30%		
SG+(m): Specifying the cross sectional dimensions of the culvert does strengthen the SG slightly, but the solution remains a generic type with only the general shape and dimensions of the channel specified. No information on detailed dimensions, structural integrity or geotechnical considerations are required.	SD <sup>o</sup> --(m): The limited detail and potentially unrealistic culvert structures dislocate the artefact from significant ontic relations	SD <sup>d</sup> -(l): The culvert channel dimensions are determined in relation to a range of calculated peak discharge rates, and what it means to attenuate the flow rate by 30%. But the very limited consideration of the culvert itself places it low in the category.
<p><b>U2: inferences (detailing the solution)</b></p> <p>The bulk of the work requires student to calculate the flood discharge for a range of return periods. The tasks focus on the different procedures used to estimate potential floods in a catchment area, and although the context is real and affects the calculations, the evaluation lies in the procedures and answers in discursive form. In the end, each method provides a different flood discharge and these results need to be evaluated in the context of the specific catchment. This is a trajectory from a real but simplified context, through hydrology knowledge to simplified aspects of an imaginary artefact.</p> <p>Although the input data for the calculations needs to be extracted from the context, the bulk of the work is in discursive form until the end when the symbolic results need to be interpreted in terms of ontic relations in order to make material decisions about the culvert.</p>		
SG+++↑SG-↓SG+: From a specific context (SG++), procedural hydrology calculations are imposed on the context (SG-) in order to make decisions about a generic artefact (SG+)	SD <sup>o</sup> -↑SD <sup>o</sup> --↓SD <sup>o</sup> -: The catchment area and the input data for the procedural hydrology calculations are developed from an understanding of the topography, which has to be read in terms of watercourses, watersheds and drainage points (SD <sup>o</sup> -). Once determined, the ontic relations are severed (SD <sup>o</sup> --) until the calculated values are interpreted in relation to simple discrete aspects of the catchment area (SD <sup>o</sup> -(l))	SD <sup>d</sup> -→SD <sup>d</sup> -↑SD <sup>d</sup> +: The catchment area is defined in terms of contours, a specialised symbolic language (SD <sup>d</sup> -). Based on the technical details of the context, students perform a number of procedure calculations, each of which predicts a peak flood discharge for a range of return periods (SD <sup>d</sup> -). The significant part of the discursive relations lies in the comparison between results (SD <sup>d</sup> +) and the judgement in relation to the context as to which calculations are most representative of the likely reality. This requires the symbolic results to be evaluated in relation to each other and the ontic relations.
<b>U2: Recontextualisation</b>		
<b>Classification:</b> Although the context refers to a real catchment area, only the specialised aspects of the catchment area that pertain to hydrology are of any relevance, and all the calculations are hydrology calculations (the aspects of the culvert relating to structural integrity or geotechnical interactions are excluded from the task). Although the solutions have the potential for limited variation, the essence of the solutions are convergent.	<b>Framing:</b> Students are stepped through 7 precisely defined tasks, beginning with identifying and reading a specific catchment, through a range of procedural hydrology calculations, culminating in making a judgement about the relevance and accuracy of the various calculations in relation to the specific catchment. The requirements are clear and students are positioned unambiguously as students.	
++C: the task is specialised and restricted to hydrology, and the solution is essentially convergent. The task is very strongly classified.	++F: selection and sequence of knowledge is explicitly controlled in the task, the evaluative criteria and the social position are unambiguous. The task is very strongly framed.	

### U3: Sewage reticulation

<p><b>U3: Project description</b></p> <p>The third project investigated in the Urban Engineering stream is located in an urban water services design course. Students design the reticulation for water, sewage and stormwater through a sequence of three projects. This analysis focuses on the sewer reticulation, which is the second of the three projects and draws on the same data as the previous water reticulation project. The reticulation system for a defined area in the vicinity of the university campus, and need to imagine that the existing infrastructure does not exist. The design involves estimating the AADD (annual average daily demand) for the (imagined) new development based on the (actually existing) land use. Based on the AADD, a sewage load can be estimated and the system required to handle this demands can be designed.</p>		
<p><b>Context (outer environment)</b></p> <p>Each year students are assigned a fixed area in the vicinity of the university for which they are required to design the water services (potable water, sewerage and drainage). There are two significant recontextualising moves from the 'real' situation introduced to make the project manageable in the time frame in the first instance, and to provide some level of comparative basis for novice designers in the second. Firstly the design is artificially bounded; the problem is set up that there is no transfer across the boundaries, no links to the water services beyond the boundaries, no stormwater flow into the boundaries. Secondly the design</p>		

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is imaginary in the sense the infrastructure already exists, in a fully serviced and functional form. Students are required to 'imagine' that they are to provide the water services prior to development, but they are expected to use the existing infrastructure as a basis for approximating the demand on the services. This is a complex balancing act between what is (and the precision with which it is expected to be provided input into the design) and the resultant design (that would really be developed prior to the finalisation of the infrastructure, and consequently a rough estimate). Students are also provided with the data for the digital elevation model of the actual area under consideration, including details of the existing infrastructure.

Although the existing context is real, students are expected to *imagine* a context without the existing infrastructure and at the same time use the existing infrastructure to inform the design.

<p>SG+(m): The context exists as a real area, including rich existing infrastructural detail (SG++). But students are expected to imagine the prescribed area without the existing infrastructure as a more generic space (SG+) while at the same time using the existing infrastructure to inform their design.</p>	<p>SD<sup>o</sup>+(h): The context exists as a coherent whole, with complex embedded interdependencies (including existing infrastructure that will influence the solution, and human involvement that adds uncertainty to the scenario). But the inclusion of the DEM and zoning details in the supplementary documentation does implicitly begin to identify what is significant to the design and what can be omitted from the design. The area is large enough to include a range of usage types, and consequently a range of contextually based judgements. In conjunction with the interdependence between contours, zoning (with associated water demand approximations) and existing road layout remain simultaneously interdependent.</p>	<p>SD<sup>d</sup>+(l): Although the initial brief shows an aerial photograph of the area under consideration, the supplementary documentation provides technical details in specialised symbolic form (DEM - and associated models). Students need both the technical literacy to extract the relevant details from the sources, as well as the ability to read the symbolic representations. The language used in the brief also locates this project within a particular disciplinary specialisation - students do not need to identify the relevant specialised knowledge before proceeding. Although the specialised information is provided sequentially, students do need to build up an integrated understanding of the context in specialised disciplinary form as part of the development of the solution, the brief is therefore coded low in the strong category.</p>
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**U3: Artefact (inner environment)**

Although the course covers the design of three water services, this analysis is restricted to the design of the sewage reticulation system. It is the second of the projects in the course and requires some input from the first project (water reticulation) as a basis for estimating the sewage demand. The type of artefact (gravity driven water borne sewage reticulation, with a single discharge point) is fully defined in the brief and there is no scope for conceptual alternatives. This locates the solution within a particular conceptual body of knowledge, and limits the scope of the theoretical contribution to the solution. It also defines the level of complexity of the artefact. The size of the area and the range of infrastructure included is selected in order to include a range of usage types, and consequently a range of contextually based judgements. It is also large enough that the pipe network layout is not obvious, and a range of possible configurations exists.

<p>SG+(h): The sewage reticulation system required is expected to be a gravity driven water borne system even though it is not explicitly specified in the brief. There is no scope to explore alternative sewage systems, placing it high in the category.</p>	<p>SD<sup>o</sup>-(h): There is limited detail on the required artefact, and each detail can be considered independently. The implications of gravity driven implied that all pipes must flow downhill, the water borne nature of the service contributes to defining the capacity requirement of the system, and the single discharge point constrains the potential network. These have complex consequences for the solution, with a high level of interdependence.</p>	<p>SD<sup>d</sup>-(m): Located as it is the course, the specification of the detailing of the sewage system is implicitly driven by the disciplinary norms of the field, with associated procedural sequences of calculations. The design guidelines define the level of detail and impose meaning on the artefact.</p>
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**U3: solution (details of artefact - inner environment):**

The solution primarily consists of a technical drawing of the specific water service (in this case the sewage reticulation), including the specification of pipe and manhole positions (in relation to the existing infrastructure and contours of the area); the position of the sewage discharge point, and a cost estimate. Pipe network details are provided by pipe length, diameter and gradient (based on the capacity required and flow rate approximations) and manhole details provide the invert and cover levels of the pipe endpoints (based on interfacing with the ground level and gradient requirements for flow). The accompanying report documents all assumptions made, justifies decisions taken and provides details of the mathematical modelling used to determine the technical specifications of the design.

<p>SG++(h): the solution provides rich detail of a specific instantiation of a sewage reticulation system proposed for a specific area. It is uniquely informed by the context, and the technical drawing</p>	<p>SD<sup>o</sup>+(l): The solution represents the output of interdependent contextual reasoning in response to a complex context. It shows the simultaneous interdependence between ground cover</p>	<p>SD<sup>d</sup>-(h): The solution is presented in technical symbolic language, in rich detail which encodes position in relation to the reticulation system and the existing infrastructure, dimensions based on</p>
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provide sufficient detail to enable the construction of the proposed solution.	and pipe slope, existing infrastructure (servitudes and erfs), pipe intersections and manhole details.	procedural calculations and contextual judgements. The complexity of the network and the multiple disciplinary considerations places it high in the category.
<p><b>U3: inferences (detailing the solution)</b>  Students need to make sense of the context in both specialised (contours, servitudes, water demand estimates) and unspecialised (assumptions of usage, assumptions about diurnal and seasonal variation) ways. From these students need to develop technical specifications in terms of performance requirements (flow rates). Based on an appreciation of 'downhill flow' students construct a typical dendritic network, based on standard engineering guidelines including maximum pipe lengths, standard diameters, intersection requirements, maximum and minimum cover requirements in relation to the existing contours etc. They test their network using relatively simple computer based flow rate models to model the potential sewage flow. Iteratively changing the network as reverse flows are predicted. Once an adequate flow is predicted based on the assumed input data, the solution is detailed according to engineering standards using technical representations.</p>		
<p>SG++↑SG+→ SG+↓ SG++:</p> <p>From a specific and existing precinct (SG++), students need to imagine a more generic area (SG+) for the purpose of the design. Into this space they impose a type of sewage system (gravity fed water borne sewage) (SG+) and move through a number of iterations until they determine an adequate solution that they detail in terms of position, dimensions and interaction with the existing infrastructure (SG++).</p>	<p>SD<sup>o++</sup>↓ SD<sup>o+</sup>↓ SD<sup>o-</sup>↑ SD<sup>o+</sup>:</p> <p>From an existing complex precinct (SD<sup>o++</sup>) student identify relevant characteristics (mostly in relation to position and usage). The initial layout of the network is based on an intuitive understanding of the interaction between slope, spacing and flow rates (SD<sup>o+</sup>), which is then replaced with a computer model that focuses only on the resultant flow rates and directions (SD<sup>o-</sup>). With a working network, the detailing returns to very ontic considerations of space, slope and usage (SD<sup>o+</sup>).</p>	<p>SD<sup>d-</sup>↑ SD<sup>d-</sup>→ SD<sup>d-</sup>:</p> <p>In addition to the existing context, students need to interpret technical details about contours, zoning and servitudes, presented as GIS data (SD<sup>d-</sup>(l)). Once developed from the more complex ontic relations relatively simple flow modeling is done to check flow rate and direction predictions (SD<sup>d-</sup>(h)). The solution is then presented as a technical drawing SD<sup>d-</sup>(h).</p>
<p><b>U3: Recontextualisation</b></p>		
<p><b>Classification</b></p> <p>Being located in a disciplinary course, the specialised knowledge required is restricted to that associated with water services, but even here the course is very applied rather than specialised. Much of the inferential reasoning relies on a judgement of contextual factors, and the solution, although restricted to gravity fed water borne sewage system, is otherwise somewhat divergent.</p>	<p><b>Framing</b></p> <p>Students are positioned as professional consulting engineers and are expected to create a company name and mimic a consultant's report. However they are not allowed access to the client, and must make decisions based on this simulated environment. It is a contradictory relationship that students need to navigate with care. The disciplinary knowledge is suggested by the location of the project in an urban water services course, but there is limited prescription of the particular approaches or sequence of decisions to take. The evaluative criteria are implicitly based on producing an 'adequate' design that conforms to a 'professional' presentation.</p>	
<p>-C: There is some bounding of the project by locating it in a course, and restricting the solution to a gravity fed sewage system but there is significant interaction between specialised and unspecialised knowledge required in order to make design decisions based on procedural calculations judged in relation to a context, and the final pipe layout and sewage flow can take many configurations. Overall though the project is weakly classified.</p>	<p>--F: Although the location of the project in the urban water services course suggests the relevant knowledge, selection and sequence are not specified. The evaluative criteria are based on a professional judgement and remain unclear, and the social hierarchy is particularly difficult to navigate</p>	

#### U4: Emmarentia Dam road

##### U4: Project description

The fourth design in the Urban Engineering stream is located in an urban design and management course and involves the geometric design of a small section of road located somewhere in the country set as a 105 minute test. The test format significantly constrains the design project.

"Design an urban arterial road with design speed of 60km/h from point A to point B as indicated on the attached plan and longitudinal section1. A number of photographs are attached to illustrate it further.

Choose a suitable size of box culvert - or series of box culverts - of standard size 2.4 x 2.4m or 3.0 x 3.0m - to accommodate the design flood. Assume a catchment area of 8km<sup>2</sup> and a storm duration of 2 hours.

Assume stake values (SV) and elevations of 0m and 1627.25m respectively for point A, 945m and 1596.4m respectively for point B, and 875m and 1591.5m respectively for the Low point in the stream bed at the existing

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<p>bridge (which will be replaced by the box culverts).</p> <p>Calculate the finished road level on the centre-line at a stake value of 860m.</p> <p>Draw a cross section of the road at a stake value of 860m. Use an undistorted scale for the cross section (i.e. use the same scale for both vertical and horizontal axes). On the cross section, also show the existing ground line along the streambed. Make simplifying assumptions in the determination of the streambed.</p> <p>Extend the cross section approximately 20m beyond the toe of fill on either side of the road. Indicate key road levels and offsets (i.e. horizontal distances) from the centre line of the road on the cross section (including centre line and shoulder breakpoint).</p> <p>Assume a deck thickness of 200mm for the culvert, and minimum road layerworks cover of 150mm over the deck of the culvert.</p> <p>Show all assumptions, design decisions and calculations, which must include VPIs, BVCs, EVCs, gradients of all tangents, curve lengths, K values. Set out your calculations so that they could be readily understood and checked by a colleague in an engineering design office.</p> <p>Indicate key elements of your design on the longitudinal section and cross section."</p>		
<p><b>U4: Context (outer environment)</b></p> <p>The context is <i>real</i> and provided to students in both a detailed contour map to show the elevations of the entire area and photographs to elaborate a more everyday sense of the area. However the photos merely reinforce the design speed given as 60km/h.</p> <p>This context has been categorised as <i>real</i>, because the context is specific, detailed and accessible to the students, but in the brief the lecturer does most of the work of diagnosis and simplifies the context into sequential discursive terms. This brief shows an example of how a simplified context can be derived from a real context in the brief, without losing the connections to the real.</p>		
<p>SG++(l): The context is a <b>specific</b> area with relevant contextual detail provided for students.</p>	<p>SD<sup>o</sup>-(m): The only required information on the context relates to the bearing and elevation of the route. Although additional information about the area is provided, from which the road type and design speed would be inferred, the design speed of 60km/h and the road classification are prescribed. The input information for hydrology and flood water considerations are defined without requiring the students to read the context.</p>	<p>SD<sup>d</sup>-(l): The elevations along the prescribed route represented in specialised form, the additional information in unspecialised form is not required for the task. The problem is set up to eliminate the need to consider horizontal alignment and is restricted to vertical alignment, with associated sequential procedural calculations. Each term needs to be considered, but can be treated sequentially.</p>
<p><b>U4: Artefact (inner environment)</b></p> <p>The required artefact is a short section of road defined by vertical alignment consideration to account for the existing contours, design speed and sight lines. The road is straight, so horizontal alignment considerations are excluded. The addition of the stream crossing and culvert, along with a defined cross section means that hydrological considerations are also required.</p>		
<p>SG++(l): Although not every aspect of the road is specified in the brief (the vertical alignment, cross section and culvert considerations need consideration) the route, and the aspects than need to be considered are prescribed and make this a particular instantiation of a road section, although low in the category, on the boundary with they type categorisation.</p>	<p>SD<sup>o</sup>-(l): By prescribing the requirements of the road design the significant ontic relations have been identified for the students, restricting it to vertical alignment without simultaneous horizontal alignment considerations simplified the artefact. The cross section at only one point is required. This sequential prescription that focuses on discrete aspects of the road allows the simultaneous interdependencies to be disaggregated and treated sequentially.</p>	<p>SD<sup>d</sup>-(h): The requirements for the artefact are described in specialised terms, but the sequential instructions function to separate and identify key discursive concepts that can be treated sequentially. They do however indicate required procedural calculations placing this high in the weak category.</p>
<p><b>U4: Solution:</b></p> <p>Because the design was conducted as a test in very limited time, the scope of the solution was tightly constrained. However, the solution specifications were precise and specific to points designated in the road. Students needed to consider hydrology and vertical geometric alignment aspects in response to the specific context. The solution included precise technical specifications, and the procedural calculations behind them.</p>		
<p>SG-(h): The solution involves the specification of some key technical details at points prescribed in the brief. As such the solution is the output of a conceptual body of knowledge. However, the solution conforms to the unique context and precise if limited</p>	<p>SD<sup>o</sup>--(h): The calculated elevations and section details are presented as discrete values, somewhat dislocated from the artefact and context.</p>	<p>SD<sup>d</sup>-(h): The solution is based on procedural specialised calculations, and while following the procedures does included hydrology and alignment aspects. The solution requires insight into these disciplines.</p>

detail is provided, which places it high in the category.		
<b>U4: inferences (detailing the solution) - see Appendix 4:</b>		
SG++→ SG++→ SG++→ SG++	SD <sup>o+</sup> (l)↓SD <sup>o-</sup> (h)↑SD <sup>o+</sup> (m)↓SD <sup>o+</sup> (l)	SD <sup>d-</sup> (h)↑↑SD <sup>d+</sup> (m)↓↓SD <sup>d-</sup> (h)↑SD <sup>d-</sup> (h)
<b>U4: Recontextualisation</b>		
<b>Classification:</b> Although the task requires students to use specialised knowledge in a real context, the relevant aspects of the context are described in specialised language, very limited engagement with the contextual or everyday aspects of the context or artefact are required. The solution incorporates geometric design and hydrology, which is standard for road design, so although weakening the classification slightly, it is not significant. The task is a test with a convergent solution	<b>Framing:</b> The required knowledge is defined and sequenced precisely in the instructions, as a test students are positioned as students and the evaluative criteria are clearly stipulated in the instructions.	
+C: The knowledge, the disciplines and the solution are all strongly classified, but the inclusion of geometric design and hydrology, and the application to a real, if symbolically represented context weakens the classification very slightly.	++ F: All aspects of the task are strongly framed.	

### S1: Parking structure

<b>S1: Project description</b> The first design project in the structural engineering stream is located in the first structures course and involves the analysis of the loading on an imaginary and simplified structure. The design culminates with the calculation of the axial loads on the bottom columns.		
<b>S1: Context (outer environment)</b> No context is provided, but the function of the structure as a parking structure does introduce simplified contextual details required for the project that relate to the live load, which is given as 4kN/m <sup>2</sup> . The context is further simplified in that potential wind loading ignored. There is no requirement for the context to be read, or translated into symbolic representation. The context could be categorised as <i>simplified</i> (similar to M1 and M3), or in fact <i>absent</i> (similar to M4 and S3), either way, students do not need to deal with ontic relations pertaining to the context.		
SG-(m): The limited contextual reference to the function of the structure (as a parking garage), from which the live loading is prescribed is theoretically imposed rather than emergent.	SD <sup>o-</sup> (l): No consideration of ontic relations is required to determine the interaction between the artefact and any context.	SD <sup>d-</sup> (l): The single contextual detail required is provided as a loading distribution of 4kN/m <sup>2</sup>
<b>S1 Artefact (inner environment) [compare M1]</b> The structure is supposed to be a parking garage, but it has been idealised beyond recognition as a parking structure; only the details relevant to the loading analysis are provided. There is no way for vehicles to get to the second level, nor their drivers to get out of the building, all reference to access ramps or stairwells, which would make the structure real, have been eliminated. The cantilevered roof on level three is a particularly poor functional design and the third column needed to support it would interfere with vehicle flow. This would suggest that the layout of the 'parking garage' is designed to introduce conceptual complications rather than for functional reasons. As such, the parking structure is completely imaginary and dislocated from reality. This is reiterated by the drawings provided, which although in the form of technical drawings, do not conform to technical drawing standards and conventions, and are more reminiscent of textbook diagrams. The dimensions for this imaginary structure are given in a separate table, further dislocating the structure from the realities of the world, and separating the particularities of any unique structure. The work required to identify and separate the aspects of the context and artefact that are relevant has been done in the brief, without any elaboration on the process of simplification.		
SG-(h): Although the parking structure may be seen as a generic structure (SG+), the level of detail given is determined by the conceptual requirements of a loading analysis rather than emerging from functional or contextual details. Meaning lies in the conceptual interpretation of load and dimensions relevant to the loading analysis rather than emergent from the any real structure. But the prescribed dimensions place this high in the category	SD <sup>o-</sup> (h): The structure consists of slabs and columns (structural elements). While the load path transfers the load between the various elements interdependently, the structure does allow sequential treatment (SD <sup>o-</sup> ). However the defined dimensions reduce the need to consider interdependencies, and the structure has been idealised to a point of being unrealistic by the disregard of key structural features, for example access ramps or stairwells, shear walls or brickwork enclosures. One of the main dislocating features of the artefact is the positioning of a column without regard for the material implications of the load	SD <sup>d+</sup> (l): The configuration of the structure is such that its functional reality is limited, rather the configuration is defined in order to introduce as wide a range of conceptual complications as possible within the limited scope of the analysis. But the elimination of any real considerations keeps the discursive relations low in the category.

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	transfer, rather focusing on providing an analytical variant. The dislocation is further emphasised by the diagrammatic rather than technical nature of the sketches provided. This shifts the artefact into the dislocated category (SD <sup>o--</sup> ), although the load path places it high in the category.	
<p><b>S1: Solution:</b> The solution consists of the accumulated loading acting on each of the columns in the structure, reported as an axial compressive load measured in kN acting on each column.</p>		
SG-(m): The solution, although detailing the loads on 'specific' columns, represents these loads as generic conceptually applied representations of the imaginary structure.	SD <sup>o--</sup> -(m): The solution reduces the accumulated loading to compression loads on discrete columns, which can be reported largely independently of any fundamental understanding of the simplified structure itself.	SD <sup>d</sup> -(l): The solution is reported in specialised, but discrete form. Although presented as a single discrete answer, the solution is based on a prescribed sequence of procedural calculations, placing it in the middle of the category.
<p><b>S1: inferences (detailing the solution) - see appendix 4</b> The unrealistically simplified structure, specified sizes of the structural elements, and complete stripping of the context reduces the requirement of understanding the ontic relations to simple discrete, unconnected ideas. Most of the approximations and assumptions required to analyse the structure are procedurally defined either in standard analytical procedures or from the loading codes. Complex ontic interactions are simply ignored. For example, because "types of connections are not considered" it is possible to make the simplification that "bending moments are present but are not considered in the analysis" but this link is not made explicitly, instead the two points are made independently.</p> <p>A large part of structural design involves the material consequences of the structural element dimensions, and their consequent contribution to the load that they have to support. The associated analytical procedures model these loads and check them against the load that the material can support. In a real design this would involve an iterative process of the estimation of element sizes, the resulting loads. If the elements are found to be too small to support the loads, their size would need to be increased, which in turn would increase the loading they apply and the new proposed structure would need to be checked again. Increased element sizes require additional materials, which in turn increases the cost. This iterative process between using discursive techniques to model the material relations, and making material changes has been completely eliminated in this design by specifying the element dimensions in the brief. The significance of the ontic relations has been stripped and replaced with discrete sequential discursive relations.</p>		
SG+→SG+↓SG--→SG--→SG-↓SG--→SG--	SD <sup>o--</sup> -(h)↑SD <sup>o</sup> +(l)↓SD <sup>o--</sup> -(m)→SD <sup>o--</sup> -(m)↓SD <sup>o--</sup> -(m)↓SD <sup>o--</sup> -(l)↑SD <sup>o--</sup> -(m)	SD <sup>d</sup> -(l)→SD <sup>d</sup> -(l)↑SD <sup>d</sup> -(m)→SD <sup>d</sup> -(m)↑SD <sup>d</sup> +(m)↓SD <sup>d</sup> +(l)↓SD <sup>d</sup> -(h)
<p><b>S1: Recontextualisation</b></p>		
<p><b>Classification:</b> Although ostensibly the task is the application of a body of specialised conceptual knowledge to a 'real' structure, the simplified and unrealistic structure, defined more by the intention to require particular conceptually defined procedures than emergent from any real structure, defines the task as strongly bounded from the world. The analysis is restricted to structural mechanics and the solution is convergent.</p>	<p><b>Framing:</b> Students are provided a list of eight discrete tasks to follow in order to complete the task. The steps define the knowledge and sequence of application in small discrete steps. The solution culminates in the 'correct' calculation of the axial loads on the columns. The task is very clearly an academic exercise with no professional ambiguity.</p>	
++C: By restricting the knowledge requirements to structural mechanics and the artefact to a simplified unrealistic structure with a convergent solution, the task is very strongly classified.	++ F: The knowledge requirements and sequence of procedures are explicitly laid out, with clear requirements for the correct solution. Other than a vague reference to the profession: "other engineers should be able to follow your workings and check on their correctness " there is no ambiguity in the social relations; the task is a clearly academic exercise.	

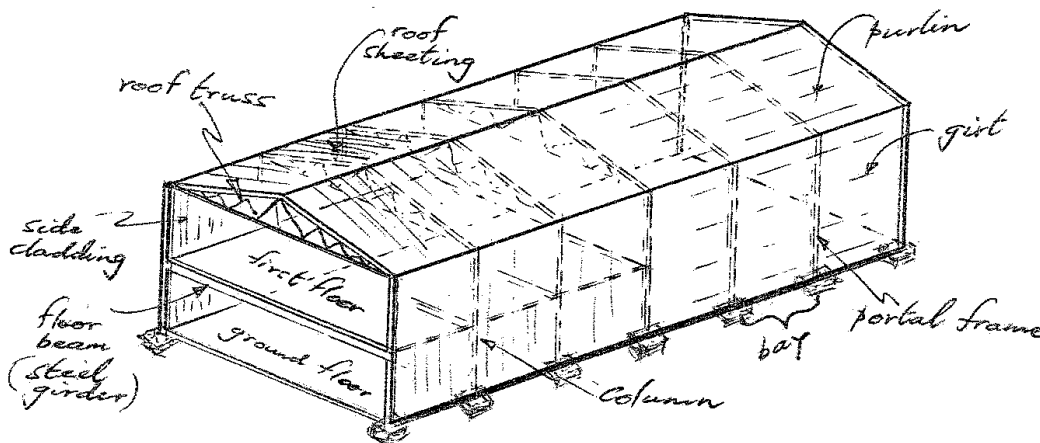
**S2: Steel structure**

<p><b>S2: Project description</b> The second design project in the structural engineering stream is located in the second structures course and involves the detailing of a steel structure through a sequence of tasks in which students detail each of the structural elements in the structure. The project culminates with a full set of technical drawings detailing the design.</p>		
<p><b>S2: Context (outer environment)</b> The only contextual detail required pertains to determining the wind loading and is given in discrete technical items in the first task: "Farmland area near Cape Town (suggests regional wind conditions) and an assumed altitude of 30m asl. Although the context includes contradictory or ambiguous details, because they are irrelevant to understanding the problem, the context can be seen as <i>simplified</i>.</p>		
SG-(h): The only contextual details	SD <sup>o--</sup> -(h): The categorisation of the area	SD <sup>d</sup> -(h): Each contextual feature is

<p>required and given are defined by the conceptual requirements of the analysis rather than emerging from the context. Although similar to M6 in terms of using the regional wind conditions (SG+(I)), the more ambiguous contextual information "building is situated in an industrial/farmland area near Cape Town" highlights the irrelevance of the context and the conceptually <b>imposed</b> rather than contextually emergent nature of the relevant details.</p>	<p>as "farmland", the Cape Town regional wind conditions and the altitude asl are each used to read factors of a table in the loading code. As such they can be treated as disconnected items rather than requiring any understanding. No other contextual detail is given or required.</p>	<p>defined in technical form related to specialised knowledge requirements, but they have been identified and separated and are dealt with sequentially. The wind loading raises the position in the category.</p>
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**S2: Artefact (inner environment)**

The artefact is a steel structure with a fully defined layout and identified key structural elements. Students are required to analyse the loading on the structure and specify the dimensions of the structural elements, and detail the steel connections as a combination of welded and bolted joints.

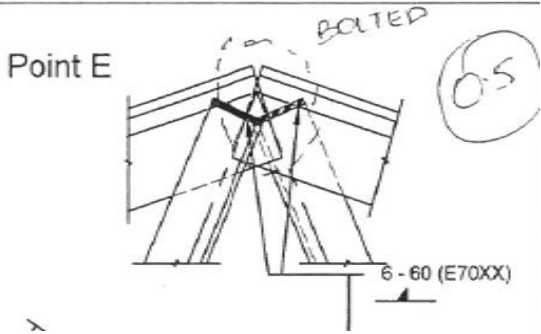


The presentation of the artefact in the brief, although a pictorial view, is a standard conceptual representation of an artefact, and consequently a simple form of specialised representation.

<p>SG++(I): The layout and key structural elements of the artefact are defined to an extent that the artefact takes a particular structural form. Although the element detailing is not defined, hence placing the artefact low in the very strong category</p>	<p>SD<sup>o</sup>-(m): Because the artefact is defined in terms of structural element choices and layout, students do not have to engage with material options and their consequences, therefore although there are simultaneous interdependencies between elements, these do not have to be considered, instead each element can be considered independently and sequentially. But the influence of sequential decisions on each other does place it in the middle of category</p>	<p>SD<sup>d</sup>-(h): The structural elements are labelled using specialised terms, which are associated with analytical procedures, but at the level of understanding the artefact these can be separated and treated sequentially. But they do indicate the need to use some more complex procedural calculations. The pictorial sketch is also a simple form of specialised design communication.</p>
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**S2: Solution:**

The solution details the specific dimensions of each of the structural elements identified in the brief, presented in many cases in detailed technical drawings. For example the wall girts are specified as cold-formed lipped Z-sections [125x65x20x2.0], which incorporated both manufacturing instructions, section shape designation, cross sectional dimensions associated with the shape designation and length. The connections are detailed in form and manufacturing detail, which requires consideration of load, geometric compatibility and manufacturing options and accessibility.



The solution further increases the specificity of the artefact, and strengthens the technical detailing. But the nature of the solution, presented in sequential assignments, imposes separateness on the design.

SG++(h): The solution details the specifics of the artefact further.

SD<sup>o</sup>-(h): Each structural element is detailed separately, and although there are some interdependencies, these are treated sequentially. But the independent detailing by students raises it high in the category.

SD<sup>d</sup>-(m): The fully specification of the structure and associated technical drawings are the result of multiple disciplinary procedural calculations. The step-by-step instructions in the brief reduce the code to the middle of the category.

**S2: inferences (detailing the solution):**

The bulk of the design work detailing the structural elements involves following specialised procedures which incorporate both ways of making ontic assumptions and ways of modelling the loads, deflections and strength characteristics of each element type. These procedures are laid out codes of practice, and operate as a way to simplify very complex ontic relations and translate them into symbolic form, and proceduralise complex discursive relations in relation to typical material cases. Although the codes of practice considerably simplify both ontic and discursive relations and allow them to be considered sequentially, an appreciation of both the underlying real mechanisms and the discursive antecedents are required as the inferential chains become longer.

For example, the loading codes define how to determine a normalised wind speed and resultant pressure effect, but this result needs to be considered in relation to the building geometry, and a recognition that the wind direction changes and with it the geometric interaction. The code specifies how to approximate the upwind, downwind, roof slope, internal and external pressure, and these need to be considered in conjunction with the dead load (element mass) in the various configurations. Insight beyond the symbolic results of the procedural calculations is required to make informed design decisions, about what to calculate, which are the critical loading configurations and how to combine the various loading contributions in each of the subsequent tasks.

With the relevant loading configurations determined, and the magnitude of the load approximated based on the loading code, the element sizes can be determined so as to be large enough not to 'fail' (bend beyond defined limits or yield). But the sequence of sizing is important because the cladding adds to the loading on the purlins and girts, which with the roof truss add to the loading on the columns etc. By defining the sequence of tasks in the brief students do not need to make sense of these ontic interdependencies, and can instead treat them sequentially without appreciation.

The final joint specification is a return to important ontic relations in terms of geometric compatibility in addition to procedural strength calculations. The three dimensional sections need to be connected such that flat sides requiring bolting or welding are actually in contact and can fit together.

SG++↓SG-↑↑SG++: Generally the inferential chains begin with the particular artefact or structural element, which needs to be described in more general terms in order to model the performance, general laws, specialised for application to particular structural elements in the codes of practice are imposed on the particular configuration. Judgements are made as to the adequacy of the result of the procedural calculations in relation to the specific case. This follows a pattern of progressively weakening and then strengthening the semantic gravity, as each element is detailed.

SD<sup>o</sup>-(h)↓SD<sup>o</sup>-(l)↑SD<sup>o</sup>-(h): The task is essentially reduced to determining the effect of the loading on the various structural members. Although there are complex interdependencies between the loading of the various structural elements (SD<sup>o</sup>+), by defining the sequence of tasks, these interdependencies are identified by the lecturer and can largely be treated sequentially by the students (SD<sup>o</sup>-). The procedural calculations themselves act as proxies for the complex ontic relations, and simplify them into discrete steps. However, at the end of the procedural calculations, the results need to be considered in relation to the overall structure, increasing the semantic density of the ontic relations somewhat. But the reasoning remains in

SD<sup>d</sup>-(l)↑SD<sup>d</sup>+(l)↓SD<sup>d</sup>-(l): Overall the project is limited to consideration of strength and deflection of the various structural elements under an approximation of the likely loading on the structure, which suggests SD<sup>d</sup>-(h). The calculations are procedural, and the sequence is defined in the codes of practice, but they are based on complex theoretical models of material responses (continuum mechanics) and would not make sense with a reasonable appreciation of the concepts and relations between concepts on which the procedures are based. Although both the codes, and the prescribes sequence of tasks function to identify and separate the various concepts, meaning lies in the relation of the concepts to each other

	the weak category.	(SD <sup>d</sup> (I)). The general inferential chains follow cycles of listed technical specifications given in the brief (SDd-(I)) through complex procedural calculations (SD <sup>d</sup> (I)) and finally a result, reported as a discrete specialised symbol (SDd-(I)), which needs to be judged in relation to the ontic realities.
<b>S2: Recontextualisation</b>		
<b>Classification:</b> The project is limited to structural design considerations based on codes of practice, while the codes of practice shift pure disciplinary knowledge in the direction of applied sciences, the relevant knowledge is firmly bounded. There is very little need to consider contextual aspects, as they are given in specialised form in the brief. Because of the tightly defined structural layout and element prescription there is no scope for divergence in the solution, and the calculations can be checked for accuracy.		<b>Framing:</b> The relevant knowledge and sequence of tasks is prescribed explicitly in the brief. The requirements of the solution is clear, and although the brief sets up the students as professional engineer, other than the mention of a 'client' there is no need for students to mimic professional expectations. The sequencing and evaluation are unambiguously academic.
+C: The strongly bounded specialised knowledge and convergent solution keep the project strongly classified, but the use of codes of practice weakens the classification very slightly because generalisable theory is specialised to typical cases in the codes of practice.		++ F: The selection and sequencing, and evaluative criteria are explicit and unambiguous, the social relations position students unproblematically as students.

### S3: Concrete slab

<b>S3: Project description</b> The third design project in the structural engineering stream is located in the third structures course. Students categorise and size a range of concrete slab and beam configurations provided in an single floor of a multi-storey building.		
<b>S3: Context (outer environment)</b> No context is provided, although the live load defined in the brief as "the imposed service load $w_i = 4 \text{ kN/m}^2$ applied uniformly all over the slab" would normally be derived from the use to which the structure is put in operation. If anything, the context would be described as extremely <i>simplified</i> .		
SG-(I): the live load prescribed in the brief is imposed as a requirement for the procedural calculations, and would be determined from the purpose of the structure, but no purpose is mentioned (I).	SD <sup>o</sup> -(vI): No reference to any context is required, but the single technical designation that would be derived from the context is provided in the brief and requires no reference to its material origin..	SD <sup>d</sup> -(I): A single technical designation that would be derived from the context is provided to prescribe the live loading.
<b>S3: Artefact (inner environment)</b> The artefact is described in the brief as "a typical reinforced concrete suspended floor" it is suspended on beams and supported by columns. But it is completely simplified and dislocated from any real structure. Like the task in S1, the "slabs" are set up to illustrate a range of theoretical variations rather than to perform any real material function. However, the artefact differs from S1 in that the specifics of the relation between the beams and each slab that spans them need to be categorised in order to identify the appropriate calculation procedure.		
SG-(I): Although the claim that the artefact is "a typical reinforced concrete suspended floor" suggests SG+, the logic of the slab configuration is to include as wide a range of possible slab configurations rather than to perform a material function. The layout is therefore imposed from a body of specialised knowledge rather than emergent from any contextual reality (SG-). The dislocation of the slab from significant structural detail places it very low in the category.	SD <sup>o</sup> -(I): Each slab does need to be considered in terms of its supports and its basic dimensions in order to characterise it, but other than that there is very little consideration of the ontic relations required in this task. These are discrete and simple considerations (SD <sup>o</sup> -). But the disconnected nature of the slab suggests a somewhat disconnectedness between ontic relations, placing it low in the category	SD <sup>d</sup> +(I): the artefact details provided in the brief list technical specifications and the slab is represented as a partial technical drawing with specialised designations. Although conforming to technical drawing conventions, it slides very close to a diagrammatic textbook representation, which reduces the specialisation of the knowledge. Each 'slab' in the overall layout can be categorised independently of the others, and sized following sequential procedures (SD <sup>d</sup> -). But the collection of different slabs is set up to highlight comparisons between analytical techniques for sizing each of the slabs.
<b>S3: Solution:</b> The solution consists of a table that lists the dimensions (length: given in the brief; breadth & height: calculated and then modified		

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for geometric compatibility) for each of the structural elements labelled in the brief.

Table 1: Slab panel classification, length, depth and height.

Panel No.	Classification	Effective Depth	Length L (mm)	Depth $d_{slab}$ (mm)	Height $h_{slab}$ (mm)	
A	Cantilever	L/7	1,400	200	230	230
B	Two-way spanning, one short span end continuous	L/29	4,100	141	171	170
C	Two-way spanning, one short span end continuous	L/29	4,100	141	171	170
	One-way spanning, one span end	L/23		178		

SG+(m): Although the solution specifies the overall dimensions of each slab or beam, they are still coded as generic elements because the structure does not hold together as an integrated artefact.

SD<sup>o</sup>--(h): The separation of each slab and beam functions to dislocated the elements from each other. The presentation of the solution in a table rather than as a dimensioned technical drawing undermines the connectedness and emphasises the dislocation and categorisation of each calculation as a discrete entity (SD<sup>o</sup>--). However, the sizing of elements that link in the structure do need to be considered in relation to each other, which places it high in the category.

SD<sup>d</sup>-(l): The solution does not show the procedural calculations behind the listed dimensions, so although listed with the reference to technical slab classifications and precise labels and symbols, the knowledge on which the specified dimensions are based is not visible.

**S3: inferences (detailing the solution):**

There is very limited information in the solution or marking memo to indicate the nature of the inferences. However, it appears from the instructions in the brief, and the location of the project in a structures course that the following process is most likely:

- The beam or slab is classified in relation to its support and L/d ratio from a list provided in the brief, for example:

"one-way spanning, one span end continuous  $d = L/23$ " [S3:b2]

- Based on the given loading conditions prescribed in the brief the minimum allowable dimensions are calculated following the procedural calculations laid out in the ultimate limit state code of practice.
- The calculated dimensions are judged in relation to each other where they connect and modified on the basis of geometric compatibility

SG+↓SG-↑↑SG++: the logic of specialisation follows a type categorisation, imposing the appropriate procedural calculations and finally specialising the dimensions in relation to both the calculations and the specifics of the geometric compatibility

SD<sup>o</sup>-(l)↓SD<sup>o</sup>-(vl)↑SD<sup>o</sup>-(l): By stripping the structure of ontic complexity, students can treat each slab as a discrete element. Within the category there is a slight weakening of the ontic relations once the categorisation of the slab has been made and while the calculations are performed, followed by a slight strengthening as the dimensions are judged in relation to one or two other elements.

SD<sup>d</sup>-(vl)↑SD<sup>d</sup>-(m)↓SD<sup>d</sup>-(vl): Although the descriptors are specialised, there is very limited requirement for a coherent appreciation of the knowledge on which structures is founded. The procedural calculations are an increase in the SD<sup>d</sup>, but can be followed procedurally, step by step. And the solution merely lists the results, further weakening the SD.

**S3: Recontextualisation**

The context is completely stripped and the structure is reduced to an idealised slab supported on beams and columns, the reduction of the material details places this firmly in the structures discipline. The use of codes of practice to do the procedural calculations both strengthens the framing and brings the reasoning closer to 'the world'. Codes of practice function to regionalise structural mechanics knowledge. The solution is presented as a list of analytically correct values without backup calculations or justifications, as prescribed in the instructions

**Classification:**

Only structures considerations are required, and the solution is convergent and precise. The use of codes of practice does weaken the classification very slightly.

**Framing:**

The knowledge is clearly limited to structures and the use of codes of practice, the sequencing is implicit, but not open. The codes of practice function to strengthen the framing over selection and sequencing. The requirements for the solution are clear and there is no professional modelling to create ambiguity.

+C: All aspects are strongly classified, but the regionalisation inherent in the use of codes of practice weakens the classification very slightly.

++ F: All aspects are strongly framed

### S4: Parking garage

#### S4: Project description

The fourth design project in the structural engineering stream is located in the fourth structures course. Students are required to design a multi-storey parking garage on a defined piece of land to meet the increased parking capacity demands in the area. They need to conceptualise the structure for the first time, consider aspects of demand, vehicle access and geotechnical issues in addition to the structural aspects. Because of time constraints, the design is not complete in every detail, but the selections of details is left to the students to determine.

#### S4: Context (outer environment)

The parking garage is to be located

"under the three rugby fields of the UCT upper campus. The rugby fields must be reinstated, albeit about 2 m higher, with new E-W road, footpath and cycle way connections with Stanley Road, below the M3 freeway" [S4:b1]

The specific context is given in the brief provides real material constraints to the solution, including overall dimensions, number of levels possible, limits to entrance and exit points. The layout of the parking spacing and configuration is informed by transportation planning norms, as are the entry and exit details. Standards specify safety considerations in terms of ventilation, emergency exit requirements and fire standards, all of which need to be considered. The nature of an underground parking close to existing structures means that geotechnical considerations and drainage details (hydrology and geotechnics) are necessary.

The context is *real* and accessible to students both in a lived embodied experience and as defined through the lens of the multiple disciplinary specialisations that they have learned in the course of their prior courses.

SG<sup>m</sup> the context is again the UCT campus, a real, and specific context.

SD<sup>o</sup>+(l): the context requires an integrated understanding of the multiple material influences at play, but their more advanced knowledge of various disciplinary specialisations can help students to untangle the more important aspects from the less important ones, this can function to weaken the SD<sup>o</sup>. Located in the structures course, privileges ontic relations that relate to structural form and function, further weakening SD<sup>o</sup>.

SD<sup>d</sup>+(h): There is an expectation that students will draw on multiple disciplinary specialisations simultaneously in order to make sense of and organise their understanding of the context. The disciplinary input is sometimes at a more general than detailed level, requiring a coherent insight into the specialisations, but not detailed analysis. Again, the location in a structures course privileges specialised structures knowledge, but insights from geotechnical and transportation engineering locate it high in the category.

#### S4: Artefact (inner environment)

A parking garage is a relatively simple structure, but in relation to the contextual details that students need to consider, the complexity of both the discursive and ontic relations in relation to the structure are increased. The structure needs to be understood in context, and in order to develop a functional layout along with detailing adequate dimensions to safely support the applied loads, and because the brief does not specify the artefact in detail, student need to develop the understanding themselves.

SG<sup>+</sup>(l): A parking garage is a structural type, but the layout and detailing is left to the discretion of the student weakening the SG of the prescription.

SD<sup>o</sup>++(l): Like the context, the structure needs to be understood as a complex artefact with multiple influences. The lack of prescription in the brief leaves the identification to the students, but codes of practice do help to direct significant aspects to some extent.

SD<sup>d</sup>+(h): Being located in a structures course at the end of the trajectory of structures indicates that structural analysis is a significant disciplinary consideration. Although students are expected to incorporate insights from other disciplines, these tend to be in relation to the context rather than the artefact directly.

#### S4: Solution

The solution is presented as a report detailing the layout and dimensions of various structural elements. The focus is on the assumptions and design decisions, but the lack of a final detailed technical drawing to hold the design together undermines the coherence of the final design and retains unnecessary detail and complexity relating to the inferences.

SG<sup>++</sup>(l): the structure is specified in precise and unique detail, although the scope of the design means that many aspects are left unspecified.

SD<sup>o</sup>+(m): The lack of a comprehensive set of drawings both increases the ontic SD by not simplifying them in a final output, and leaves them somewhat disjointed as each aspect is considered sequentially, but not integrated into a final design

SD<sup>d</sup>+(h): because the solution lies in the inferential reasoning rather than being summarised in a technical drawing the solution requires focus on the inferential disciplinary knowledge

#### S4: inferences (detailing the solution):

The inferences typically follow waves from making sense of the specifics of the artefact in context, both in terms of the ontic relations, and informed by discursive insights from multiple disciplines. For example, parking requires entry and exit points, which recruits transportation planning insights, a shift from specific material issues to more general discursive insights. These insights direct specific details, such as entry and exit points, spacing and parking orientation. All structures require foundations,

APPENDIX 2

and understanding the geotechnical details of the context including drainage concerns requires those disciplines to be recruited. When engaged in conceptual design, the inferences tend to draw simultaneously on multiple disciplines, but at a relatively simple level, so contours, geotechnical and existing traffic patterns feed into capacity and layout decisions. Once the detailing phase begins, each aspect tends to be modelled analytically using far more detailed and complex mathematical modelling procedures; sizing the structural elements draws on structural mechanics without concern for other disciplines. The modelling introduces more general conceptual theory imposed on the structure and ends with a very abstract answer which needs to be interpreted in terms of what it means for the structure. Students need to go through many of these cycles as they size each structural element

<p>SG+++↓SG+↑SG+++↓↓SG-↑↑SG+++: there are multiple cycles, beginning with the specific context, weakening the SG to account for typical contextual influences, strengthening the SG to incorporate them in the artefact and specialise the artefact, weakening the SG to use a procedures from particular disciplinary specialisation imposed on the structure to model performance and then strengthening the SG to make specific decisions in relation to the artefact as the artefact is specified in increasing specificity and detail.</p>	<p>SD<sup>o</sup>+++↓↓SD<sup>o</sup>-↑SD<sup>o</sup>+↓SD<sup>o</sup>--↑↑SD<sup>o</sup>+: the inferential chains begin with an embedded understanding or the extremely complex context in relation to a general appreciation for the structure as a complex artefact, the embedded nature of these things needs to be simplified by identifying key aspects of each, often informed by disciplinary insights, but also emergent from a coherent understanding. These sequential insights need to be considered in relation to each other in order to make conceptual decisions. Once the layout is decided, the various structural elements can be dislocated from each other and analysed independently, but decisions about the final dimensions requires the models to be considered in relation to the whole structure.</p>	<p>SD<sup>d</sup>--↑↑SD<sup>d</sup>+(l) SD<sup>d</sup>--: Initially the structure and context can be experienced in unspecialised form, but the introduction of disciplinary specialisation helps to simplify the ontic complexity by separating significant aspects and eliminating superfluous detail. Once some key conceptual design decisions are made the detailing of the structure draws in individual disciplinary specialisations, and identifies and uses sequential procedural calculations. The final specification reduces the description of the artefact to sequential details, but presented in technical drawings and specifications.</p>
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**S4: Recontextualisation**

<p><b>Classification:</b> Students need to draw on multiple disciplinary specialisations, although being located in a structures course does privilege structural mechanics over other disciplines. They need to draw on both specialised and unspecialised knowledge, and because the structural layout is not prescribed in the brief, the solution is completely divergent.</p>	<p><b>Framing:</b> Although structural mechanics is an important disciplinary knowledge field, students need to identify and select from a wide range of other disciplines too. The sequence is only defined by a standard design process of conceptual design, detailing and consideration of construction. How students proceed through the various aspects of the structural design is left to them to determine. Although the students are required to present their design proposal to a 'client', there does not appear to be much ambiguity introduced by this role-play. Because of time constraints, the design is not complete in every detail, but the selections of details is left to the students to determine, this leaves some control of the assessment criteria in the hands of the students, but also introduces ambiguity</p>
<p>--C: The project is weakly classified in terms of specialisation, disciplinarily and convergence of the solution.</p>	<p>-F: Selection and sequencing of knowledge is left to the student to determine, and is compounded by the decisions about what to focus on and what to leave out because of time constraints. This further weakens the framing by not specifying the evaluative criteria precisely. Although there is a potential for ambiguous social relations, these do not appear too serious in this project.</p>

**C5: Future foreshore**

<p><b>C5: Project description</b> The 9th civil engineering project involved a development proposal for the Cape Town foreshore area, a piece of land between the centre of Cape Town, the harbour, and a large tourist centre. Students were required to propose an overall development plan to improve the precinct, including the full detail design of a number of key infrastructural elements. Typical infrastructural elements selected by students included multi-storey buildings, on/off-ramps to link the incomplete elevated freeway system with the existing road network, integrated public transport systems, water/sewage/stormwater reticulation systems, basement and retaining structures amongst other possibilities.</p>
<p><b>C5: Context (outer environment)</b> The context is real and specific, "The north Foreshore precinct is a derelict part of the city characterised by neglected and unused open spaces and remnants of an older freeway-building era. Yet there is great potential to make use of this precinct to create a vibrant, mixed use area, open and attractive to all Capetonians, demonstrating principles of integration and sustainability, and</p>

<p>possibly re-establishing the historical link between central Cape Town and the sea. Major new planned projects in this area and in relation to the Port make this task an urgent one." 02-FF</p> <p>Student have access to this precinct both in unspecialised ways through their experiences in the precinct and site visits to the precinct, and specialised in documents detailing geotechnical conditions, GIS data on contours, land use existing services, transportation reports, planning documents, architectural drawings etc. Student were also required to attend seminars by professionals working in related projects, including a</p> <ul style="list-style-type: none"> <li>• A civil engineer and sustainable transport specialist) history of transportation planning in Cape Town</li> <li>• A consulting engineer with experience in international infrastructure projects</li> <li>• Representatives from Western Cape Provincial Government Department of Economic Development and economic development in the Province.</li> <li>• Student presentations of prior related projects (CEM, costing; Architecture, building designs within precinct; Urban planning, precinct plans)</li> </ul> <p>Although these supplementary materials add complexity to the context, they also shift the context out of a horizontal towards more vertical discourse.</p> <p>The context is <i>real</i> and accessible on many levels to the students.</p>		
<p>SG++(h): The context is specifically defined as a precinct in the Cape Town Foreshore area.</p>	<p>SD<sup>o</sup>+(h): Students need to get to know the complex embedded real aspects of the foreshore in order to identify significant features and discard others and to consequently locate their design. Some of the supplementary documentation and presentations do begin to identify some of the key issues in the context, but students are required to investigate further and draw on their own interpretations too. The initial stage of stripping irrelevant detail and identifying significant aspects retains a high level of integrated insight, placing it high in the category.</p>	<p>SD<sup>d</sup>++(l): Initially the context is presented in everyday or unspecialised terms and students are expected to draw on their own experiences of the context (SD<sup>d</sup>--(h)). As the project progresses, supplementary notes and presentations do begin to introduce specialised knowledge, and students are required to collect additional specialised information into the precinct themselves, this significant increase in the specialised knowledge of the precinct (is part the inferential process of diagnosis).</p>
<p><b>C5: Artefact (inner environment)</b></p> <p>This is the only project in which the artefact is not prescribed. Students are instructed to develop a plan for the precinct which includes the development or modification of infrastructural elements, and are required to each detail one of the infrastructural elements. But they are left to decide on what they would each like to design. Examples included but were not restricted to multi-storey buildings, on/off-ramps to link the incomplete elevated freeway system with the existing road network, integrated public transport systems, water/sewage/stormwater reticulation systems, basement and retaining structures.</p>		
<p>SG-(h): the prescription of an infrastructural element was coded as a conceptually imposed generic artefact, more general than an artefact type, but close to the boundary with type..</p>	<p>SD<sup>o</sup>++(m): The ontic relations are coded as strong SD because in order to design an infrastructural element from scratch requires a coherent appreciation of the vast potential of what it can be and how it can function.</p>	<p>SD<sup>d</sup>++(l): The design of an artefact with such limited prescription can require multiple disciplinary insights to develop to a point of being safely operational. Although some artefact, such as water services, may draw on fewer disciplines and consequently code at a lower SD</p>
<p><b>C5: Solution</b></p> <p>The solution presented in a set of drawing representing the full development plan, and technical drawings detailing the technical design. The solution is evaluated based on these drawings, a limited report detailing the key design decisions and an individual oral examination based on the presentation and defence of design justifications founded on multiple disciplinary specialisations.</p> <p>The solution includes an integrated development plan for the precinct including proposals for infrastructural development to upgrade the precinct within a financially viable plan, and the detailing of one infrastructural element per group member. The detail design included design calculations based on disciplinary procedures in order to model relevant aspects of performance. These might include structural strength determinations, geometric alignment of roads to accommodate defined vehicle design speeds, flow capacities for water services, ground conditions to support building foundations etc. Students were also required to produce technical drawings detailing aspects of their designs.</p>		
<p>SG++(h): The solution involved detailing the artefacts in context, or specialising them to perform in the specific context</p>	<p>SD<sup>o</sup>+(m): The solution included identifying and specifying layouts and dimensions of the artefact taking into account multiple simultaneously interacting influences. However, the artefact is never built, so never embedded back in the context and tested in the world. The solution is judged based on what the student identifies as significant. This restricts the solution (if judged</p>	<p>SD<sup>d</sup>-(h): The drawings presented summarise the output of the design process so that the solution can be described in simple technical language. The relations between the multiple drawings raise the position in the category. In the oral examination, the solution is judged based on the design justifications founded on multiple disciplinary specialisations SD<sup>d</sup>++(l).</p>

		adequate) to the strong category.	
<p><b>C5: inferences (detailing the solution):</b>                  The inferences typically follow the same sort of patterns described in S4, waves from making sense of the specifics of the artefact in context, both in terms of the ontic relations, and informed by discursive insights from multiple disciplines. However, because the context is larger and the selection of infrastructural elements is far wider, there are far more cycles of inference and far more variation possible.                  When engaged in conceptual design, the inferences tend to draw simultaneously on multiple disciplines, but at a relatively simple level, so contours, geotechnical and existing traffic patterns feed into capacity and layout decisions. Once the detailing phase begins, each aspect tends to be modelled analytically using far more detailed and complex mathematical modelling procedures; sizing a range of elements draws on a very wide range of disciplines, some defined by the infrastructural element being designed, others by interaction with associated element. But like S4 the modelling introduces more general conceptual theory imposed on the artefact and ends with a very abstract answer which needs to be interpreted in terms of what it means for the artefact, and those around it. Students need to go through many of these cycles as they model the performance of the artefact in order to determine its performance.</p>			
<p>SG<sup>++</sup>↓SG<sup>+</sup>↑SG<sup>++</sup>↓↓SG<sup>-</sup>↑↑SG<sup>++</sup>:                  repeated cycles between the specifics of the particular context into more generic descriptions amenable to technical analysis</p>	<p>SD<sup>°++</sup>↓↓SD<sup>°-</sup>↑SD<sup>°+</sup>↓SD<sup>°--</sup>↑↑SD<sup>°+</sup>:                  cycles that originate in the complex context/artefacts and extract salient and relevant aspects out of the full context/artefacts for the purpose of particular technical analyses.</p>	<p>SD<sup>d--</sup>↑↑SD<sup>d+(l)</sup> ↓ SD<sup>d-(h)</sup> ↓ SD<sup>d-(l)</sup>:                  from an initial experiential and common sense understanding of the context, the addition of disciplinary information and codes of practice cyclically increase and decrease the complexity of the disciplinary interpretations of the context/artefacts.</p>	
<p><b>C5: Recontextualisation</b></p>			
<p><b>Classification:</b>                  The project draws on specialised and unspecialised knowledge, and draws on multiple disciplines. The solution is completely open and divergent.</p>	<p><b>Framing:</b>                  Very little about this project is specified except the three submission dates. Students need to make sense of the context and plan the precinct with minimal guidance either explicitly in the brief, or implicitly by location in a course. With no specification of knowledge selection, the sequence is open too. On of the major challenges in the course is that students are positioned as professional engineers with very little academic guidance, yet they are subject to academic evaluation, on the basis of adequacy. There are no formal evaluative criteria, instead an internal academic and external professional engineer judge the submission on the basis of 'professional adequacy'. With the very weak framing of everything else, this was an extremely challenging project</p>		
<p>--C: The project is very weakly classified in all respects</p>	<p>-- F: Selection and sequencing of knowledge was extremely weakly framed, compounded with ambiguous social positioning and very unclear evaluative criteria, the project was so weakly framed as to be very distressing for most student.</p>		

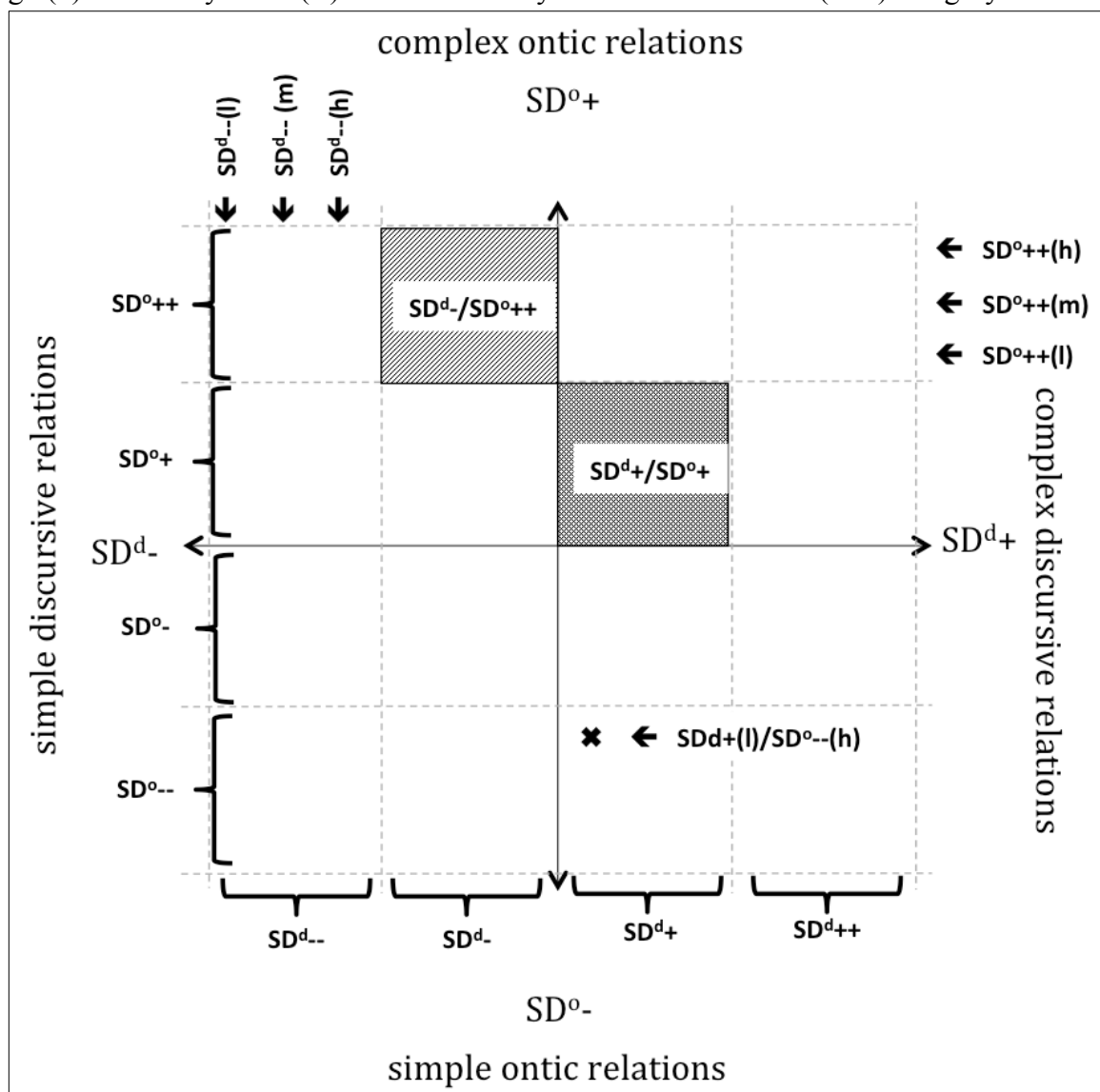
### Appendix 3 Semantic density graphics

The figure below explains the graphs that illustrate the findings of the LCT(Semantics) analysis presented in chapter 6.

Each row represents a different category of  $SD^0$ ;  $SD^{0++}$  at the top and  $SD^{0--}$  at the bottom  
 Each column represents a different category of  $SD^d$ ;  $SD^{d--}$  on the left and  $SD^{d++}$  on the right

Each cell represents a semantic code;  $SD^d-/SD^{0++}$  and  $SD^{d+}/SD^{0+}$  are illustrated in the figure

Within each cell a relative complexity is represented by high (h), medium (m) and low (l).  
 The position  $\times$  represents the code  $SD^{d+(l)}/SD^{0--(h)}$ ;  
 low (l) in the strong (+) semantic density of the discursive relations ( $SD^d$ ) category and  
 high (h) in the very weak (--) semantic density of the ontic relations ( $SD^0$ ) category.



## Appendix 4 Inferential reasoning

### *Inferential steps M3 (Gearbox design)*

The basis of reading the inferential network for M3 (Gearbox design) is the same as that described for M1 (Bearing mounting) in section 6.3.4. But the artefact was substantially more complex than M1. The multiple components (gears, shafts, bearings and a housing) all interact and function in interdependent ways, requiring consideration of geometric compatibility (for both operation and assembly), functional predictability (able to deliver the required load and power at the required speed) and reliability (strong enough to not break under load or fatigue). The complexity of M3 ( $SD^0+$ ) resulted in far more inferential steps than M1, resembling more of an inferential network than an inferential chain.

The inferences for M3 are shown in a sequence of three diagrams each building on the previous diagram. The first diagram shows the first two steps, the next adds steps 3 and 4 and finally the last shows all six steps.

As for M1, the context ( $\square$ ) in M3 was simplified, but with a little more detail provided ( $SG-/SD^0--(h)/SD^d-(m)$ ). The artefact ( $\bullet$ ) had substantially more components that interact in interdependent ways, and need to be considered simultaneously, although modelled sequentially as prescribed in the brief ( $SG+/SD^0+(l)/SD^d-(m)$ ). The solution ( $\times$ ) for M3, was coded ( $SG++/SD^0+/SD^d-$ ), a specific instantiation of a gearbox, with multiple simultaneously interdependent components, represented in a technical drawing, but including assembly instructions which increase the semantic density of the ontic relations. In order to get to the solution, multiple steps were required, and some iteration between steps was necessary.

The chain of inferences laid out in the marking memo suggest the following sequence:

1. Firstly the **number of teeth** on each gear was determined. In order for the input and output shafts to rotate in the same direction, a two stage gearbox was needed, because a gear pair reverses the direction of rotation of the shafts. To ease the assembly the input and output shafts need to be on the same horizontal plane, but if the gear pairs do not have the same number of teeth they will not be coaxial. Using gear pairs with the same module (tooth size) and similar ratios minimises the distance between the shaft axes. The ratio of gear teeth is the same as the ratio of shaft speeds, but because all gears have whole teeth, there are not infinite possibilities of gear ratios and consequently the shaft speed may not be exactly the required speed ( $SG+/SD^0+(l)/SD^d-(l)$ ). The inference require input from the context ( $\square$ ) as well as an appreciation for the artefact ( $\bullet$ ).
2. The second step was to determine the **gear forces** and size the width of the gear required to carry the forces developed. The determination of the gear forces is a shift away from contextual particulars into a representational form that can transcend contexts ( $SG-$ ). The type of gear required for 'low noise' introduces an axial load in the system as a result of the helical angle, but this is defined along with the pressure

angle for the gear teeth prescribed. Although the geometry of the gear (diameter, module, tooth shape and number) determines the forces, the actual calculations are conceptually defined and the only ontic consideration is that the direction of the helix chosen determines the direction of the axial load induced ( $SD^0-(l)$ ). Although prescribed in the brief, it results in a reasonably complex vector analysis that can then be used to determine the width of the gears needed to support the power transmitted. The calculations, although procedural, embed fatigue, stress analysis and strain limitations simultaneously ( $SD^d+(l)$ ), and require some discursive insight to apply competently. In addition to contextual and artefact considerations, decisions made in the first step also have consequences for the second step.

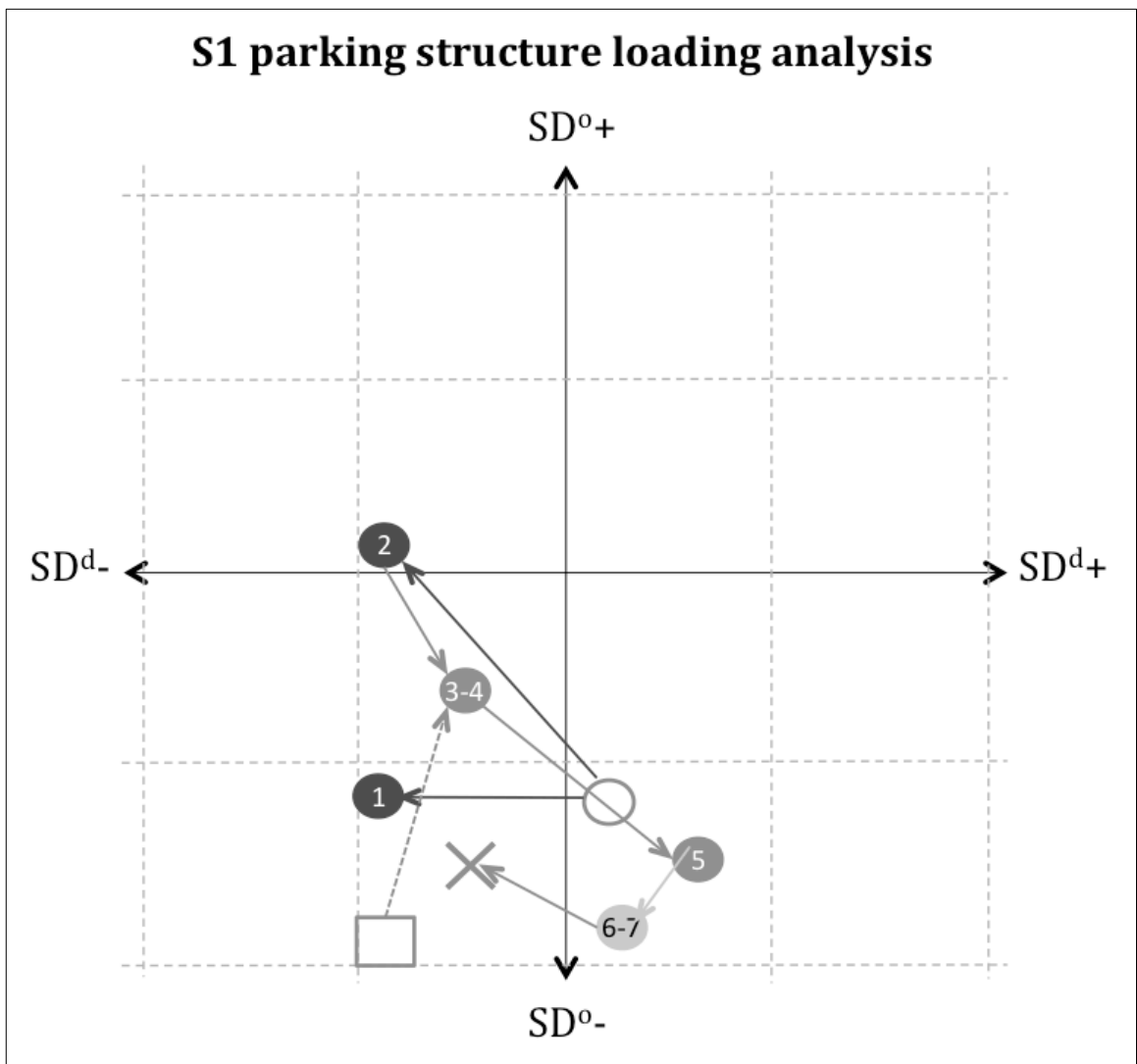
3. The specification of the required **gear width** ( $SG++$ ) follows a standard prescribed procedure. Although based on models and tests of gear strength and failure, in order to determine the width of the gear required to transmit the required load, a procedural calculation can be used. Although the calculations do embed fatigue, stress analysis and strain limitations simultaneously, no conceptual understanding of these interrelations are actually required to perform the calculations ( $SD^d-(m)$ ). Because the procedures are well established, and because all material input data is provided as discrete items in the brief, the ontic relations can be treated as discrete and dislocated input variables in the calculations ( $SD^0--(h)$ ). Input from the context and artefact force calculations fed into the tooth width calculations, which in turn defined part of the solution
4. The **layout** of the bearings and gears on shafts depends on the direction of the gear forces as well as assembly and manufacturing considerations. Each shaft requires one locating and one floating bearing. The direction of the axial load determines which bearing should be locating (locate the shaft in place axially) and floating (allow the shaft some axial movement to accommodate any thermal expansion and dimensional variability). Raised shoulders on the shaft function to locate the bearings on the shaft, but the position of the shoulders may be restricted by assembly considerations. The width of the seats is determined by the width of each component seated on the shafts. The design of the **housing** is a geometric puzzle that includes a casing that can house all the gearbox parts, locate them as intended for operation, and allow assembly (and disassembly) of the component parts into an assembled whole ( $SD^0+(h)$ ). The layout and housing are then fully specified ( $SG++$ ) in a technical drawing ( $SD^d-$ ).
5. The **diameters** of the various shaft sections are determined ( $SG++$ ) from the interaction between the forces transmitted from the gears, the location of the forces which depend on the lengths of the various shaft sections and the material used for the shaft ( $SD^0+(l)$ ). The process of designing the shafts involves in iterative process of checking shaft sizes in a complex three dimensional vector system, selection of appropriate two dimensional systems in which to do the deflection and strength calculations, the use of principle of superposition to determine the resultant three dimensional stress and deflections, and a check on the tested shaft size. A solid foundation in mechanics is required ( $SD^d+(h)$ ). The diameter specifications are based

on gear sizes and forces, the layout of the gearbox, and once determined feed into the solution.

6. The **selection of appropriate bearings** (SG++) depends on the resultant gear forces and the shaft geometry. The procedures of selection are the same as for M1 (SD<sup>d-</sup>(m)), but this time the forces are as a result of real material interactions rather than just prescribed, and the geometric interactions are more complex, because the shaft size needs to first be determined from strength and deflection calculations, and the assembly considerations are real and therefore more complex (SD<sup>o+</sup>(m)).

***Inferential steps S1 (Parking structure)***

The S1 context was simplified<sup>33</sup> (SG-/SD<sup>o--</sup>(l)/SD<sup>d-</sup>(l)), the artefact was idealised (SG-/SD<sup>o--</sup>(h)/SD<sup>d+</sup>(l)) and the solution was represented by dislocated discursive concepts (SG-/SD<sup>o--</sup>(m)/SD<sup>d-</sup>(m)).



A list of 8 inferential steps was provided in an addendum to the S1 project brief:

<sup>33</sup> SG is not coded with any reference to a relative position within a category, while the SD does have a relative internal category coding (l/m/h). This is simply because of the nature of the diagrams

Step 1 - “Take note of all dimensions [tabulated] that have been assigned to you as well as the unit weights of concrete and steel.” (SG+/SD<sup>o</sup>--(h)/SD<sup>d</sup>-(l))<sup>34</sup>

Step 2 - “Take a good look at the structure and try to isolate the various members i.e. beams and columns with a view of figuring out how the loads imposed due to the concrete slab and steel beam will contribute to each. It is advisable you make a rough sketch on scrap paper temporarily. Consider all beams continuous and likewise for all slabs.” (SG+/SD<sup>o</sup>+(l)/SD<sup>d</sup>-(l))

The first two steps weaken the semantic density of the discursive relations and strengthen the semantic density of the ontic relations as attention is drawn to the (albeit idealised) structure. The context was only drawn on implicitly in relation to the specified applied loads.

Step 3 - “Assign live loads to all suspended floors excluding the roof slab (level 3) according to the SANS code that has been provided to you taking note of the purpose for which the building will be constructed.” (SG-/SD<sup>o</sup>-(m)/SD<sup>d</sup>-(m))

Step 4 - “Divide the slabs into their respective tributary areas to determine what loads will be acting on the beams from the slabs. Don’t forget the self weight of the beams.” (SG-/SD<sup>o</sup>-(m)/SD<sup>d</sup>-(m))

The third and fourth steps are sequential, and both represent shifts to the application of conceptual knowledge onto the contextual detail, representing a weakening of the semantic gravity (SG↓) and the semantic density of the ontic relations (SD<sup>o</sup>↓), and a strengthening of the semantic density of the discursive relations (SD<sup>d</sup>↑).

Step 5 - “Calculate the dead and live loads for each tributary area including the self weights of the beams and cumulate the individual loads which act on each beam.” (SG-/SD<sup>o</sup>--(m)/SD<sup>d</sup>+(m))

Step five remains conceptual; but further weakens the semantic density of the ontic relations (SD<sup>o</sup>↓) and significantly increases the semantic density of the discursive relations (SD<sup>d</sup>↑).

Step 6 - “Draw your final sketches after the calculations to depict the point loads acting on the various beams.” (SG--/SD<sup>o</sup>--(l)/SD<sup>d</sup>+(l))

Step 7 - “Calculate your support reactions and from your sketches determine the reactions at the columns.” (SG--/SD<sup>o</sup>--(m)/SD<sup>d</sup>-(h))

Although students are instructed to sketch in the sixth step and the seventh uses the sketch, the sketch is a conceptualisation of the loading distribution in order to develop reaction force and bending moment calculations – these are generic representations intended to transcend contexts. The shift from distributed loads to approximate point loads further severs the ontic relations (SD<sup>o</sup>↓) and weakens the semantic density of the discursive relations (SD<sup>d</sup>↓) by making simplifying assumptions that simplify the mathematical modelling.

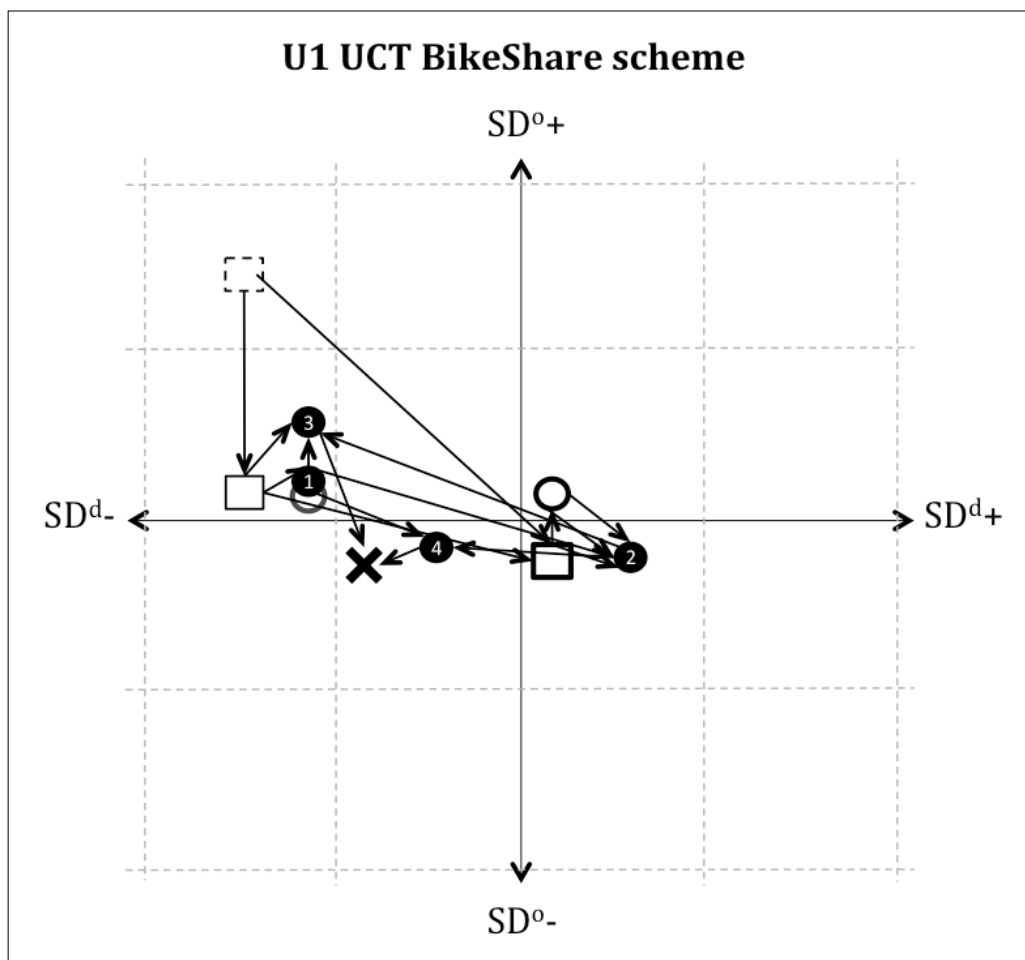
Step 8 - “Sum the reactions in each column to determine the total load acting on the columns and at the base of each column. Don’t forget the factored self weight of the columns.” (SG--/SD<sup>o</sup>--(m)/SD<sup>d</sup>-(h))

Step 8 represents the final solution (X). It reintroduces the lower level columns and links the simple summation of the output of previous discursive relations to a single material entity.

<sup>34</sup> The coding justifications are provided in appendix 2

**Inferential steps U1 (Bikeshare scheme)**

U1 (Bikeshare scheme) represents a fundamentally different project, one in which the ontic relations dominate, in some cases at the expense of the discursive relations. In this project there are two distinct aspects to the solution, that relating to the surveyed route and terrain changes, and that related to the specification of the details of the bikeshare scheme itself. Although the surveying and the Digital Evaluation Model are the focus of evaluation, the bikeshare scheme provides input for design decisions.



U1 drew on a real context ( $\square$ ), ( $SG++/SD^{o++}/SD^{d--}$ ). Initially students needed to draw on their experience of the context, and identify salient contextual features, weakening the semantic density of the ontic relations ( $SG++/SD^{o+}(1)/SD^{d--}$ ). From this initial interpretation they identified an appropriate route and surveyed it, again weakening the semantic density of the ontic relations by focusing solely on the spatial aspects of the context, and increasing the semantic density of the discursive relations by introducing the survey map ( $SG++/SD^{o-}(h)/SD^{d+}(l)$ ). Making sense of the context required engagement with the real context in both specialised and un specialised ways, which in turn informed each other. Both disciplinary meaning and everyday meaning informed the design of the artefact.

The artefact ( $\bullet$ ) can also be seen as two distinct parts, the bikeshare scheme itself, an intuitive, relatively generic solution founded un specialised knowledge ( $SG+/SD^{o+}(1)/SD^{d--}$

(h)) and the requirements to modify to terrain of specific route, requiring disciplinary knowledge ( $SG^{++}/SD^{0+(l)}/SD^{d+(l)}$ ). Both aspects of the artefact inform multiple inferential steps, again in a network rather than a chain.

The inferential steps required to specialise the solution drew on both context and artefact (both everyday and disciplinary insights into the route):

- Step 1 - From a sense of the campus, the various route options and a feel for what it would mean to cycle on the campus students select a route. This decision draws an everyday understanding of both the context and artefact. ( $SG^{++}/SD^{0+(l)}/SD^{d--(h)}$ )
- Step 2 - Once selected students survey the route. The surveying task integrates specialised knowledge skills and procedures of surveying, and simultaneously reduces the focus to only the formal representation of the terrain in the area of interest ( $SG^{++}/SD^{0-(h)}/SD^{d+(m)}$ ). The survey develops the context, but also draws on step 1, and an understanding of the functionality of the artefact.
- Step 3 - The third step develops the bikeshare scheme in detail, but mostly drawing on unspecialised knowledge. Students select bicycles and accessories, develop a bike 'shelter', a structure - but without consideration of structural engineering, detail the logistics of the borrowing and bicycle location. They do however need to consider the context and route ( $SG^{++}/SD^{0+(m)}/SD^{d--(h)}$ ),.
- Step 4 - These specific but unspecialised details inform modifications to the terrain, for example, the modification of gradients to facilitate moderately competent cyclists ( $SG^{++}/SD^{0+(l)}/SD^{d-(h)}$ ).

The modifications to the terrain proposed in step 4 are represented in the final solution (X), which as is typical of a technical drawing, strips the complex ontic and discursive reasoning and represents the solution in simple technical specifications that can be read sequentially, but because the drawing principles appear not to have been strictly followed it places low in the  $SD^d$ - category ( $SG^{++}/SD^{0-(h)}/SD^{d-(l)}$ ).