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The WiSE Approach to Engineering Educational Environments

Craig Geoffrey McLauchlan
University of Wollongong

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Supervisors: Associate Professor P. Ciufo & Dr T. Goldfinch

The University of Wollongong
The Faculty of Engineering and Information Sciences

Abstract

Developing teaching laboratories for complex applied technical fields can be expensive and carries significant risk for the sponsoring University or institution. Laboratories are typically developed as projects requiring development of sophisticated systems (including hardware, software, and curriculum) delivered as a functioning whole that is: useful to staff, attractive to students and produces the required educational outcomes. All within constraints of cost, time, space and staffing.

The application of Electric Motor and Drive (EMD) systems in developed society is emblematic of complex applied technical fields that engineering students must be prepared for. EMD systems are hugely important to developed society with over 40% of all electrical power flowing through them (Waide & Brunner, 2011); improving the efficiency of their use represents a large and realistic opportunity to improve the environmental sustainability and financial performance of developed society (Naucler & Enkvist, 2009).

Deficiencies in student knowledge and skill to apply EMD systems were observed at the University of Wollongong (UOW); this coincided with the availability of grant funding and interest from industry partners in the creation of a new EMD systems teaching laboratory. A project was completed that created integrated equipment and curriculum called the Electric Motor and Drive Education Tool (EMDET) which gained acceptance by the project stakeholders. Equipment which Engineers Australia (2013) deemed 'probably amongst the best in any Australian University' .

The acceptance of the EMDET was attributed to the *systems engineering* approach taken by the project, that on review was found to include novel *engineering education* augmentations. The impact of the novel approach - dubbed the Wisdom Steered Execution (WiSE) Approach - was evaluated by examining the EMDET as

a case study to determine its worth for future use. The case study synthesised an assessment of the *EMDET* linking project outcomes to the impact of *WiSE* taking into account external factors observed during laboratory teaching.

The novel *WiSE Approach* was found to be valuable during the EMDET project by positively impacting the equipment and curriculum, however the assessment identified both strengths and potential weaknesses of the approach. These indicate that the *WiSE Approach* could be recommended as beneficial, when used in a suitable context.

The selection and use of a project evaluation metric raised a number of issues, the metric used scenarios based on industrial accounts of mistakes with EMD systems - *war stories* - as a measure of student readiness for practice, and therefore project success. Completing these scenarios require students to combine knowledge from throughout the undergraduate curriculum and apply it in context; a process termed an *ensemble performance*. Student attainment in this metric was surprisingly poor within the EMDET project largely due to the difficulties with the ensemble performance. On review it was found that the overall degree curriculum at UOW did not support students in developing the ability to deliver the ensemble performance, and consequently the evaluation metric was more aspirational than was anticipated.

The war stories were found to be a valuable motivating focus that connected design and construction processes with student outcomes. An unexpected strength of the war story observed was to motivate *educationally reflective* design and construction during the project. This was defined as alterations to hardware and software motivated by the pedagogical imperatives of training students to succeed in practice with EMD systems.

The WiSE Approach included a pedagogical model developed by analogy to a closed loop feedback controller. This model provided technical staff with a familiar conception that proved valuable in resolving complex interactions between educational issues and equipment development, in particular facilitating reflective design and construction. The model also allowed insights from the field of control engineering to be applied to teaching and learning.

Prior to making large expenditure on a laboratory and adopting the *WiSE Approach* institutions need to consider how the laboratory created will fit within the overall curriculum - not just a single subject. The *WiSE Approach* aims to deliver students ready for practice and project success is judged on this; this readiness is founded on student ability to deliver an ensemble performance. If the overall curriculum does not support students in developing this ability the context may not support the use of the *WiSE Approach*; in the extreme case the project goals inherent within WiSE may be overly aspirational and not attainable in the context of the overall curriculum. It may be that curriculum changes are necessary prior to the use of WiSE to develop teaching laboratories to fit within the curriculum. The experience with the EMDET would indicate that electrical engineering curricula at UOW may need review to determine if there are sufficient opportunities for students to develop the ensemble performances required for successful industrial practice. Based upon the results of industry survey other institutions may also benefit from a similar review of the electrical engineering curricula.

Institutions should also confirm the *WiSE Approach* is appropriate to the specific commercial circumstances, considering expertise and labour. The creation of integrated equipment and curriculum mandated by *WiSE* required a tightly coupled technical and educational skillset and extensive amounts of labour; for the EMDET project this labour was available free of charge to the project. While appropriate within the context of a University research project in partnership with industry, careful consideration should be given before using the *WiSE Approach* in a purely commercial context. In particular the amount of labour, expertise and potential for project iterations may pose a commercial risk.

For any future project using *WiSE* it is important that realistic project acceptance criteria are established. *WiSE* sets high expectations of student outcomes, uses these outcomes as project goals, and reflectively iterates the project adjusting equipment and curriculum to attain them. This process carries the risk of a project becoming an open ended commitment and fundamentally moving away from the definition of a project as something finite in time and resources. To avoid these issues the project acceptance criteria should be carefully considered and should also recognise that at some point the project (and iterative changes) must end and normal ongoing reflective teaching practice by the end user must begin.

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Finally I would like to thank my parents Sue and Laurie, and my family who have always encouraged and supported my studies at University.

Statement of Originality

I, Craig Geoffrey McLauchlan, declare that this thesis, submitted as part of the requirements for the award of Doctor of Philosophy, in the Faculty of Engineering and Information Sciences , University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications or assessment at any other academic institution.

Signature: ____________________________

Print Name: ____________________________

Student ID Number: 9723141

Date: ____________________________

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Abbreviations and Symbols

3P	Presage process product model of teaching an learning
DAQ	Data Acquisition (system)
DOL	Direct On Line motor starting
EMD	Electric motor and drive
GUI	Graphical User Interface
HMI	Human Machine Interface
EA	Engineers Australia
IO	Input and Output
LCQA	Linguistic Cognitive Question and Answer Model
LED	Light Emitting Diode
PC	Personal Computer
PED	Power Electronics and Drives course
PLC	Programmable Logic Controller
PM	Project Management
PWM	Pulse Width Modulation
RMS	Root Mean Square
SCADA	Supervisory Control and Data Acquisition
SOLO	Structure of Observed Learning Outcomes taxonomy
VI	Virtual Instrument
VSD	Variable Speed Drive
UOW	University of Wollongong

List of Publications

The following is a list of publications relating directly to the research presented in this thesis:

McLauchlan, C., Ciufo, P., & Perera, S. (2013). A reflective closed loop approach for implementing a new authentic assessment-based teaching facility for electric motor and drive systems. *Proceedings of the 24th Annual Conference of the Australasian Association for Engineering Education AAEE2013*

McLauchlan, C., Ciufo, P., & Goldfinch, T. (2016) An Electrical Motor and Drives Laboratory to Prepare Students for Industrial Practice In *Power System Technology (POWERCON), 2016 IEEE International Conference*

Part I

Study Background and Methodology

Chapter 1

Introduction

An electric motor and drive (EMD) system is one of the most common ways that electricity is turned into mechanical motion. Most commonly, electrical power from an electric transmission system is converted to mechanical power in a rotating load. Within an EMD system the motor is the device that converts electricity to rotating shaft power and the drive controls how electricity from the transmission system is applied to the motor. The complexity of the drive can range from simply connecting the motor to the power supply through to altering the nature of the electrical power applied (AC-DC, frequency, voltage).

The effective and efficient use of electric motor and drive (EMD) systems is very important to modern society given their ubiquity, necessity, and their environmental impact. It has been estimated that 43-46 percent of all electrical energy generated is used in electric motor and drive systems (Waide & Brunner, 2011). This simple but profound statistic establishes the importance of EMD systems when its consequences are considered. The vast quantity of electrical energy used by these systems demonstrates their pervasiveness and necessity to modern society. EMD systems are also a key area of opportunity for improvements in energy efficiency, given the rising concerns over climate change and sustainable energy usage (Naucler & Enkvist, 2009).

The responsibility for utilising EMD systems for the benefit of society falls to the profession of engineering. To effectively utilise these systems, engineers require a large body of theoretical knowledge and a complementary range of practical skills which a university education is expected to provide.

In 2008 a review of the electrical engineering curriculum at the University of Wollongong (UOW) identified the need to strengthen teaching in EMD systems; this coincided with an external accreditation audit that found the ‘Current laboratory facilities which support the teaching of electrical machines drives and power systems are considered inadequate’ (Engineers Australia, 2013). The lack of facilities and need to strengthen teaching led to the observation of a discrepancy between the skills possessed by engineering graduates and those required to successfully practice with EMD systems. Given that EMD systems are important to society and the need for effective engineering practice in this area, this discrepancy, or ‘knowledge gap’, was of serious concern and is the motivation for the work presented in this research.

To address the knowledge gap and accreditation audit, UOW would need a new capability for laboratory training with modern EMD systems to prepare students for practice. An opportunity to develop this capability arose from a Federal Government grant that coincided with interest shown by manufacturers of industrial EMD equipment. The Government grant to establish a new research institute included funding for a new power electronics and drives teaching laboratory (UOW, 2009), a portion of which was allocated to the development of appropriate EMD teaching facilities. At the same time, two EMD equipment manufacturers had approached UOW with an interest in collaboratively developing EMD training facilities.

This project developed the Electrical Motor and Drives Education Tool (EMDET) that consisted of equipment and curriculum that was used to teach two cohorts of final year undergraduate and postgraduate students and consequently was accepted by the project stakeholders. A subsequent accreditation audit included EMDET in its review and found that the concerns raised in 2008 had been satisfactorily addressed. This provision of equipment to close the knowledge gap, stakeholder acceptance of EMDET and addressing the concerns of the 2008 accreditation audit, were attributed to the method used to execute the project.

Initially, the EMDET project would provide equipment for a teaching laboratory, but in the early stages this scope expanded to provide students with the knowledge needed to succeed in industrial practice with EMD systems. This change was inspired by stories encountered during industrial consultation on which types of equipment to include in EMDET. Throughout the consultation there were many accounts, or 'war stories', of costly mistakes being made in the use of EMD systems that resulted in the loss of time, money, and professional reputations. These accounts had a common theme of mistakes being made due to fundamental misunderstandings of the basic operation of common industrial motor and drive components. This naturally evoked the desire to help students avoid making similar mistakes and prompted the project scope to be set as delivering the requisite *knowledge and skill* in students.

The change in scope from providing equipment to solving a problem by means of a complex system moved the project into the arena of *systems engineering* which (Hitchins, 2007, p. 91) defines as 'the art and science of creating whole solutions to complex problems'. Along with the change in scope, there was an implicit recognition that there were many ways to address the problem, and many stakeholders with different and possibly competing interests, all of which posed a risk to the university funding the development of this new laboratory. Consequently, the view formed that there is no single perfect solution but there are good solutions that would 'balance the critical system attributes from the standpoint of the success of the development program and of the value of the system to the user' (Kossiakoff & Sweet, 2003). This viewpoint of a balanced solution is another hallmark of systems engineering.

Upon review of the EMDET project the method used to execute the project conformed to the systems engineering Vee model (Hutchison et al., 2014; Forsberg et al., 2000) with a number of novel augmentations that were developed by researcher. These augmentations adapted the generally applicable Vee model to the specific task of creating an engineering teaching laboratory. This augmented model is called the Wisdom Steered Execution (WiSE) Approach; it added five distinct elements to adapt the general Vee model to the specific purpose of *engineering education*:

- a project deliverable of student competency to practice in the field of engineering
- a measure of competency (evaluation metric) developed to assess readiness for practice
- a scope of delivery set including integrated equipment and curriculum

- an educationally reflective closed loop development approach to ensure equipment and curriculum together deliver the desired competency
- an explicit model of teaching and learning (based on an analogy to a closed loop feedback controller) that would suit staff with technical backgrounds

Once the novel and specific nature of WISE was recognised, the scope of the research work expanded to assess how it would on the EMDET project. This would be done by examining the EMDET project as a case study to evaluate potential linkages between the method and the outcomes. The opportunity was also taken for a more rigorous assessment of the operation of the EMDET in the laboratory during teaching of a third student cohort as part of a formal case study methodology.

From the initial stages of the work a similarity between changing student knowledge by training and controlling a physical system using a classical closed loop feedback controller (Ogata, 1997) was noticed as shown in Figure 1.1. The dynamics and interactions described by the engineering concept of a closed loop feedback controller were analogous to those of teaching and learning. This similarity resonated with the technical staff involved with the project so the model was built into the WiSE Approach and used throughout the development of the EMDET.

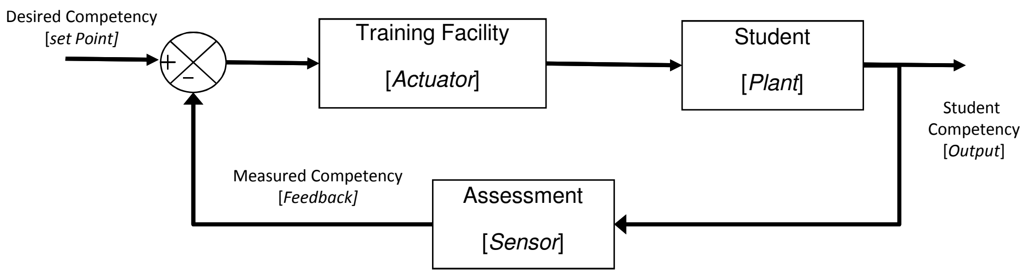


Figure 1.1: The Closed Loop Model and its analogy to training adapted from Ogata (1997).

The deliverable of knowledge and skill along with the closed loop conception of education led to the view that purpose of the project was to complete the closed loop system around the student to provide competency. The project then had to provide the other components of the loop such as the actuator, sensor, comparator and set point, or equivalently, the training equipment, curriculum, assessment and educational objectives, which is more than the original scope of equipment only.

1.1 Purpose Statement and Research Questions

The purpose of this thesis was to critically evaluate the novel *WiSE Approach* to determine whether it could benefit other similar *engineering education* projects that are developing teaching laboratory equipment for engineering or other applied technical fields. This research uses the EMDET project as a case study to answer the following research questions:

1. What were the significant success and failures within the EMDET project which led to its overall success or failure?
2. What impact did this novel project process have on the significant success and failures?
3. What is the scope of applicability of the aspects identified?

1.2 Path of the research and its original contributions

When reading this work it is useful to recognise the path that the research took, the WiSE Approach was in a sense an unexpected discovery as the work did not originally set out with the explicit intention of developing a new project approach. The work started as a project, and it was after development of the prototype that a meta-analysis of the project discovered that the approach taken approximated the Vee model, and furthermore that adaptations had been made (creating the WiSE Approach) which were potentially of value to the academic community. A case study evaluation was the undertaken to critically evaluate the WiSE Approach.

The original contributions to research in this work are:

- adding five distinct augmentations to the systems engineering Vee model to adapt for use in engineering education, in doing so creating the WiSE Approach
- using the WiSE Approach to implement an engineering education focussed project delivering the EMDET
- critically evaluating the performance of the WiSE Approach by carrying out a rigorous case study assessment of the EMDET project

1.3 Structure of this thesis

This Thesis is arranged in three major sections: the background for the case study, the data from the case study, and an analysis of the case study:

1. Case study background in part I
   (a) **Literature Review**: this chapter reviews the literature pertaining to engineering teaching laboratories for EMD systems
   (b) **Establishing the *WiSE Approach***: this chapter explains the motivation at UOW for the work, describes the educational theory required to utilise the closed loop controller analogy to teaching and learning described the project process used named the *WiSE Approach* as an augmentation to the standard systems engineering Vee Model
   (c) **Methodology**: this chapter establishes the research questions for the study and describes the methodology used to evaluate the impact of the WiSE Approach on the EMDET project
2. the EMDET Case Study in part II
   (a) **Requirements:** this chapter is a describes the need that is to be fulfilled by the project, from the user's perspective.
   (b) **Specifications:** translates requirements from the users perspective into something that designers can use to drive the design process; it also establishes key philosophies used to develop the tool
   (c) **System Design:** articulates the system design formulated by the designers based on the requirements and specifications
   (d) **Detailed Design:** describes the development of the design as a collaboration between designers and constructors such that it could be physically realised
   (e) **Assembly:** describes the physical realisation of the tool by the Constructors
   (f) **Component Testing:** describes testing of the individual components within the EMDET by the Constructors and Designers
   (g) **Integration Testing:** describes testing of the interaction of the individual components within the overall system by the Designers

(h) **System Testing:** describes the testing the complete system undertaken collaboratively by the Designers and representatives of the User's of

(i) **Acceptance Testing:** describes the deployment of the EMDET by the user's as final testing to ensure that the project deliverable met the requirements of its context and the teachers who would use it

3. Analysis and Synthesis in part III

(a) **Introduction:** this chapter describes the structure of the overall analysis and how separate analytical tools were used to synthesise answers to the research questions

(b) **Project Evaluation Analysis:** establishes the success and shortcomings of the project

(c) **Pattern Matching Analysis:** determines the impact of the novel aspects of the *WiSE Approach*

(d) **Decision Tree:** represents the EMDET project as a series of decisions with the impact of WiSE mapped to them

(e) **Grounded Theory Analysis:** examines the conduct of the laboratory classes to identify relevant factors outside the control of the project team

(f) **Discussion**: carries out a synthesis linking project success to the impact of the *WiSE Approach* using decision making as a causal linkage taking into account outside factors identified. Derives key learnings from assessing of the EMDET project

(g) **Conclusion**: appraises the impact of the *WiSE Approach* and its potential use in other projects, and future research that could extend the work presented in this thesis

Chapter 2

Literature Review

The use of laboratory facilities to educate students in the use of modern equipment and techniques is widespread in engineering in general and EMD systems in particular. This chapter presents the outcomes of a literature review to develop and use laboratories to educate engineering students at University level. This literature review was guided by two questions:

- What issues need to be addressed when developing laboratory teaching facilities for EMD systems and engineering teaching laboratories ?
- How have others developed laboratory teaching facilities that focus on EMD systems?

2.1 Engineering Teaching Laboratories

This literature review explored the challenges faced by institutions, students, and educators in designing, developing and using of laboratory facilities to train students in EMD systems and the related fields of power electronics and power systems. During this literature review, a number of institutional, pedagogical, and technical issues were identified that would need to be addressed.

From the standpoint of the educational institution sponsoring the creation of such a laboratory,the motivations, constraints, and the process for implementing the laboratory must be defined. From a pedagogical perspective, it is important to understand the teaching objectives, the boundaries of laboratory teaching and how it fits into the structure of engineering education, and how this teaching and learning is expected to occur. The technical concerns centred on the components and systems required, and how should they function, but more importantly, how is the institution to judge its success when the institutional, pedagogical, and technical concerns are considered?

This section of the literature review sought to determine how others had addressed the institutional, pedagogical, and technical concerns of implementing a teaching laboratory in order to identify an approach that could be implemented at the University of Wollongong.

2.2 Institutional concerns

A university laboratory can fulfil a broad range of tasks such as testing, certification, research and development, and teaching, each of which has specific concerns. This thesis addresses laboratories used primarily for teaching, whilst recognising there are also other possible functions. The definition of a teaching laboratory is very broad because it includes a variety of teaching modes and activities ranging from computer simulation to full scale industrial hardware. Given this wide range of possibilities it is crucial during the creation of a laboratory for an institution to clearly define what is motivating the creation of a laboratory, what is constraining the creation and how will the laboratory be created.

The creation of a laboratory will often require significant resources from the sponsoring institution typically including staff time, physical space and money. The use or resources has attendant risk, so the process used to create a teaching laboratory must be acceptable to the sponsoring institution, particularly addressing the motivations and constraints. Delivering a teaching laboratory is usually undertaken as a project because it uses resources (finance, personnel and time) to provide a defined outcome (Tregoe & Kepner, 1981). Consequently the project management methods used, including the management of risk, must be acceptable to the sponsoring institution; these issues are examined in more detail in section 2.2.

A review of the literature describing teaching laboratories for EMD systems and allied fields has identified a number of key motivations for their creation, these include augmenting classroom teaching, preparing students for further postgraduate and research studies, and preparing students for professional industrial practice.

Laboratory experiences were cited as a valuable addition to traditional classroom teaching and can augment it in a variety of ways, including: Illustration (Gedra 2002) or reinforcement of abstract concepts (Collins, 2009; Oriti et al., 2014), complementing analytical approaches with experiential methods (Diblk & Beran, 2010), and verification of modelling and simulation (Oriti et al., 2014) presented in the classroom.

Laboratory experiences are identified as being valuable in preparing students for further advanced university study and preparation for careers in research and development (N. Mohan et al., 2003; Panaitescu et al., 2002).

Laboratory experiences in EMD systems and allied fields are considered to be very important in preparing students for professional industrial practice (Gedra et al., 2004) because these experiences provide students the opportunity to perform the synthesis of knowledge from a number of subject areas (Balog, Sorchini, Kimball, Chapman, Krein, & Sauer, 2005) required to successfully utilise EMD systems. They also illustrate that the performance of systems can be governed by the details of implementation as much as the fundamental theories of operation (P. Krein, 1993).

The motivation for creating a teaching laboratory shapes its design and impacts on the final form of the laboratory and accompanying curriculum; for example a laboratory designed to augment classroom teaching may take a variety of forms; it could be entirely virtual (Keyhani et al., 2002), use low cost miniature components (Shirsavar et al., 2006), custom built components unsuitable for industry (Diblk & Beran, 2010), or full scale industrial components (Collins, 2009). A laboratory specifically intended to prepare students for industrial practice is more likely to include full scale industrial hardware (Antonino-Daviu et al., 2014; Buechner, 2005;

Serrano-Iribaarnegaray, 1995). Given the wide reaching ramifications on design, clearly defining the motivation for developing the laboratory is crucial.

The literature also detailed a number of institutional concerns that provided constraints on the development of a laboratory; these included cost (Shirsavar et al., 2006; Gross & Hesse, 1979), the space available (Balog, Sorchini, Kimball, Chapman, & Krein, 2005; Venkataramanan, 2004), potential utilisation of the equipment (Panaitescu et al., 2002; Gross & Hesse, 1979), the staffing required (Gross & Hesse, 1979; Oriti et al., 2014), the logistical requirements (Oriti et al., 2014; Fraile-Ardanuy et al., 2013), the perceived relevance of the field of practice and research (Panaitescu et al., 2002; Gedra et al., 2004), the attraction of students (Panaitescu et al., 2002; Gedra et al., 2004) how laboratory teaching is integrated into a course of study(Collins, 2009), and the potential audience the laboratory could serve (Panaitescu et al., 2002; Gedra et al., 2004). All of these concerns and their relative importance to the institution sponsoring the development of teaching laboratories had profound impact on their final form.

Within the literature, motivations for laboratory creation interacted with institutional constraints to dictate its final form; for instance, teaching laboratories with similar motivations had different final forms based on constraints faced by the institutions creating the laboratory. Balog, Sorchini, Kimball, Chapman, & Krein (2005) and Keyhani et al. (2002) both cite motivations of providing practical experience to students working with EMD systems; particularly the required synthesis of knowledge from various areas of electrical engineering such as circuit theory, control systems, electronics, semiconductor devices, etc. Keyhani et al. (2002)) developed a completely virtual laboratory on the basis of constraints in the cost of construction, maintenance cost, the space required, safety, and staff requirements. Balog, Sorchini, Kimball, Chapman, Krein, & Sauer (2005) used a hardware 'blue box' approach and developed a series of modular power electronic assemblies that were combined in different ways to form various devices; this was based on continuing with the previous approach that the institution had successfully used in the past. Collins (2009) and Shirsavar et al. (2006) both cite linking theory and practice as a motivation for creating a laboratory. Based on constraints of cost and the electrical and mechanical hazards involved with typical EMD systems, Shirsavar et al. (2006)

opted for low cost (circa U.S. $25)(Shirsavar et al., 2006, p. 387) miniature DC and induction motors operated by low power three phase inverters created on a small custom made printed circuit board (PCB); whereas Collins (2009) used equipment based around 1 kW industrial motors and drives with extensive data acquisition and control. The constraints cited by Collins were to make the laboratory support various courses of study, to increase the equipment utilisation, and reducing overall space requirements.

One of the major contemporary concerns for laboratory teaching in EMD systems and allied fields is the use of virtual and remotely accessed laboratories as an alternative to physical attendance. Catering to the needs of distance education students (Oriti et al., 2014) or enabling remote learning (Collins, 2009) is very attractive to institutions because they can address issues of laboratory utilisation, staffing levels, logistics, and student attraction. There are concerns around the educational effectiveness of these laboratories, particularly if the motivation is preparing students for industrial practice. Opinions on the effectiveness of the laboratories differ; proponents of physical attendance warn of a 'dangerous trend in Universities to move away from hardware to purely software based laboratories' (Panaitescu et al., 2002, p. 455) and arguing that 'remotely located hardware can obfuscate the difference between simulation and verification' (Balog, Sorchini, Kimball, Chapman, Krein, & Sauer, 2005, p. 539). Proponents of remotely accessed labs argue the pedagogical effectiveness of the approach (Oriti et al., 2014; Fraile-Ardanuy et al., 2013) typically using anecdotal evidence or surveys of student feedback as justification. The question of whether student opinion is an appropriate measure to determine whether a laboratory experience has provided effective preparation for industrial practice is often not addressed. Corter et al. (2011, p. 2065) in a study comparing learning outcomes for laboratories using different delivery modes 'suggest caution in using student self-reports of learning effectiveness as a proxy for the real thing...'

A major issue between the proponents and detractors is whether the experience provided by remote laboratories in EMD systems and allied fields will prepare a student for practice when compared to physical laboratory attendance. The concept of adequacy is not addressed in the literature reviewed specifically on EMD systems, however it is dealt within the broader literature on laboratory education and education.

Underlying the evaluation of remote laboratories is a fundamental issue identified by Feisel & Rosa (2005) that throughout the literature, the motivations for creating an engineering teaching laboratory are seldom developed into clear educational objectives. therefore it is difficult to judge the success or otherwise of a teaching laboratory without a clear statement of what educational objectives it was intended to achieve. This makes evaluating the arguments for and against virtual and remote laboratories difficult, because it is unclear whether the proponents for and against have the same criteria for evaluating the laboratory as an educational experience. The development of educational objectives for a teaching laboratory is a key pedagogical concern which is expanded on in section 2.4.1.

Ma & Nickerson (2006) undertook a literature review comparing hands-on simulated and remote laboratories, then making a number of key observations. They noted a 'lack of agreement of what constitutes effectiveness in student learning, and evangelism for one or another possible format without sufficient empirical evidence' (Ma & Nickerson, 2006, p. 7), and that 'advocates measure against different educational objectives', e.g developing concepts, design skills, social skills or professional skills (Ma & Nickerson, 2006, p. 7).

Ma & Nickerson (2006, p. 10) noted that hands-on laboratories are extensively mediated by computers for a variety of reasons, including control and data acquisition, which raises some question about the difference between hands on labs in this case and other forms of mediation. One important consideration is that industry and engineering practice are now heavily mediated by computers, so it is becoming much more important to understand the limits of mediation. For example, the position that a computer is commanding a piece of equipment (e.g. a flow control valve) is not necessarily the same as the actual physical position of the equipment, for example the flow control valve may be stuck, the attached actuator may be out of calibration, or the physical piece of equipment takes time to move from one commanded position to another. While this may seem subtle, it is very important because it is often the cause of problems in industrial plant. Understanding this particular example is expected of industrial automation engineers, but it is also usually first experienced when concurrently dealing with both the mediated and the real experience.

(Ma & Nickerson, 2006, p. 14) also find that the 'effectiveness of laboratories may be affected by how much students believe in them' which is a function of fidelity. Miller cited in (Ma & Nickerson, 2006, p. 10) identifies two kinds of fidelity: engineering and psychological. 'Engineering fidelity concentrates on the closeness of simulated environments to physical surroundings, while psychological fidelity is seen as the determining factor for the effectiveness of a simulation device' Miller, cited in (Ma & Nickerson, 2006, p. 12), relates fidelity to the concept of 'presence' to view the possible interaction between the two kinds of fidelity. They also assert that it is possible to have fidelity of one sense without necessarily having the other, so students could experience psychological fidelity in an entirely simulated experience which has limited engineering fidelity but be mentally present and engaged by the experience. Similarly, a student may physically be in a hands on laboratory with a high degree of engineering fidelity but be distracted or let others take over experimentation, in which case they individually have low psychological fidelity because they are not mentally present. (Ma & Nickerson, 2006), suggest that 'it is important to focus on how student's mental activities are engaged with coping in the laboratory' and that other factors such as motivation, peer collaboration, error corrective feedback and the richness of the media should be considered. The concept of fidelity is used in many other contexts including aviation simulators (Baarspul, 1990; Foster et al., 2007; Page, 2000) and the training of medical practitioners (Munro, 2012; Rosen, 2008), when taken in consideration with the learning objectives of a laboratory it provides a useful definition that can be used to assess the adequacy of a teaching laboratory and usefully inform the process of creating a laboratory.

(Corter et al., 2011) conducted a study in an attempt to compare the learning outcomes for hands on, remotely operated, and simulation based educational laboratories. This was conducted on a sophomore level laboratory class investigating the stress distribution on classical cantilever beam setups with and without a hole (Corter et al., 2011, p. 2058). The research question was to consider how the mode of delivery (hands on, remote or simulated) and data collection method (individual or collaborative) affected student learning outcomes; these were judged by their attainment and students questionnaires addressing the amount of time spent in various tasks within the laboratory (receiving instruction, setting up, collecting data, analysing data and writing a report), and student satisfaction with the laboratory experience.

After adjusting the results of student test scores Corter et al. (2011) found that the 'collaborative hands on mode and individual remote modes had significant correlation with higher student attainment' (Corter et al., 2011, p. 2062); the other combinations were all statistically similar. They go on to state that 'students can learn effectively with all three types' of mediation (Corter et al., 2011, p. 2065).

One significant finding in correlating the results of student evaluations and their actual assessments (Corter et al., 2011, p. 2065) 'suggest caution in using student self reports or learning effectiveness as a proxy for the real thing: across all participants and conditions the correlation of the test core with the student-related effectiveness summary score was effectively zero'.

Heywood (2006, Chap 15. p. 398) identify 'a major problem relates to the validity of exit questionnaires that ask students to state whether or not their skills have changed as a result of the course. Surely the final examination or some other independent criterion such as performance in a project should have been designed to give such information'.

While student opinion is important because it relates to their recruitment, retention, and the possible impact of student morale on performance, it should not be considered as a reliable indicator of student attainment. It is better considered as part of a comprehensive evaluation program.

In the Corter et al. (2011) study, the remote learning and simulation student still had to physically attend a class at a set time, so these two modes of teaching were not free in space or time and did not make use of some of the key advantages of these delivery modes.

A key consideration in the development of a new engineering teaching laboratory is whether the mode of delivery allows the educational objectives to be met in light of the constraints faced by the institution. As with many engineering design problems the final outcome balances a number of competing design imperatives.

2.3 Process for Implementing the Laboratory

Within the literature on EMD laboratories, numerous institutional concerns with the creation of engineering laboratories were identified, but none of the literature addressed the *process* by which the institution ensured that the creation of the laboratory addressed these concerns. Developing teaching laboratories for EMD systems requires significant expenditures of resources to create complex systems (including hardware, software,producers, and teaching materials) to deliver educational outcomes. Ultimately the original motivation for creating the laboratory must be addressed within the constraints

In essence these are concerns in the fields of management, project management, and risk management, of which there are extensive works of literature in these fields. While not specifically addressed in the EMD literature, a number of applied technical fields address management and risk issues that bear similarities to the development of EMD labs such as software engineering (Rook, 1986; Royce, 1970), and the development of simulators for the aviation industry (Baarspul, 1990). The work in these fields can be considered a subset of systems engineering (Buede, 2016; Hitchins, 2007; Kossiakoff & Sweet, 2003). Literature was reviewed on project management and systems engineering in general, and for the applied technical fields (software engineering, aviation simulation) to identify the issues that the process used to develop a laboratory had to address for the sponsoring institution. Interestingly systems engineering approaches have been taken to curriculum design in engineering education (Berdonés et al., 2013; Rompelman & de Graaf, 2000), however the review of literature did not find a systems engineering approach to implementing laboratories for engineering education.

The creation of an engineering laboratory will typically be a project, as defined by the Project Management Institute (Anbari, 2004, p. 3); its creation process will be temporary, focussed on delivering a 'unique product or service' and will likely be a 'progressive elaboration'. That is, the development process will be a series of steps that continue in increments. The process would begin with an institutional need and a scope of delivery, then development of a concept, which would be converted into a design and so on, but as the work progresses new issues may be uncovered that add to or alter original statement of need, so the project and design process includes a potential for iteration.

The creation process, or *project*, will involve stakeholders who are defined as individuals and organisations that are actively involved in or can impact or be impacted by the conduct of a project (Anbari, 2004, p. 24), (Nicholas & Steyn, 2008, p. 54). For an engineering teaching laboratory this would include the sponsoring institution, the students, teachers, and the project team creating the lab (designers, constructors, project managers, etc.). During the conduct of the project the actions of the project team must be coordinated in the interests of the stakeholders; this coordination is *project management* (PM) defined as 'the application of knowledge, skills, tools and techniques to project activities in order to meet project requirements' (Anbari, 2004). Project management functions include (Anbari, 2004):

- identifying requirements
- establishing objectives
- balancing (often) competing demands for quality, scope, time and cost
- adapting specifications, plans and approach to address the concerns and expectations of stakeholders

The laboratory to be delivered by the project is a '... collection of hardware, software, people, facilities and procedures organised to accomplish some common objectives' which is how (Buede, 2016) defines a *system*. Its creation will require '.. an interdisciplinary approach ... defining customer needs ... documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem. ' which is a definition of *systems engineering* from the International Council of System Engineering (INCOSE) cited in (Hitchins, 2007, pp. 88-89). Many other definitions for systems engineering are in use; Buede (2016, p. 10) pragmatically defines it as the 'engineering discipline that develops, matches and trades off requirements, functions and alternate system resources to achieve a cost effective, life cycle balanced product based upon the needs of the stakeholders'. Hitchins (2007, p. 91) succinctly defines it as 'the art and science of creating whole solutions to complex problems'. All three definitions of systems engineering offered by INCOSE, (Buede, 2016) and (Hitchins, 2007) apply to the process of creating an engineering teaching laboratory.

Project management and systems engineering are both required to deliver an engineering teaching laboratory, so there is clearly an overlap between them. Kossiakoff & Sweet (2003) describe areas shared by both (e.g. task definition, risk management, customer interaction), areas that are the domain of systems engineering alone (e.g. system architecture, technical coordination, system integration) and the domain of project management alone (e.g project planning, resource allocation, cost management). (Kossiakoff & Sweet, 2003) represent this overlap using a Venn diagram in Figure 2.1.

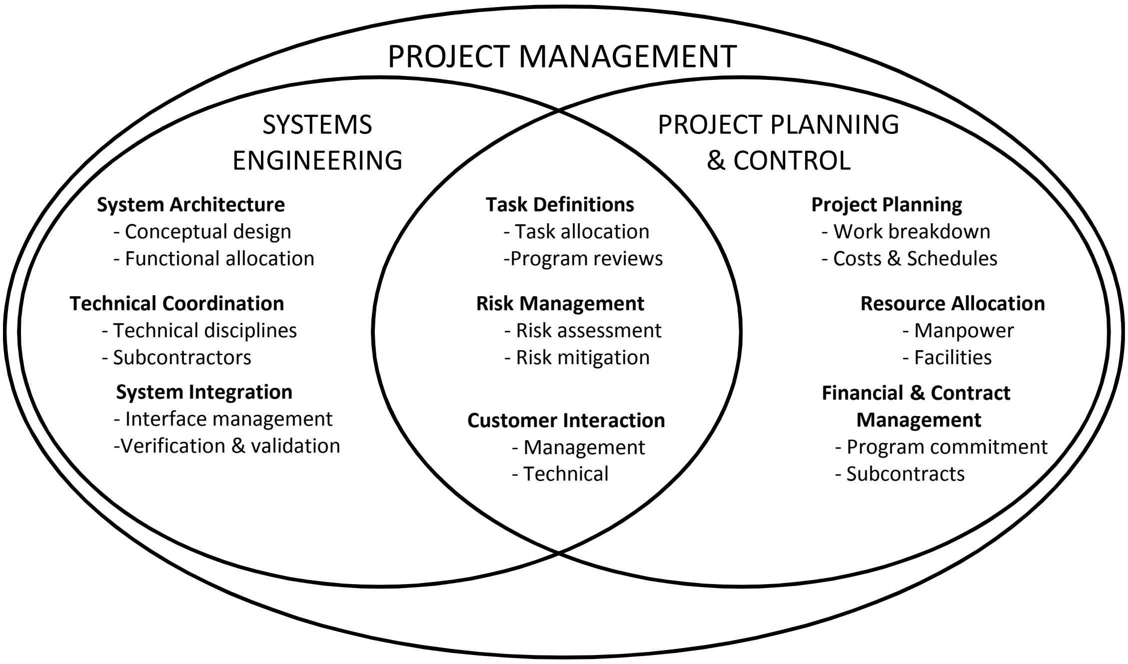


Figure 2.1: The overlap of Systems Engineering and Project Management (Kossiakoff & Sweet, 2003)

The primary focus of this thesis is in the areas shared by both project management and systems engineering, which (Sharon et al., 2011) describes as systems engineering management - a hybrid of the two. Sharon et al. (2011) makes a useful working distinction between them by describing systems engineering as occurring in the 'product domain' and project management as the 'project domain'.

The literature reviewed considers that the concepts of verification, validation and fidelity are very important in applied technical fields, where verification is the process of ensuring that what is delivered meets the stated requirement (Buede, 2016, p. 12),(Engel, 2010, p. 16), and validation is the process of confirming that the stakeholders's needs have been met (Buede, 2016, p. 12)(Engel, 2010, p. 16). These ensure what is delivered suits the final user in their context and also recognises that the original statement of need may have been incomplete or inaccurate and therefore must be amended and the remainder of the system adjusted accordingly. Fidelity refers to both the engineering, and psychological fidelity as defined by Miller cited in (Ma & Nickerson, 2006, p. 10); it may be summarised as the closeness of the training environment to real world practice.

To successfully deliver an engineering teaching lab in EMD systems as required here (including exemplary features in Section 2.5.9 with required fidelity) a complex systems engineering product must be developed and delivered as a project, with project management, to ensure that institutional motivations (of delivering quality engineering education) are met within the constraints. The process including the *systems engineering* (Buede, 2016, p. 10) functions and the *project management* (Anbari, 2004) functions described here must be acceptable to the sponsoring institution. The issues of verification, validation, and providing the required fidelity are important in gaining institutional acceptance for the process to be used.

2.4 Pedagogical Concerns

The literature review also identified that during the design, development, and use of teaching laboratories it is important to understand the educational objectives from a pedagogical perspective, how is teaching and learning expected to occur, how will the effectiveness be judged, what are the boundaries of laboratory teaching, and how will it fit into the overall structure of an engineering course?

2.4.1 Educational Objectives

Educational objectives are affected by the motivations for creating a teaching laboratory and the context within which this occurs because the relationship between them can often be complex. Ernst (1983) and Feisel & Rosa (2005) in particular identify the importance of learning objectives for engineering teaching laboratories, and stated that these objectives should be derived from the motivations for creating a teaching laboratory and be a refinement of them. Feisel & Rosa (2005) cite a lack of coherent objectives for the engineering teaching laboratories described in literature as limiting their effectiveness. Educational objectives should:

1. Shape the (re)development of a teaching laboratory
2. form the basis for judging student attainment
3. form the basis for judging the success of the teaching laboratory

According to Feisel & Rosa (2005) engineering education literature has not addressed the learning objectives for teaching laboratories adequately, even though they are addressed within the broader engineering education literature (Rompelman, 2000; Stefanovic et al., 2015; Behrens et al., 2010). In particular they argue there has been no general agreement on explicit learning objectives for engineering teaching laboratories, a problem identified by the Accreditation Board for Engineering and Technology (ABET) when distance education programs began to apply for accreditation for engineering programs. Feisel & Rosa (2005) also report that varying levels of rigour are used in literature to address laboratory learning objectives; with some authors providing precisely stated objectives, some stating them in terms that are difficult to assess whether their goals are reached, while others 'assume the objectives will be taken for granted and that their contribution is to report on the laboratory apparatus, a process they have developed ..." (Feisel & Rosa, 2005, p. 123).

The literature pertaining to EMD teaching laboratories reviewed addressed educational objectives in various ways from differing perspectives; some authors make vague statements about the importance of laboratory teaching to the training of engineers before describing their laboratory apparatus or process (P. T. Krein & Sauer, 1992; Conejo et al., 2007). Some make broad statements of the educational intent of laboratory training as, providing hands on experience (Gedra et al., 2004; Molina-Garca et al., 2008), preparing students for industry (N. Mohan et al., 2003) or adding to classroom teaching (Oriti et al., 2014). Some authors provide an outline of the courses within a degree program that would make use of a laboratory without defining what the learning objectives are, or how the laboratory would contribute to them (Collins, 2009). Some authors did provide a list of learning objectives but did not explicitly relate them to the development of a laboratory, student assessment, or laboratory performance (Shirsavar et al., 2006). Some articles were effectively subject outlines with detailed descriptions of course objectives, content, and assessment, but did not describe how they are related or used to develop and operate a teaching laboratory (Emadi, 2005).

A small number of authors in the literature reviewed on EMD teaching laboratories addressed learning objectives in enough detail to relate them to the development of laboratories, student assessment, and an assessment of the laboratory itself, but they did so from various perspectives. Antonino-Daviu et al. (2014) provided objectives that focused on two laboratory exercises dealing with predictive maintenance for electric machines; these objectives also related to student attainment, as well as development of the laboratory teaching delivery using collaborative and remote learning modes. The authors described the equipment used within the laboratories and the proposed assessment methods. Antonino-Daviu et al. (2014, p. 79) also claim that the 'usefulness of the laboratory sessions has been proven through several indicators such as the increase in average attendance at these sessions and the enhancement of the scores in the evaluation questions related to the laboratory sessions in the individual exam ', however there is no evidence of this claim given, and the validity of the methods is not addressed.

Schubert et al. (2009) identified learning objectives used to design laboratory equipment and procedures for a single laboratory exercise which targeted early year students modelling small (1.5 Watt) DC motors and experimentally determining the model parameters. Student performance in meeting the laboratory objectives was assessed by comparison of their results to instructor solutions. The performance of the laboratory equipment and procedures were critically assessed by direct observation, the performance of the student cohort as a whole, student questionnaires and final exam performance. Direct observation of students undertaking the laboratory exercises led to a number of technical and logistical improvements, and a review of the submissions from the cohort identified that issues such as time pressures were a problem.

The laboratory was assessed subjectively and objectively; subjectively via student questionnaires and the objectively by reviewing the results of student exams. The questionnaires addressed how confident students were in their subject knowledge before and after the laboratory, with the results indicating an increase in confidence in the areas addressed by the laboratory objectives. Schubert et al. (2009) attempted to use student performance in a final exam that contained a question addressing the subject matter of the laboratory material to objectively measure the effect of the laboratory. Unfortunately students were not obliged to address the material related to the laboratory in the exam.

A number of strengths and weaknesses are evident in the approach taken by Schubert et al. (2009); the strengths included the definition of learning objectives, the use of these objectives in developing the lab, and student assessment and assessment of the laboratory. One particular strength was that Schubert et al. (2009) looked for an improvement in educational outcomes that could be attributed to the teaching laboratory by implementing the same assessment instrument before and after the laboratory to look for a step change in attainment.

There are some potential weaknesses in the approach taken by Schubert et al. (2009); while there is a broad match between the definition of learning objectives and the assessment there is no strict correspondence between them. Also Schubert et al. (2009) do not address the value of the student's subjective opinion of confidence in their own ability in an area of knowledge; particularly the relationship between student confidence and actual ability in the subject area. Within literature Corter et al. (2011, p. 2065) 'suggest caution in using student self-reports of learning effectiveness as a proxy for the real thing' in regards to student laboratories. There are also some difficulties associated with the objective measurement used, including that students were not obliged to complete the relevant exam question, the linkage between the laboratory exercise and exam question was not specified and the attribution of student performance in the question to the laboratory was not justified in any detail.

Venkataramanan (2004) provided detailed learning objectives for a 15 week long subject and used them to develop laboratory equipment and assess student attainment; however they were not used to explicitly assess the success of laboratories in delivering educational outcomes within the students. Student attainment marks and student evaluation of the course were given as total scores for the subject rather than addressing performance against the learning criteria. According to (Venkataramanan, 2004, p. 124) 'controlled instruments to perform a comparative and comprehensive learning assessment were not conducted '.

Feisel & Rosa (2005) analysis of learning objectives applies to the literature reviewed on EMD teaching laboratories when it is considered in the round. Only a small number of authors state the learning objectives for their laboratories in enough detail to relate them to the development and assessment of the laboratories. None of the authors in the literature reviewed stated the educational objectives, then related them to the development of the laboratories and student assessment, and then used the learning objectives to assess the performance of the laboratory teaching in a robust way. This represents a gap in the literature.

The usefully stated learning objectives for EMD teaching laboratories ranged in specificity; from a single laboratory exercise (Antonino-Daviu et al., 2014) to applying to a subject within an electrical engineering course (Venkataramanan 2004). None of them were fundamental enough to be applicable to an entire undergraduate course or to different disciplines of engineering, neither did they refer to any such fundamental listing. Feisel & Rosa (2005) describe a process undertaken cooperatively by the Accreditation Board for Engineering and Technology (ABET) and the American Society for Engineering Education (ASEE) during a colloquy (Feisel & Peterson, 2002) to identify the fundamental goals of engineering teaching laboratories (Feisel et al., 2002). These goals are presented in Table 2.1.

This list can be used to create the educational objectives for a specific laboratory, this may be within EMD systems or any other engineering discipline. This approach is not applied in the literature reviewed on EMD teaching laboratories, nor in literature reviewed via citation of Feisel & Rosa (2005), and therefore represents a gap in the literature.

2.4.2 How Teaching and Learning is Expected to Occur

Within the literature reviewed on EMD teaching laboratories, most of the authors did not nominate a theory or conception of how teaching or learning was expected

Table 2.1: The fundamental goals of engineering teaching laboratories (Feisel et al., 2002)

Objective	Title	Description: *By completing the laboratories in the engineering undergraduate curriculum you will be able to....*
1	Instrumentation	Apply appropriate sensors, instrumentation, and/or software tools to make measurements of physical quantities.
2	Models	Identify the strengths and limitations of theoretical models as predictors of real world behaviours. This may include evaluating whether a theory adequately describes a physical event and establishing or validating a relationship between measured data and underlying physical principles.
3	Experiment	Devise an experimental approach, specify appropriate equipment and procedures, implement these procedures, and interpret the resulting data to characterize an engineering material, component, or system.
4	Data Analysis	Demonstrate the ability to collect, analyse, and interpret data, and to form and support conclusions. Make order of magnitude judgments, and know measurement unit systems and conversions.
5	Design	Design, build, or assemble a part, product, or system, including using specific methodologies, equipment, or materials; meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements.
6	Learn from Failure	Recognize unsuccessful outcomes due to faulty equipment, parts, code, construction, process, or design, and then re-engineer effective solutions
7	Creativity	Demonstrate appropriate levels of independent thought, creativity, and capability in real-world problem solving.
8	Psychomotor	Demonstrate competence in selection, modification, and operation of appropriate engineering tools and resources
9	Safety	Recognize health, safety, and environmental issues related to technological processes and activities, and deal with them responsibly.
10	Communication	Communicate effectively about laboratory work with a specific audience, both orally and in writing, at levels ranging from executive summaries to comprehensive technical reports.
11	Teamwork	Work effectively in teams, including structure individual and joint accountability; assign roles, responsibilities, and tasks; monitor progress; meet deadlines; and integrate individual contributions into a final deliverable.
12	Ethics in the Lab	Behave with highest ethical standards, including reporting information objectively and interacting with integrity.
13	Sensory Awareness	Use the human senses to gather information and to make sound engineering judgments in formulating conclusions about real-world problems.

to occur within the laboratories described. It could be inferred that some took a constructivist viewpoint e.g. (Schubert et al., 2009; Diblk & Beran, 2010) during the development of the laboratories, however only Dal (2013) and Venkataramanan (2004) explicitly described a theoretical conception of teaching and learning that was used in the development of an EMD laboratory.

2.4.3 Judging the Pedagogical Effectiveness of Teaching Laboratories

Judging the effectiveness of a laboratory based upon the objectives and the conception of teaching and learning chosen should be considered as a research study, but this raises the issue of the methodology to be used for this judgement. Crotty cited in Case & Light (2011) provides a positioning of methodology in relation to the research process which provides a useful framework both for a comparative assessment of the literature on engineering teaching laboratories reviewed, and planning how to evaluate the success of a laboratory implementation. Crotty identifies four key elements of the research process: epistemology, theoretical perspective, methodology and methods. Epistemology refers to 'the theory of knowledge embedded in the theoretical perspective' (Case & Light, 2011, p. 188); this would include the pedagogical model of teaching and learning chosen. The theoretical perspective is the philosophy underpinning the design of the research, such as positivist, post positivist, and interpretivism, etc. (Case & Light, 2011, p. 188). Methods are the specific tests or procedures used to gather and analyse the data, and the methodology is the structure or strategy in which the methods sit.

Within the literature reviewed on engineering teaching laboratories many authors addressed some of the three pedagogical issues identified so far (educational objectives, a model of teaching and learning and judgement of effectiveness), however only a minority dealt with all three in one work. In particular three examples are presented in enough detail for a comparison using Crotty's framework (Case & Light, 2011): Venkataramanan (2004) dealt with all of these issues in development laboratory equipment and program to accompany a semester course on EMD systems; Dal (2013) addressed them in the implementation of a revised semester course on the control of adjustable speed drives; and Abdulwahed & Nagy (2009) dealt with them in the revision of a laboratory lesson for undergraduate chemical engineers that introduced a virtual laboratory simulation as preparation for the hands-on laboratory.

All three authors used what appeared to be a constructivist epistemology; Venkataramanan (2004) and Abdulwahed & Nagy (2009) explicitly used Kolb's Experiential Theory of Learning (Kolb 2004) or a derivative of this, while Dal (2013, p. 461) took what was described as an 'active learning' strategy within a conception of education as a closed loop process; this appears to be at least implicitly constructivist. The constructivist approach is compatible with the traditional view of engineering laboratory teaching where students learn by doing (Feisel & Rosa, 2005). The epistemology used to develop a laboratory has a profound impact on the analysis of student learning and the results of teaching; it also shaped the delivery of the curriculum in all three cases and impacted upon the equipment layout in the case of Venkataramanan (2004).

These three authors used a theoretical perspective founded on deduction (Trochim, 2006) that looked to measure the effect that teaching has on the students; that is, they started with a theoretical base, formulated a hypothesis, and made observations that confirmed or contradicted the theory. This is contrasted against an inductive process (Trochim, 2006) that could start with observations, look for patterns, and formulate a tentative hypothesis leading to a conclusion or theory. All three authors used a variety of methods to measure the effectiveness of teaching in what could be considered triangulation, as used by Borrego et al. (2009); including direct observation of students during teaching, and the results of their assessment and feedback in the form of student evaluations. The measurements were attempted in both 'absolute' and 'relative' terms. Absolute measurement is used in the sense that student attainment was measured against the stated educational objectives at the outset of the teaching; whereas relative assessment is used to measure the change in student attainment before and after teaching. Although the authors did not explicitly state their perspectives, they all followed deductive processes, and could be considered to be somewhere between positivist and post positivist. The premise that the results of education could be positively detected and measured is positivist whereas the use of triangulation tends towards a post-positivist viewpoint. This distinction is important because an inductive theoretical perspective such as interpretisim or critical theory (Case & Light, 2011) would have resulted in very different research methodologies.

These authors used a mix of methods to judge the success of the teaching; Venkataramanan (2004, p. 134) used student course results and student evaluations. Venkataramanan's students achieved results of between 60% and 94% with an average of 82%, however the author laments that 'Unfortunately data for a detailed comparison of student performance with a similar course offered in a classical format is not readily available' . Venkataramanan also uses student evaluations for a comparative assessment of the new pedagogy in the absence of 'controlled instruments to perform comparative and comprehensive learning effectiveness assessment' claiming a higher level of student satisfaction based on these results.

Dal (2013, p. 467) used student results for a component within the course, the overall course results, student evaluation and direct observation to measure the success of the teaching. Dal used a before and after testing method to evaluate the effect of homework and tutorial exercises in augmenting the lecture presentation for one component of the course. The results from two successive cohorts of students were used with a pass rate of 45% for previous course being compared to the pass rate of approximately 60% for the revised course. Dal uses student evaluations in an attempt to assess the effectiveness of the course methodology and improvement in student knowledge and practical skills. Interestingly Dal claims that '...the effectiveness of the course and materials' and the students '...gained the requisite skills for modelling, implementing, reporting and teamwork.' in spite of what could be considered a low pass rate for the course. While not explicitly stated as a method of measurement, Dal uses direct observation of student progress in the classroom.

Abdulwahed & Nagy (2009) used student results for a laboratory exercise and student evaluations of the parent course to judge the success of the teaching. Abdulwaheed & Nagy looked to create an experimental and control group of students; the experimental group participated in a virtual simulation of a laboratory to prepare them for a subsequent hands-on laboratory and improve educational outcomes by improving cognitive activation of what is referred to as prehension within the experiential model of learning developed by Kolb (1984). A test was given to both the experimental and control groups before and after the hands on laboratory teaching, statistical analysis indicates that the students attending the virtual lab had better results in both tests. This formed much of the basis for claiming the new pedagogical approach is successful.

The process of selecting the control group was problematic and casts doubt on the conclusions of Abdulwahed & Nagy (2009). Within the process students were divided into four groups, each with approximately even attainment scores for the previous academic year in an attempt to control for student ability. Two of the four groups were to be nominally used as the experimental groups with the remaining two the control group, however this was not implemented. Citing ethical and logistical issues attendance of the experimental groups at the virtual lab was not compulsory, and not all students selected attended; only the students who attended the virtual lab were used in the experimental group. Moreover in an attempt to avoid discrimination issues, the additional virtual laboratory simulation materials were made available to the entire student cohort including the control group. The result of the selection process is that it is entirely plausible that the optional virtual lab session attracted students who were already more motivated than their colleagues, regardless of the new pedagogy, and these students achieved higher marks by dint of more teaching contact hours and work on that particular piece of assessment than their fellows. This is unfortunately just as plausible as the authors claims of improved student performance due to a superior pedagogical method based on the information provided.

Abdulwahed & Nagy (2009, p. 290) also used a student evaluation questionnaire to judge success, in particular they cite the responses to the question 'Would you like the idea of conducting post-lab real experimentation though the internet (i.e. from your home PC) after the lab for enhancing your report findings or testing further ideas ' being higher in the experimental group as proof of activating the prehension dimension and motivating students. Unfortunately the wording of this question is problematic because it would probably appeal to students with higher inherent motivation because it gives them access to additional learning resources which they can use at their own discretion and convenience. Moreover the answers provided to this question may also be further evidence of the deficiencies of the experimental group selection process. This issue highlights the complexities of writing useful questionnaires raised by Heywood (2006, p. 406).

The assessment methods used by Venkataramanan, Dal and Abdulwaheed & Nagy raise the question of what kind of measurement should be used for student attainment, absolute or relative? This depends upon the aim(s) of the assessment, which could be to determine if student have reached the goals of teaching, or to compare the performance of one group of students to others, or to determine if there has been a noticeable improvement in students after training. If the aim is to determine if students are ready for professional practice, an absolute measurement of each cohort would seem appropriate. If a comparison between methods of pedagogy is the aim, a relative measurement between multiple student cohorts may be more suitable. If detecting the impact of training is the aim, relative assessment of a single student cohort before and after training would be appropriate.

Interestingly Venkataramanan (2004) laments the lack of a relative measure of success with all students succeeding by an absolute measure, whereas Dal (2013) claims success on the basis of a relative measure when by absolute standards 40% of students failed the course. In Venkateramanan's case it could be argued that it is unimportant how the current cohort of students performed with respect to their predecessors because they achieved the desired educational objectives of teaching, whereas Dal's approach could be judged a failure because the cohort performed poorly in absolute terms.

Abdulwahed & Nagy (2009) raised questions regarding the appropriateness of an experimental control group in judging the success of teaching. Firstly if the judgement of teaching success is to be to an absolute standard, then a control group is perhaps of little value, but if the relative judgement of success is to be used the ethical concern is that '... the students in a control group are at a disadvantage to those who receive the experimental treatment ' (Heywood, 2006, p. 398), which seems at odds with the typical motivation of educational research to improve student outcomes. There are also the logistical issues raised by Abdulwahed & Nagy (2009, p. 288) involved in administering experimental control groups and their different education. It would therefore seem that a control group approach is only appropriate if a relative measure of success will be used and that there are compelling reasons for this approach given the ethical and logistical problems associated with it in educational research.

2.5 Technical Concerns

Literature was reviewed to find similar equipment developed with similar educational aims, to prepare students for industrial practice with EMD systems. The features of the equipment described within the literature were examined to inform the development of the tool for the University of Wollongong. From a number of similar projects the following list of features and issues for consideration in the design of the EMDET was synthesised:

2.5.1 Flexibility

This relates to whether the equipment can be configured to teach students a variety of lessons rather than having a single purpose. Typically this included reconfigurable hardware to enable different types of motors, drives and loads to be investigated. For example:

- motors: asynchronous AC, synchronous AC, DC Motor
- drive types: Direct On Line (DOL) Start, inverters, DC converters
- load types: constant torque (winches) , squared torque (fan blowers)

The number of different electric motor and drive types available precludes using all of them in any one facility, therefore a design decision is needed to select a subset of them. Some facilities used a single motor and drive type while others chose to include a variety of motor and drives. Two facilities in particular included a wide variety of motor and drive types, one at the University of Illinois (P. Krein, 1993) and the other at Dresden University of Technology (Buechner, 2005). The Illinois facility included DC,AC Synchronous, Squirrel cage and wound rotor motors with a DC converter, AC pulse width modulated Inverters (PWM) and triac soft starter available as drives for the appropriate motors. The Dresden facility included a wound rotor Induction (WRIM) and DC machines. The WRIM included the ability to alter rotor resistance and configure the stator in star or delta. DC converters, DOL starters, PWM and four quadrant inverters were available to drive the appropriate motors.

From the literature reviewed the most of the equipment used a second motor (acting as a generator) as a load, usually a DC machine. Some facilities could control the torque of the generator to simulate different types of mechanical loads,while others ran the motors with no load, or when the equipment was small (tens of watts), having the student load the machines by hand. None of the facilities reviewed included a variety of real mechanical load types (e.g. fluid pumps, fans, winches).

2.5.2 Equipment Controllability

This relates to the capability of the equipment control the speed and torque in the motor and/or the load. Controlling motor speed is the fundamental purpose of many EMD systems. Control of the load allows for a full exploration of the motor capability, and also the potential to simulate a variety of real world loads.

Most of the facilities in the literature reviewed included some sort of speed control system for the motor, the most popular being DC converters and PWM inverters. A number of facilities also allowed for control of load torque; a facility at the University of Zagreb (Rovišan et al., 2008; **?**) focused on controlling the torque of a DC machine used as a load to resemble different mechanical loads. In particular the machine could simulate linear and squared torque speed load characteristics that are found in pumps and fans.

2.5.3 Fidelity

This relates to the degree of engineering fidelity as defined by Miller, cited in (Ma & Nickerson, 2006, p. 10) that is inherent within the equipment; is the equipment similar to what students would encounter in professional practice? The major concerns identified from the literature are:

- Equipment power levels: Is the equipment dealing with kilowatts of power and amperes of current or watts and milliamperes?
- Is the power manifested as mechanical power that can be appreciated by students? For example with equipment using a motor generator arrangement for power flow there is little or no appreciable difference between a few watts of power and many kilowatts of power being transmitted. If water is pumped or a loaded conveyor belt moved students can more readily appreciate the levels of power involved.
- Is it real industrial equipment or only suitable for use in a laboratory? Will using the equipment familiarise students with the kind of equipment they will encounter in professional practice?
- Industrial drive systems harness kilowatts of electrical and mechanical power so they are inherently hazardous. Safely dealing with these hazards is a significant issue in industry, so student teaching in this area would be valuable training in preparation for professional practice.

Many of the facilities in the literature focused on machines dealing with tens of watts of power, usually for reasons of cost and the inherent safety of low power systems. A number of facilities used motors in the 1-3 kW range with only the facilities described by (Buechner, 2005) and (Rovišan et al., 2008) having ratings greater than 5kW. None of the teaching facilities in the literature manifested large amounts of mechanical power; all of the equipment over 1 kW used electric motors as loads with the visible manifestation of mechanical power being a rotating motor shaft.

The only facility to physically manifest power was a facility developed by a European consortium including the Universities of Brussels, Darmstadt and Valencia (Serrano-Iribaarnegaray, 1995). In addition to regenerative loads, this facility included a three axis positioner table that could be driven within a 500 x 540 x 75mm envelope by AC servomotors.

Most of the facilities reviewed used equipment and configurations only suitable for laboratory usage, and while some utilised industrial components they were implemented in such a way as to only be suitable for laboratory use.

Two facilities focused on using real industrial equipment in an industrial configuration, one at Clemson University (Collins, 2009) and the other by the previously mentioned European consortium (Serrano-Iribaarnegaray, 1995). The Clemson University facility used industrial motors and drive system components to reflect their use in industry, but it did not use an industrial style control architecture, they used a personal computer with National Instruments LabVIEW controlling the equipment. The European facility also used industrial motor and drive systems, in particular it used an industrial control architecture to operate the equipment and interface with the user.

Some papers explicitly dealt with the safety issues of running laboratory exercises as design considerations. None however looked at the opportunity to prepare students for safely dealing with drive systems in practice using the teaching facilities. There is however a significant body of literature dealing with safety in a broader electrical engineering context (Story, 1996; Wu, 2008; Rowland et al., 2004).

2.5.4 Power Flow

This relates to how the equipment deals with the shaft power output of the motor; is it dissipated by some sort of load, whether it is mechanical, or electrical? How is this power dissipation addressed because significant quantities of thermal or mechanical power can be difficult to deal with in a laboratory, for example:

- heat from resistive loads may make laboratories uncomfortable or ultimately dangerous
- pumped liquids must be safely contained; water under pressure is of particular concern in laboratories dealing with electrical instruction
- low pressure air from fan systems create noise problems that could disrupt student learning

Alternatively is the shaft output power regenerated into the electrical power supply? While avoiding many problems it does lack fidelity, as described above. Only one facility provided a significant load to a motor other than a generator; this was the European consortium which included a three axis positioner table (Serrano-Iribaarnegaray, 1995). The other facilities either utilised a generator, no load, or in the case of some small equipment, they could be loaded by hand.

2.5.5 Teaching Audience

This issue relates to the prior academic achievement of students and the required coverage of material, in particular:

- Student level of education: Are the students undergraduate, postgraduate or professional practitioners? Of particular importance is the stage of undergraduate students are to be taught, from first to final year.
- What discipline of students are to be taught: electrical Engineers only, or will mechatronic and mechanical engineers to be taught as well?

Much of the literature describing similar facilities did not explicitly describe the intended audience. Those that did variously aimed at addressing undergraduate, graduate and continuing education students. The facilities focussed on the education of electrical engineering students, but some intended to include students in other fields including mechatronic, computer, mechanical and civil engineering.

2.5.6 Approach to EMD Systems - Component Level or Whole of System?

Does the equipment require students to deal with the devices at a circuit level or at a whole of system level? E.g. will students be required to wire up an inverter from diodes and transistors or will they use a commercially available unit? of the literature reviewed only Collins (2009) raised and addressed this issue, most authors appeared to have an approach set as a requirement for the development of the equipment.

Most of the facilities reviewed in the literature took a circuit level approach requiring students to construct drive systems in a variety of ways; for example some required students to construct drives from preconfigured assemblies (P. Krein, 1993; Panaitescu et al., 2002) whereas others required students to construct circuit boards, program microcontrollers and set firing sequences of semiconductor switches to drive a motor appropriately (Chu et al., 2008).

A minority of facilities utilised drive systems at the system level; they were constructed to prepare students for practice by teaching them using types of equipment commonly used in industry in a realistic industrial configuration. The facilities described by Buechner (2005); Collins (2009); Serrano-Iribaarnegaray (1995) exemplified this approach.

Selecting a circuit or system level approach depends on the purpose of the teaching. A circuit level approach is better suited to train students who will design, build, or repair drive equipment, while a system level approach is better for students who would install, maintain, and operate EMD systems. Ideally, students would be exposed to both levels of teaching to give them a broader experience and capability. Collins (2009) recommends a systems level approach on the basis that only a relatively small number of students will be involved with drives at the detail design level compared to those who would need to implement and use EMD systems.

2.5.7 Equipment Control and Human Interaction

This issues relates to the manner in which control decisions are enacted within the equipment and how the human user interacts with it. Specifically this includes how are components within the system controlled? How does a human operator interact with the system? How are key parameters measured, displayed and recorded? Are real industrial control systems used or are they specialist laboratory systems?

In the literature systems were controlled by various means; many used personal computers (PC) with appropriate control software and IO boards, often using national instruments Labview and Matlab software. Some systems used microcontrollers, either custom built or commercially available with custom code. A minority of systems used industrial controllers including programmable logic controllers.

Those facilities using low power levels tended to use one of two control schemes; a PC with an interface card connected to semiconductor firing circuits such as that described by (Huang et al., 1990), the second was a low cost microcontroller directly connected to the firing circuits. Here the user would program the microcontroller using a PC via a communications link such as that described by Chu et al. (2008).

The facilities using higher power levels tended to take one of two approaches. The first was similar to many of the low power facilities using a PC with an interface card, which was connected to commercial motor drive units rather than to semiconductor firing circuits (Collins, 2009). The second was to utilise an industrial control architecture using programmable logic controllers or industrial grade computers (Buechner, 2005; Serrano-Iribaarnegaray, 1995).

Within the literature operators interacted with the facilities in a variety of ways:

- Control via software on a PC was the most common method. This included when the PC executed the control function and when it was an interface to another control unit
- Propriety interface screens connected to Programmable Logic Controllers

All the facilities in the literature utilised PCs to some extent. The high power facilities tended to use them as an interface between the operator and drive equipment, whereas the low power facilities would use the PC to control the motor drive circuitry.

Key parameters were measured displayed and recorded using:

- oscilloscopes connected to the relevant components in the circuits
- transducers connected to the controller
- transducers and data acquisition cards (or units) connected to a standalone PC
- panel meters and manual recording

The most popular methods were data acquisition cards connected to a PC and oscilloscopes. The approach to data acquisition appeared to be related to the type of control system used. The systems using industrial control systems appeared to use them for data acquisition, whereas specialist laboratory control systems tended utilise PCs with IO boards that could acquire data or separate specialist data acquisition units.

A potential concern with using industrial control systems for acquisition is the sampling frequency available. For example, typical industrial programmable logic controllers are typically limited to sampling data at approximately 1 KHz (Toshiba, 2010), whereas typical switching frequencies for industrial power electronic drives are 3 kHz and higher ("Micromaster 420 Operating Instructions", 2006) ("Micromaster 420 Operating Instructions", 2006; "Advanced User Guide Unidrive SP", 2003). A PLC sampling at 1 kHz cannot sample voltages and currents at a high enough frequency to display the voltage and current disturbances caused by the drive switching, so a specialist data acquisition unit or oscilloscope is needed. Interestingly, none of the facilities in the literature reviewed appeared to take a hybrid approach utilising an industrial controller supplemented by specialist data acquisition.

2.5.8 Teaching in Fields Allied to EMD systems

This relates to the purpose of the equipment, is it solely for training students about EMD systems, or is it to be used for training in other related areas of engineering such as control theory, electrical power quality etc? While much of the literature focuses purely on EMD systems many facilities were intended to train students in allied fields. Some were constructed to include power distribution, power quality (Arsalan et al., 2002; Balog, Sorchini, Kimball, Chapman, & Krein, 2005; Buechner, 2005), control theory and automation (Huang et al., 1990; Bejan et al., 2009; Serrano-Iribaarnegaray, 1995) within the scope of teaching.

2.5.9 Exemplar Equipment

Some teaching facilities within the literature can be considered as exemplars for the EMDET because they addressed most of the key technical features identified very well. Importantly the selection of exemplar equipment is based upon the similarity of institutional and pedagogical concerns (identified in Section 2.2) driving the EMDET project. These concerns included that the work was motivated by the educational objective of preparing students for industrial practice with EMD systems, significant funding was available along with capability from the industrial partners, particularly that described by Collins (2009), Buechner (2005) and

Serrano-Iribaarnegaray (1995) which addressed most of the issues identified with the intent of preparing students for practice with EMD systems. In particular they:

- allow flexibility of load by controlling the torque absorbed by the load
- allow for flexible control of the motor including both control of motor speed and the use of different motor drive systems
- provide fidelity to EMD systems found within industry by utilising power levels and equipment commonly found in industry
- approach EMD systems at a system level as most practitioners would
- allow teaching in allied fields of power distribution, power quality, automation and control

2.6 Judging the Success of the Laboratory

The final issue addressed in the literature review was how should an institution judge the success of the laboratory considering the institutional, pedagogical and technical concerns? This would include determining whether the original motivation was addressed by the laboratory within the constraints? Was this done in a way acceptable to the institution? Were any shortfalls in performance addressed? Pedagogically, were the educational objectives defined and, students assessed accordingly? Was this assessment used as part of the assessment of laboratory delivery? Where the boundaries of teaching defined and did they fit into the overall engineering curriculum? Was the process by which teaching and learning expected to occur addressed in a pedagogically sound manner? Technically were appropriate components chosen and do they function together correctly to deliver on the pedagogical and institutional concerns?

Within the literature reviewed only (Schubert et al., 2009) and (Dal, 2013) presented significant attempts where the authors had explicitly set educational goals for the equipment, tested student attainment against them and taken appropriate corrective action when they were not met. Some authors made mention of increased student satisfaction either informally or formally after teaching on new lab equipment, but they did report any systematic approach relating educational goals to student attainment. Schubert's approach (Schubert et al., 2009) addressed a number of the key features for judgement of success:

- design objectives were set for the laboratory described. These included both educational and equipment concerns
- the teaching audience was defined as second year (sophomore) undergraduate students
- the outcome of learning was measured for comparison to the laboratory objectives. Three methods were used:
  - direct observation of student performance in laboratory work
  - student attainment in the laboratory exercise was assessed
  - questionnaires were issued before and after laboratory work to assess the student's attainment. These surveyed student's perception of their own knowledge of the material presented in the laboratory and their confidence in applying it to other contexts.
- changes in the laboratory were made based on the observed student performance and attainment in laboratory exercises:
  - experimental procedures were altered to improve accuracy of student results, to give students the opportunity to detect problems in their results, to avoid equipment issues and to alleviate time pressures to allow all exercises to be completed
  - changes and additions were made to laboratory equipment to improve accuracy of results and avoid equipment issues

There are some areas for potential improvement to the approach taken by (Schubert et al., 2009):

- the educational goals stated were focused on a single laboratory aimed at students with minimal knowledge of the subject. The paper did not describe if or how they fitted into an overarching goal for student attainment such as the desired competency of students with wisdom in the field of EMD systems
- although three methods of measurement were used, only two of them were explicitly used as part of a feedback process. The paper did not describe that

the questionnaires were used in a closed loop manner to correct any under performance

- the questionnaires were based on student's opinion of their own knowledge and confidence in applying it in other contexts. They made no reference to any external standard of competency. No assessment of the objectivity of these measures was made in the paper

Schubert's (Schubert et al., 2009) equipment comprehensively fulfilled the design requirements set of it, including the use of a DC motor for theoretical simplicity, very low cost equipment and the potential for twenty students to work simultaneously. These requirements differ from those at UOW and necessarily meant that Schubert's equipment performed poorly against the exemplar equipment described in section 2.5.9 particularly fidelity and a systematic approach. Of specific concern were the use of 1.5W DC motors loaded by a wooden clothespin clamped on the output.

Dal's approach explicitly (Dal, 2013) presented a closed loop model of education similar to figure 1.1. Dal's approach focused on providing feedback to students to improve their performance rather than considering changes to the equipment or curriculum. Nevertheless Dal addressed a number of the key issues in judging success:

- design objectives were set for the homework exercises; these were set in the context of higher level objectives to meet expectations of an industrial society
- the teaching audience was defined as undergraduate students
- The outcome of student learning was measured for comparison to the homework objectives:
  - observation and student attainment in a group presentation on the homework exercise was assessed
  - two different sets of questionnaires were used:
    1. questionnaires were issues before and after the homework exercise to test their knowledge
    2. a questionnaire on the student opinion of the educational method employed
- students have two chances to submit their homework assignments; after the

first submission feedback is given by the instructor to enable them to improve their performance on a second submission

There are a number of areas for potential improvement in the approach taken by (Dal, 2013):

- the design objectives for the equipment used were not explicitly addressed. A description of the equipment chosen was given but not in reference to meeting explicit design criteria
- the feedback process focused on the students themselves, it did not appear to include the possibility of changes in the equipment or curriculum

Dal's equipment performed extremely poorly in the key features identified in 2.5.9 particularly fidelity. The experimentation is entirely software and simulation based using MATLAB/Simulink and a DSP control board to simulate EMD systems and operated plant. No physical equipment was used.

2.7 Summary

From the general review of the literature addressing institutional, pedagogical, technical concerns and judgement of success a gap in the literature has been identified to comprehensively address the following issues within a single work:

- define an institutions motivations for creating the laboratory and the constraints
- define and agree on a method acceptable to the institution to deliver the laboratory.
- pedagogically develop the required educational objectives and link these to a fundamental list of objectives for an engineering curriculum. Define the limitations of learning in the lab and connection to the broader curriculum
- comprehensively use the educational objectives developed to:
  - shape the (re)development of a teaching laboratory
  - form the basis for judging the attainment of students being taught
  - judge the success of the teaching laboratory
- use an explicit pedagogical model of teaching and learning in development, delivery and assessment of the Engineering Teaching Laboratory
- combine all the exemplary technical features identified in the literature for the

objectives set

- apply usefully triangulated methods for pedagogical assessment (objective, subjective, absolute and relative)
- evaluate the effectiveness of the teaching laboratory as a research study using Crotty's framework (epistemology theoretical perspective methodology Methods)
- during evaluation of effectiveness address institutional, technical, pedagogical issues from the institutions perspective, including whether the original motivation was properly addressed within the constraints
- where any shortfalls in performance addressed?

While most of these have been dealt with in the entire body of literature reviewed very few addressed a significant proportion of the issues and none addressed them all comprehensively in a single work.

Chapter 3

Establishing the WiSE Project Approach

This chapter describes how the WiSE Approach was established that was used to deliver the EMDET project. It also presents a narrow review of literature to address concerns specific to the EMDET and WiSE and describes the structure and reasoning behind the WiSE approach.

3.1 The Knowledge Gap

The knowledge gap that motivated this work was characterised by listing the knowledge and practical skills engineers need to successfully practice with EMD systems and then comparing it to the skills that engineering students could reasonably be expected to gain from their undergraduate courses. The list was compiled by: consulting with industry and EMD equipment suppliers, reviewing the Engineers Australia accreditation guidelines (Engineers Australia, 2016) reviewing the engineering literature, primarily focussing on textbooks intended for training of both practicing and undergraduate engineers (Drury, 2009; Wildy, 2006; Toro, 1995; N. Mohan, 2003; T. U. Mohan & Robbins, 2003; Cook et al., 1998). This knowledge was categorised by both the area and depth of knowledge expected of the graduate, depending on their are specialisation. The opportunities for students to gain the required knowledge was compiled by reviewing the curriculum details of the Undergraduate Electrical, Mechanical and Mechatronic engineering degrees at the University of Wollongong (Univeristy of Wollogong, 2010a,b).

The list of the knowledge and skills required was compared to the opportunities given to students to gain them, and any shortfalls identified; these collectively defined the knowledge gap. The list of knowledge required, opportunities and the resulting gaps identified is shown in Figure 3.1. The knowledge gap identified was significant; nearly all areas of knowledge identified as being necessary for each discipline were either absent or the required depth was not available from the training within the curriculum.

3.2 An Overview of the Closed Loop Model of Education

Within the literature reviewed on EMD teaching laboratories, some authors (Dal, 2013; Venkataramanan, 2004) used pedagogical models of teaching and learning in the design of laboratories and student assessment. Venkataramanan (2004) utilised a model of teaching and learning called an ‘inquiry-based learning process’ to inform the design of the laboratory layout and the procedures; this process was founded on Kolb’s Learning Style Inventory (KLSI) arising from Kolb’s Theory of Experiential Learning (Kolb, 1984).

Dal (2013) employed what was variously described as a ‘closed loop process control’ or ‘signal flow diagram’ representation of the teaching and learning process; according to Dal the ‘strategy conforms to active learning concepts advocated by international societies such as ASEE, CDIO and SEFI’ (Dal, 2013, p. 461), however Dal does not define what is meant by active learning and the referencing provided does not lead to a definition either.

Nonetheless Dal’s work does endorse using an engineering conception of a closed loop process, informed by educational theory, as a useful pedagogical model of teaching and learning for developing engineering teaching laboratories. The attraction is that a concept familiar to engineers could be a used to address the educational aspects of developing a teaching laboratory, assessing student attainment and laboratory

	Electrical			Mechanical			Mechatronic		
Knowledge or Skill	Expectation	Potential Attainment	Gap	Expectation	Potential Attainment	Gap	Expectation	Potential Attainment	Gap
Safety									
Electrical Equipment	B	N	✗	B	N	✗	B	N	✗
Rotating Equipment	B	N	✗	B	N	✗	B	N	✗
Fundamentals of loads, motors and drives									
Torque speed curves	A	B	✗	B	N	✗	I	B	✗
Load types	A	B	✗	B	N	✗	I	B	✗
Motor types	A	A	✓	B	N	✗	I	B	✗
Motor speed & torque capabilities	A	B	✗	B	N	✗	I	B	✗
Drive types	A	B	✗	B	N	✗	I	B	✗
Drive Capabilities	A	B	✗	B	N	✗	I	B	✗
Matching motor & loads	A	B	✗	B	N	✗	I	B	✗
Induction motor characteristics									
Speed (based on construction)	A	I	✗	B	N	✗	I	B	✗
Torque speed curve	A	I	✗	B	N	✗	I	B	✗
Current Consumption	A	I	✗	B	N	✗	I	B	✗
Effect of supply voltage (magnitude & frequency)	A	I	✗	B	N	✗	I	B	✗
Mechanical Vs. Electrical parameters	A	I	✗	B	N	✗	I	B	✗
Power Factor	A	B	✗	N	N	✓	B	N	✗
Motor Cooling	A	B	✗	N	N	✓	B	N	✗
Induction Motor Drive characteristics									
Components of a drive system	I	B	✗	N	N		B	N	✗
Characteristics of Direct On Line Starting	I	B	✗	B	N	✗	B	N	✗
Characteristics of Soft Starters	I	N	✗	B	N	✗	B	N	✗
Characteristics of Variable Speed Drives	I	B	✗	B	N	✗	B	N	✗
Interaction of motor & Drive	I	B	✗	N	N	✓	B	N	✗
Drive design	I	B	✗	N	N	✓	B	N	✗
Drive Construction	I	B	✗	N	N	✓	B	N	✗
Motor, drive Load systems									
Motor Sizing	I	B	✗	B	N	✗	I	N	✗
Motor Duty Rating	I	B	✗	N	N	✓	B	N	✗
Power Quality Issues	I	B	✗	N	N	✓	B	N	✗
Variable speed & power saving	I	B	✗	B	N	✗	B	N	✗
Shaft speed & position sensing	I	B	✗	N	N	✓	B	N	✗
Shaft Speed Control Schemes	I	B	✗	N	N	✓	B	N	✗
Shaft Position Control Schemes	I	B	✗	N	N	✓	B	N	✗

symbol	nomenclature	description
B	Basic Awareness	Has an appreciation of the broad outline of fundamental issues involved. Qualitative understanding of important parameters. Importantly can recognise when more detailed understanding is required
I	Intermediate Understanding	Understands fundamental issues and their implications with an appreciation of advanced topics. Can quantify fundamentals and has qualitative understanding of advanced issues.
A	Advanced Understanding	Understands fundamental through to complex issues. Able to deal with all levels of the subject qualitatively and quantitatively.
N	Nil understanding	No understanding required

Figure 3.1: Knowledge Gap

performance. This would be of particular use during the design, construction, commissioning and testing of laboratory equipment and curriculum.

As described in section 1 teaching and learning throughout the EDMET project was addressed using an analogy to a closed loop feedback control system, shown (again for convenience) in Figure 3.2. Viewing teaching and learning via this analogy provided a number of benefits: it facilitated clear definition of the components involved; described their interaction and uncovered issues that had to be dealt with for successful operation of the EMDET.

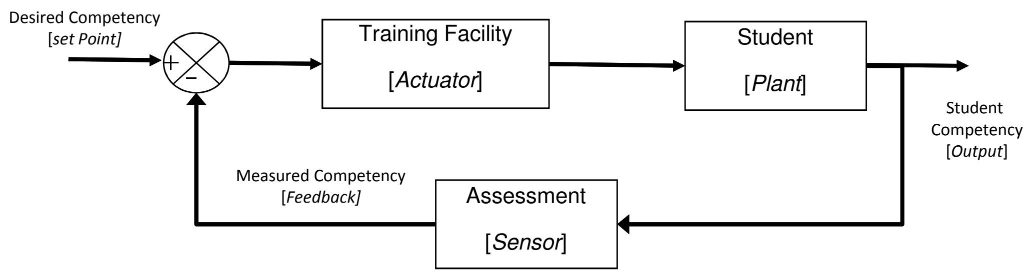


Figure 3.2: The Closed Loop Model and its analogy to training adapted from Ogata (1997).

To make use of this model relevant educational theory must be associated with it so that the dynamics and interactions of teaching and learning can be described in the same way it would a physical control system. Table 3.1 lists issues from the physical perspective of the closed loop model and their analogue requiring relevant educational theory. These theories were selected on the basis that they clearly, appropriately and expeditiously dealt with the problems faced by the engineering project and suited the closed loop analogy approach. While the theories selected from academic literature are well recognised there are many others of similar intent; no argument is made here for the superiority of the theories selected over any others. The review intended to find sufficient educational theory to allow the engineering project to proceed, not to compare educational theory.

Sections 3.2.1 to 3.2.8 describe the educational theory selected to establish the analogy and address the questions raised by table 3.1.

Table 3.1: Control system to educational analogue.

Component	Control System Issues		Educational Analogue
Output	What is the desired output of the system? How is it usefully defined?	Student Competency	What is the desired level of student competency sought? How is this level of competency defined?
Plant	What does the plant consist of? How does it operate? How is the quality of plant operation assessed? What are the limits of plant behaviour?	Student	What is the definition of the student audience? How do students learn? How can we assess the quality of student learning (from ignorance to competency)? What are the limitations of students learning – how much can they learn?
Actuator	How does the actuator drive the plant? What does the actuator consist of? How do plant and actuator interact?	Training	How can students be taught? What should the training facility consist of? How do students and teaching interact?
Sensor	How is the output measured? What are the limitations of measurement? What can impact the accuracy of measurement (signal & noise)?	Assessment	How is student knowledge and competency measured? What can affect the accuracy of student assessment?
Set point	How is the set point established to maximise the chances of the desired output?	Desired Competency	How a target level of skill and knowledge is measurably defined? How do these maximise the chances of competency?
Error Detector	How is the feedback measurement comparable with a set point? Is a useful error signal generated to drive the actuator?	Attainment	Are the results of the student assessment comparable with the educational objectives? Can a difference between the desired and measured competency be found to usefully influence training facility?

3.2.1 Student Competency

The measure of student competency selected was a crucial aspect of this project because it would fundamentally shape both project methodology, and the design of the tool itself. It would also provide the means to gauge the ultimate success of the tool in producing engineering graduates with the ability to successfully utilise EMD systems in practice. Consequently a useful and measurable definition of student competency was required to guide the project design and assessment of overall success.

During the early stages of the project it was considered that adding theoretical and practical components to existing degree programs utilising traditional assessment techniques would address the knowledge gap. However, during industry consultation to define the knowledge gap it became apparent that the traditional assessment techniques may not be comprehensive enough to accurately measure if a student is competent to practice with EMD systems; therefore a more comprehensive measure was required.

The need for a more comprehensive measure was inspired by industry accounts of costly technical mistakes made repeatedly by engineers attempting to utilise electric motors and drives. These accounts or 'war stories' were uncovered during industry surveys attempting to determine the skill required by graduate engineers, and define the knowledge gap (described in section 3.1). The mistakes made by the engineers involved in the war stories could have been avoided with a level of competency that was not readily measured using traditional assessment techniques.

The degree of competency required to avoid these mistakes is multi-layered. It means that students must not only understand what EMD systems are and how to use them, they must also also know the reasons why they are used in this way. In the field of information studies, this level of understanding is succinctly defined by Zeleny (2006) as wisdom. Importantly Zeleny's wisdom is hierarchical nature; including the layers of understanding what things are, how to use them and why. By utilising this definition of wisdom the desired output of the teaching facility could be usefully defined as engineers that practice with wisdom in the field of EMD systems. In simple terms, given a problem in their field of expertise a wise engineer would know what to do; how to do it and why it should be done in a particular way, in the specific circumstances.

Zeleny's definition of wisdom is part of what is called the data-information-knowledge-wisdom hierarchy (DIKW) in the information and knowledge literature (Rowley, 2007). This hierarchy is often presented as a pyramid to illustrate that stages successively build on each other; so information is built on data, knowledge is built on information and so on. This hierarchy can be illustrated via an analogy to baking as shown in Figure 3.3 adapted from Rowley (2007); Zeleny (2006).

	Definition	**Analogy (baking bread)**	**Purpose**
Data	Discrete objective facts or observations	The elements in bread: (water, yeast, starch etc.)	
Information	Data organised into meaningful order.	The ingredients and recipe.	Know-What
Knowledge	Information absorbed into the mind of an individual	An understanding to mix and bake the bread in a particular kitchen.	Know-How
Wisdom	A depth of understanding to explain why the information is structured as it is. In what context is it relevant?	Why does the recipe result in bread? What effect will altering the recipe have? What are the alternatives if an ingredient is not available?	Know-Why

Figure 3.3: The Data Information Knowledge Wisdom (DIKW) hierarchy adapted from Rowley (2007); Zeleny (2006).

Understanding the multi-layered nature of the required wisdom is important to avoid potential problems in training by setting the desired level of competency properly. Training and assessment can easily be set to reach the lower levels of the DIKW hierarchy only, e.g. merely presenting information to students and having them recite it back on cue is no guarantee that they will convert it into the knowledge and wisdom desired. Ideally, training should encourage them to absorb the information, understand its reasoning, its use and derivation.

Setting the desired competency appropriately at the top of the DIKW Hierarchy shaped the training and assessment of students to maximise the chances of instilling the wisdom desired and to determine if the training has been successful.

3.2.2 The Student

Although simple, a definition of the intended student audience was fundamental to the development of the tool. The intended student audience for the project included a variety of disciplines and educational levels. Electrical, mechanical and mechatronic engineering students were to be taught at the undergraduate, post graduate and continuing education levels.

3.2.3 Student Learning

A number of important issues regarding student learning required educational theories to address; for example, how do students learn? What is the quality of student learning? How much can a student be expected to learn?

The constructivist theory of learning was chosen to address the issue of how students learn, this theory holds that a student learns by doing and they must actively construct their knowledge from their experiences (J. Biggs, 2003; Kafai & Resnick, 1996). The major tenets of this theory (J. Biggs, 2003; Higher Education Academy Engineering Subject Centre, 2011; Tyler, 1949; Kafai & Resnick, 1996; Marlowe & Page, 2005) are:

- learners actively construct and reconstruct knowledge out of their experiences in the world
- forming new relationships with (existing) knowledge is as important as forming new representations of knowledge
- learners are most likely to become intellectually engaged when they are working on personally meaningful activities and projects

These tenets are very appropriate to student laboratory learning and engineering practice. The last tenet raises the issue of student motivation, also requiring educational theory. The expectancy-value theory of motivation (Feather cited in J. Biggs (2003)) is often used with constructivism; this states that two factors motivate learning:

1. the perceived value of the knowledge (its importance to the learner)
2. the expectancy of successfully learning (learning is perceived as possible)

3.2.4 Quality of Learning

While Constructivism informs us about how students learn, it does not give us an objective means to assess the quality of understanding a student has attained. A theory that facilitates the assessment of understanding is the Structure of Observed Learning Outcome (SOLO) Taxonomy as described by J. Biggs (2003). This structure accommodates a range of understanding from basic to comprehensive by describing five levels of understanding, each with an increasing level of sophistication.

1. Prestrutcural: there is little or no understanding of the topic at this level. Understanding if any is at an individual word level
2. Unistructural: a student may understand one facet of many in a topic, but misses other important attributes
3. Multistructural: a student understands multiple facets of a topic but these are not connected within a coherent structure, and they are addressed independently
4. Relational: all the important facets of a topic are understood and they are related to one another within a coherent structure of understanding
5. Extended abstract: a students understanding goes beyond what is given. The coherent structured understanding of the relational level is applied at a higher level, or applied to other relevant domains

Within the SOLO taxonomy the levels of understanding can also be described as verbs that a student is capable of. Figure 3.4shows these verbs alongside a visual representation of the Levels within SOLO (J. Biggs, 2003). Biggs also describes the lower levels of SOLO as quantitative and the higher levels as qualitative. During the lower quantitative stages the amount of detail in student responses increases, whereas in the higher qualitative stages information becomes integrated into a coherent structure.

The SOLO taxonomy can be usefully related to the DIKW hierarchy and the desired goal of wisdom in students. The lower quantitative stages described by Biggs are where students are in the data and information stages of the hierarchy. The higher qualitative stages of the SOLO taxonomy are indicative of students achieving knowledge and wisdom.

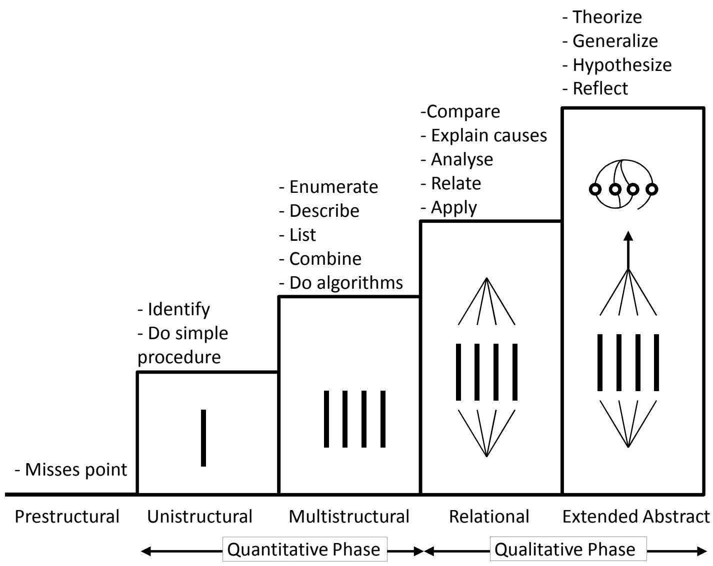
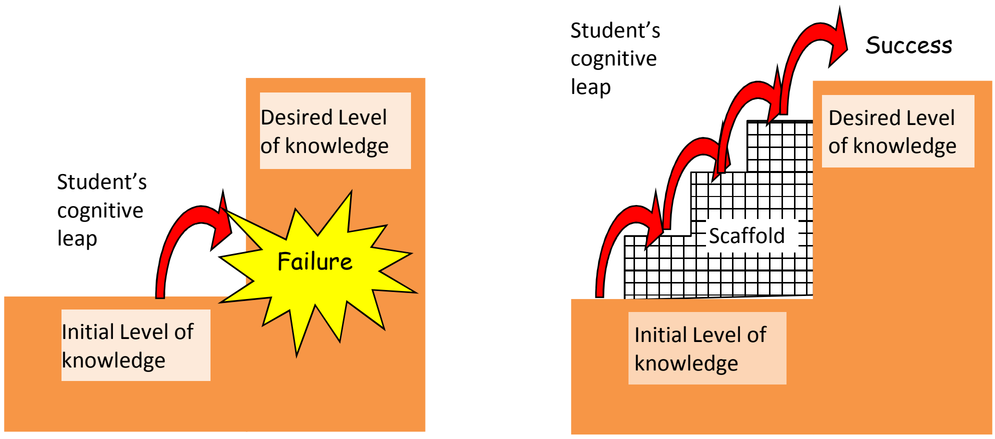


Figure 3.4: Structure of Observed Learning Outcome (SOLO) Taxonomy (J. Biggs, 2003).

3.2.5 Limitations of learning

The final major issue relating to student learning is how much can a student learn at once, and how does teaching impact on the amount a student can learn? Answering these questions in an absolute quantitative sense is difficult and depends upon the circumstances of the student, their context and what is to be learnt. However, within the context of a closed feedback loop qualitative information about the behaviour of students helps to design the training that is delivered to students. Theories of instructional scaffolding, the zone of proximal development (ZPD) and the cognitive leap address the issue; these theories inform us that a student's ability to learn a skill or master a concept is finite and importantly depends upon the instruction that they are given.

One of the earliest theories addressing this issue is Vygotsky's zone of proximal development (ZPD) (Harland, 2003; Lipscomb et al., 2010) which postulates that there is a zone of knowledge that a student can learn themselves, and immediately outside this is a finite zone that the student could potentially understand with assistance. Within this model, the movement of the student from one level to another within a single learning exercise can be described as a cognitive leap (Sheppard, 2009). The theory of instructional scaffolding (Lipscomb et al., 2010; Blanton et al., 2003; Benson, 1997; Linder et al., 2006) can be used to encapsulate these ideas in a



(a) Unachievable cognitive leap **(b)** Scaffolding provides achievable leaps

Figure 3.5: Instructional Scaffolding

way that is compatible with the SOLO taxonomy and constructivism.

The theory of instructional scaffolding borrows from the common use of scaffolding, where it is a temporary structure which allows otherwise inaccessible heights to be reached. In an educational sense, by tutoring and teaching a student can be assisted to learn something they could not understand by themselves. Instructional scaffolding has a number of important facets:

- the student is at an initial level of knowledge and ability
- they wish to ascend to a higher level of knowledge and ability but cannot do so unaided. The cognitive leap between levels is beyond the ability of the student
- instruction can break the ascent into to a series of achievable cognitive leaps for the student
- the assistance of the instruction is temporary; once the student has reached (mastered) the higher level of knowledge they can work at that level unassisted, so the scaffolding to assist the student to this level can then be removed

The function of instructional scaffolding can be understood in a visual representation in Figure 3.5 which compares a student attempting to learn something beyond their ability individually, then with instruction.

In Figure 3.5a the student's ability to make a cognitive leap is insufficient to move to the next level of knowledge. In the Figure 3.5b the appropriate instructional scaffolding breaks the leap into a series of achievable leaps for the student, so they are able to master the desired level of knowledge.

The small steps provided by the scaffold are not necessarily dividing a large concept into smaller ones, although this is certainly one option, because a single concept cannot always be divided, so the scaffolding in this case woudl be instructive assistance. This could include activating student background knowledge, encouraging dialogue among peers, prompts, questioning, coaching, etc. (Lipscomb et al., 2010).

There are striking similarities between the visual representations of instructional scaffolding and the SOLO taxonomy, in particular both convey a staged progressive development of knowledge. The similarity means they can be used together in a complementary manner if one considers that instructional scaffolding is the means of assisting student progression up the the levels of the SOLO taxonomy.

The theory of constructivism is actually implicit within instructional scaffolding. While an instructor contributes to the learning process, ultimately it is what the student does and learns in the process that allows them to achieve the new level of knowledge. If the student is not actively involved they will not learn adequately and will not have mastered the new level of knowledge, as would be the case if the instructor gave the answer to the problem without any involvement or understanding from the student. The result they will not have actually achieved the desired level of knowledge because they are unable to work at that level unassisted.

The theories of constructivism, the cognitive leap, instructional scaffolding, the zone of proximate development and the SOLO taxonomy provide the means to answer the questions: How do students learn? What is the quality of student learning? How much can a student be expected to learn? The answers are:

- in order to learn, students must be actively involved. They learn by doing
- the activity should be personally meaningful to the student
- connecting the existing knowledge can be as important as new knowledge
- there is a range of quality to student understanding of a concept or subject. The SOLO taxonomy provides a useful way to assess this ranging from ignorance to mastery of a concept or subject
- a student's ability to learn in a single learning exercise is finite
- there is a difference between what a student can learn unaided and what they

can learn with instruction

- instruction should break down an unachievable learning exercise for a student into a smaller series of achievable exercises.

According to these theories and within the context of their laboratory training students would need to be actively involved, and work with EMD equipment. The work should be relevant to professional practice, and this relevance should be evident to the student. The concepts presented to students within the laboratory work should link with each other, and the students previous training. The quality of understanding desired in students should be understood here by using the SOLO taxonomy. The learning exercises required of a student in the laboratory curriculum should be achievable, if not by the student in isolation they should be with appropriate instruction.

3.2.6 Training

Of crucial importance to the design of a tool to address the knowledge gap are the questions: How can students be taught? What should a training facility consist of? How do students and teaching interact? The principles of authentic assessment, constructive alignment, and the Tyler rationale can answer these questions.

Authentic assessment is a concept that training and assessment is 'True to practice' (Jolly, unpub.). Student training and assessment is carried out in conditions as close as possible to the work place, so the key principles of authentic assessment are that it (Janesick, 2006):

- is realistic;
- requires judgement and innovation
- requires students to do the subject
- Aassess students capability to use a repertoire of skills

The principle of constructive alignment is that a curriculum is designed so that the learning activities and assessment tasks are aligned with the intended learning outcomes. In a similar manner, the Tyler (1949) rationale poses four fundamental questions that must be answered when developing a curriculum:

1. What educational purposes should the school seek to attain?
2. What educational experiences can be provided that are likely to attain these purposes?
3. How can these educational experiences be effectively organised?
4. How can we determine whether these purposes are being attained?

Significantly the Tyler Rationale dictates that a closed loop approach is taken to teaching. According to the rationale and foregoing principles the laboratory equipment should ideally be the same or as close as possible to what is used in practice, and the students should interact with this equipment in a way that matches common industrial conditions and situations. Teaching should have clear educational goals, and the training and assessment of the students should be directly linked to them, and the training should be effectively organised and assessed used to ensure it is successful.

When these principles are combined with the idea of a student's capability to make a cognitive leap, the conditions under which a student is trained and assessed should, at the very least, be close enough to real practice so that a student can achieve the cognitive leap required to go from a training situation to real world practice.

The close relationship of the educational goals, the training exercises, the training equipment and the assessment would suggest that the equipment and curriculum should be developed concurrently to ensure that they are mutually supportive.

3.2.7 Assessment

In a physical closed loop system, the measurement of the output is crucial to control. Key issues in the teaching context are how can student knowledge and competency be measured, and what can affect the accuracy of this measurement? The desired output of the tool is engineers that can successfully practice with EMD systems. This was further defined as engineers that can practice with wisdom as defined by the DIKW hierarchy. The inspiration from industrial war stories can also be a potential way to measure student wisdom, so the desired output can therefore be defined as students who will not make the same mistakes as those involved in the war stories because they have enough wisdom to successfully avoid the mistakes of others. These stories could therefore be used as the basis of hypothetical scenarios which could be put to students, and those who can successfully negotiate these scenarios would be achieving the desired wisdom.

While the war story scenarios have the potential to positively identify if a student has reached the desired wisdom, they are unable to diagnose the partial mastery of a subject. They can detect success, but cannot quantify the magnitude of a failure. For example a student may fail because they are a long way from the desired competency; they do not know what the EMD system is, how to use it or why. Alternatively a student could be close to the desired level of competency, understanding what the system is and how to use it, but not why. The scenario assessment is unsuited to distinguishing between these levels of understanding.

Traditional forms of assessment such as laboratory work books are still very important to distinguish between levels of understanding achieved. If the assessment items are formulated using the principle of constructive alignment and follow the Tyler Rationale, they will have clear educational goals leading towards the desired wisdom and associated assessment tasks. Therefore student progression through them will be indicative of their progress towards the desired wisdom, and diagnostic of their level of understanding.

There are many things that can affect student achievement, and understanding them is critical to understanding the accuracy of measuring of student performance. From an engineering standpoint, what is the signal we are attempting to measure and what is the noise that may affect our measurement?

The signal we are attempting to measure is student achievement, particularly due to the performance of the tool to be provided by the project (curriculum and training equipment). The noise sources we would like to exclude are factors beyond the ability of the equipment and curriculum to control, such as poor student linguistic ability, lack of prior learning, and an inexperienced teacher, etc. The presage, process and product (3P) model of teaching and learning provides a framework that allows some insight into these issues (J. Biggs, 2003; J. B. Biggs, 1993).

This model recognises that the quality of a learning outcome can be affected by the student, the teaching, the teaching environment and their interactions before during and after a specific learning activity. It provides a visual representation that usefully highlights the potential interactions between the various factors. The presage stage encapsulates issues prior to the learning activity, the process stage during learning and the final outcome in the product stage. For example, referring to Figure 3.6 from (J. Biggs, 2003; J. B. Biggs, 1993), a lack of student linguistic ability or lack of prior learning are student factors in the presage stage. Similarly an inexperienced teacher is a teaching context issue in the presage stage.

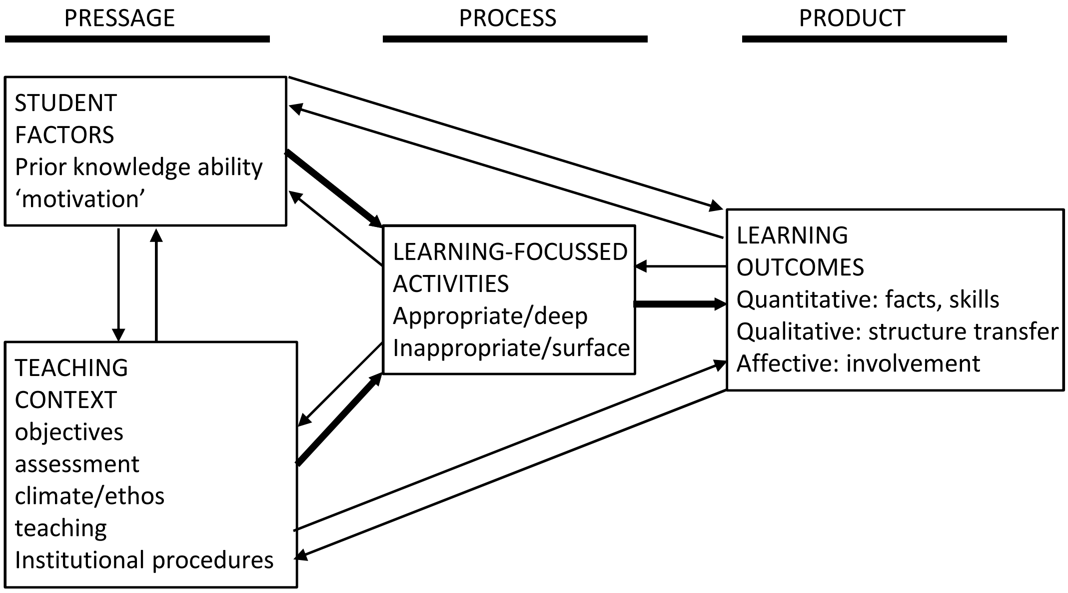


Figure 3.6: The presage, process and product (3P) model of teaching and learning (J. Biggs, 2003; J. B. Biggs, 1993)

The 3P model can be used as a framework to look at signals and noises in the educational process. Importantly this model identifies a number of 'sources of noise' that can affect results which are not readily apparent from war story scenarios or traditional methods of assessment. This would indicate that observation of the teaching and learning activities in process is recommended to allow detection of these noise issues. The use of multiple methods of measurement to eliminate noise from the signal is effectively using a triangulated method of assessment (Borrego et al., 2009).

3.2.8 Attainment

The attainment is, in closed loop terms, generation of an error signal that can usefully drive the behaviour of the actuator. To create a useful signal it requires that the results of student assessment are comparable with the desired competency, and that a difference between the two can be found to usefully influence training.

These issues have largely been dealt with; the war story scenarios can determine if students have reached the desired wisdom but cannot usefully diagnose lesser understanding. Properly designed educational objectives and associated assessments are crucial to providing enough error signal to drive necessary changes in the teaching and to allow the closed loop to properly function.

3.2.9 The Closed Loop Approach and Reflection

The closed loop approach can be considered to be a form of what is known as reflection within educational theory (J. Biggs, 2003), where the outcome of teaching is assessed and compared with the intended goals and corrections made if they differ. The benefits of the closed loop controller analogy is a clear framework in which to analyse the educational process, that brings insights from the field of control engineering to the process of education.

Reflection can be applied to both students, and teachers depending on the point of view taken; when applied from the teacher's perspective it is called reflective practice (Brockbank & McGill, 2007; J. Biggs, 2003) and from the student perspective it is called reflective learning (Brockbank & McGill, 2007). The closed loop controller analogy incorporates these concepts and can illustrate some differences by considering how they act to correct a shortfall in performance. Reflective learning is applied by the student, and acts to correct performance by making changes within the student (plant); reflective practice applies to the remainder of the loop where corrections can be made in the teaching (actuator), assessment (sensor), or the competency sought (set-point). The difference between them is who is actively working to correct performance and what they can influence.

Of critical importance to the closed loop approach and its equivalent reflective practices is active participation; from the teacher in reflective practice and from the student in reflective learning. The WiSE project process acts directly upon the training facility, assessment and desired competencies, making changes to these to correct shortfalls in performance. Therefore, using the closed loop approach in the execution of the project will naturally implement the principles of reflective practice. The student cannot be directly acted upon by the project, the student must choose to be involved in this process; so from the perspective of this project the active involvement of the student can only be enabled and encouraged. Firstly students must be aware of the competencies sought and their performance against these to enable them to be reflective if they so choose. Secondly reflection can be encouraged by motivating learning and by including reflective aspects in the teaching and assessment. Given the perceived value of the closed loop approach to education, enlisting the active involvement of the student was judged as equally valuable.

Figure 3.7 provides a visual summary of the relationship between the closed loop controller analogy and the educational theories selected to address the issues identified.

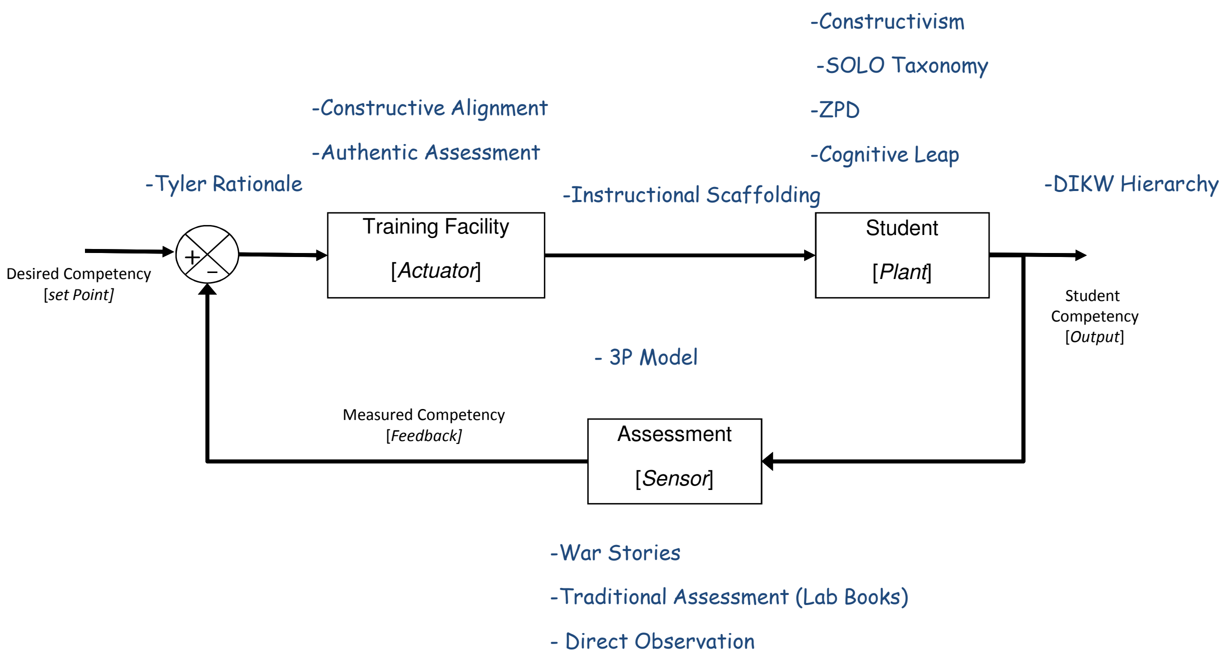


Figure 3.7: The closed loop controller analogy and the educational theories

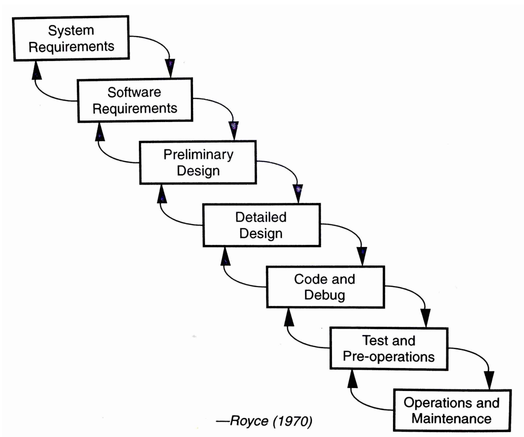
3.3 Models of project execution, systems engineering and the WiSE Approach

The creation of a new EMD teaching laboratory at UOW required a project to deliver a system. Accordingly, both project management and systems engineering processes were used to address the institutional concerns in creating the EMDET, that were later identified as the WiSE Approach. Literature was reviewed for similar models of systems engineering and project management so that the WiSE Approach could be appropriately placed within it. The criteria of similarity that this model needed to fulfil were:

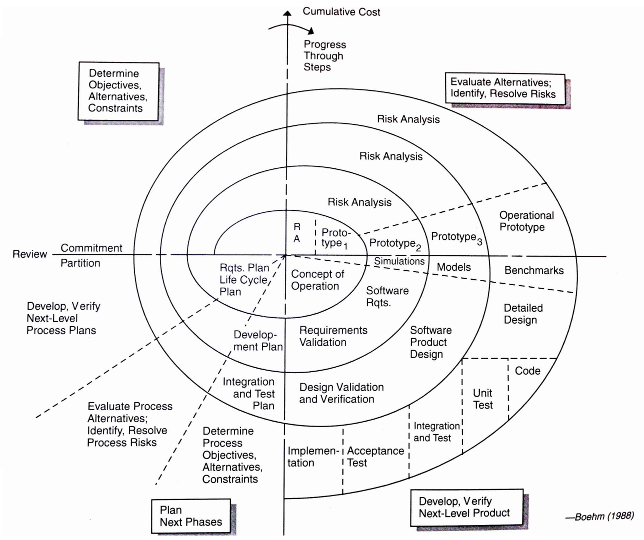
- 'ordered of the stages involved in ... development and evolution and to establish the transition criteria...' between phases (Boehm, 1988)
- allowed for the interaction of various parties in the project team who would necessarily be from different (parts of) organisations and have different skill sets - users, designers, constructor and project manager
- allow for the progressive elaboration (Anbari, 2004) and development of a statement of need through design to a functioning complex system. This would be through a process of decomposition and recomposition (Buede, 2016, p. 11)
- allow for the naturally iterative process of design
- cater for the interdisciplinary nature of the work required (electrical, mechanical, software and educational input)
- provide opportunity to deliver a system that has 'the best balance of the critical system attributes'(Kossiakoff & Sweet, 2003, p. 15) from the perspective of the stakeholders which importantly requires delivery of *pedagogical* outcomes and management of risk
- includes processes of verification and validation to control risk

There are many models within systems engineering and project management literature, and since the work at UOW lay largely within the overlap of project management and systems engineering domains, models appropriate to both were reviewed. Royce's waterfall in Figure 3.8a from Buede (2016) has been used extensively in software engineering (Blanchard & Fabrycky, 2006, p. 33)(Forsberg et al., 2000, p. 22). Many have criticised this model for its unrealistic assumption that iterations between widely separated phases are not allowed for. Interestingly Royce introduced this model as a starting point in an argument that ultimately proposed a different model, however the waterfall model was taken up by industry. The waterfall model was initially presented by Royce, its flaws were identified (including many of the subsequent criticisms) and a number of other models presented as potential solutions. Within the context of UOW the fundamental structure of the model does not set the expectation that stages of decomposition (define stakeholders need, design) (Engel, 2010) should have corresponding stages of recomposition (build, integrate and test) (Engel, 2010)

Boehm (1988) offered the spiral model to alleviate some of these concerns as shown in Figure 3.8b from Buede (2016) including much greater emphasis on iteration and the composition functions within the project. Criticisms of this model include that the 'spiral representation can be confusing' (Forsberg et al., 2000) when attempting to understand the stage a project is in, and that risk management occurs at discrete times within a project (Forsberg et al., 2000) when it is actually an ongoing task throughout the project.



(a) Royce waterfall model from Buede (2016)



(b) Boehm (1988) sprial model

Figure 3.8: Models of engineering process

To answer criticisms of the waterfall, spiral and other models of project execution Forsberg et al. (2000) proposed the Vee model shown in Figure 3.9 to visualise the technical aspects of a project to manage them. The model explicitly includes in the fundamental vee shape the decomposition process (left half of the Vee) and the recomposition process (right half of the vee), with each stage of decomposition having an explicit corresponding recomposition stage. The model also includes the explicit possibility of iterating between successive phases on each side of the Vee and across the Vee when verifying that the requirements of the earlier phases have been met. This allows for both large and small project iterations that are more clearly understood than in the spiral representation of a project.

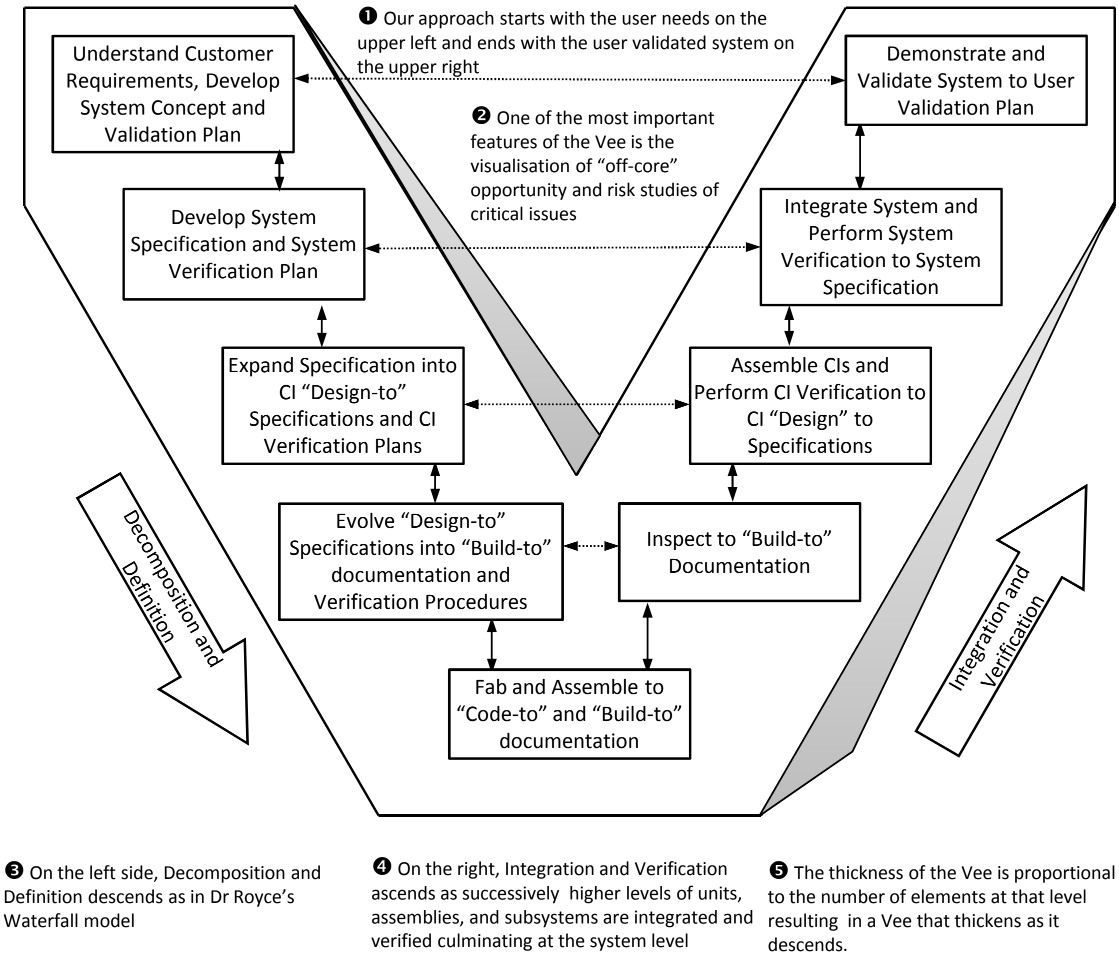


Figure 3.9: The vee model of project execution (Forsberg et al., 2000)

This model is intended to control the 'technical aspects' of a project alongside a 'business' aspect and a 'budget' aspect (Forsberg et al., 2000, p. 33) and thus could be understood to represent the process where concerns about project management and systems engineering overlap, as shown in figure 2.1. Within the literature the Vee model is variously referred to as a project management model Forsberg et al. (2000); BMI German Federal Government Commissioner for Information Technology (2006) and a systems life cycle or process model (Blanchard & Fabrycky 2006, p. 3; Buede 2016, p. 9-10; Engel 2010; Christie 2008, p. 23). This distinction is of little importance at UOW because the work lays within the overlap of both project management and systems engineering.

The Vee model closely matches the method of execution used during the development of EMDET but a number of processes were used to address the engineering educational concerns of delivering a teaching laboratory that are not present within the Vee model.

3.4 Augmentation of the Vee model for use at UOW - the Genesis of the WiSE Approach

The Vee model fulfilled many of the criteria identified, but the Vee model is general in nature, and can be applied to many fields outside of creating equipment for teaching. The Vee model used here lacked a number of key features of the approach used to deliver the EMDET at UOW:

- there was no explicit pedagogical foundation that was compatible with the Systems Engineering and Project Management process, and the closed loop model described in section 3.2
- there was no inbuilt guidance on the statement of need or verification methods to ensure that educational success was achieved, thus meeting the institutions motivation for creating the lab
- the iteration within the Vee model could be implicitly considered as focussing on the technical aspects (hardware and software) of a project and potentially risk overlooking the pedagogical aspects. Explicitly codifying the pedagogical aspects within the verification process by incorporating aspects of educational reflection (J. Biggs, 2003) could reduce this risk.

The WiSE Approach looked to address these shortcomings, it takes the Systems Engineering (or Project Management) Vee model of execution and adds the following *engineering education* augmentations:

- the deliverable of the closed loop development process is student competency to practice in the field of engineering. This both:
  - assists in risk management for the sponsoring institution as it sets the project to deliver the outcome desired (educational outcomes), not an intermediate step (e.g. equipment only)
  - allows some freedom for the project team to address educational issues

by making changes in the sphere most appropriate to the problem (e.g. changing equipment, curriculum, or both) rather than being restricted (e.g. changes to equipment only)

- a measure of competency (evaluation metric) was developed to assess readiness for practice
- the scope of delivery includes integrated equipment and curriculum
- the development takes an educationally reflective closed loop approach to ensure that equipment and curriculum together, deliver the desired competency using principles of action research (Kemmis et al., 2013; Klein, 2012; Lewin, 1946; Hinchey, 2008)
- the model uses an explicit pedagogical model of teaching and learning (based on the analogy of a closed loop feedback controller) that is:
  - compatible with the parent closed loop project approach
  - suitable for use by staff with technical backgrounds based on a familiar analogy

The Vee model used as a basis for WiSE is shown in Figure 3.10 noting the key features that are lacking; the WiSE Approach including augmentations is shown in Figure 3.11.

Within the interpretation of the Vee model used here and the subsequent WiSE approach there are a number of features important to project execution:

- there are 3 distinct parties directly involved in various stages of the project and their interaction needs to be managed. These are the Users, Designers and Constructors
- the process starts at the definition of the need to be addressed and concludes with acceptance of the system by the end User
- the left wing of the vee shows the process of design, from defining the requirements of the project, successively decomposing these into design specifications, through a design process culminating in construction
- the right wing of the vee shows the recomposition process of testing the components and integrating them into a system that can ultimately be accepted as meeting the high level requirements
- the area between the wings of the vee shows the process of verification and validation of the system, where each stage of testing has a corresponding stage

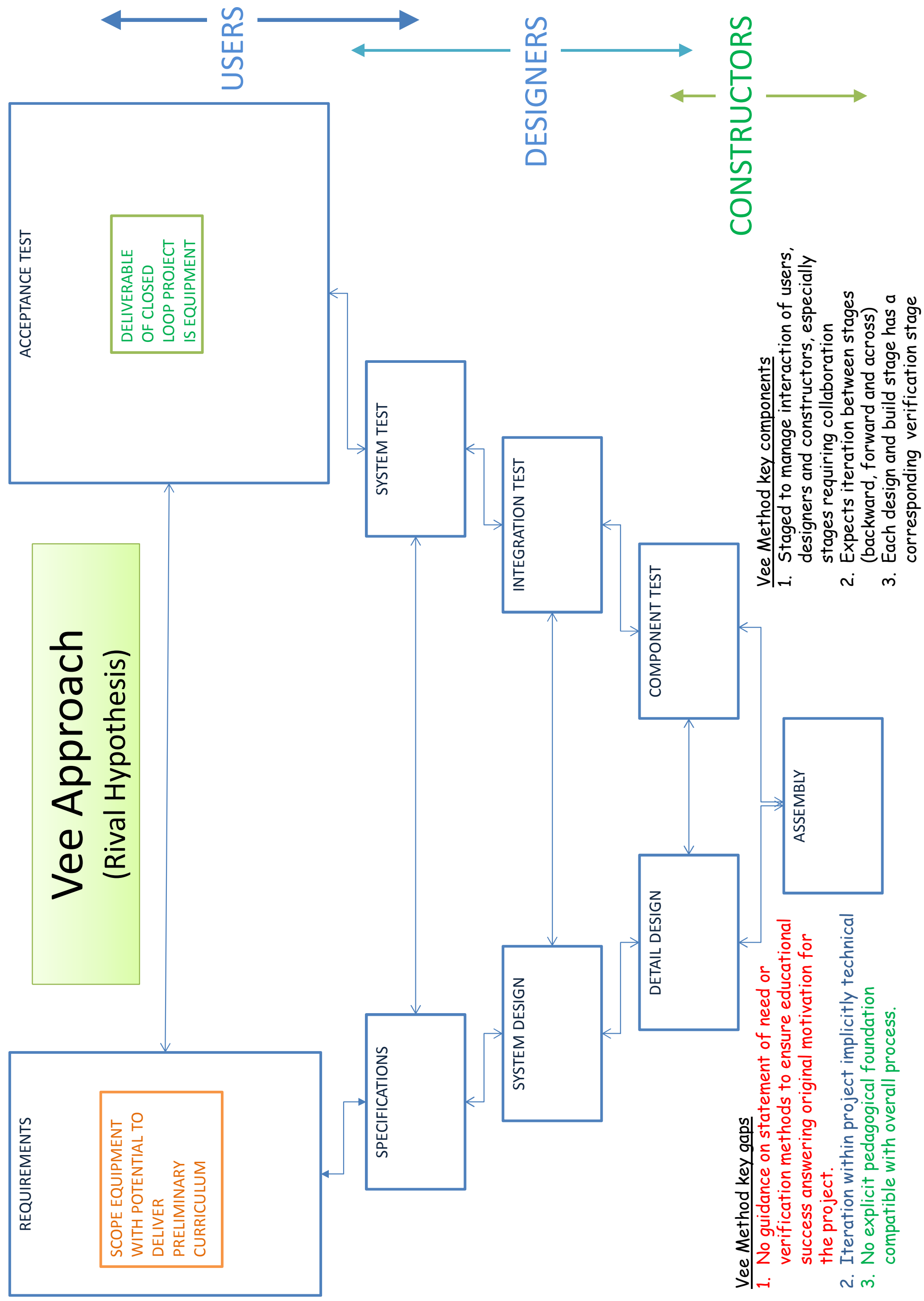


Figure 3.10: Project Vee Model.

of the design which it much satisfy to be deemed complete, e.g. the integration test must answer all or the requirements of the system design. This also ensures

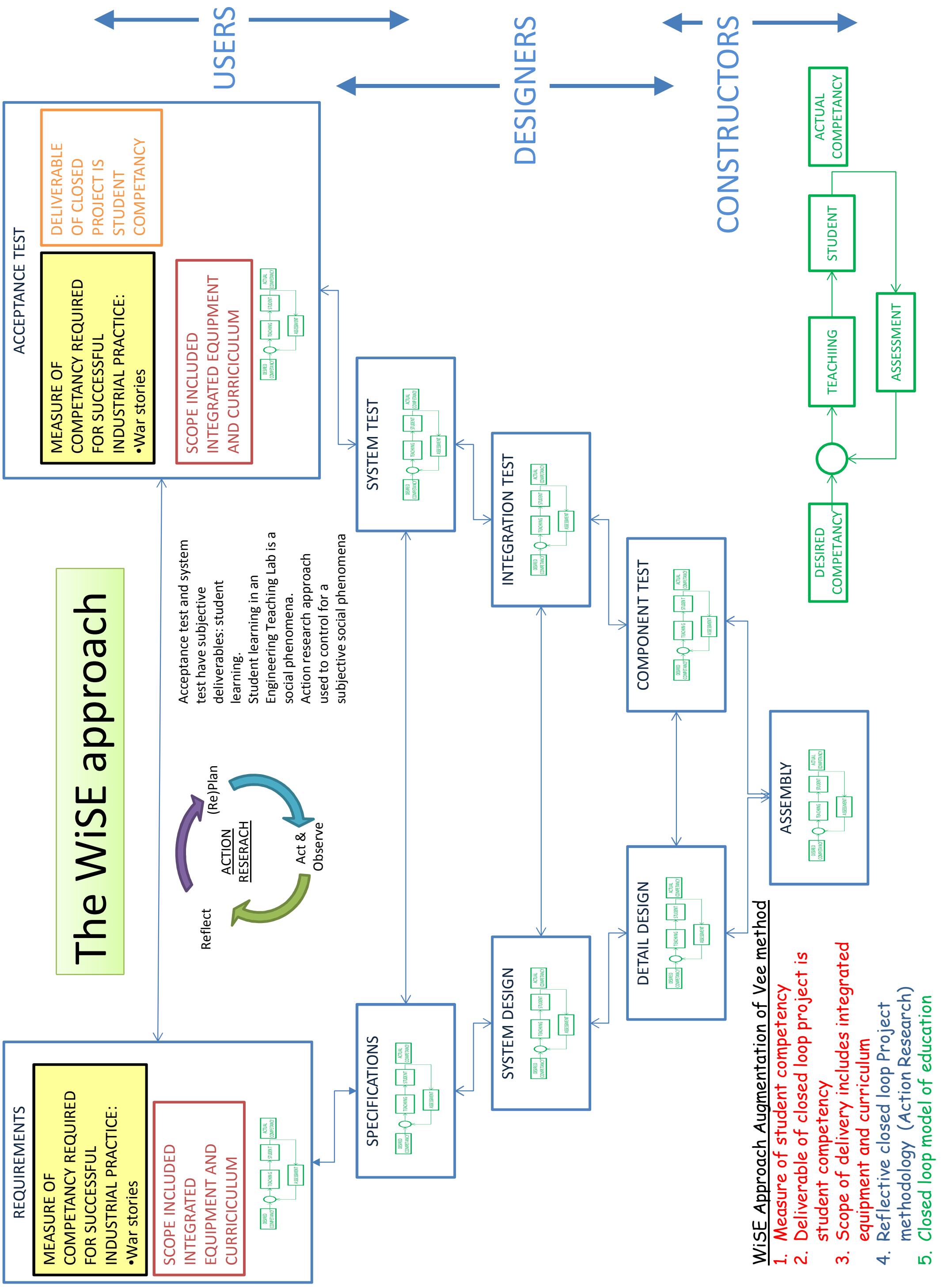


Figure 3.11: The WiSE Approach

that development is a closed loop process

- the arrows between the various stages illustrate the potential iteration that may occur throughout this process before it is completed, e.g. a problem found in the assembly stage may require a change in the system specification, which in turn will alter system design, which in turn alters detailed design and finally addresses the issue uncovered at assembly

The stages of the process and interaction between parties are briefly outlined here:

- Requirements Definition (Users): The need to be fulfilled by the project is established and described along with the relevant context. This description is largely written from the point of view of the final users of the project outcome, and is used to create requirements that the system must ultimately fulfil in order to be successful
- System Specification (Users → Designers): The requirements are translated into a set of specifications that the design must fulfil. This translates a description of need from the User's perspective into a description of what the design must achieve from the designers perspective. These specifications outline the parameters in which the system would be designed and operated and began to describe the overall system architecture.
- System Design (Designers): A system is then designed that would answer the specification and requirements. The system architecture is decided upon, the components required (both equipment and curriculum) for the system are identified, and their interaction is specified
- Detailed Design (Designers → Constructors): Each of the components within the specified architecture are designed or selected to properly function as a system in enough detail for assembly.
- Assembly (Constructors): The system designed is physically constructed.
- Component Test (Constructors → Designers): Each component within the system is tested in isolation to ensure that it functions as required by the detail design.
- Integration Test (Designers): Key groupings of components are tested to ensure they interact and function correctly when combined into a system.
- System Test (Designers → Users): The system test aims to confirm that what is produced meets the designers' intent. The entire group of components is operated as a system to confirm that they operate according to the system design to ensure that it meets the specifications.
- Acceptance Test (Users): The system is tested to check that it fulfils the need that initiated the project, and the test ensures that the system fulfils the requirements within the relevant context.

The EDMET was created using the WiSE Approach to address the knowledge gap observed at UOW. Within this chapter the knowledge gap motivating the creation of EMDET was defined, the model of teaching and learning used throughout the EMDET project was developed, models of project execution were examined and, in relation to these the WiSE Approach was presented.

Chapter 4

Methodology

The purpose of this chapter is to establish the methodology used to assess the performance of the WiSE Approach as a project execution process, by evaluating how well the WiSE Approach carried out the project to deliver the EMDET.

It is important to distinguish here between the prescribed sequence of steps used in executing the project, and the logical framework and procedure used to assess how well that sequence performed. Both of these are commonly referred to as methodology; but to avoid confusion within this document the sequence of steps used to execute the project are referred to as a *process*, which means the WiSE approach is a project execution process. The logical framework and procedure used to assess the performance of the WiSE Approach is referred to as a *methodology*. This chapter will establish a methodology to evaluate the performance of the WiSE Approach as a project process.

To evaluate the WiSE approach a number of definitions and a theoretical framework for the assessment is needed. Within this framework it is important to define what a project is, what it provides, how it is conducted and who is impacted by the project. This requires definitions for a project, the project outcome (that may be a produce or a service), project process and the project stakeholders.

According to the Project Management Body of Knowledge (Project Management, 2013) a project can be defined as temporary endeavour undertaken to create a unique product or service that has objectives, defined start and end dates and resource limitations that it must work within. (Nicholas & Steyn, 2008, p. xxvi) elaborate upon this and specify a number of characteristics of a project:

1. a project involves a single definable purpose and well defined end-items, deliverable or results
2. every project is unique in that it requires something different than was done previously
3. projects are temporary activities
4. projects cut across organisational and functional lines
5. given that each project is unique it involves unfamiliarity and risk
6. the organisation has something at stake when doing the project
7. a project is a process of working to achieve a goal with a life cycle consisting of several distinct phases.

What a project is to provide or the project outcome can be considered in terms of result for expenditure. An important consideration in many projects is how well the deliverables are understood, and utilised by the end users; this is sometimes defined as client acceptance (Pinto, 2013, p. 13). The overall success or failure of the project is judged by the final balance achieved between results for expenditure together with acceptance by the end users.

The conduct of a project or the project process is an ordered and recognised sequenced of steps to achieve project objectives by controlled utilisation of resources. According to Nicholas & Steyn (2008, p. xxxiii) this process is composed of 'organisation structure, information processing, and practices and procedures that permit integration of all project elements, tasks, resources, information, stakeholders etc. '. Furthermore this process provides the means for the key project functions of:

1. identification of tasks
2. identification of resource requirements and costs
3. establishing of priorities
4. planning and updating schedules
5. monitoring and controlling end item quality and performance
6. measuring project performance

The people who may impact a project or be impacted by the conduct of the project are called the stakeholders (Nicholas & Steyn, 2008, p. 54). There are many potential stakeholders within a project; including:

- the original sponsors of the project
- the owners of the final project outcome
- the end user of the project
- the project team (e.g. Project Manager, Designers, Constructors)
- those involved in the location of the project (Residents, occupants, neighbours, etc.)
- those responsible for the project or its environs (e.g. Governing bodies, regulatory authorities etc.)

Having established the key definitions, a methodology is needed that can critically evaluate whether or not the assertion that the EMDT project was successful due to the WiSE approach. The methodology will evaluate how the use of WiSE Approach as a project process affected the EMDET project, and what impact it had on project outcomes and stakeholders; this evaluation will be carried out as a case study. According to (Yin, 2009, p. 29) there are five key areas of design that the methodology of a research case study should address:

1. a study's questions
2. it's propositions
3. its units(s) of analysis
4. the logic linking the data to the propositions
5. the criteria for interpreting the findings

Each of these issues needs to be addressed to create a rigorous case study.

4.1 The Study's Questions

For a case study the questions to be addressed must be specified (Yin, 2009) with care to enable the case study to produce meaningful research. The general perception that the EMDET project was successful, the attribution to the WiSE approach and its potential worth for future projects can be divided into a three part hypothesis:

1. the EMDET project was successful and;
2. the project success was due to the use of a novel project process - the WiSE Approach
3. the aspects of the WiSE approach responsible for the project success could be worthwhile replicating in similar projects

This hypothesis has three problems, firstly, it has an inbuilt positive bias towards the project process. Secondly, it will tend to exclude some potential conclusions. Thirdly, it is potentially absolutist in nature and it may identify complete success or complete failure, excluding the possibility of a partial result. A more comprehensive approach would be to modify the hypothesis to investigate three key questions for the case study that derived from the original hypothesis:

1. What were the significant successes and failures within the EMDET project which led to its overall success or failure?
2. What impact did this novel project process have on the significant success and failures? In particular:
   (a) How does the novel process relate to the significant success and failures?
   (b) What aspects or parts of the novel process led to success and should be promoted?
   (c) What aspects or parts led to failure and should be avoided?
3. What is the scope of applicability of the findings?

The answers to the first two questions broadly outline four potential hypotheses to be evaluated by the case study:

1. the project (or aspects of it) was *successful*, and this *was due* to the use of the novel approach
   - aspects of the novel project process are related to the significant successes within the project and they led to overall project success. This would tend to confirm the worth of the novel approach
2. the project (or aspects of it) was *successful* but this *was not due* to the novel approach
   - aspects of the novel project approach are not related to the significant successes, or they are related to failures within the project, but the project

was still successful overall. This would tend to refute the worth of the novel process or aspects within it

3. the project (or aspects of it) was *unsuccessful*, and this *was due* to the novel approach
    - aspects of the novel project process were related to the significant failures of the project and they led to overall project failure. This would tend to deny the worth of the novel approach or aspects within it
4. the project (or aspects of it) was *unsuccessful* but this *was not due* to the use of the novel approach
    - aspects of the novel project approach are not related to the significant failures, or they are related to successes within the project but the project was still unsuccessful overall. Influences outside the project team or stakeholders caused the project to fail or there may not be enough information to evaluate the worth of the novel process in this case

4.2 Study's Propositions

To address the study's questions decisions must be made to direct the examination; this means determining what should be examined within the scope of the study and what evidence should be sought? The study's questions may not define the scope of examination in themselves, to progress a study propositions must be established to direct the examination (Yin, 2009). The questions of the EMDET case study are founded on the propositions that:

1. that success or failure of the EMDET project can be assessed; furthermore it can be related to the impact of the project process. The assessment should address the project as a whole, as well as its significant constituent parts
2. the process used to execute the EMDET project impacted upon the final outcomes; furthermore the novel aspects of the WiSE approach had an effect

The first proposition must be further developed to address the two component issues: How is success judged? How is a causal linkage established between impact(s) and success (or failure)?

The judgement of project success can be in absolute or relative terms, apply to whole or part(s) of the project and should account for factors outside of the control of project stakeholders. Assessment in absolute terms considers project performance against fixed standards such as time, cost, deliverables etc., while ultimately using the fundamental definition of a project and assessing the result achieved for stakeholders against expenditure. Whereas a relative assessment considers performance and uses the project itself as a baseline when considered in a reflective manner, e.g. parts of the project that could be improved, issues that may have arisen in the absence of the novel project process, etc.

The judgement of success should recognise that a project may not be a single indivisible entity and may consist of a number of discrete parts. A project that is successful overall may have parts within it that were failures, and vice versa, so the judgement of the project must allow for this. Part of judgement is identifying the cause(s) of the outcome, which can come from factors within and outside of the control of the project. A rigorous judgement should address the potential for outside factors impacting the final outcome.

To enable the second proposition to direct the examination of the EMDET case study, it can be developed further to state that within the conduct of the project, project decision making, or the products of the project, a pattern of impacts (either direct or indirect) from the project process should be evident. Furthermore, these impacts should be related to the novel aspects of the project process. Since the WiSE approach is adaptation of a standard approach, the novel aspects are the five augmentations that the WiSE Approach adds to the standard systems engineering Vee model project process.

A direct impact within this methodology is defined as where an augmentation in itself has caused decisions to made, action to be taken, or products to be altered, etc. An indirect impact is where the augmentation has interacted with the standard vee model project process to cause a different course of action to be taken than would have been the case if the Vee model alone was used.

Based upon this proposition a pattern of potential impacts resulting from the novel aspects of the WiSE approach can be predicted throughout the EMDET project, and then be compared to the empirical evidence of the case study. This is the analytic technique of pattern matching using non-equivalent dependant variables as defined by Yin (2009, P. 136). The correlation of predicated outcomes to empirical evidence will allow inferences to be drawn regarding the effect of the WiSE approach. The impact of the novel aspects of the WiSE approach on the project found via pattern matching needs to then be linked to the project outcomes.

Some of the predicted impacts provided by the pattern matching process may apply directly to the project outcomes (time, cost, deliverables), however other predictions may relate to how the project will be conducted (identifying tasks, establishing priorities, controlling quality, etc.). To usefully answer the research questions, a predicted impact must ultimately be related to the project outcomes.

It is proposed that decision making can form the causal linkage between the predicted impacts of the project process and project outcomes; there are four key arguments for this proposition: Firstly many of the predicted impacts will be the direct effects of the project process on decision making within the project. Secondly, project outcomes of time, cost and deliverables will all be affected by the decision making within the project; the absolute and relative judgements of project success or failure can likely be related to project decision making and from there to predicted impacts. Thirdly, the execution of a project can be usefully viewed as a series of decisions beginning at inception and terminating at the close of the project. The totality of these decisions can be assessed and conclusions can be drawn. A similar method has been used to assess the implementation of government programmes (Pressman & Wildavsky, 1979). Lastly by evaluating the relationship between the impacts of the project process on the totality of decisions made in the project leading to project success (or failure), an overall judgement of how the process affected the entire project can be formed.

4.3 The Unit of Analysis

In order to conduct a case study, its scope and boundaries must be defined (Yin, 2009). This study will focus on the project delivering the EMDET, beginning at conception in 2009 through delivery of prototype, delivery of production models, and teaching three cohorts of students in 2012, 2013 and 2015. The stakeholders in the EMDET project in this study are:

- the Project Control Group administering the Government Grant for the new research facility (UOW, 2009), this was the project sponsor
- the School of Electrical, Computer and Telecommunications Engineering (SECTE) at the University of Wollongong, the owner of the final project outcome
- the end users are a group involved with the electrical engineering subject *ECTE412/812/912 Power Electronics and Drives*; this group includes the academic subject coordinator, the Laboratory Demonstrators, and students enrolled in the subject. Throughout this document thid subject will be refereed to as the Power Electronics and Drives (PED) course.
- the project team consisting of:
  - the project manager, who is the author of this work working as a post-graduate student within SECTE
  - the designers including personnel from Emerson Control techniques (the industry partner), the author and academics from within SECTE
  - the constructors, from Emerson Control Techniques
- those involved in the location of the project were the future occupants of the new research facility
- the governing bodies relevant to the project, particularly Engineers Australia (EA) responsible for engineering course accreditation.

This case study will examine the EMDET through the stages of the WiSE Approach from the definitions of requirements to acceptance testing during laboratory teaching within the PED course.

4.4 Logic Linking the Data to the Propositions

The case study methodology must establish the logic used to link data gathered to propositions established (Yin, 2009), particularly how the data should be gathered, analysed and synthesised to answer the study's questions. The logic proposed here is that the WiSE Approach has impacted project decision making, and decision making ultimately determines project success. Therefore, data on the success of the EMDET project must be gathered, the impact that the novel aspects of WiSE Approach had on the project determined, a potential correlation between the project success and the novel aspects of WiSE evaluated (using decision making as a linkage), and the potential factors outside the control of the stakeholders on project success considered.

4.4.1 Judgement of project success

The second proposition of the analysis deals with the assessment of the project success; is proposes that project success can be absolute or relative, apply to the whole or part(s) of the project and should account for factors outside of the control of project stakeholders. How will data be gathered with regard to this proposition?

The fundamental definitions of a project and project outcome yield a set of absolute measures of success for the overall project:

- What where the deliverables for the project? Were they met?
- What resources were assigned to the project? How many were utilised?
- What was the time allowed for the project? Did it work within it?
- Was the project accepted by the stakeholders?

When the answers to these questions are considered together the overall project can be assessed properly; in particular, was the project outcome worthwhile when considered in terms of result for expenditure? Was there sufficient acceptance project outcomes by the relevant stakeholders of the project outcome? In the field of project evaluation this kind of assessment is called an ‘outcome evaluation’ (Thomas, 2012, p. 21), a ‘component evaluation’ can also be carried out on the project (Thomas, 2012, p. 21) where the individual stages within a project are assessed. When applied to the WiSE approach this would involve determining what the stage deliverables were, and if they were met. By conducting outcome and component evaluations the project is assessed in absolute terms to determine if part(s) or the entire project was successful in accordance with the propositions of the case study.

The project is also be evaluated in relative terms, which is sometimes referred to as 'lessons learned' (Thomas, 2012, pp. 21 29-40); this can encompass a variety reflective processes that review the conduct of a project. These may include project debriefs, close out reviews, etc. An example of this kind of analysis is called Keep, Stop, Start (Vilasini & Neitzert, 2012; Cole, 2012), that consists of asking reflective questions of the project participants after (and potentially during) a project:

- What should the project team *keep* doing: what went well and was successful, what are the effective practices that should be continued?
- What should the project team *stop* doing? What did not go well? What are the ineffective practises that should be discontinued?
- What should the project team *start* doing? What was not anticipated or dealt with properly? What new practices need to be implemented?

The *component evaluation*, *outcome evaluation* and *lessons learned* evaluations will be carried by reviewing the project documentation, records, correspondence, and accounts from project stakeholders. These accounts from stakeholders may also include interviews or structured feedback, such as student course evaluations. Collectively, the component evaluation, outcome evaluation and lessons learned evaluations will be referred to as a *project evaluation*.

4.4.2 Representation of Project Decision Making

As well as project success, the first proposition of the analysis deals with the linkage between project success and the impact of the project process; furthermore that this linkage is made by reviewing the project decision making. For the purposes of this case study, how will this project be presented as a series of events and decisions? What are the significant events and decisions? This can be done graphically in the form of a decision tree as shown in Figure 4.1; this facilitates the causal linkage of project process to project outcomes. For the purposes of this work the tree consists of decisions and events defined as:

- A *decision* being where one or more options were available and one was chosen
- An *event* being a necessary action or undertaking - a causal link in the project that either required no decision, or was the only available option

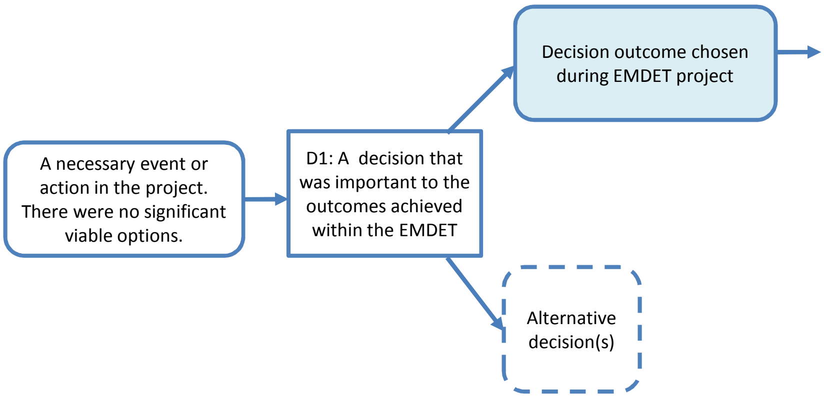


Figure 4.1: An example of a decision tree including an event and a decision

4.4.3 Evaluating the Impact of Process on the Project

The first proposition posits there is a predictable pattern of impacts (direct and indirect) on the project as a result of using the WiSE approach, and furthermore they are related to the WiSE augmentations. The individual augmentations of the WiSE approach were considered and their potential direct effects (positive and negative) on the project were predicted, these are presented in Chapter 15 immediately next to their usage.

The possibility that the WiSE approach having unforeseen impacts upon the conduct of the project must be recognised. During the pattern matching analysis vigilance must be exercised to identify any potential pattern of impact not predicted a priori, at the very least the data set should be explicitly evaluated for this possibility. Once the impacts of the project process have been identified, they can mapped onto the decision tree in preparation for linkage with the project outcomes.

4.4.4 Outside Factors

To account for potentially confounding factors outside the control of the project team or stakeholders, the parts of the project including direct student teaching and assessment (first acceptance testing phase and afterwards) can be evaluated separately;in those parts of the project without student teaching the major factors to consider are changes in scope or requirements after project inception that are imposed on the project team by the other stakeholders (sponsors, owners, users, governing bodies). Changes of this nature would be evident in project documentation and correspondence, and would likely be found in the project evaluation. From the beginning of acceptance testing and onwards, direct student teaching and learning must assess the interaction of the students, equipment, curriculum and teaching because Within this interaction there are a number of factors that are outside the control of the project team and the project stakeholders. A more thorough analysis of the teaching in progress is required to identify these factors.

During direct teaching and assessment of student learning a qualitative *grounded theory* approach (Case & Light, 2011) will be taken to evaluate the interaction between equipment, curriculum, students and teaching. This approach is sometimes referred to as a 'constant comparative method' where 'theory is generated from the data at hand' (Case & Light, 2011, p. 193) it is a structured ongoing, iterative process of gathering and analysing data. The grounded theory approach to be implemented on the EMDET case study will consist of gathering qualitative data from laboratory demonstrators through interviews and reflective journals during, and after teaching. This data is then analysed through the constant comparative method iteratively in stages.

The first stage is referred as 'open coding' (Case & Light, 2011, p. 193) where similar incidents from the qualitative data are grouped into categories to identify themes. New incidents are carefully compared to the previous members of a group before being added; this stage will progressively develop themes and categories for incidents. The second stage is called 'axial coding' (Case & Light, 2011, p. 193) which uses the themes identified by the previous open coding stage, and all of the data is retested to ensure it is properly categorised. The third stage is to check the categories and themes for overlap and relationships between them, and if necessary they are reviewed and refined. The data collection and the stages of analysis continue until what is termed theoretical saturation is reached, where no additional categories, themes or relationships are identified.

This grounded theory assessment aims to identify the factors affecting the overall project outcomes, particularly those outside the control of the project team and stakeholders so that they can be properly taken into account when assessing the project.

4.4.5 Linkage of Success (or Failure) to Project Process - Data Synthesis

The linkage of success to project process was achieved by synthesis of the information derived from the three analytical tools (project evaluation, pattern matching and grounded theory analysis) using decision making as a causal linkage between them. Figure 4.2 represents how the results from the analytical tools were combined to address the research questions in the following sequence of steps:

1. the significant project successes and failures were identified using a *Project Evaluation* process (comprising an outcome evaluation, a component evaluation and lessons learned evaluation)
2. The impact the novel aspects of the WiSE Approach had on the conduct of the project was evaluated using a *Pattern Matching* analysis
3. project decision making and events were captured on a *Decision Tree* to represent the project in preparation for using decision making as a causal link between project approach and project outcomes
4. potential outside influences on the project were identified using a *Grounded Theory* analysis
5. the final *synthesis* is performed linking approach to decisions to outcomes by:
   (a) linking significant success and failures to key decisions
   (b) assessing the impact of the WiSE Approach on the key decisions
   (c) accounting for any relevant outside influences

4.4.6 Deriving the Impact of the individual WiSE Augmentations on the Project

The *project evaluation* analysis will identify success (and failures) within the project. The synthesis of the three analytical tools will naturally provide the impact of all of the WiSE augmentations for each success. This can be considered as populating a

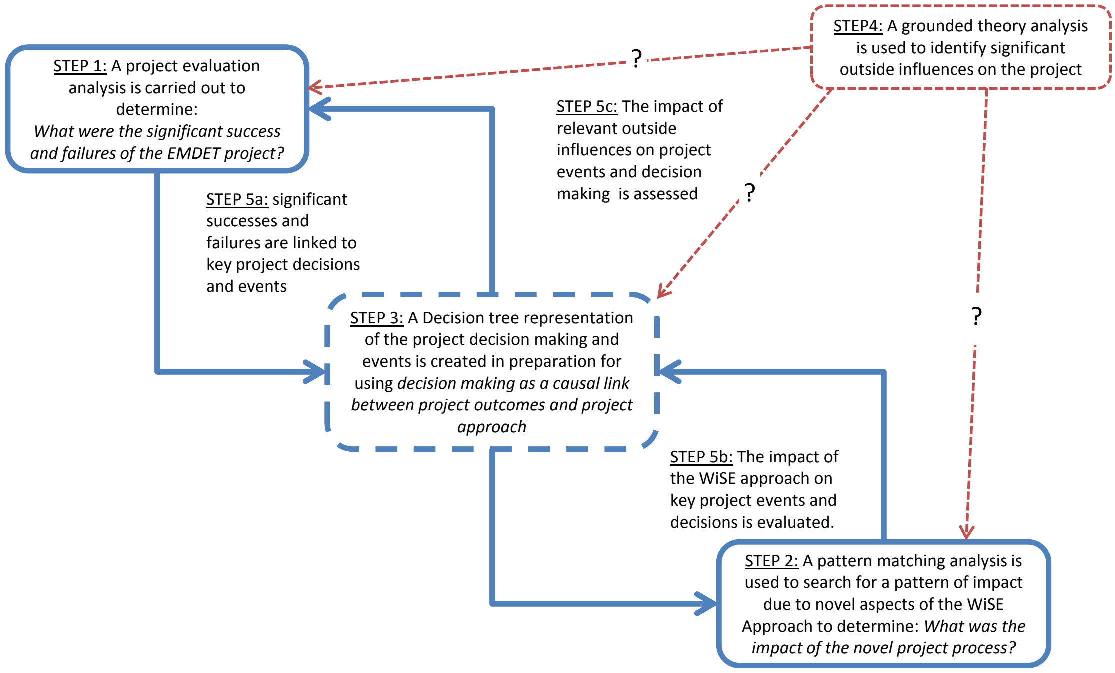


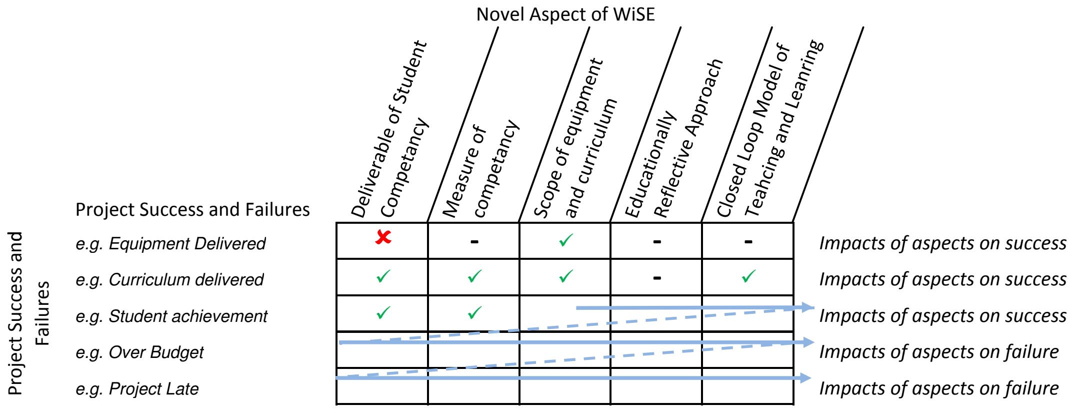
Figure 4.2: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

matrix which relates project success to the novel aspects of the project process row by row as shown in Figure 4.3a. Once this process is completed and the matrix is populated the impact of each novel aspect of the project process is encoded in each column of the matrix and the overall aggregate effect of the novel aspect can be found by reading the relevant column as shown in Figure 4.3b.

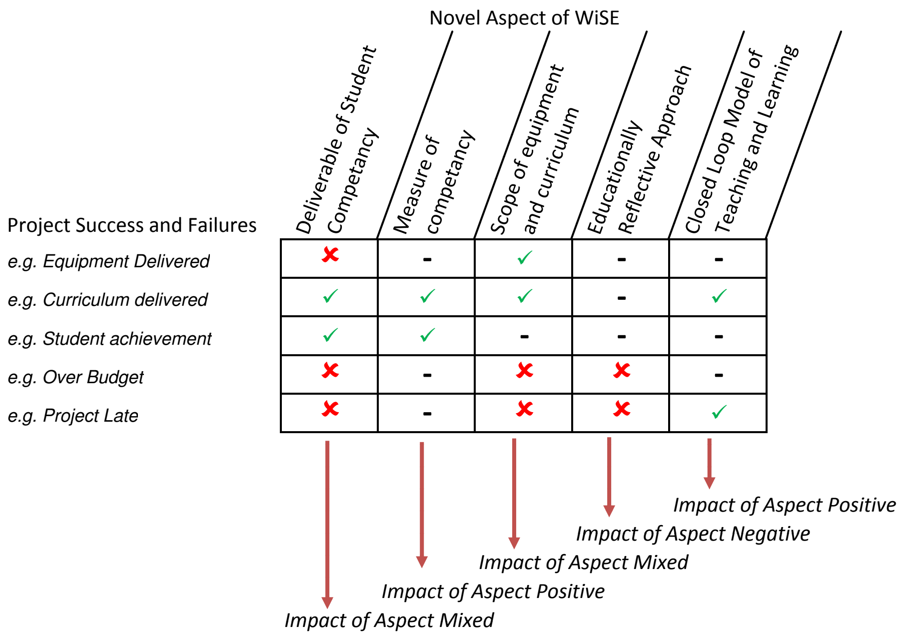
4.5 The Criteria for Interpreting the Findings

The criteria used to assess the findings must be established, in particular this case study should identify the most likely explanation for the results observed within the EMDET project case study based on the results of the synthesis. Determining the most likely explanation requires that credible rival explanations have been identified and addressed, (Yin, 2009, p. 135) identified broad categories for rival explanations that should be considered. The initial general perception of success and attribution to the WiSE Approach can serve as a source of inspiration for potential rival explanations that should be considered during the analysis of the empirical findings. The rival explanations that will require consideration include:

- the same or better results could have been achieved by delivering the EMDET project using a standard project process (e.g. vee model) followed by good reflective teaching, ultimately the WiSE approach (or the augmentations) did not actually contribute in a meaningful way
- the results achieved were due to the experimenter effect where the the researcher involved with the project inadvertently affected the results (e.g. students are taught to the assessment tool, rather than the desired competency)
- that positive student results could be due to their knowledge and ability of students prior training with the EMDET equipment; the equipment and curriculum did not positively affect the students
- that improvements in student attainment could be due to work of students outside the curriculum delivered as part of the EMDET project. A trend of improving results over the cohorts assessed could be due to students passing answers and information to successive cohorts, rather than improvements in the curriculum using the WiSE Approach



(a) Populating matrix during review of project successes and failures. Considering each success or failure identified - the impacts of the novel aspects are listed



(b) Assessment of each aspect of WiSE by reviewing populated matrix. The impact of each novel aspect can be considered across all successes (and failures).

Figure 4.3: Construction of and use of a Matrix relating project success to impact of the novel aspects of WiSE.

The first rival explanation deserves attention because it will form one of the major criteria for interpreting findings throughout the analysis. The proposition that the novel aspects of the WiSE approach impacted the project outcomes implies that the same outcomes (success or failure) would not have been reached using a standard project process; on this basis an assessment in relative terms using a standard approach as a baseline for comparison would seem appropriate. As the WiSE Approach is an augmentation of the standard systems engineering Vee model, the Vee model is a convenient and logical baseline for this comparison. Attributing the success of the EMDET project to the WiSE Approach in absolute terms when translated to terms relative to the vee model baseline becomes equivalent to attributing the success (or failure) of the project to the augmentations the WiSE approach adds to the vee model. The study's questions are constructed in the expectation that this key rival explanation will be one of the major criteria used to assess the findings.

4.5.1 Assessment of Decision Making

The method of analysis will use decision making as a causal link between project outcomes and the impact of the project process. It is therefore important to develop criteria for assessing decision making. According to Tregoe & Kepner (1981) the important components of the decision making process that should be considered when evaluating a decision, these include (Tregoe & Kepner, 1981, p. 84):

- recognising that a decision must be made
- defining the decision
- identifying the factors that impact upon the decision and their relative priority
- identifying the potential alternatives
- identifying the potential consequences of the alternatives
- selecting one of the alternatives

Given its importance to the analysis, some justification must be given to the proposition that decision making is to be used as a causal linkage between project process and outcomes. A comparison can be made between the components of decision making identified by (Tregoe & Kepner, 1981, p. 84) and of the project process (Nicholas & Steyn, 2008, p. xxxiii) as shown in Figure 4.4 where the strongly interrelated components are linked by arrows. It is evident that there are considerable similarities between the two, or they can be considered as overlapping as decision making is integral to a project process, which supports the proposition

Decision Process	Links	Project Process
Recognising that a decision must be made	↔	Identification of tasks
Defining the decision		Identification of resource requirements and costs
Identifying the factors that impact upon the decision and their relative priority	↔	Establishing of priorities
Identifying the potential alternatives		Planning and updating schedules
Identifying the potential consequences of the alternatives	↔	Monitoring and controlling end item quality and performance
Selecting one of the alternatives		Measuring project performance

Figure 4.4: The linkage between project process and decision making

4.5.2 What is the scope of applicability of the aspects identified?

The last question of the study looks to establish the applicability of the findings of the case study. This question will consider under what circumstances the conclusions of the study remain valid. In particular the recommendations must be reviewed against the context of the EMDET project and scope of the case study in to identify circumstances in which the conclusions would largely apply, partially apply and would not apply.

Part II

The Case Study

Chapter 5

Case Study: Requirements Phase

The requirements phase of the project established and described the need to be fulfilled by the project along with the relevant context. Within this phase the users established a statement of need that was progressively decomposed into a design and then recomposed into the final project outcome. The University needed a tool to assist in training students to properly utilise EMD systems in practice, with a particular focus on addressing the observed knowledge gap. This tool would consist of equipment and an associated curriculum which would operate as a coherent system and collectively became known as the Electrical Motor and Drives Education Tool (EMDET). Contextually, the EMDET would be part of a laboratory teaching program delivered concurrently with a course of lectures. Creation of the EMDET was undertaken as an engineering project, the scope of which was set to include both equipment and educational outcomes. This chapter describes how UOW's need was developed into a set of requirements to be delivered by the project; these were categorised as educational, contextual, technical and project requirements for the purposes of describing the case study.

5.1 Educational Requirements

The primary motivation for the EMDET project was to address an educational need, therefore determining the educational requirements is of paramount importance. The educational requirements can be defined by addressing the questions raised by the closed loop analogy presented in table 3.1. These questions help to establish the educational requirements and also elicit important contextual issues that will impact upon the EMDET. The EMDET had to consist of both equipment and curriculum to address the knowledge gap identified in section 3.1, these fall in the 'forward' path of the closed loop analogy (including error signal, actuator and plant). The questions arising from the forward path of the closed loop to define the educational requirements of the EMDET are:

- What is the definition of the student audience?
- What approaches to teaching students will be taken?
- What will students be taught to address the knowledge gap?
- What are the limitations of student learning?
- What should the training facility consist of?

Since this project is being undertaken in a closed loop fashion, the 'reverse' or 'feedback' path of the closed loop is critical (including the sensor, error detector, and the set point). The questions arising from the reverse path of the closed loop in Table 3.1 to define the educational requirements of the EMDET are:

- How will student knowledge and competency be measured?
- How can the quality of student learning be assessed?
- What can affect the accuracy of this measurement?
- Are the results of student assessment comparable with the target skill level?
- How is the target level of skill and knowledge measurably defined?
- How does the target maximise the chance of competency?

By addressing these questions an overall definition of the educational requirements for the EMEDT can be generated; these questions are addressed in sections 5.1.1 to 5.1.7.

5.1.1 Audience

The students come from electrical, mechatronic and mechanical engineering fields. While the most students would be taught at the undergraduate level, the equipment should also cater for postgraduate and continuing education students. As a starting point it would be expected that the students would be in the later years of their undergraduate engineering training and would have mastered a variety of fundamental engineering skills prior to be taught with the EMDET. This includes topics such as

3-phase electrical power calculations, the dynamics of rotating systems and signal processing.

5.1.2 Teaching Approach

The teaching approach will utilise the concepts of Authentic Assessment, Constructivism, Constructive Alignment and the Tyler Rationale outlined in section 3.2. These principles will impact the design of both the equipment, and the associated curriculum.

Authentic Assessment principles dictate that the equipment students use is ideally the same as, or as close as possible to what is used in practice. Equivalently, there should be *fidelity* between the equipment being used to teach, and what students would likely encounter in industry. Constructivist principles dictate that students must be actively involved with the equipment and that the activities must be personally meaningful. The students should actively use and interact with the equipment as they would in professional practice, thus exposing students to common industrial equipment and situations. The principles of Constructive Alignment and the Tyler Rationale dictate that the curriculum associated with the equipment should clearly state the educational goals to be attained, the experiences for students to learn, including their structure, and the methods of assessment. The assessment of student learning should be directly linked to the goal of preparing students to use EMD systems.

5.1.3 What will Students be Taught?

The EMDET must deliver a curriculum that will address the knowledge gap; this would be a key requirement driving its development. A preliminary curriculum of laboratory instruction was formulated drawing on three key inputs. Firstly, the list of knowledge and skills identified in Section 3.1 when characterising the knowledge gap. Secondly, it was decided that the EMDET would take a 'whole of system' approach to EMD systems because other equipment had been arranged for teaching at the component level. Thirdly, the opportunity should be taken to incorporate the ability to teach in allied fields, particularly electrical power quality and control theory. The preliminary curriculum is shown in Appendix A.

This preliminary curriculum was intended to address a number of the fundamental goals of engineering teaching laboratories as described by Feisel & Rosa (2005) and presented in table 2.1. It would address many of the objectives, with a strong focus on *Instrumentation*, *Models*, *Experiment* and *Data Analysis*. To a lesser extent the objectives of *Psychomotor*, *Safety*, *Teamwork*, *Ethics in the Laboratory* and *Sensory Awareness* would also be addressed.

The students to be taught with the EMDET were expected to undertake a course of lectures on the theory of EMD systems concurrently with laboratory work. Accordingly, most of the theoretical background material would be delivered by the lectures, and the laboratory curriculum would only be expected to provide theory not explicitly provided in the lectures or judged to be pertinent as a reminder.

5.1.4 Learning Limitations

Students can only learn a finite amount within a single learning exercise; furthermore students will need to be taught a significant amount of knowledge to bring them to the desired level of engineering wisdom. Therefore this knowledge must be broken down into attainable steps, and placed within an appropriate structure of exercises to take students from their initial level of ability to the desired wisdom. In other words the teaching must consist of a curriculum that delivers the knowledge in a series of achievable cognitive leaps. Importantly the final training received by the students should be sufficiently close to what students would encounter in real practice, so that **the cognitive leap between training and real practice is achievable for the graduates**.

5.1.5 Constitution of Equipment

The equipment included within the EMDET must match the preliminary curriculum, this has two fundamental consequences for design. First, if the curriculum specifically addresses a device or piece of hardware the EMDET must include it.

Second, if the curriculum addresses particular physical phenomena (currents, voltages, shaft torque, etc.) they must be present in the EMDET and (importantly) be **visible** to students.

5.1.6 Assessment of Learning Quality

The assessment of students must be able to both identify if a student has achieved the desired level of competency, and to diagnose a partial mastery of the material being delivered. In terms of the closed loop model, student assessment is the sensor that must be able to discern if the output has reached the set point, or determine how far away it is. The assessment should also identify the causes of any shortfalls in student learning and whether they are due to the student, the teaching, the equipment or the learning environment; that is the assessment should be able to discern a *signal* from the likely sources of *noise*. To reach these goals a triangulated assessment approach was chosen:

- scenario assessment: by posing to students real industrial scenarios ('war stories') that require the level of wisdom desired to successfully negotiate, the desired competency could be identified
- traditional Laboratory work book assessment: by using staged exercises and questions the students progression through the DIKW hierarchy could be assessed, and a partial mastery of the material being delivered could be evaluated
- direct observation: by observing laboratory classes in progress, issues preventing student learning outside of the curriculum being delivered could be identified, e.g. hardware faults within the EMDET, poor student linguistic ability, lack of prior learning, etc.

5.1.7 Target Level of Skill

The desired outcome of training students with the EMDET is that they are able to successfully practice in the field of EMD systems. This is defined as students who can practice with wisdom, as used in the DIKW hierarchy. Setting the goal of student training to be achievement at this high level of understanding should maximise a student's opportunity to avoid the costly technical mistakes reported by industry described in Section 3.2.1. For the purposes of assessment this target level is defined as students who are able to successfully negotiate the war story scenarios developed from the industry survey.

5.2 Contextual

A number of contextual issues impacted upon the requirements of the tool, such as the students to be taught, the location of the new power electronics and drives laboratory, and the interest of EMD equipment manufacturers who were partners in the design process. Students would not necessarily have had significant training in working safely with dangerous voltages, so the equipment and curriculum must be appropriately designed to protect students from electrical hazards contained within them.

There were some contextual constraints on the EMDET, particularity regarding the potential loads used; since the laboratory was part of a new research institute being constructed (UOW, 2009) in compliance with some rigorous energy efficiency and environmental standards (Australia, 2016) the equipment should avoid unnecessarily wasting energy. It was also decided that the use of water or noisy mechanical systems would be avoided. Water was problematic because the new laboratory would contain electrical equipment, some of which would not be suitable for use close to fluid handling equipment. Noise was also an issue as the laboratory was adjacent to offices and common areas so the permissible noise levels in this setting would be limited.

Two industrial partners expressed interest in being involved with the development of the EMDET; Siemens Australia made a donation of hardware including inverters and motors; Emerson Control Techniques expressed interest in a rigorous partnership encompassing the design, construction, commissioning and final use of the tool. UOW wished to accommodate both of these partners in the project.

5.3 Technical

The hardware would consist at a minimum of a motor drive connected to the 3-phase mains electrical supply, an electric motor, a load of some description and a control system. This is shown schematically in figure 5.1:

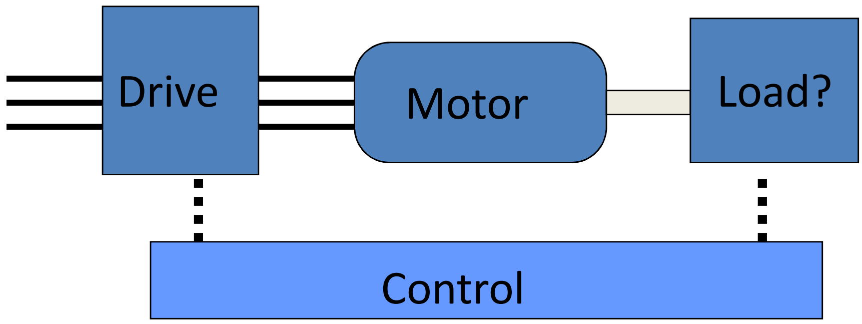


Figure 5.1: System schematic

The motor would be a squirrel cage induction motor because it is the most frequently encountered in industry Wildy (2006). The drive(s) would at minimum include an inverter or Variable Speed Drive (VSD).

5.4 Project Management Requirements

The project requirements centred on the effective and efficient use of university resources to provide the desired outcome because the EMDET project would consume limited resources (time, money and space within the new laboratory), the constraints had to be specified. The EMEDT provided must be good enough to perform as required; therefore the minimum levels of quality had to be established and systems enacted to drive the project to deliver them. Before the resources could be committed to develop the tool, the University had to be sufficiently confident that the outcome would be achieved; this required that the level of risk inherent in the project be managed to an acceptable level.

5.4.1 Resources

The project had to fit within the budget and time assigned to the new laboratory as part of the construction of the new research institute called the SMART Infrastructure facility (UOW, 2009). There was also a set amount of floor space assigned to the new laboratory that the EMDET had to fit within, while allowing for all of the other equipment, furniture and activities planned for the new laboratory. The tool had to be ready for installation in the new laboratories soon after they were completed in 2011 and ready for teaching in early 2012.

5.4.2 Quality

To perform as required and to address the knowledge gap identified the tool had to be of sufficient quality. This required establishing both the required standard of quality, and the systems to drive the project to meet or exceed these. The standard of quality required was captured within a document called a Customer Requirement Specification (CRS) ("Customer Requirement Specification", 2006), the systemic methods used to realise the standard were the overall closed loop approach of the project and the verification checks inherent within the WiSE approach described in Sections 10 to 13.

5.4.3 Risk Management

In order for the project to be successful a working design had to constructed and delivered within the required timeframe and budget. The risk that the project would not provide the required outcome within the resources assigned had to be reduced to a level acceptable to the University. Since many factors could potentially cause the project to fail; these individual risks contributed to an overall risk of failure.

The risks posed by the design were controlled by a combination of the WISE Approach, building a prototype for evaluation and the managing the personnel involved in the project. The WiSE Approach assists with the technical complexity of the project by breaking it down into manageable components. The decision to produce and assess a single working prototype before committing to the larger quantity required to fully outfit the laboratory was a significant risk control strategy. The selection and continued involvement of key personnel (with significant experience in successfully using EMD systems in industry and on other projects) from the inception of the design through to construction and delivery meant that the original design intent could be carried successfully through the entire project, particularly when changes were required during construction and commissioning.

The potential risks posed to the project in terms of context, purpose, quality, quantity, resources and time largely stemmed from three sources: (i) a lack of accurate definition and understanding of the project goals during the establishment of a project, (ii) monitoring and management during project execution and, (iii) the complexity of the design. These risks were all significant and a number of strategies were used to control them to a satisfactory level. The risk posed by a lack of definition and understanding was controlled by using the WiSE Approach that spends significant effort establishing project context and purpose during design phases; similarly the risks posed by a lack of monitoring and management of the project were controlled in the verification stages inherent to the WiSE approach.

Chapter 6

Case Study: Specifications Phase

The specification stage provided a brief that drove the subsequent system design and detailed design project phases. Within this phase both the users and designers decomposed the statement of need from the requirements phase into a form usable by the designers. This typically involved both translation from a user perspective to a designers perspective, and included elaboration where the statement of need is incomplete. The statement of need was developed further and in some areas augmented by some original conceptual design.

Some design issues were difficult to translate in terms of education, contextual, technical, and project concerns because they simultaneously impacted on several categories of requirement, so several overarching design philosophies were formulated that could address these multifaceted issues. The specification stage outlines both the design philosophies formulated as well as a detailed listing of features and functions that must be included in the finished product as an input to the subsequent stages.

The requirements determined from the user's perspective did not constitute a complete design brief, and some key high level design decisions, called organisational schema, had to be made to develop a detailed specification. They were as follows:

- high level configuration of equipment and flow of power within the tool
- configuration of the control system
- linkage between operational and educational concerns to the power and control

system

- method used to convert educational requirements into a functioning curriculum

After the philosophies and key organisational schema were determined a more detailed listing of the design specification could be completed. The remainder of this chapter enumerates the philosophies formulated, the schema determined, and the detailed specification that would form the brief for the system and detailed design stages.

6.1 Design Philosophies

The design philosophies formulated were primarily motivated by educational needs but had significant impact on the technical, contextual and project aspects of the specification. The educational issues centred around equipment constitution, approach to teaching and content of the curriculum. Corresponding philosophies were developed under the labels of constitution, fidelity and flexibility.

6.1.1 Equipment Constitution

To meet all the requirements the tool it must consist of hardware, software, procedures and a curriculum; all of which must be mutually compatible and function together to allow the curriculum to be delivered. If any of these elements are missing or incompatible then the tool will not deliver the desired outcome.

6.1.2 Fidelity

The philosophy of fidelity was motivated by considerations of the required approach to teaching and the underlying issues of authentic assessment and equipment fidelity. This philosophy had three major aspects:

- real industrial components should be used in a typical configuration that students could reasonably expect to see when they enter industry
- the amount of simulation used in teaching is minimised. As a minimum shaft torque and speed should be at industrial levels and ideally the power would

be physically manifested

- real industrial SCADA should have a laboratory grade data acquisition system overlaid

6.1.3 Flexibility

The philosophy of flexibility stems from the extent and variety within the list of knowledge and skills to be taught to students; this philosophy had two major aspects:

- there should be flexibility and modularity in the equipment and the control systems
  - ideally a number of typical industrial drive systems should be available for use, and they can be selected in a modular fashion
  - the code controlling the equipment should be modular, and it should allow for reconfiguring the drives and loads with a minimum of code alteration
  - the load should be flexible and able to demonstrate a variety of load characteristics; ideally changing loads should be quick, simple, and not need mechanical coupling or switching of loads
- the equipment should be future proofed
  - all physical phenomena relevant to the list of knowledge and skill within the system is present and visible
  - the modularity of the system should allow future needs to be met with a minimum of modification, ideally only software changes would be required

6.2 Organisational Schema

A number of high level design decisions were made to generate a specification that would allow the system and detail design stages to proceed. These decisions were manifested in four key organisational schema:

- the high level configuration of equipment and flow of power within the tool
- the configuration of the control system to be used
- the linkage between operational and educational concerns to power and control system

- the curriculum design methodology

6.2.1 Power flow

One of the key issues for the design of the tool was how would power from the motor be dealt with, and what sort of load would be used, a real mechanical load or an electrical load? A number of requirements and design philosophies contributed to the selection criteria for a load; some of the criteria were mandatory, and others were desirable:

- the mandatory criteria that the load had to fulfil included:
  - the load had to be flexible to allow students to investigate the characteristics of different loads encountered in industry (linear torque, squared torque etc.)
  - the loads had to fit within project budgetary constraints
  - the loads must be safe to operate within the confines of the new power electronics and drives laboratory
- the desirable criteria included:
  - the loads would allow power to be appreciably manifested.
  - the load would utilise typical industrial equipment
  - the loads would be low cost to maximise the funding available for data acquisition and other systems
  - the loads would be energy efficient and not waste power unnecessarily

An electrical load was selected based on these criteria; this was primarily a reflective compromise between flexibility and fidelity, with the electrical load being superior in all aspects other than the manifestation of power. The electrical load chosen still had to be refined to a specific kind of electrical load, so the selection criteria were refined and applied to a number of potential options that could be used as an electrical load.

- the refined mandatory criteria that the electrical load had to fulfil included:
  - a flexible and controllable load that could realistically simulate real mechanical loads
  - the equipment, generators, drives, brakes, and loads had to fit within budgetary constraints, so rare and non-standard equipment or equipment requiring extensive design and development would be costly and should be avoided
  - the loads must be appropriate to use within the confines of the power

electronics and drives laboratories, which meant that heat dissipation would be an important consideration

- the desirable criteria for the electrical load were refined to include:
  - the loads be low cost to maximise the funding available for data acquisition and other systems
  - the load should ideally utilise typical industrial motor and drive equipment
  - the load be capable of regenerating power into the supply

An induction motor with a regenerative drive was selected due to its superior performance against all the selection criteria; all the other options were judged to be overly expensive.

Once an induction motor with a regenerative drive was selected, the power flow schema was now complete as shown in Figure 6.1. The system would consist of two motors coupled together each with a separate drive. During operation electrical power would flow from the 3-phase mains supply, through Drive 1 to Motor 1. Motor 1 would convert the electrical power to mechanical power which would be transmitted via the coupling to Motor 2. Motor 2 would convert the mechanical power to electrical power which would be regenerated back into the 3 phase mains via Drive 2.

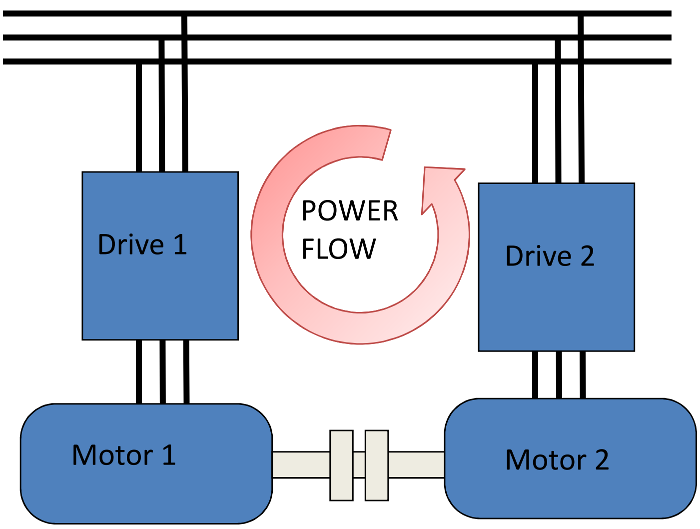


Figure 6.1: Power Flow Schema.

6.2.2 Control system

Some key issues regarding the control system were resolved to allow a specification to be generated and the subsequent design stage to proceed; they included what kind of hardware would be used, how would students and lab supervisors interact with the equipment, and where would control decisions be made? These decisions were influenced by the design philosophies of flexibility and fidelity, and the requirements of context described in section 5.2 and equipment constitution in section 5.1.5. Specifically the control system should:

- be flexible and modular to allow drives to be reconfigured and different mechanical systems to be simulated with simple software changes
- ensure that all the relevant physical phenomena are present and importantly visible via data acquisition
- use real industrial control equipment in a typical configuration
- use a real industrial SCADA system with a laboratory grade data acquisition system overlaid
- provide protection for students and equipment from dangerous equipment operation; students should not be able to command the equipment to damage itself

To operate the motors and drives within the power flow schema, hardware for the control system is needed including a controller, operator interface devices, transducers for data acquisition and ancillary equipment. Three major options were considered for the controller: the first was to utilise a Personal Computer (PC) likely augmented by a data acquisition card. The second option was to use a dedicated industrial controller such as a programmable logic controller (PLC). The last option considered was to use relatively simple electromechanical controls in the drive panel. The use of electro-mechanical controls was quickly dismissed because they could not deliver the sophistication and modularity of control required. The use of a PC as a controller for the EMDET raised two major concerns: reliability and fidelity. Firstly, the controller would be controlling kilowatts of electrical and mechanical power and be responsible for equipment and student safety; the reliability of a PC in this role was in some doubt. Secondly most industrial control systems use dedicated controllers such as Programmable Logic Controllers (PLC), distributed control systems (DCS) or micro-controllers; so using a PC would conflict with the fidelity philosophy. Therefore a PLC or other industrial system was selected as the controller.

Two kinds of operator interface were deemed necessary, low level devices (single purpose) and a sophisticated interface for utilising the complex functionality of the EMDET. An emergency stop button, indication lamps and some push buttons for enunciating equipment faults were nominated as low level devices. A PC equipped with graphical interface software (refereed to as Human Machine Interface (HMI) software) was selected for the high level interface between operator and PLC as is often done in industry. Noting that the PC would solely be an interface with the PLC and not act as a controller.

Transducers would be required to provide experimental data by monitoring currents, voltages, shaft torque and speed. The data would be displayed via both panel meters (low level interface) and through a data acquisition card and software on the PC (high level interface).

6.2.3 Linking operational and educational need to equipment specification

An organisational schema was needed to create a *linkage* between operational and educational concerns outlined in the requirements phase of the project, to the design for the power and control system addressed in the system and detail design phases. This would map the needs of basic operation of the motors and drives, and the educational requirements of the curriculum ,to the specific functionality necessary in the power and control equipment. A linkage matrix was created to accomplish this mapping.

The matrix consisted of columns denoting the major power and control system components, and rows denoting each of the basic functions or specific lessons to be delivered by the EMDET. For each function (or lesson) the requirements of each of the major components to perform this function were identified and specified. This included the basic functionality required in any electric motor system, the preliminary curriculum drafted, and the power flow and control system schema outlined in Sections 6.2.1 and 6.2.2. The matrix was fully developed iteratively throughout the specifications and system design phases. An extract of the matrix is shown in Table D.1 in Appendix D.

As well as linking the requirements and design stages of the project, the matrix fulfilled two other valuable functions. Firstly it prompted a full description of the specifications required for the tool and secondly, provided a convenient means to extract the specifications for each of the major components from the comprehensive specification of the EMDET. When each basic function (or lesson) was considered the matrix prompted consideration of what role all of the major system components would play in that function. In particular blank spaces in the matrix would often identify oversights in the specification; during review blank spaces would prompt a reconsideration of the role each system component played in a particular function. Most functions required some involvement of all components, so only rarely were blank spaces left in the matrix.

6.3 Curriculum Design Methodology

The final organisational schema was a methodology to link the educational requirements to the creation of the curriculum in the system and detail design phases; this would need to both clarify the learning objectives and then address the four components of the Tyler Rationale (described in Section 3.2.6). A three stage methodology was used; the first was to translate the educational requirements into objectives more suited to curriculum design; the second was to break the overall list of educational objectives into a proposed curriculum of discrete lessons; the third was to plan individual lessons in accordance with the Tyler rationale. This methodology spanned three of the phases of the WiSE Approach.

In the first stage, the preliminary curriculum and the requirements specified for the student audience, teaching context and target level of skill (Section 3.2) were used to synthesise a statement of educational objectives in what Tyler (1949) described as content-behaviour form. This revision included the desired student behaviour in relation to content and resulted in a significant expansion of the educational objectives; this in turn required a corresponding expansion in the content and detail of the preliminary curriculum. This was carried out during the specification phases of the WiSE Approach.

The next stage was to break the statement of educational objectives in content behaviour form into a series of discrete lessons suitable for use as part of an undergraduate course. These discrete lessons were then placed in an order by utilising the preliminary curriculum from the requirements (Appendix A) phase as a guide. This was carried out in the System Design phase of the WiSE Approach.

Lastly, the individual lessons within the proposed curriculum must address the educational objectives that are stated in content and behaviour form. Each of the lessons must deal with the four key questions of the Tyler Rationale in order to be effective; Tyler (1949) utilised a table with four columns (one for each questions of the rationale) to plan each of these lessons. The table was completed for each lesson by using the following process:

- the objectives to be addressed by the lesson are stated clearly in terms of content and behaviour
- the learning experiences to be provided to meet the objectives are formulated
- organisation of the experiences is determined
- the method of assessing student attainment of the objective is decided

This tabular representation of the Tyler Rationale can then be used to produce the materials to be presented to the students; such as lecture content and laboratory work books. This was carried out in the detail design phase of the WiSE Approach.

6.4 Specification Detail

With the philosophies and organisational schema determined, a detailed specification was developed that, together with the user requirements, would form a complete design brief for the system design and detailed design phases. This specification was based on the previous requirements stage and is a translation from the user's perspective to the designers. User requirements are interpreted and further developed and, where necessary augmented by some original conceptual design to enable the subsequent design phases. These detailed specifications are categorised in the same way as the user requirements into educational, contextual, technical and project concerns.

6.5 Detailed Educational Specifications

6.5.1 Audience

In the specification stage a decision was made to focus on developing the EMDET for use in a specific electrical engineering final year elective in power electronics and drives: the PED course. This would be the first implementation of the EMDET at the University with the expectation that it would be usable by other disciplines and levels of education in future. This decision was driven by concerns about project scope, adjustments to existing University courses and the representative nature of the students undertaking this course.

The PED course is a mixture of undergraduate electrical engineering students in their final year of study and post graduate students typically studying a Masters coursework degree in engineering. The course consists of lectures, tutorials and five laboratory sessions; three would be on power electronics at a detail level and the remaining two would study electric motors and drives at the systemic level utilising the EMDET.

Pragmatically focusing on teaching one elective made the scope of educational work involved with the project of comparable magnitude to the hardware and software development. Focussing on teaching a single elective was also a realistic entry point into the current teaching curriculum; the PED course was already undergoing revision and including the use of the EMDET did not add an undue burden to the academic staff administering the course.

To ensure that the acceptance test phase of the project would be valid, the cohort of students taught during this stage must be representative of future students. The requirements phase defined the initial audience to be undergraduate, post graduate and continuing education students in the electrical, mechanical and mechatronic disciplines. The PED course included undergraduate and postgraduate students meaning that acceptance testing would include various levels of prior student attainment. It was judged that if the needs of the electrical engineering students could be met, so too would the needs of mechanical and mechatronic students because the training required for the students specialising in electrical engineering is typically more rigorous than that required by students in other disciplines.

While utilising the EMDET to teach the PED course was adjudged to form a satisfactory acceptance test, the EMDET must still address all of the items identified as part of the knowledge gap. Accordingly the EMDET must be able to teach any of the items identified as part of the knowledge gap in Section 5.1.3, not just those covered by the PED course.

6.5.2 Learning Limitations

With the audience limited to two laboratory sessions focussing on EMD systems within the PED course, the time available became an important constraint on what the students could learn. This limited the amount of content that could be delivered to students, so there was not enough time to deliver the entire preliminary curriculum outlined in the Requirements phase. Therefore the curriculum was revised to suit the timeframe available.

The material presented in the laboratory sessions must be in a series of cognitive leaps that are achievable by students. This meant that the curriculum material must start at a level of understanding within a student's capability, and that each exercise within a laboratory session is within the student's abilitiy to increase their understanding. Accordingly, the level of prior understanding that could be expected of students had to be defined and the material delivered to students be achievable within two allotted laboratory sessions.

The level of understanding possessed by students prior to their laboratory work was considered in terms of academic and applied knowledge. Defining the academic knowledge that students could be reasonably expected to have prior to the PED course laboratory work was relatively straightforward; in order to enrol in the PED course undergraduate students had to demonstrate English language proficiency and complete a number of pre-requisite courses and postgraduate students had to demonstrate a similar level of ability. The pre-requisite courses of the undergraduate degree were reviewed and the relevant understanding from these courses was compiled. The PED course also included a series of lectures in addition to the laboratory work, so the material presented in these lectures was also included in the definition of prior understanding.

The applied knowledge was more difficult to gauge accurately; while undergraduate students have to complete industrial placements within their course, there is no stipulation on what this consists of, or if they will work with EMD systems. Postgraduate students had no such requirement and their prior applied knowledge was unknown. It was therefore likely that students within the course would have a range of prior applied knowledge of EMD systems with many having no skills whatsoever.

Based on the pre-requisite subjects needed to enrol in the PED course and the lectures delivered as part of the subject students were assumed to have the following academic knowledge prior to their laboratory work (Univeristy of Wollogong, 2010b,a):

- fundamental physics including electromagnetism, Newton's Laws of motion and rotational dynamics
- basic circuit theory including complex impedances and phasor representations of current, voltage and power
- signal processing knowledge including harmonic representation of signals, signal filtering and knowledge of data acquisition systems
- fundamental knowledge of the measurement of electrical quantities and the instrumentation required to do so
- analysis of 3-phase electrical systems and 1-phase equivalent circuits used to simplify this analysis
- basic AC machine theory including the 1-phase equivalent circuit of an induction motor, synchronous speed, slip and machine efficiency

- knowledge of power electronic components and basic operation of various motor drives including a pulse width modulated (PWM) inverter

For the purposes of developing EMDET a conservative approach taken to the decision on what prior applied knowledge on EMD systems students would be assumed to have. It was assumed that many students would have no prior applied knowledge of EMD systems, would not know what an EMD system looked like in an industrial setting, how they were typically operated, or how to work safely with these systems.

6.5.3 What Students Will Be Taught

To help develop the educational objectives in content-behaviour form, a picture was created of what a graduate engineer possessing the desired wisdom would be able to describe about the major components of a real EMD system to another engineer. This picture was drawn using a 'macro view' of the EMD system, and was synthesised from the preliminary curriculum considering how an engineer with wisdom would interact with an EMD system at the 'macro' level. This picture was a useful intermediate step that readily facilitated the development of educational objectives in the content behaviour format and is shown in Figure E.1 of Appendix E. In particular the key components of an EMD system to be addressed during teaching were identified from this picture: mechanical loads, electrical motors, electrical drives, the power supply, and the system as a whole

Tyler (1949) identifies some broad types of behaviour in relation to setting educational objectives, they include: understanding important facts and principles, familiarity with sources of dependable information and the ability to apply principles. A more complete description of these is included in Appendix E.2.

The final set of objectives was compiled by considering each of the five key components of the EMD system and the behaviour types that a wise engineer should be able to display in relation to them. To illustrate the final form of the objectives, the following is an example extracted from the more comprehensive listing: if a wise engineer were asked to estimate the mechanical output power of a 3-phase squirrel cage induction motor based on some measurement of motor current they would be able to exhibit the following behaviour types as identified by Tylor in relation to the electric motor:

- identify the relevant principles and formulae involved:
  - understand the relationship between real, apparent, and reactive power
  - understand that real electrical power is a product of voltage, current and power factor; and that the machine's mechanical output is related to the electrical power by the machine's efficiency
  - understand the typical supply voltages used for induction motors
  - be able to use the equations for electrical power and mechanical power.
    - $P_{1\phi} = V_{ln} \times I \times pf, P_{3\phi} = V_{ll} \times I \times pf$
    - $P_{mech} = P_{elec} \times efficiency$
- information:
  - understand that most motors have their critical parameters on the motor nameplate, e.g. mechanical efficiency and motor power factor.
  - if a motor nameplate was missing be able to locate information e.g. from a manufacturer's website
  - without a nameplate or manufacturer's data be able to give reasonable approximations of motor power factor and efficiency. e.g efficiency between 70 and 90%
- application of principles:
  - given the current drawn by the motor and the other parameters located from the nameplate or estimated, be able to calculate the mechanical power output

Similar considerations were made in relation to the other components of the EMD system, and the final listing of objectives in content behaviour format was compiled. The objectives was then finalised in considering the learning limitations of the students and the PED course delivery to determine a curriculum. An extract of educational objectives developed in content behaviour form is presented in AppendixE Table E.1.

With the revised content to be delivered to the PED course identified, it was important to identify the course material that would not be dealt with in the PED course that the equipment should still be capable of teaching. This material is listed in Appendix F, and although this material would not be tested on students in the acceptance test phase of the project, it would be checked during the system test phase to ensure that the capability to teach in these areas existed.

6.5.4 Teaching Approach

The philosophies and organisational schema had added enough detail to the teaching approach from the requirements phase to allow the design to progress, so no further detailed specifications were required for the teaching approach.

6.5.5 Constitution of Equipment

The educational concerns of the equipment constitution were captured by the linkage matrix described in Section 6.2.3. Importantly, all of the physical phenomena required to teach the lessons identified for both the PED course and other future courses had to be visible. Typically these would require sensors and equipment to display their output to users.

6.5.6 Assessment of Learning Quality

The scenario assessment was to be carried out both before and after the student training with the EMDET to determine its effect; particularly to check if a change in student wisdom had occurred during training. The same fundamental questions would be delivered before and after the training under the guise of different industrial 'war story' scenarios.

The Laboratory work books would be created to both deliver the revised curriculum, and to carry out a detailed assessment of student learning. To deliver the curriculum the work books would include background material relevant to the exercise, the experimental procedure and questions requiring analysis of experimental results. The analysis questions would come from the development of individual lessons using the Tyler Rationale during the detail design phase, and would provide the detailed assessment of student learning.

Direct observation of students would be carried out for the entire PED course cohort during the laboratory sessions to detect issues affecting student learning outside of the equipment or curriculum being delivered. This observation would be guided by the closed loop analogy of education to discriminate between issues with the equipment or curriculum affecting student attainment (signal), or other influences (noise) identified in the 3P model of teaching and learning described in Section 3.2.7.

6.5.7 Target Level of Skill

The target level of skill was defined in the requirements phase as students who could successfully negotiate war story scenarios from the industry survey. In view of the revisions made to the PED course curriculum in the specifications stage the war stories used would have to be relevant to the content of the two laboratory sessions on EMD systems. Therefore it was decided that the war stories would focus on:

- the torque-speed behaviour of a squirrel cage induction motor
- the fundamental electrical characteristics of a squirrel cage induction motor
- the behaviour of a squirrel cage induction motor when operated by various types of drive
- basic torque speed characteristics of common mechanical loads

6.6 Detailed Contextual Specifications

Students undertaking the PED course would not necessarily have had significant electrical safety training prior to the course, so they would not have may not not be able to work safely with dangerous levels of voltage and power within the laboratory. Therefore they should not be required to directly interact with any voltages above Extra Low Voltage; defined by Australian Standard ("AS/NZS 3000:2007 Wiring Rules", 2007) as voltages not exceeding 50 VAC or 120 V ripple free DC.

This requirement significantly affected the kind of data acquisition system to be used on the EMDET and how it would potentially be configured. Students would need to measure a number of circuit parameters during their laboratory work at voltages above ELV, so these circuit parameters would either be measured by equipment that students did not need to physically interact with or be reduced to ELV via transducers. It was anticipated that transducers would be required for the data acquisition system; particularly if the design of the laboratory exercises required students to select which circuit parameters were connected to the data acquisition system.

If the EMDET was to be reconfigured electrically or mechanically students should not physically carry this out, and if electrical reconfiguration was needed it should be carried out remotely (e.g. via relays and contactors). Similarly, any mechanical reconfiguration would be carried out remotely or the course designed such that it could be done prior to the laboratory sessions by University staff. However, options requiring mechanical reconfiguration by staff should be avoided if possible.

The two industrial partners involved with the project determined some of the equipment that would be used. Siemens Australia had donatated of Micromaster PWM inverters that would form part of the equipment. Emerson Control Techniques would be involved in a larger capacity; in particular the load would utilise Control Techniques inverters in a regenerating configuration ("Advanced User Guide Unidrive SP", 2003; "Installation Guide Unidrive SP Regen", 2007).

6.7 Detailed Technical Specifications

6.7.1 Power flow and SCADA Linkage

The schema for power flow and the control system schema developed earlier were combined as shown in Figure 6.2; this began to identify the linkage between the SCADA system and power handling equipment and began to develop a more comprehensive picture of the system to be delivered by the subsequent design stages. The system would consist of:

- Motor 1 and Drive 1
  - power would flow from the mains into Drive 1; including the Siemens Micromatser Inverter. This would be connected to and controlled by the SCADA system.
  - Drive 1 would supply electrical power to Motor 1, which would convert it to mechanical shaft power.
- Motor 1 is directly coupled to Motor 2 and transmits the mechanical power via this connection.
- Motor 2 and Drive 2.
  - mechanical power flowing into Motor 2 would be converted to electrical

power.
  – Drive 2 would regenerate the power from Motor 2 back into the mains supply. This would be done by Control Techniques inverters which would be connected to and controlled by the SCADA system

- SCADA would consist of the PLC, any local panel mounted controls, transducers, data acquisition systems to connect transducers to a PC and the communications links required between all of these components. Transducers would be required to measure both mechanical and electrical power throughout the EMDET.
- a Human Machine Interface (HMI) consisting of a PC and industrial software would form the connection between the users of the equipment and the PLC which ultimately operates the drive equipment.

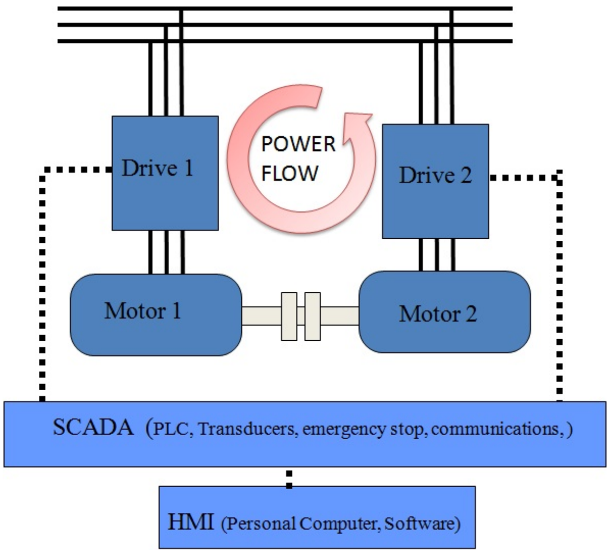


Figure 6.2: Power Flow Schema and SCADA linkage

6.8 Detailed Project Management Specifications

6.8.1 Resources

The funding available for the prototype would be approximately $40,000; with a projected budget of $160,000 being available for the final production units to be utilised in the laboratory. The SMART building would be completed in 2011 and fit out and commissioning must be completed ready for teaching in early 2012. The floor space available was given in the requirements stage with the equipment being required to fit within the proposed layout given on the architectural plans.

Chapter 7

Case Study: System Design

The system design phase decomposed the specification into a high level design. Within this phase the designers determined the architecture of the equipment and curriculum required to address the specifications (and therefore the requirements) within the constraints imposed by the context and project.

Accordingly this phase dealt with educational, technical, contextual and project issues, where the educational and technical concerns become the primary concerns and contextual and project issues became influencing factors. While the precise point where this phase ends and the succeeding Detail Design phase begins can be vague, it is typically reached when two conditions are met; firstly all of the design tasks required for the detail design phase can be identified; and secondly the designers begin to require extensive input from the Constructors to allow work to progress.

In this chapter the educational objectives determined in the specifications stage are developed into a curriculum of discrete lessons; the contextual issues that influenced the design of the equipment are described, and the technical development of the system architecture is detailed. The physical layout of the equipment that will utilise the laboratory space and resources assigned to the project is presented, and the key changes that were made to the system between the prototype and final version are enumerated. Finally, a list of design tasks to be completed during the Detail Design phase in collaboration with the Constructors is identified.

7.1 Educational System Design

The statement of educational objectives determined in section 6.5.3 had to be broken down into a curriculum of discrete lessons. The preliminary curriculum from section 5.1.3 was reviewed and based based on the level of prior knowledge assumed, the time available to the PED course laboratory sessions and what students might reasonably be expected to learn within the time allotted the following revised course was proposed

- laboratory Session one:
  - industrial Safety: the equipment would utilise levels of power that are potentially lethal, and based on the presumption that students would have no prior knowledge of working safely with this kind of equipment and power levels, they would require appropriate safety training.
  - introduction to the Industrial EMD systems and the Laboratory equipment: assuming no prior experience with EMD systems the students would be introduced to the major components of an EMD system in a simplistic way and guided through the operation of the equipment and laboratories.
  - the torque-speed behaviour of a squirrel cage induction motor: students would experimentally measure and map out the torque speed characteristic of an induction motor connected to a standard 3 phase supply. The torque speed curve of an induction motor is fundamental to understanding motor behaviour.
- laboratory Session Two
  - the characteristic of a squirrel cage induction motor: students would investigate the behaviour of a squirrel cage induction motor under different electrical supply and mechanical loading conditions.
  - characteristics of loads with the common simple torque-speed behaviours, drives and EMD systems: students would investigate the behaviour of different combinations of simple mechanical load, induction motor and drive system.

This revised course retained the 'macro view' approach to the course proposed in the Requirements that is needed for successful practice with industrial EMD systems; it began by dealing with the safety aspects of the equipment, and then introduced students to the motor, considerations of the load, the drive and finally the motor, load and drive together as a system. This is shown schematically in 7.1.

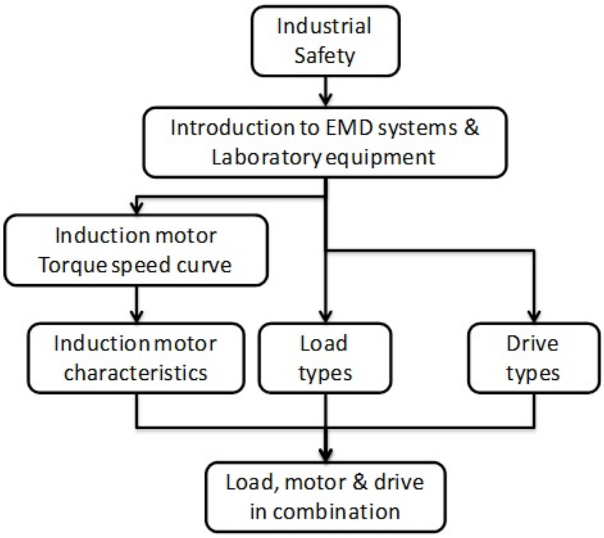


Figure 7.1: Schematic representation of revised course in EMD systems.

7.2 Contextual Issues Impacting on the System Design

The industrial partners involved with the project had a major impact on the system design; Siemens had donated Micromaster PWM inverters that would form Drive 1 and Emerson Control Techniques equipment would be used for Drive 2.

Siemens Australia had donated a number of 3 kW Micromaster PWM drives; this size was deemed appropriate for the laboratory equipment because with a full load current of around 6.5A this fulfilled the philosophy of fidelity developed in section 6.1.2. Due to the nature of the power flow in the system (shown in figure 6.1) all the components in the system must be of a similar size and therefore selection of this drive established the size of components.

The Siemens Micromaster drive was a fairly typical Pulse Width Modulated (PWM) inverter suitable for mono directional power flow. Drive 2 had to be capable of bi-directional power flow, or regenerative operation, and a Control Techniques Unidrive was inverter was chosen for this drive. The Unidrive uses a different approach to most other drives on the market to achieve a regenerative operation; this impacted on the hardware required and the associated control system.

A determining factor in the system design was the capacity of the Unidrive to increase its capability by the installation of small hardware modules called Solutions Modules offering additional control and automation functionality. Each Unidrive can accept up to three modules, there include additional processors, digital and analogue I/O, and various communication network protocols. This meant that the PLC required for the SCADA system (section 6.2.2) could be provided by a solutions module installed in one of the Unidrives. For connectivity to other components the PLC could be augmented by a network communications card or additional discrete I/O. Therefore these modules could potentially fulfil a number of the requirements of the SCADA system.

The particular module used for a PLC was the SM Applications module; it had two features of particular importance: firstly it was capable of carrying out calculations at a relatively high speed for a PLC, secondly it connected directly to the RAM of the drive it was mounted in. The speed of calculation and communication with Drive 2 would determine the ability of the system to simulate the dynamic characteristics of a load. To behave like a real load the PLC must be able to recalculate the load torque and communicate these to Drive 2 several times within one time constant of the physical system being simulated. The applications module could execute code within 250 micro seconds while subject to constraints described below; this meant that loads with time constants on the order of 1 millisecond (which would include many real world loads) could be realistically simulated.

7.3 Technical

The System Design can be developed further by separating the circuitry design into power and control aspects. Essentially, the details of the EMD components which handle high levels of power are considered separately to the details of the associated SCADA system; this simplifies and streamlines the design process. While the details of the two systems are separated it is important to note that the points of interconnection between the power and control aspects of the circuits are still retained within the designs.

7.3.1 Power Side Circuit Diagram

The requirements and specifications were used to develop the power handling circuit as shown in Figure 7.2. There are multiple options that can be used as Drive 1 depending on the laboratory, these include a Siemens Micromaster PWM inverter and a Direct On Line (DOL) starter. These options are switched in and out by electrical relays that prevent two parallel drives being activated at once. Drive 2 consists of two Control Techniques Unidrives arranged in a regenerating configuration with supporting hardware to allow it to power and regenerate to the AC mains.

The preliminary circuit diagram incorporates the data acquisition requirements to measure the EMD system power flow. Current and voltage transducers are needed on the supply to Drive 1, Motor 1, Drive 2 and Motor 2. Mechanical power transmission between Motor 1 and Motor 2 is measured by a torque transducer and shaft speed sensor These are connected to a data acquisition system which is in turn connected to the Student PC.

7.3.2 Supervisory Control and Data Acquisition (SCADA)

The SCADA configuration used for the final system is shown in figure 7.3, the major components identified in the specifications (Section 6.2.2) have been refined and communication linkages established.

7.3.3 Control Side Circuit Diagram

The preliminary circuit diagram presented in Figure 7.2 was used to further develop the control circuit including the interconnections between each of the drives, the PLC, transducers, and panel mounted equipment needed to operate the EMDET.

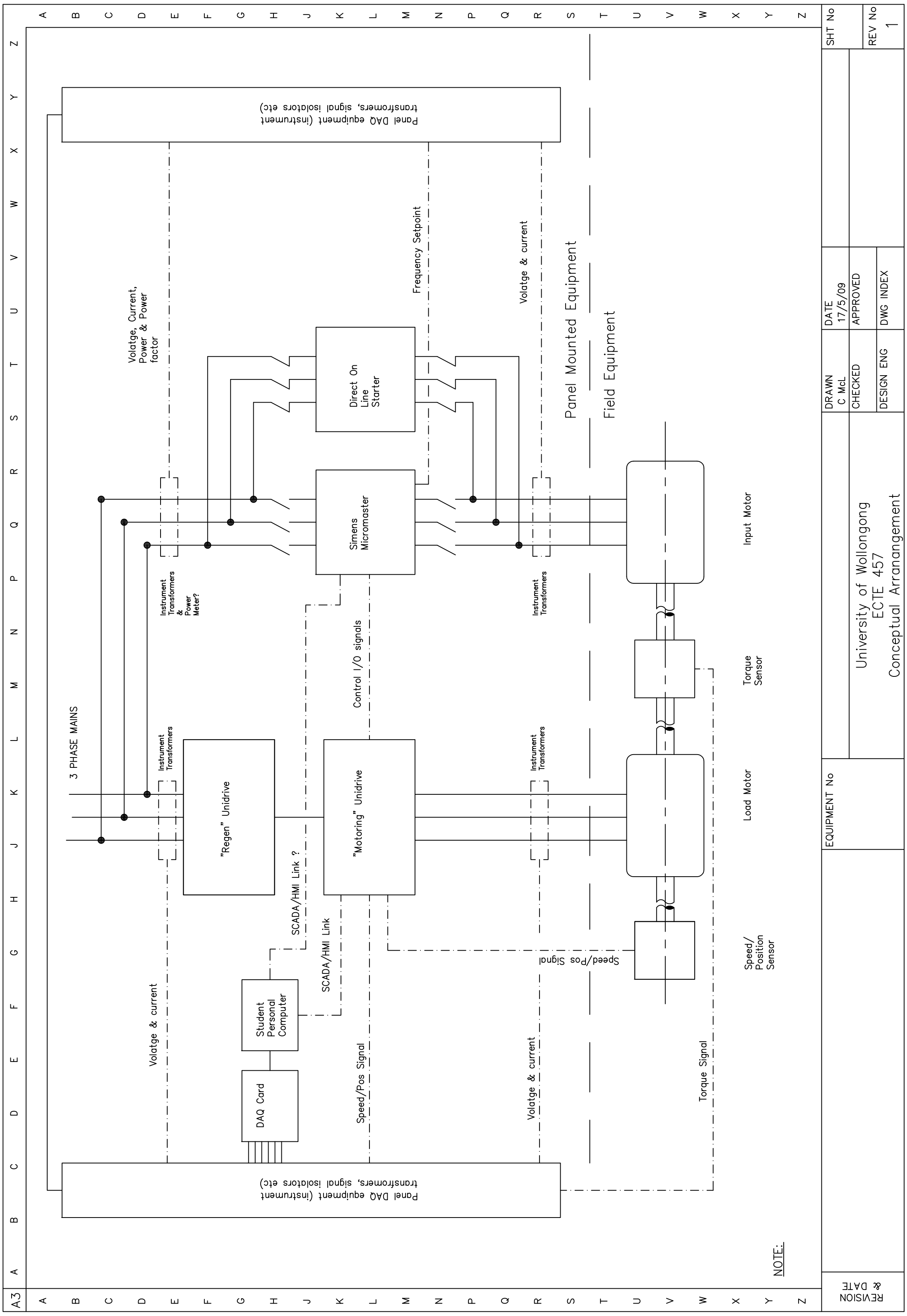


Figure 7.2: Conceptual power handling arrangement.

7.4 Data Acquisition

As described in the specification phase (section 6.1.2) a laboratory grade data acquisition system was needed to overlay the industrial SCADA system. Industrial

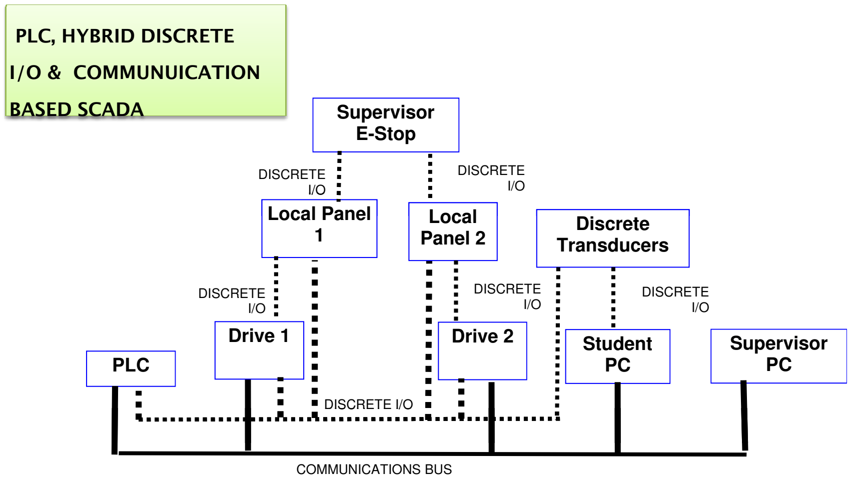


Figure 7.3: SCADA Configuration used for final system.

SCADA systems are typically limited in the number of signals they can capture and the frequency with which they can sample. In order to be able to capture the necessary data related to power quality the current waveforms of the EMD systems had to be captured, including effects due to the switching frequency of the solid state power electronics. For teaching purposes it was necessary to identify the frequency of the waveform as well as to recognise the shape of the waveform created by the switching. This is important around PWM drives because the input and output current waveforms have important non-sinusoidal aspects caused by the switching frequency.

Recognition, in this sense, has an important link to the curriculum and cognitive leaps during learning. During laboratory work students may not have a prior understanding of what the waveforms should be (sinusoidal, square wave, etc.), and will be investigating them experimentally. If the waveform was distorted due to low sampling frequencies this may present an unnecessary cognitive leap. This meant that the sampling frequency be significantly higher than the switching frequency to examine these non-sinusoidal aspects, so a notional sampling frequency of 100 kHz was therefore chosen so that the waveform created by a variety of typical switching frequencies could be seen.

The 100 kHz sampling rate was much faster than could be expected of the PLC and SCADA system; the fastest task within the PLC runs much slower than the 100 kHz desired. Therefore, a number of transducer signals would need to be sent to both the PLC and the data acquisition system to ensure that they were logged at an appropriate frequency.

7.5 Arrangement of the EMDET

A conceptual outline of the entire EMDET is shown in Figure 7.4; this figure shows the connections between the power circuit, the SCADA, and the Human Machine Interface (HMI). It is also a succinct summary of these components as they would appear to a user of the system.

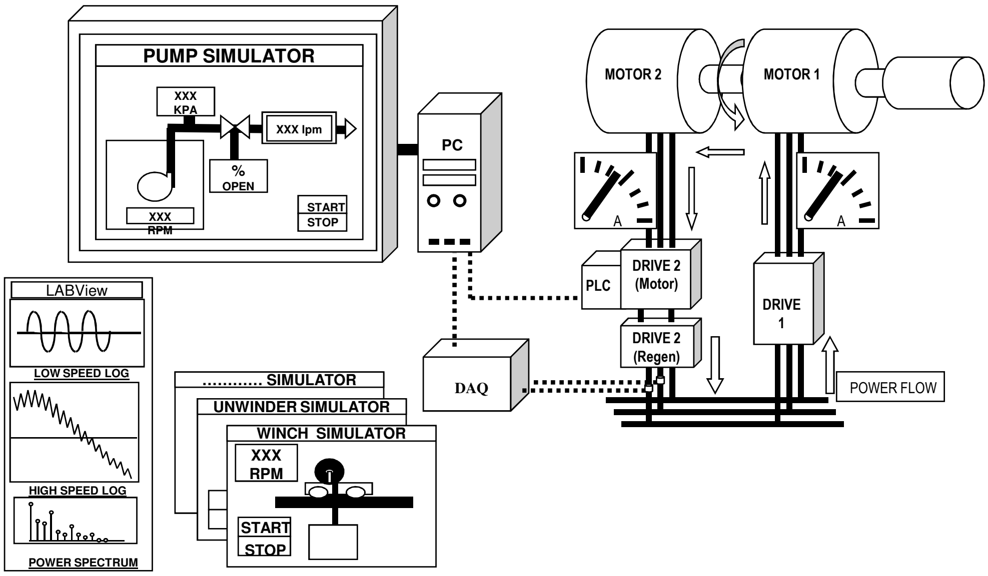


Figure 7.4: Overall EMDET system configuration.

Within this figure the power flow described in the specifications (Section 6.2.1) is clear, including the AC mains, Drive 1, Motor 1 the mechanical coupling to Motor 2 and Drive 2 regenerating to the AC mains. The PLC mounted within Drive 2 forms the connection between the power circuit and the SCADA. The major components of the SCADA system and their interconnections are shown including the PLC, the data acquisition system, the PC and the HMI software. The role of the HMI as the conduit between the PLC, the data acquisition and the human user of the equipment is evident. The HMI consists of a series of graphic screens, each created to teach a particular lesson or carry out a basic system function. The data acquisition system is shown both connected to transducers within the system and to the PC. Students will access and analyse the data via data acquisition software on the PC. The pictorial representation notionally shows views of low speed and high speed traces of physical system parameters, as well as spectral analysis of the signals.

7.6 Load Control

One of the most important capabilities of the EMDET was to simulate a variety of real world loads to give students an authentic learning experience to prepare them for industrial practice. This would be done by using an induction motor and regenerative drive, as described in the specifications (Section 6.2.1). To realise this operation the SCADA system must determine the torque that a simulated load would absorb and communicate this to drive 2 to act upon.

The methodology decided on was that a load would be represented by a torque-speed curve; a representation showing the torque that a load would absorb when driven to various speeds. The real shaft speed of the system would be measured and the torque required would be calculated within the PLC from the speed using the torque speed curve of the load being simulated. The calculated load torque would be transmitted to the motoring Unidrive within Drive 2 which would then provide this torque through Motor 2. The representation of the torque speed curves would use a number of methods; where adequate, simple mathematical relationships (e.g. linear, squared) would be used. Where more sophisticated behaviours were needed a lookup table of speeds and torque would be used with interpolation between the given points. This is shown schematically in Figure 7.5

7.7 Project

7.7.1 Resources

The key project resource addressed at the system design phase was the use of space within the SMART Infrastructure facility as described in Sections 5.4.1 and 6.8.1. Preliminary mechanical arrangements of the equipment were drafted as shown in

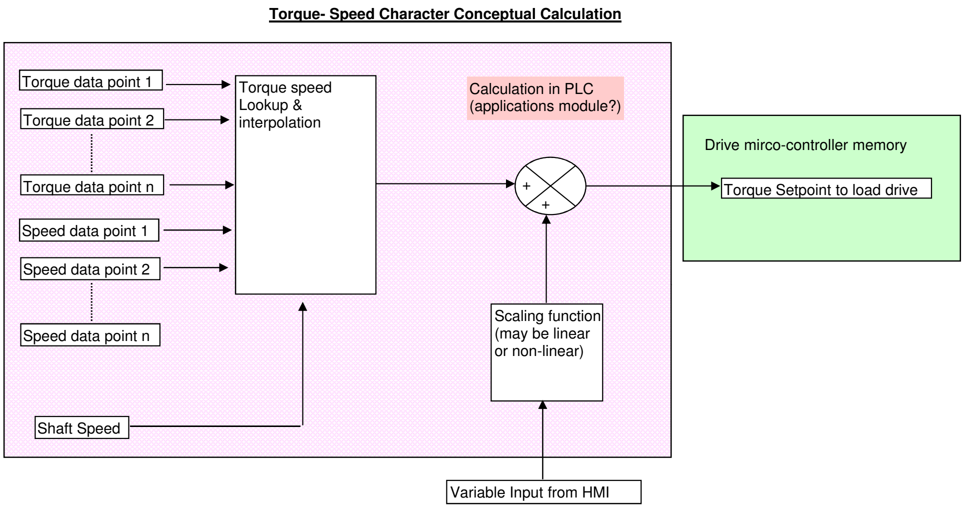


Figure 7.5: Load torque control.

Figures 7.6 and 7.7, these were based upon the overall system arrangement (Figure 7.5) and the power handling equipment donated by Siemens Australia (Section 5.2).Each EMDET would be as shown in Figure 7.6, and would consist of two induction motors coupled together on a frame, a laboratory bench with PC mounted on it and a panel containing the drives and associated equipment. The laboratory space would allow for up to eight of these to be installed accounting for the power reticulation and other furniture required within the laboratory.

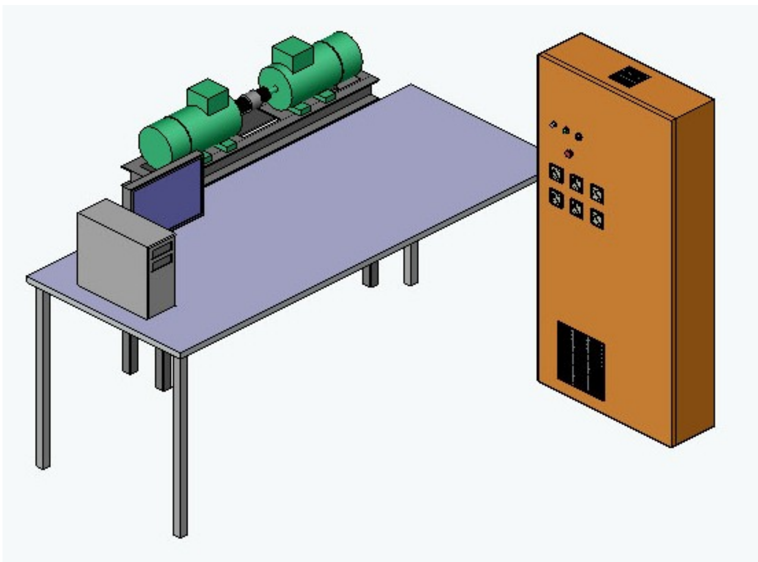


Figure 7.6: Preliminary equipment layout of a single laboratory bench.

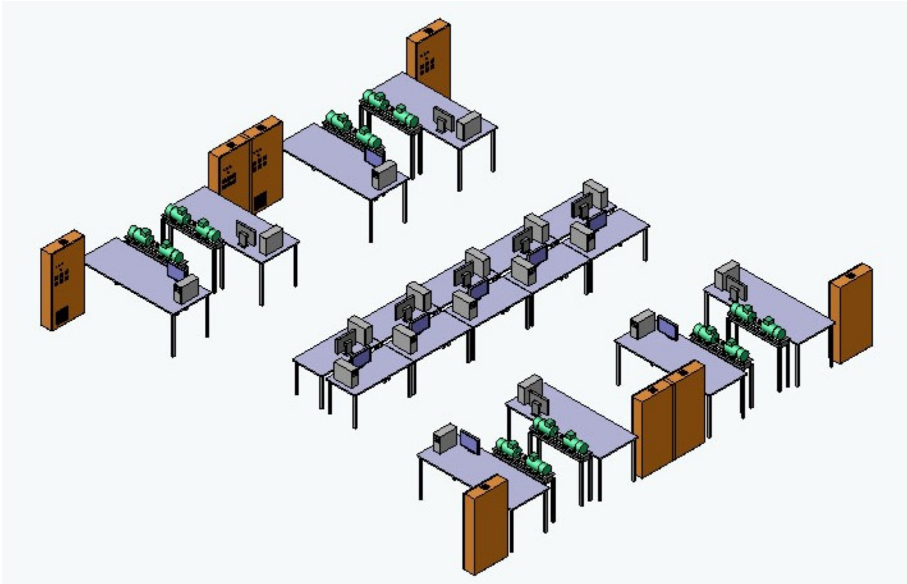


Figure 7.7: Preliminary equipment layout of the entire laboratory.

7.7.2 Risk Management: Prototype and Final

Two of the most important risk control strategies in this project were the iterative build-test nature of the WiSE Approach and the plan to build and evaluate a prototype version of the EMDET before building the final production versions. A number of significant design changes were made to the EMDET via iteration within the process of developing the prototype, between the prototype and final versions of the EMDET, and while developing the final EMDET.

In order to provide a clear and logical description, the development of the EMDET is presented in its final form as a result of these iterations, with attention called to important iterations and its results separately. In reality these design changes occurred at various stages throughout the WiSE Approach and between the prototype and final versions. Each change meant revisiting various stages of the WiSE Approach, and many changes were made requiring multiple iterations though the WiSE Approach.

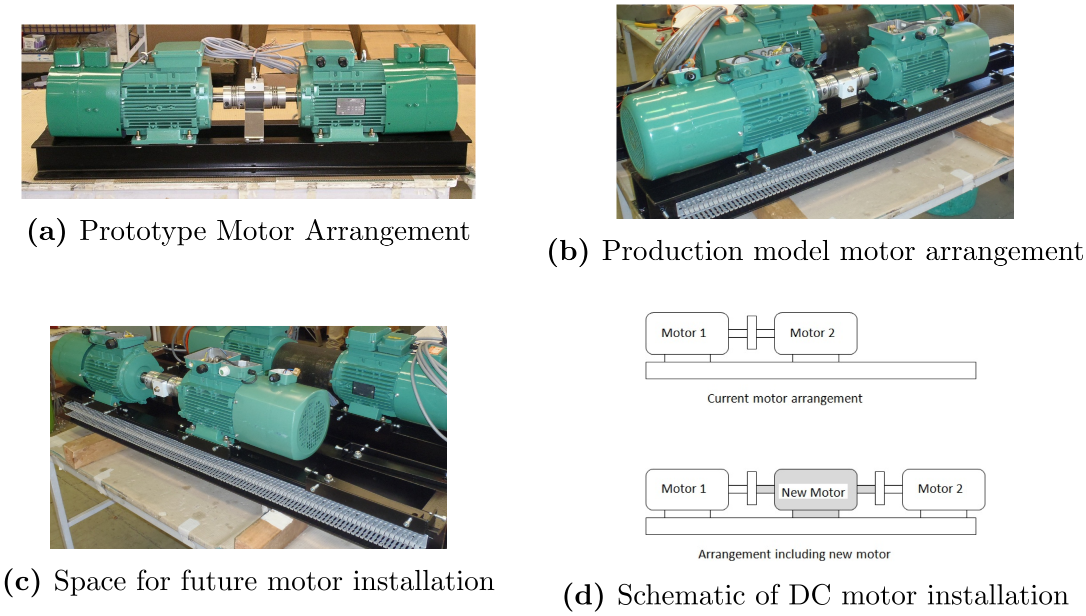
These changes illustrate the value of using the WiSE Approach to developing the equipment and building a prototype for evaluation. Many of the changes were significant, and in the absence of an iterative (WiSE) Approach, these issues would not have been properly addressed in the final EMDET delivered to the Users. The changes relevant to the system design stage are described here; similar changes which occurred throughout the project are presented in the chapter that best aids reader comprehension.

The major change made to the EMDET was the relative sizes of Motor 1 and Motor 2. Guided by the philosophy of Fidelity (Section 6.1.2) the largest motor supported by the Siemens Micromaster inverters was used on the prototype. Accordingly, on the prototype, 3kW four pole motors were used as Motor 1 and Motor 2. The major issue was that since the motors were the same size, Motor 2 was unable to reliably stall Motor 1, which meant that the full torque speed character of Motor 1 cound bot be measured, as required for laboratory exercise one.

This exercise was judged to be of crucial importance for two reasons; firstly the shape of the induction torque speed curve is essential to understanding its behaviour. Experimentally measuring the shape would be a highly effective way of imparting wisdom in relation to the motor behaviour to students and would assist students in the war story scenario assessment detailed in Section 8.4.2. Secondly, the exercise would be a full and complete test of the EMDET and all its components, so the exercise would be used as one of the key measures of project success.

Therefore Motor 1 was reduced in size to 2.2kW and Motor 2 increased to 4kW; this meant that Motor 2 could reliably and accurately stall Motor 1 and allow its full torque speed character to be examined. The 4kW motor was delta connected, which required important changes to the data acquisition system that are described more fully in Section 8.1.3. The change in power also necessitated a minor mechanical change because the motor frame sizes were slightly different, this is shown in Figures 7.8a and 7.8b.

An additional change was made to the system after producing the prototype to enable potential teaching with motors other than squirrel cage induction motors, such as DC motors. The mounting frame holding the two motors was extended to allow for an additional motor as shown in Figure 7.8c. If the requirement for teaching with a new type of motor arose, the system could be upgraded to suit.



(a) Prototype Motor Arrangement

(b) Production model motor arrangement

(c) Space for future motor installation

(d) Schematic of DC motor installation

Figure 7.8: Motor arrangements

7.8 Tasks for the Detailed Design Phase

At the completion of the System Design stage the technical and educational design tasks for the Detail Design were identified. Educationally, each of the exercises within the revised course requires development into the tabular representation of the Tyler Rationale. Further technical design was required on the power side design, the SCADA system and the mechanical arrangement. These design tasks are summarised below:

- power side
  - selection of the motor drives and motors
  - design and selection of mode change:
  - design of personal safety, thermal and electrical protections
  - electrical sensors selected and located within the circuitry
  - additional equipment required for future teaching
- SCADA
  - design of the communications between devices
  - design of software architecture for the PLC, HMI and DAQ
  - signals for logging and an appropriate data acquisition system selected
  - software packages for HMI, PLC and DAQ selected
  - the load control types and methodologies designed
- the mechanical arrangement of the system had to be designed including the motor and panel mounting

Chapter 8

Case Study: Detailed Design

During the detailed design phase, the system design completed for the EMDET was developed until a sufficient level of detail was achieved to allow the tool to be constructed. Within this phase the designers and constructors worked collaboratively to complete the decomposition process by developing the system design until the point where the constructors were able to work independently. The constructors were able to effectively deal with minutiae of the technical design (wiring loom layout, selection of switches, lights, etc.) and consequently the level of detail required was not exhaustive. The development of the system design comprised the educational and technical tasks outlined in Section 7.8.

8.1 Technical

The technical issues in the detail design were the power design, control side design, data acquisition system, SCADA system and mechanical arrangement of the EMDET. These lead to the production of a set of electrical and mechanical construction drawings along with enough documentation to allow the software to be written during the construction phase of the project. While the definition of a SCADA system would typically include the control side design and data acquisition system ,these have already been addressed within their own sections for clarity and as a legacy of the development process within the project. The control side design and data acquisition sections deal with hardware design and the configuration required for these functions, while the SCADA section details the interface for the human operator, the software, and the algorithms needed to operate the equipment.

8.1.1 Power Side Design

The power side design addressed the selection of the motor drives, the design of equipment to change equipment mode, protection equipment, location of electrical sensors within the equipment, and additional equipment for future teaching.

In the final design, one of three drive types could be selected as Drive 1 supplying Motor 1. This was driven by the revised curriculum and the war story scenario assessment described in Section 8.4.2. The drives included a direct on line (DOL) contactor, a thyristor controlled soft starter and a PWM Inverter. Drive 2 utilised a regenerative drive that was also capable of vector operation. It was judged that these represented a spectrum of drive options commonly used with squirrel cage induction motors in industry. Drive 2 consisted of two Unidrive inverters in a regenerative configuration as described in 7.2. When needed, each drive had to be selected and appropriately connected to the relevant motor. Consequently it was decided to use remotely operable contactors with position feedback connected to the PLC to switch the different components in and out and provide the required configuration.

The power side equipment required safety, thermal, and electrical protection. The safety protection would disconnect the motors from power in the event that the emergency stop was activated. Australian equipment design standards ("AS 4024 Safeguarding Machinery", 2014) dictated that two devices would make the disconnection for redundancy; it was decided to utilise both the contactors supplying the drives, and the contacrors connecting the drives to the motors. In the event that the emergency stop was used, both of these contactors should be opened.

Thermal protection was required for the equipment within the panel, the induction motors, and some of the power filtering equipment. A standard fan was provided to ventilate the panel and keep the components inside cool. The curriculum required that the Motors operate at low speeds and high torque for some exercises; so cooling fans independent of the motor shaft were specified for both induction motors to cater for this. To enable students to investigate the effects of motor cooling, a contactor was included so the fans could be shut off if an experiment required it. However; given the potential for motor overheating with this kind investigation, motor mounted thermistors were specified to allow motor temperature to be monitored.

Sensors were required to detect the current and voltage signals throughout the power side of the circuit to deliver the curriculum developed. Of particular importance was selecting the reference for the voltage signals on the induction motors and accompanying current measurements. Students typically analyse three-phase systems using single-phase equivalent circuits and are accustomed to dealing with the voltages and currents applied to one phase of a three-phase motor; usually these are line currents and line to neutral voltages. It was therefore judged important to provide voltages measurements that avoid introducing unnecessarily obstructive cognitive leaps of dealing with unfamiliar measurements. A difficulty emerged because when an induction motor is supplied by a drive with a DC bus such as the PWM inverter, the bus completely disconnects the motor from any relationship to the supply neutral, so a line-to-neutral voltage measurement is meaningless and a reference voltage relevant to the driven motor is required.

In order for students to address the motor circuit as a single-phase equivalent they must have the voltage applied to a single phase of motor windings and the resulting current flow. For the star connected Motor 1, using the motor star point as a voltage reference and then measuring the associated line current could give the required quantities. Since Motor 2 was delta connected, there were slightly different issues in addressing it with a single-phase equivalent circuit; a line-to-line voltage was selected as this was the voltage applied across one of the motor windings. A line current associated with the line-to-line voltage was not available at the drive as by definition the line current in a delta connection is shared between two of the motor windings; therefore the motor winding current associated with the line-to-line voltage measurement was chosen. This however, required that a transducer be placed inside the motor terminal box.

8.1.2 Control Side Design

The control side addressed the signal connections between the PLC, the drives, and the low level interface devices (switches and lamps), the design of the emergency stop circuitry, and the control power supply.

8.1.3 Data Acquisition system

The detailed design of the data acquisition system required selection of the signals to be acquired, the transducers to detect them, and the equipment that would acquire signals and transfer them to the student PCs. This system would have to capture voltages, currents, shaft speed and torque.

To measure and make the power flow around the system visible, as specified in Section 6.2.1 mechanical and electrical quantities must be measured. Ideally, all possible signals of interest within the system would be measured, however each signal measured requires a transducer and an acquisition channel, all of which can be expensive; therefore a compromise was necessary between the signals to be measured, and the total cost.

It was decided that where three-phase quantities could reasonably be assumed to be balanced a single phase of power could be measured, and where significant imbalance was likely all three phases should be measured. This compromise was judged as acceptable due to the practice of reducing three phase systems to a single phase equivalent by assuming a balanced system as described in section 8.1.1. As was the case for selecting transducer signal references, the practice is one that students would be familiar with due to their pre-requisite knowledge, and it was judged that it would not form an constructive cognitive leap for them.

With the inclusion of inductors to unbalance the voltage supplied to Motor 1 it was necessary to measure all three phases at Motor 1. The supplies to Motor 2 and to Drives 1 and 2 were considered as likely to be balanced, and economising on the placement of transducers by measuring a single phase here was a reasonable compromise. The signals selected for monitoring are listed in Table 8.1.

In Section 7.4 it was nominated that the signals of interest may have frequencies

Table 8.1: Signals for data acquisition.

Signal Location	Quantity
Supply	Voltage
Drive 1 Supply	Current
Motor 1 Phase A	Voltage
Motor 1 Phase B	Voltage
Motor 1 Phase C	Voltage
Motor 1 Phase A	Current
Motor 1 Phase B	Current
Motor 1 Phase C	Current
Drive 2 Supply	Current
Motor 2 Phase A	Voltage
Motor 2 Phase A	Current
PWM Inverter DC Bus	Voltage
Motor Shaft	Shaft Torque
Motor Shaft	Shaft Speed
PWM Inverter	Speed reference

up to 20kHz, and a notional sampling frequency of 100kHz was needed to recognise particular waveforms. The transducers required are analogue devices and should be assessed on the basis of transient response specifications, or equivalently, their available bandwidth.

The data acquisition system used was based on the National Instruments 9125 acquisition card ("NI 9215 Datasheet", 2016). It was chosen on the basis of performance, cost, and the familiarity of University staff with the associated LabView software. The selection of electrical transducers for voltage and current was also impacted by cost; so LEM transducers were selected on the basis that they offered a good combination of price and bandwidth while providing the necessary isolation. Specifically a LV25-400 transducer was selected for voltage measurement ("Voltage Transducer LV 25-400 Data Sheet", 2009) [Ref LEM Data sheet] and an HAS 50 for current measurement ("Current Transducer HAS 50 to 600-S Data Sheet", 2009).

Of the two transducers the voltage transducer was the most sensitive to the signal frequency for two reasons; firstly due to the longer rise time of the transducer and secondly due to the spectral content of the expected waveform. The most demanding signals expected were either square wave voltage signals or saw tooth current signals produced by the switching of the power electronics within the PWM inverter.

It was then necessary to determine the signal frequencies that a square wave voltage signal could be recognised when passed through the transducers, and were these within the range of switching frequencies available from the two drives used. The assessment criteria of 'recognition' was relatively subjective, however still very important because recognition of a signal should be thought of as a cognitive leap that students using the system must be able to make. The ability to recognise the waveform was crucial in adhering to the design approaches of fidelity and flexibility described in section 6.1. It was decided that the output of the transducers should allow (be an achievable cognitive leap) students to at least qualitatively determine whether the original signal was a square wave or another shape such as a saw tooth.

Consideration was given to carrying out a quantitative analysis of the filtering effect on the signals, however this was not pursued due to the assessment always returned to the subjective requirement of recognition. After a qualitative analysis that considered frequencies up to 20 kHz, it was determined that at 5 kHz a square wave signal would be apparent allowing student recognition of the signal. Therefore the transducer was judged to be adequate for signals of 5 kHz or less, and this was within the range of drive switching frequencies available.

Selecting the current transducer range was complicated by the magnitude of the start-up current of the motor. This current is significantly higher than the typical operating current, typically by a factor of five. The transducer was therefore a compromise between having enough range to measure the start-up current, and being accurate enough to measure the much lower operating currents.

The mechanical signals in the system were monitored using a torque transducer and a rotary encoder. The selection of the range for the torque transducer was impacted by concerns that mirrored those of the current transducers. So a HBM T-22 torque transducer ("T22 Toruqe Transducer Data Sheet", 2009) with a 100Nm range and accuracy of 0.2% was selected on the basis of cost, accuracy and frequency response. The rotary encoder selected was a SICK absolute encoder ("DFS Incremental Encoders", 2013) with 4096 pulses per revolution, while only shaft speed was needed for the preliminary curriculum, an absolute encoder capable of position measurement was selected to allow for future teaching requirements. The encoder was directly connected to the encoder port of the motoring Unidrive; and motor speed and acceleration were calculated in the PLC from measured shaft position, and passed to the NI9215 via an analogue output from the drive.

8.2 SCADA

The detailed design of the SCADA system included the selection of relevant software packages, the design of software algorithms and the various interfaces between the operator and the equipment. Various commercial software packages were used based on the proprietary requirements of the PLC, Drives and data acquisition system.

8.2.1 PLC Coding

The PLC controlled all the equipment comprising the tool, and this required a number of functions to be carried out:

- monitoring the operation of the hardware and providing various protective functions in case of equipment malfunction or operator error
- configuring the tool by selecting the appropriate motors and drives for an exercise using the remotely operable contactors;
- preventing switching configurations that could damage the equipment
- controlling motor operation
- simulating loads
- providing system testing to confirm proper operation and diagnostics in case of equipment malfunction
- monitoring various sensor inputs, using them for operation, provision of display to users
- accepting user inputs for configuration and operating the equipment via the HMI
- reporting equipment condition and operation to the user via the HMI

The speed of execution was an important issue for the PLC code because it was a determining factor in the dynamic response of the simulated load, and therefore the fidelity. To simulate many real world loads the code must be executed at high speed, which affected the overall structure of the code. The high speed portion of the PLC code was reserved for load simulation because the speed of execution was also limited by the amount of code being processed. Any code not required for load simulation was carried out in the low speed portion (task) of the PLC code.

The PLC code also had to cater for (potentially inexperienced) students using the EMDET and also needed to implement important protective functions. The PLC would have to manage changing between drives and simulated loads and ensure that no unsafe or damaging configurations were allowed. The PLC would also have to execute protective functions in relation to the emergency stop button, the status of the electrical drives, and the motor temperatures.

8.2.2 Load Simulation

The methods of representing the torque-speed curves presented in Section 7.6 were further developed and would notionally use one of four methods depending on whether the shape of the curve was simple or complex, and if it was fixed or variable. The four methods are summarised in Table 8.2 .

Table 8.2: Methods of load simulation via torque-speed curves.

Torque sped curve	Curve is fixed	Curve is a function of another variable
Simple Shape	Use simple fixed mathematical relationships ($T = a$, $T = a\omega$, $T= a\omega^2$, where a is constant)	Use simple fixed mathematical relationships ($T = x$, $T = x\omega$, $T= x\omega^2$, where x is a user controlled variable)
Complex Shape	Lookup table of (T, ω) pairings with interpolation between the points.	Custom code dependant on particulars of system to be simulated and requirements of the lesson being taught.

If a complex variable torque-speed behaviour was needed, the a specific piece of code was written to accommodate this characteristic. This situation is illustrated by an example in Section 8.2.3.

8.2.3 Pump Simulation

The widespread use of motor drives to save power in fluid pumping systems in industry was one of the key war stories encountered during the industry survey (Section 3.1) that inspired the scenario assessment (Section 8.4.2). Although not required specifically by the revised curriculum (section 7.1) it was decided to include a simulation of a pumping system with the tool as a System Test (Section 12) to demonstrate the capabilities of the EMDET. It was also identified as one of the most likely exercises for teaching beyond the PED course requirements, as a demonstration of the power savings and potential improvements in system control available from variable speed drive systems.

An illustrative lesson for students in this case would be to compare the power consumption at various system flow rates by first varying throttle valve position and then varying the pump speed to achieve the same end. For this to work in simulation, the throttle valve position should affect the torque absorbed; or in other words the shape of the torque speed curve is a function of the valve position. Moreover, the simulation must present the fluid flow rate to the user to reassure them that the same useful physical result is being achieved with via throttling or speed control but with differing power consumption. To carry out this kind of simulation specific code must be written based on the particulars of the real system to be simulated and the quantities required.

8.2.4 Data Acquisition Software

The major tasks to be carried out by the data acquisition software were to read the values from the transducers, apply any conversions required (scaling factors, conversion to RMS values), display the data and allow for data to be captured and exported for students to undertake off-line analysis. Accordingly, a GUI was devised for realisation using LabView which is shown in Figure 8.1

The graphic was based on the diagrammatic the power flow schema presented in section 6.2.1, where the various parameters measured throughout the system were located on the relevant parts of the diagram. In addition to the schema it was anticipated that two additional features would be of particular value: firstly a display allowing overlays of various signals so that the relationships between different signals could be seen, such as the current exited in a motor by the application of a PWM voltage. Secondly a facility to find the spectral content of any of the recorded parameters via fast fourier transform (FFT).

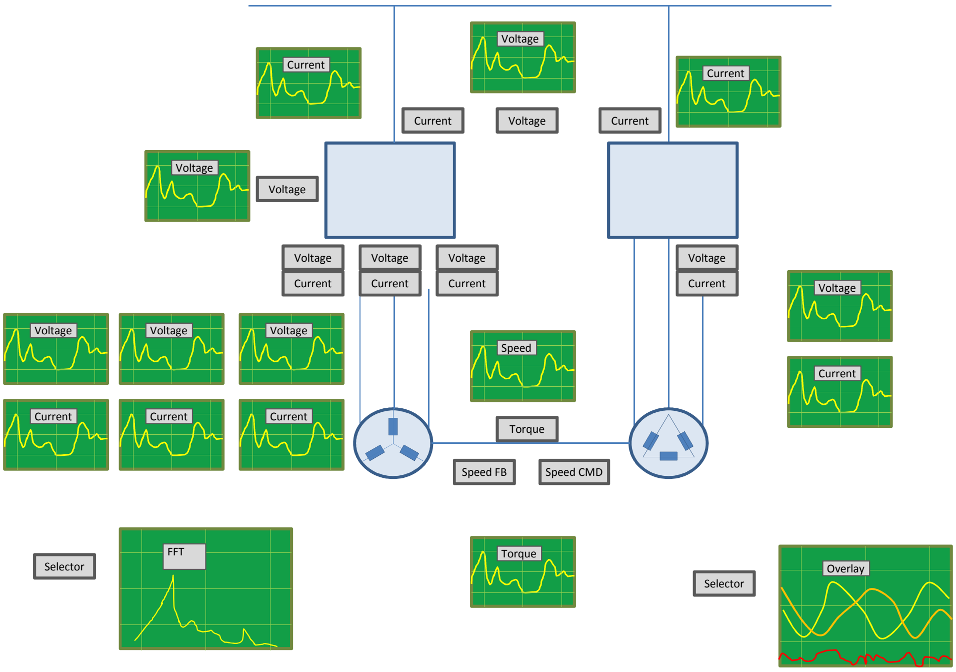


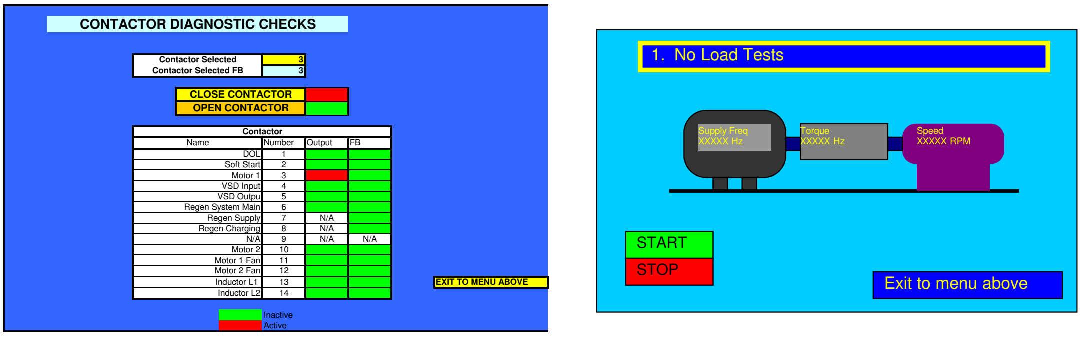
Figure 8.1: Design for data acquisition system graphical user interface..

8.2.5 Human Machine Interface (HMI)

The Users could interact with the EMDET in one of two ways; using a software interfacce at the PC (HMI of DAQ software) or, using a 'low level' interface at the equipment panel (lamps, push buttons and panel meters). Within the HMI it was envisioned there would be two broad types of interaction with the equipment: firstly carrying out the laboratory exercises and secondly carrying out maintenance or diagnostics takes on the equipment.

It was proposed that the HMI would have a GUI (or mimic as it is often referred to in industry) that consisted of a set of graphic pages organised in a structured fashion.

A proposed structure was created and a number of graphic pages drafted. The structure would consist of an initial ‘top level’ menu page that would be presented on system start-up that gave access to either a laboratory exercise or maintenance function sub menus. A number of proposed graphic screens were drafted, two of which are shown in Figure 8.2 one is carrying out diagnostic checks of contactors and the other is a sample laboratory exercise. A number of important functions are



(a) HMI Diagnostic screen

(b) Laboratory ecercise HMI

Figure 8.2: Proposed graphic screens for HMI

implicit within the HMI graphic screens, namely:

- each screen should provide a graphical representation of the processes being carried out that allows some intuitive understating of the lesson being undertaken or maintenance task being carried out
- each screen should allow navigation to and from the correct menu level
- each screen should signal the PLC of the required equipment configuration (to the PLC the mode of operation) required from the equipment
- any screen that can cause equipment to operate should not allow navigation away from the screen while equipment is in operation
- upon opening and closing screens, a number of software settings may have to be initialised

For the ‘low level’ interface, a small number of design features were decided upon to eliminate unnecessary cognitive leaps; firstly, the panel meters should be laid out in the same patterns as the Power Flow Schema presented in Section 6.2.1 to reinforce this concept, as shown in figure 8.3. Secondly, where a drive had a status lamp and reset button, these should be placed together, thirdly that the emergency stop and reset should be placed together, and finally the reset button for the emergency stop should be key operated. This would enable resetting an emergency stop to be controlled, or possibly limited to supervisory staff for safety reasons.

Figure 8.3: Panel Meter Layout.

8.3 Mechanical Design

The mechanical design of the system was straightforward, the motors would be mounted coaxially on a steel frame and connected by a torque transducer and two flexible couplings. The frame allowed for a DC motor with two shaft ends to be accommodated in future by fitting the DC motor in between the two induction motors, one of which would have to be relocated.

8.4 Educational Detail Design

8.4.1 What Students Are Taught

The next stage of educational design was to take the revised laboratory course as presented in Section 7.1 and carry out the detailed design of each lesson using the tabular representation of the Tyler Rationale specified in section 6.3 for each lesson within the course. These tables provide the material required for the laboratory workbooks to be written as part of the assembly stage, the complete set of tables used for developing all of the lessons in the curriculum are presented in Appendix H.

Completing of the table makes use of the analogy of education to a closed loop control system and the relevant educational theory identified by this approach (presented in Section 3.2). These lessons are designed to have the desired effect on the students, so they need to consider the behaviour and limitations of both teaching methods and students. The analogy to the closed loop controller is that an appropriate actuator must be designed to drive the plant to the desired behaviour in view of the limitations of both actuator and plant.

The example presented here is the exercise used to introduce students to Industrial EMD systems and the laboratory equipment, the Tyler Table is shown in table 8.3. The columns represent the four questions of the Tyler Rationale (presented in Section 3.2.6). The educational purposes of this exercise were listed in the first column and the learning experiences to meet these were entered into the second column. The third column is devoted to how the experiences should be arranged into a sensible order during the lesson and the last column lists the method used to assess whether the educational purpose has been achieved.

The educational purposes were extracted from the statement of objectives in content behaviour form presented in section 6.5.3. The process of expanding on these objectives and then selecting the appropriate learning experiences is a large part of designing a particular lesson. This process must be conducted in view of the relevant educational theory, particularly constructivism, the SOLO taxonomy, the cognitive leap, instructional scaffolding and authentic assessment.

Constructivism dictates that the students should actively use the equipment and these tasks should be personally meaningful. The lesson is introductory in nature, and will consequently aim at lower levels of understanding according to the SOLO taxonomy. The lesson should be an achievable cognitive leap or series or leaps for students, so its structure should provide sufficient instructional scaffolding to make the desired level(s) of understanding attainable by the student. Authentic assessment requires that the training be as close as possible to what would be required in industrial practice.

After the educational purposes and associated experiences are specified the experiences must be organised into a coherent order, and the the methods of assessment selected; these processes are also guided by relevant educational theory. The sequence of experiences is often crucial in allowing a student to build the required understanding and should be considered as part of the instructional scaffolding within the lesson. In selecting assessment, the structure of the Tyler Table promotes the linkage between assessment and educational objectives in accordance with the principle of Constructive Alignment

Representing the final organisation of the activities in the table may mean reordering the table or using a method of cross referencing due to the following considerations:

- a coherent listing of educational purposes in the first column may not yield the desired sequence in the third column and vice versa
- the assessment methods chosen in the fourth column may impact the organisation of the lesson
- a number of educational purposes may be achieved with a single learning experience and similar possibilities exist for assessment methods. Many permutations of combinations of this kind are possible in the relationship between possible educational objectives, learning experiences and assessment tasks

Table 8.3 uses a cross referencing approach to allow a conceptually coherent listing of objectives to be maintained where it differs from the organisation of the lesson. To illustrate this, the process of using this table for three selected educational purposes will be explained follows, these are:

1. introducing students to the various components in the system
2. teaching students the location and function of the emergency stop and the associated reset procedure.
3. teaching students the various controls that operate the tool and their location.

In the first example, students are assumed to have never seen industrial equipment or the tool itself before. The experiences nominated to meet this objective were that students would receive a brief slide presentation from the laboratory demonstrator including an explanation of Figure 7.4 with a focus on using the power flow schema. Students would also complete an exercise where they would have to identify the important system components on a photo in their lab books. The organisation would be that the students would receive the presentation first and then carry out the identification exercise. The measurement of success for this educational aim are the exercises in the student lab book, where one is to correctly label the direction and type of power flow in the system, and the other is to correctly complete the aforementioned identification exercise.

In the second example students must prove they can use the emergency stop button and carry out the associated reset procedure. The experience is that the students should use the emergency stop, see it shut down operating equipment, and then carry out the reset. The organisation is that the after the briefing and identification exercises, students would use the contactor diagnostic mode (Section 8.2.1) to start one of the motor cooling fans, shut it down using the emergency stop button, and then carry out the reset process. The measurement for success is that the students can get the system running after using the stop, and witnessed by the laboratory demonstrator who is required for the key operated reset.

The final example is that students must be taught the various controls that operate the system and where they are located. The learning experiences that fulfil this are the aforementioned use of the emergency stop and using the diagnostic mode to power up the PWM inverter and measure the voltage and current supplying its DC bus via the panel meters and the data acquisition system; specifically, they need to identify the harmonic frequencies present in the current waveform. The organisation here is that students would power up the inverter after having carried out the emergency stop exercise. There are two measures of success here; the first is that students can complete the emergency stop exercise, as this requires them to use the HMI diagnostic screens, and the panel mounted controls; the second is that students have measured current and voltage and can find the harmonic frequencies in the inverter current, these exercises require them to use the panel meters, the HMI, and the data acquisition system.

Table 8.3: Tyler table for laboratory exercise to introduce students to EMD systems.

Introduce students to Industrial EMD systems and the architecture and operation of the drives Teaching Facility

Educational Purposes	***Learning Experience***	***Organisation***	***How do we tell if we have achieved purposes***
Introduce the students to the Teaching system components at a high level so they can indentidy them (multistructural) and understand their interaction during equipment operations to prepare them to operate the system.	Brief introduction on system configuration in the system and the power flow	(1) Brief presentation on system from demonstrator focusing on energy flow.	Able to properly label direction of energy flow and energy type in review questions (6)
	Have the identify the components on a photo of the system	(2) Have students match name of components to a photo in their lab books	Able to properly label components in picture in (2)
Introduce students to a common configuration of an automated industrial system, allolw them to identify key componets and the likely interactions.	The teaching facility is set up like a typical industrial SCADA. Teaching them this will teach them a common industrial system	included in (1), (3) and (4)	If able to complete exercises (3) & (4) we have done this
Teach students how SCADA system hangs together	Brief students on system and have students use various components of the system and in their instruction identify which part of the system they are interacting with	included in (1), (3) and (4)	Able to complete Exercises (3) & (4)
HMI - PLC Comms			
PLC - Hardware			
Hardware-PLC			
PLC-HMI			
Introduce students to more advanced data acquisition that they may be able to use	Use DAQ system in exercises	Included in (4)	Be able to distinguish between what is commonly available instrumentation and lab instrumentation in review (5)
Introduce students to system components at a low enough level to allow them to operate them and understand their results	Have students perform functions that are either physically or conceptually obvious as a first introduction to the equipment.	included in (3) and (4)	Able to complete Exercises (3) & (4)
Teach students how to operate the system	Have students do an exercise that uses the main system components	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with a Human Machine Interface	Use HMI in exercises	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with panel Mounted Controls	Use panel controls in exercises	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with the Data Acquisition system	Use DAQ system in exercises	(4) Use contactor diagnostic mode to activate Siemens drive. Use DAQ system to observe voltage waveform and FFT peaks in supply voltage and Siemens supply current waveform	record voltage and current obserbed including the frequenies of the significant hamronics in the current.
Where the system can be operated from	Have the students use the controls in the different locations	included in (3) and (4)	Able to complete Exercises (3) & (4)
Various controls & their locations			
strengths & weaknesses of controls	Ask them to consider the strengths & weaknesses of the different controls	(5) ask students some review questions	
various indications & their locations	Have students use the different indications	included in (3) and (4)	Able to complete Exercises (3) & (4)
strengths & weaknesses of indications	Ask them to consider the strengths & weaknesses of the different controls	(5) ask students some review questions on relative merits of the controls	able to complete (5)
embed emergency response procedure to students (use panel E- Stop)	Use E-Stop as part of the exercises	(3) Use contactor diagnostic mode to start a cooling fan. Shut it off using the emergency stop. Reset system and get running again.	Able to complete Exercises (3) as witnessed by demonstrator during reset operation
Teach them where the system diagnostic page is and how to use it.	Use the system diagnostic as an exercise	included in (3)	Able to complete (3)
Teach them where the contactor diagnostic is	Use the contactor diagnostic as an exercise	included in (3)	Able to complete (3)
Introduce concept of energy flow though the system		(6) as part of a review question have them draw direction of power flow and label power types.	Able to complete (6)

An important feature of the last example is that one educational purpose has been addressed by multiple learning experiences and assessment exercises, which is quite often the case. The converse can also be true where multiple objectives are met by a single exercise and assessment.

8.4.2 Assessment of Learning Quality

As a result of development using the Tyler Rationale assessment would be an integral part of the laboratory workbooks. Students were also directly observed to look for any influencing factors outside of the equipment and curriculum provided within the EMDET.

The scenario assessment was intended to measure if students attained the desired wisdom via training with the equipment and curriculum. The scenario assessment before and after the laboratory sessions would necessarily be based upon the revised curriculum for delivery to the PED course to assess how effective the equipment and curriculum were in engendering the desired wisdom in students. As specified in Section 6.5.6 the same fundamental questions would be asked under the guise of different scenarios. Four fundamental themes present in several of the industrial war story accounts from industry were applicable to the revised curriculum presented; these were used as the basis of the before and after assessment. These were:

- The practical implications of the induction motor torque speed curve
- The current behaviour of an induction motor
- The effect of an inverter drive on system behaviour
- The performance of an induction motor, soft starter and a high torque load as a load-motor-drive combination.

A potential risk to the validity of this measure was students carrying out study independent of the laboratory equipment and curriculum to address the scenario assessment; this could result in successful performance being falsely attributed to the teaching. To prevent this it was decided not to include a student's performance in the scenario assessment when compiling their grade for the subject. This was done to promote an earnest response from students, especially encouraging them to admit to not being able to negotiate a scenario. This meant that the scenarios were presented to students independently of their assessable laboratory workbooks.

8.5 Contextual

At this stage of the project the contextual issues have been fully incorporated into technical and educational sections of the preceding stages of Requirement Definition, System Specification and System Design.

8.6 Project

8.6.1 Risk Management Prototype and final version

The design changes resulting from the iterative nature of the WiSE Approach along with the construction of a prototype device was discussed in Section 7.7.2. The preceding description of the detail design has incorporated many of these changes; some of the important features and iterations from the Detailed Design phase are described below.

The decision to install the panel meters in a layout corresponding to the Power Flow Schema was only reached after testing the prototype. The designers and constructors frequently found that meter readings on their own would be somewhat abstract and would have to be read in conjunction with a sketch of the overall system (Figure 7.4) to allow understanding of the physical processes involved when testing the system. In that regard relating meters to circuit functionality was a significant cognitive leap without a symbolic link between the meter readings and the overall circuit function. When this difficulty was considered along with student needs, it was judged that laying out the meters in line with the Power Flow Schema (Section 6.2) would help students to understanding the system during their work. Alternatively, using the concepts described in the literature review (Section 3.2.5) relating the meters to circuit function was a significant cognitive leap, one that could be made easier by the instructional scaffolding of arranging the meters to match the Power Flow Schema.

The contactor to disconnect one phase of Motor 1 supply was added after testing of the prototype and discussions with the constructors around the desirable functionality that was not included in the prototype.

The detailed considerations of the particular voltage reference used for Motors 1 and 2 were resolved in a number of stages. Testing of the prototype identified the issue of the inverter DC bus uncoupling Motor 1 from the mains neutral and the need to use a motor star point as a measurement reference. The issue of the delta connected motor only arose when testing the final version, when it was found that the 4kW motors were supplied in a delta connection, as described in Section 7.7.2; it was then decided that use of line to line voltages and the motor winding current was necessary. Measuring the motor winding current meant altering the motor wiring connections and placing a current transducer inside the motor terminal box.

Chapter 9

Case Study: Assembly

During the Assembly phase the constructors realised the detail designs, creating the EMDET and beginning the recomposition process within WiSE; the equipment was built from the technical designs, and the laboratory workbooks and assessment scenarios were written from the educational design. This stage was defined as complete when equipment and course materials were produced, and the involvement of the designers was needed to properly test for compliance with the detail design.

While significant to the completion of the project, much of the technical construction of the equipment was standard industrial practice, so only a brief account of this will be given. Issues of particular technical or educational significance, or where additional novel work beyond the detail design was required to complete assembly will be described. The development of software for the PLC, HMI, and data acquisition systems in particular required significant novel work.

The development of the structure and some of the important features of the laboratory workbooks are described and illustrative extracts presented. The key features of the war story assessment scenarios are described and one theme is presented in detail as a before and after scenario. The full set of scenarios is presented in Appendix C.

9.1 Educational

The educational component of the assembly consisted of creating of the laboratory workbooks and the war story scenario assessment. The laboratory workbooks were based on the Tyler Tables developed for the revised curriculum described in Section 8.4. While these tables provided the educational objectives, exercises, assessment and sequencing, they still had to be placed within a sensible structure for a laboratory exercise. The structure chosen included: an introductory scenario, exercise objectives, discussion of relevant theory, experimental procedure, review questions, and a conclusion.

The introductory scenario at the beginning of each exercise was included to motivate students and help them to make connections between laboratory work and industrial practice. These scenarios were written from the perspective of a recent graduate placed in a credible industrial situation that required knowledge of the material dealt with in the laboratory exercise to succeed. The intent of the scenario was that students would identify with the situation, and see the value in learning ho to deal with it; thus providing motivation to engage with the material in the exercise in accordance with the principles decided on in section 3.2.5. Giving the real context that the exercise applied to would assist students in making the mental connections required to develop a high level of understanding, ideally wisdom, from the information presented.

According to the principles of constructive alignment, the educational objectives for the learning exercise were stated in a clear fashion before the exercise. Following the introductory scenario, the objectives are a statement the various understandings that need to be constructed and combined within the student to enable them to deal with the situation presented. Theory relevant to the exercise was presented and discussed as part of the instructional scaffolding of the lesson. The theory would start with some basic tenets, and develop these into the model or theory that the student was to explore in the laboratory exercise. The starting point depended on the prior learning expected of students within the course; Where no prior learning was expected, the material was explained at the level of an intelligent layperson; where prior learning was expected, the explanation typically began with material presented to students in their previous year of undergraduate study or earlier. The intent was to firmly establish the lower levels of the instructional scaffolding for the lesson that students would build their learning on. This also had the added benefit of helping to prevent trivial issues of forgetting prior affecting successful learning.

The experimental procedure was then given, which had a number of important features in its layout and format:

- the procedure was divided into sections corresponding with educational objectives or a sensible grouping of objectives.
- relevant key questions were placed before the procedure had the following aims: to assist students connecting the exercise with the theory; to promote students developing higher levels of understanding through the exercise rather than following the procedure by rote, and to motivate students by connecting the exercise to the introductory scenario
- an attempt was made to keep the amount of data to be recorded manageable by selectively breaking up the procedure. This was also intended to prompt students to record the relevant data for each section, thus avoiding unnecessary rework
- the procedure was presented in a tabular form that explicitly stated which part of the equipment they were interacting with: the panel front, HMI, or data acquisition system. Table 9.1 is a sample of the format

The tabular format provided both instructional scaffolding to the student and addressed an educational objective. In industrial EMD systems operational data and control functions are often available at multiple locations: at the motor itself, on the front of the electrical panel containing the drive hardware, and in a control room on a PC with HMI software. These possibilities can be confusing, and are in themselves a significant cognitive leap. This leap can be reduced by clearly and explicitly stating which part of the equipment is to be interacted with. By directing students to interact with these different parts of the equipment the format also fulfilled the educational objective of introducing students to industrial EMD systems.

Review questions were set at the conclusion of each exercise; these were the bulk of the assessment tasks developed in the Tyler Table for each lesson. In most cases the

Table 9.1: Tabular instructions for laboratory exercises.

	System		
Step	Panel	ASTRA HMI	NI DAQ VI
Set up mode and check DAQ			
1	Ensure Panel is powered on: • 3 Phase LED's • Supply Voltage		
2		1) Open "ASTRA Run" from the desktop. 2) Open the file ECTE412_912	
3		1) Open Lab 1 *Introduction to Induction Motor* . 2) Open Exercise 5 *Motor Torque Speed Relation* .	
4		Energise Contactors	
5		Enter in a *supply frequency request* of 50 Hz	
6		Start Motors	
7	Confirm Panel Meters Working. Below Motor 1 Voltage panel meter, ensure the metering source switch is set ***star point to neutral*** .		
8			Start VI – confirm Working

exercises were to be completed within the time allotted for the lesson.

A conclusion was given at the end of the exercise that summarised the activities that students should have completed, the analysis they should have completed, and what new capability they should have as engineers. This was intended to promote students assembling a high level understanding from the exercises and insights within the laboratory, and also afford them the opportunity to assess their own performance in a closed loop fashion, engaging in reflective learning as described in Section 3.2.9.

9.1.1 Assessment of Learning Quality

The scenario assessments used to test students for wisdom before and after teaching were written on the four fundamental themes presented in Section 8.4.2. The scenarios developed for the current consumption behaviour of an induction motor theme are presented as an illustrative example; the complete set of war stories are included in Appendix C.

This theme focussed on the characteristic of an induction motor that it draws a significant amount of current without doing any mechanical work. In broad terms it can be thought that current must firstly establish a magnetic field that connects the stationary part of the motor (stator) to the rotating part (shaft); then additional current will do useful mechanical work. The initial current is referred to as 'magnetising current' or 'no load current', the magnitude of this current is typically between one quarter and one third of the full rated motor current.

The industrial survey (Section 3.1) uncovered numerous examples of mistakes being made due to misunderstanding this characteristic, most often when the induction motor and its load were mechanically disconnected (due to coupling failure etc). The typical mistake made was assuming that if some current were being drawn, some mechanical work was being done. Therefore, the induction motor and directly connected load were operating satisfactorily, and furthermore the problem was elsewhere in the associated system.

An engineer with the requisite wisdom would recognise that the current measured at the induction motor was the magnetising current, and therefore the motor is not doing any mechanical work. This often means there is a problem at the motor or the directly connected load; often the motor has become disconnected from the load.

The before and after scenarios gave students the opportunity to recognise the significance of the magnetising current. The scenario given before training was:

> You are an supervising engineer on an industrial site. A fault is reported to you - a fluid pumping system is not delivering flow as it should. You dispatch an electrician and a mechanical technician to investigate. They report back that all valves in the system are open and the pump motor is turning and drawing about 25% of its full load current. They conclude that the pump & motor are working OK and that there must be a blockage elsewhere in the system. They suggest that arrangements be made to shut down the system, disconnect the pipe work and look for blockages.
>
> Do you agree?

The scenario given after training was:

> You are a support engineer on a production line. The Chief Line Operator calls you to the control centre. When you get there they tell you there is a problem with the cooling system control. The cooling fans have been running for the last half an hour but nothing is cooling down. The Operator thinks that the temperature sensor in the control loop is likely to be faulty and suggest that you check it first. Looking at

> the operator's HMI screen you can see that: the process temperature is high and climbing; all cooling fans are reporting that they are healthy, running and drawing 33% of their full load current.
>
> What do you do?

These two scenarios were designed to appear to be different, however the differences were superficial. They key features present in both scenarios were:

- the current measured is around the magnetising current; and the conclusion that no mechanical work is being done should be reached
- misleading or irrelevant data is being offered along with the current measurement
- an incorrect diagnosis is offered based on misunderstanding the magnetising current

9.2 Technical

The mechanical and electrical assembly of the equipment was carried out by Emerson Control Techniques as an industrial partner at their premises in Sydney. The software development was carried out in parallel, with most of the programming done offline, before the hardware became available, to reduce the construction time.

9.2.1 Power Side

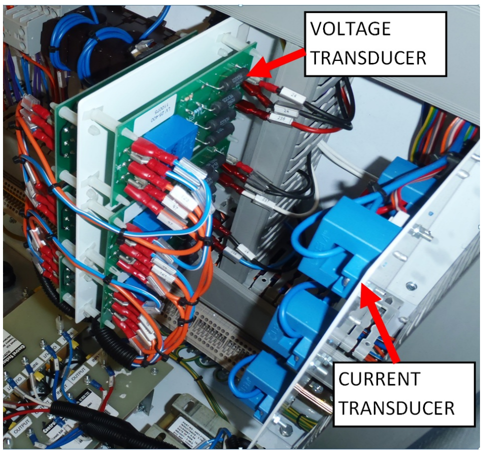
Figure 9.1 shows the final production model and prototype EMDET Assembled in the workshop of Emerson Control Techniques. In particular the panel meter layout corresponding to the power flow schema discussed in Section 8.6.1 can be seen on the production EMDET in Figure 9.1a when compared to the arbitrary layout used on the prototype EMDET in Figure 9.1b.

The LEM transducers specified in section 8.1.3 are shown in figure 9.2. The wiring required to allow the Motor 1 star point to be used as a voltage measurement reference in section 8.1.1 is shown in figure 9.2b and the placement of the current transducer to measure the winding current in the delta connected motor 2 as specified in 8.1.1 is shown in figure 9.2c

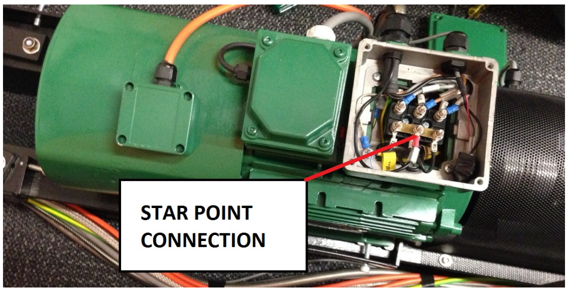
(a) Production Panel

(b) Prototype Panel

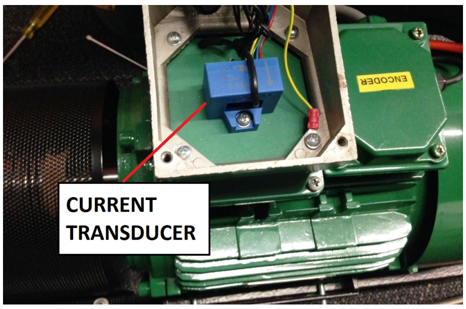
Figure 9.1: Completed electrical panel for the prototype production EMDET



(a) Prototype Panel



(b) LEM Voltage Connection at motor 1 star point



(c) LEM Current transducer at motor 2

Figure 9.2: LEM voltage and current transducer installation

9.2.2 Control Side

To provide fidelity in load simulation Drive 2 was set up to give the best available dynamic response available from the drive. The drive must accurately control to the torque set point provided by the PLC at various speeds, from zero speed (stall) to over base speed. Accordingly Drive 2 was set-up to operate in closed loop vector control mode using the shaft mounted encoder for feedback (Drury, 2009; "Advanced User Guide Unidrive SP", 2003).

To simulate a load using this mode the speed set point given to the drive was zero, and the torque limit was adjusted based on the measured shaft speed and the torque-speed curve of the simulated load. In broad terms, a real mechanical load will resist accelerating from a standstill with a certain torque speed characteristic, which is what Motor and Drive 2 were doing while being controlled of the PLC to simulate a load.

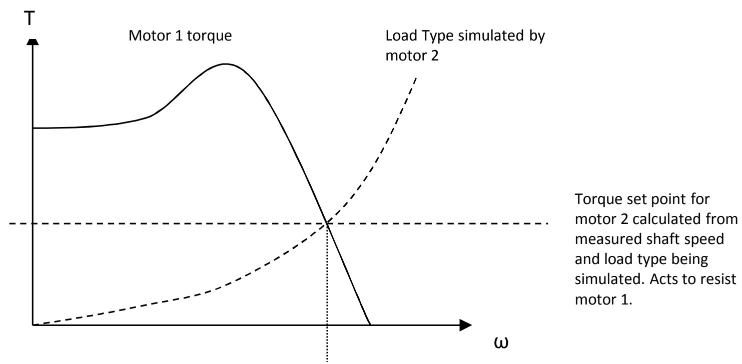
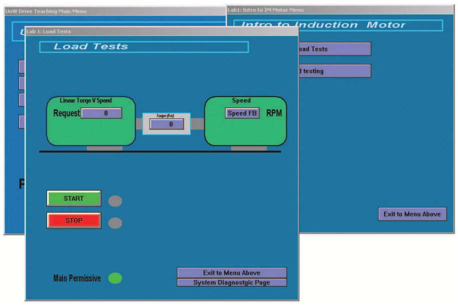


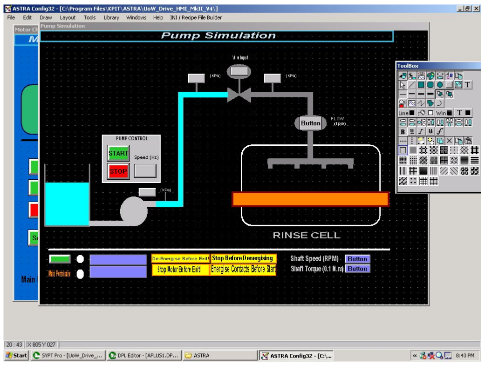
Figure 9.3: Load simulation via concept of dynamic equilibrium

9.3 SCADA

The assembly stage needed large amounts of software to be written for the PLC, the HMI and the data acquisition system. While significant and technically involved, much of the software coding was a realisation of the logic described in section 8.2. Two issues were significant for delivering the curriculum; the load simulation code in the PLC, and the data acquisition system GUI.



(a) Laboratory exercise mimic



(b) Pumping system simulation mimic

Figure 9.4: ASRTRA HMI screens for laboratory exercises

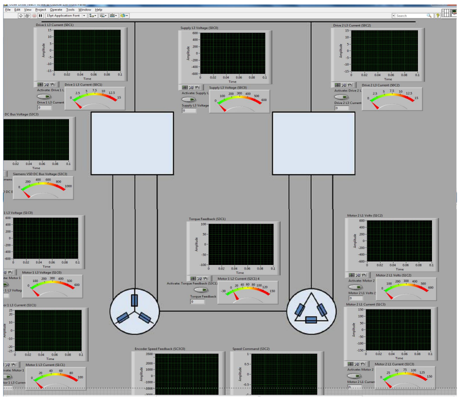
9.3.1 Load Simulation

A section of the PLC code would calculate the torque required to carry out the load simulation. The speed that this code would be execute (scan) and pass a set point to Drive 2 would be a key determinant of the fidelity of load simulation. As discussed in Section 7.2, the PLC could execute a portion of code at high speed, however this depended on the amount of code to be executed and how often physical IO was accessed. The PLC code was written to minimise the amount of code in the high speed portion of code and mitigate the access time to physical IO.

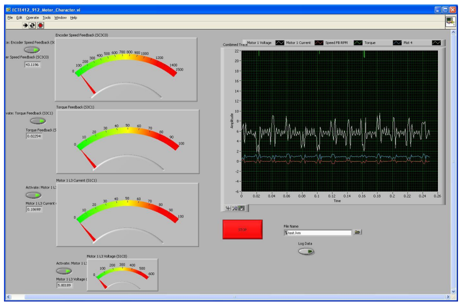
Of the load types outlined in section 8.2.2 the simple load types and load based on a lookup table were relatively straightforward to realise in the PLC. The opportunity was taken to introduce additional elements of realism to the the simulated pumping system, including a non-linear flow characteristic and position hysteresis for the flow control valve, and a pump with realistic variable mechanical efficiency. There however, were some complexities in realising the pumping system simulation due to integer calculations in the PLC.

9.3.2 HMI

The assembly of the HMI was mostly a straightforward conversion of the menu structure and draft screens from section 8.2.5 into graphic screens within ASTRA, examples of which are shown in Figure 9.4.



(a) Virtual Instrument (VI) monitoring power flow



(b) Virtual Instrument (VI) focussing on motor 1 parameters

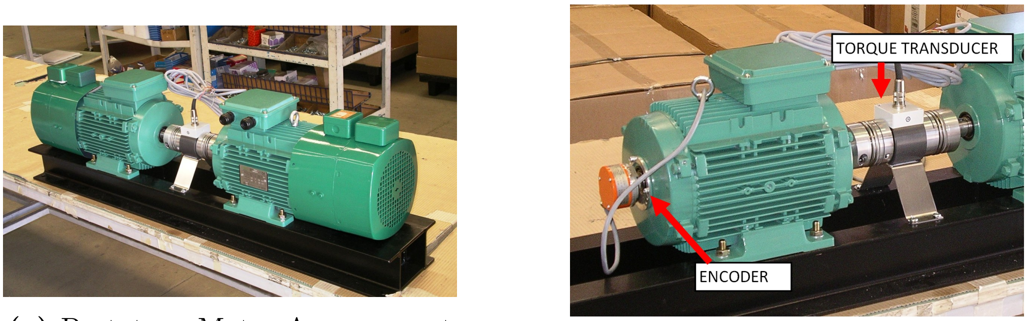
Figure 9.5: Virtual instruments assembled

9.3.3 Data Acquisition System

Two virtual instruments (VI) were created to suit the exercises with the reduced curriculum; the first was a realisation of the diagrammatic power flow schema (Figure 8.1) which is shown in Figure 9.5a. The second shown in Figure 9.5b was a reduced selection of signals related to motor 1 specifically for the exercise plotting the torque speed curve of the motor; this was created to help students with issues identified during component testing in Section 10.3.

9.4 Mechanical

The mechanical assembly was relatively straightforward, including fabrication of the steel frame, mounting and alignment of the two motors and torque transducer, and installation of a coupling guard. The final mechanical construction of the motors in the prototype is shown in Figure 9.6a. The torque transducer and shaft position encoder specified in section 8.1.3 are shown in figure 9.6b.



(a) Prototype Motor Arrangement

(b) Motor encoder and torque transducer

Figure 9.6: Motor arrangements

9.5 Project

9.5.1 Risk Management and the Iterative approach

The preceding description of the assembly of the laboratory workbook has included a number of features that were the result of the iterative nature of the VV&A approach. The scenario at the beginning of each exercise and key questions throughout the experimental procedure were introduced to address some issues identified in the acceptance testing described in section 13. It was observed that students were having difficulty in connecting the detail within the exercise to a real world application; accordingly, the scenario introduction and key questions were introduced. These features were based on formatting and approaches found in SCUBA diving instruction manuals (PADI, 1999).

Chapter 10

Case Study: Component Test

During the component test phase the constructors and designers jointly tested the EMDET to ensure that what has been assembled fulfilled the detailed design; this was the start of recomposition process that ensured that the earlier phases of design and specification had been fulfilled. Component testing of the EMDET included both curriculum and equipment; testing the curriculum consisted of proof reading and editing the curriculum materials; the equipment was tested in three stages of commissioning, each with increasing amounts of power applied to the newly assembled equipment.

The divide between component testing and integration testing can be somewhat arbitrary; the distinction made here is that the component testing stage finishes when the products of each individual constructor involved with the assembly have been tested in isolation. Here the curriculum materials and equipment were tested in isolation. The following integration testing phase ensures that the products from different constructors can work together in concert successfully by confirming that the equipment and curriculum materials work together.

10.1 Technical

The commissioning process confirms that the correct equipment is present and functions according to the detailed design. The equipment commissioning was carried out in three stages, each with increasing amounts of power applied to the newly assembled equipment. These stages were referred to as cold, warm, and hot commissioning. Cold commissioning tests the equipment without power applied, warm commissioning tests segments of the equipment when they are progressively powered up ,and hot commissioning tests with power applied to all parts of the equipment.

Testing began with a visual inspection and audit of the assembled equipment against the construction drawings during cold commissioning, and progressed through many stages, culminating in operating the equipment to produce a measurement of the torque-speed characteristic of Motor 1. Measuring the curve was a summative test of the equipment requiring both hardware and software to work together. Due to the extent of this testing, only a selection of this work is provided here.

10.1.1 Warm Commissioning

During warm commissioning, power was applied progressively to the equipment in stages and various tests were carried out. Of particular importance were checks and adjustments made to speed feedback and torque control as these they had a direct impact on the fidelity of the load simulation achieved. A check of shaft speed feedback from the encoder was carried out by running motor 1 at various frequencies using the inverter; the shaft speeds were as expected at the various supply frequencies. Several motors in the production version had an issue with speed feedback having the wrong sign because the shaft encoder wiring had been transposed.

During checks of the accuracy of Motor 2, torque control errors of up to 40% from set point were found on some of the production model EMDETS; this had serious implications for the fidelity of load simulation. The torque control carried out in Drive 2 relies on a theoretical model of the connected motor consisting of a number of parameters; these parameters can be derived either by a calculation based on the nameplate ratings, or live tests that the drives carry out on the connected motor called an ‘autotune’. The autotune process was implemented and reduced the error to within a few percent, after which scaling factors were applied to each EMDET to further improve accuracy.

10.1.2 Hot Commissioning

Hot commissioning tested if the equipment fulfilled the specifics of the detailed design stage; it consisted of progressively testing aspects of the equipment performance, building toward a summative test measuring the motor characteristic curve, which is a major objective of the revised curriculum. This progressive testing consisted of:

- mapping the steady state performance of Motor 1 and Motor 2
- testing simple simulated load types with a fixed torque speed relationship (constant, linear and squared)
- testing the transient behaviour of different combinations of drive 1 and simulated loads
- testing the performance of the pump simulation as an example of a sophisticated load
- testing the performance of the data acquisition system to confirm it could capture and display the required physical properties of the system. This stage was a crucial confirmation of the aspect of the flexibility philosophy described in section 6.1.3; namely that the important physical phenomena within the system were present and visible
- testing the performance of the HMI and PLC to ensure they could deliver the required operations
- testing the system by measuring the characteristic curve of the induction motor. This was a summative test requiring that all the motors, drives, PLC, HMI and data acquisition system operate correctly to give the desired result

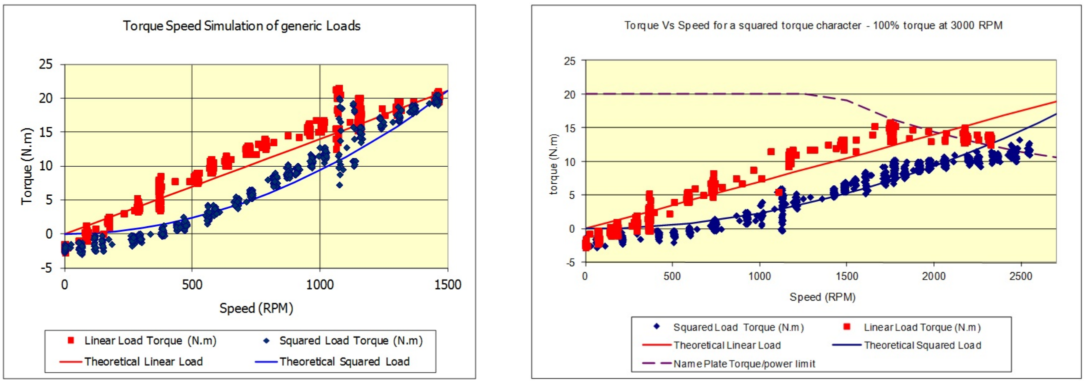
Selected parts of this process are provided here.

10.1.2.1 Load Simulation

The most important consideration was the ability of the system to simulate a load torque that varied with shaft speed that would be required for much of the revised and future curricula. Tests were carried out on simple simulated linear and squared torque loads with two proportionality constants; one that would require full motor rated torque at base speed (Figure 10.1a) and one that would require full torque at twice the base speed (Figure 10.1b).

Figure 10.1 shows that the linear and squared loads were both successfully realised, the difference between these loads is apparent between 25% and 50% of rated speed, where there is a noticeable difference between the load torque. Another interesting feature is evident at approximately 1100RPM where there is a large variation in torque, this was due to a mechanical resonance visible in the torque transducer and flexible coupling assembly. This sort of resonance was difficult to avoid due to the flexible couplings mandated by the manufacturer of the torque transducer, these behaved as torsion springs with a resonant frequency. The effects of the resonance were attenuated by small mechanical changes to the mounting, however, they could not be eliminated entirely without major mechanical modifications.

Figure 10.1b shows successful simulation of these loads up to approximately 20% over base speed. At this stage motor 1 reaches its power limit and cannot provide the torque required to drive the selected load above this speed. Loads requiring less than the full motor power at speeds up to twice the rated speed were tested successfully.



(a) Torque simulation of simple load types to 1500 RPM **(b)** Torque simulation of simple load types to 1500 RPM

Figure 10.1: Torque simulation of simple load types including linear and squared torque with speed variation

10.1.2.2 Transient behaviour Motor starting

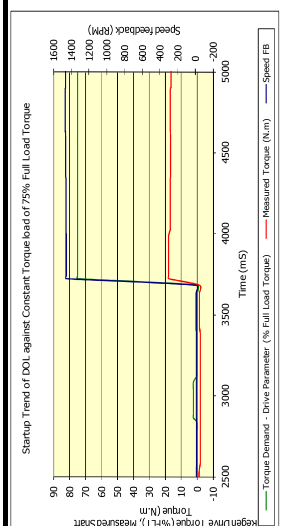
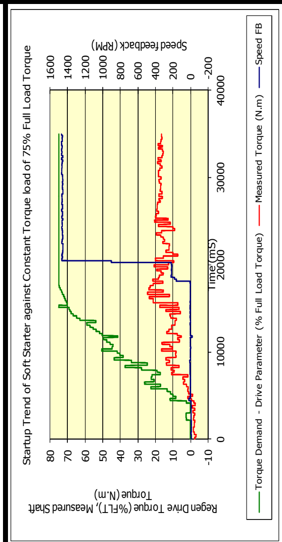
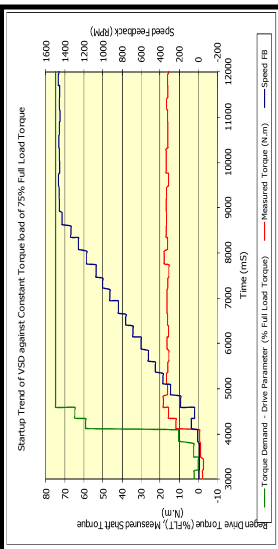
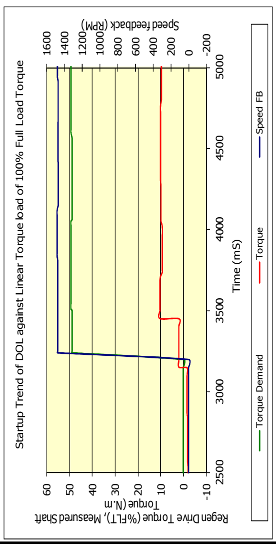
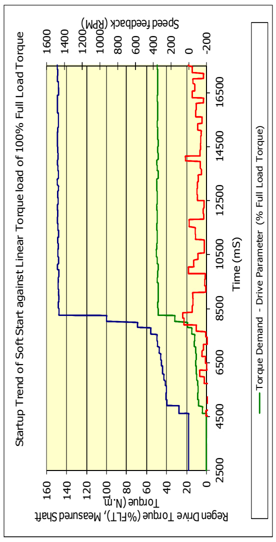
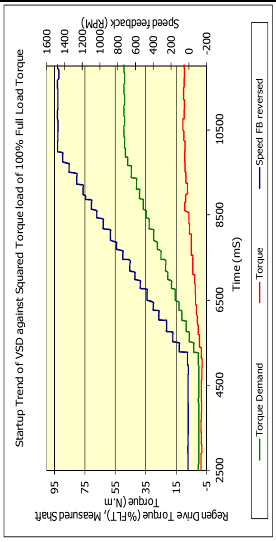
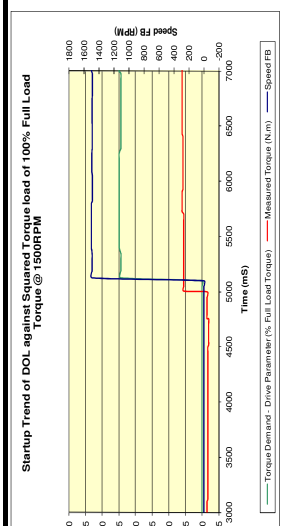
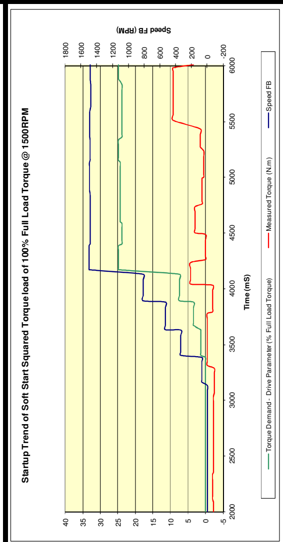
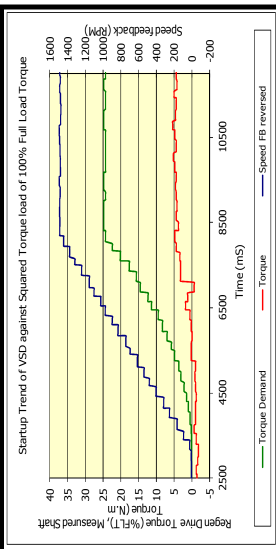
After establishing that the simple load types with a fixed torque speed curves worked, the transient behaviour of the drive, motor, and load combinations were examined. Understanding the performance of the motor, load and drive was one of the war story measures of student competency in Section 8.4.2, and it was crucial that the EMDET performance could deliver this part of the curriculum.

During this testing, the three options for Drive 1 were tested with three simple load types; constant torque, linearly increasing torque with speed, and torque increasing with the square of shaft speed. During testing, three quantities were measured; the torque reference for Drive 2, the measured shaft torque, and the measured shaft speed. These were measured for the nine tests that students would carry out to investigate each combination of load and drive type; the results are shown in Table 10.1.These drive load combinations showed the behaviour expected:

- Direct On Line:
  - regardless of the load type the DOL start is sudden and violent rapidly moving from zero to full speed.
- the soft starter has different starting behaviour based on the load type used
  - with a high constant torque load the performance is almost the same as a DOL start. This is as expected because the operating principle of the soft starter varies the voltage available at fixed frequency, and slowly increases the torque over time. Against a load requiring high torque at low speed this means the soft starter cannot drive the load until at or near full voltage, when it behaves as a DOL start. This is one of the key points to be illustrated to students
  - with a linearly increasing load torque, the soft starter reduces shaft acceleration for this load compared to a DOL start, but the acceleration is not smooth, beginning with some slow shaft acceleration followed by a sudden increase to full speed
  - with load torque proportional to the square of the shaft speed the soft starter reduces shaft acceleration for this load compared to a DOL; the soft starter works well with the load being progressively accelerated from rest, to full speed
- inverter
  - regardless of type the load, it gradually accelerates from rest to full speed regardless of its behaviour

It was particularly important that the expected behaviours were evident so they could be investigated by students in the revised ECTE 421/912 course and also provide much of the desired flexibility within the EMDET for future teaching. An investigation of the three drive types would introduce students to some of the common drive types employed in industry, and help to prepare them for industrial practice.

Table 10.1: Transient behaviour of combinations of drives and generic load types.

	DOL	Soft Start	VSD
Constant			
Linear			
Squared			

10.1.2.3 Sophisticated Load Simulation - Pump Simulation

A pump system was simulated during the assembly phase to test a sophisticated load behaviour, and as an exemplar of the EMDET fidelity and capabilities for future teaching and flexibility. The system developed is described in Section 9.3.1, including the capacity to vary the system flow via valve position or pump speed. Figure 10.2 shows the power consumption for both flow control schemes: variable valve position, and variable pump speed. The power saving available by using pump speed control instead of throttling is clearly visible. There are two more subtle effects in evidence, demonstrating the fidelity built into the EMDET:

- there is no simple mathematical relationship regarding power savings between the two schemes, as this depends on non-linear flow resistances and non linear pump behaviour (flow and efficiency)
- the uneven spacing of the valve position test points shows the non-linear behaviour of some throttling valves and the difficulty this can present in controlling fluid flow rate. This is a good demonstration of the EMDET flexibility and fidelity translating to a capability to simulate real world loads; a capability that can be used to train students in preparation for industrial practice

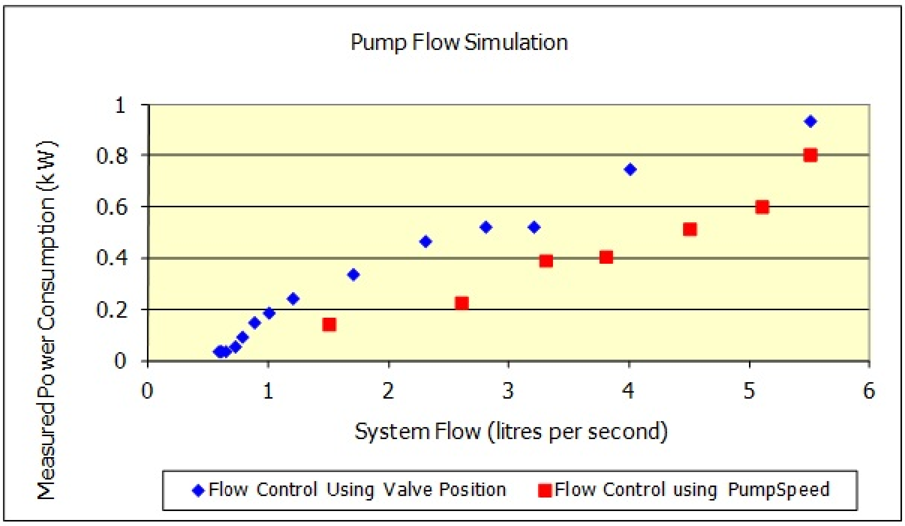


Figure 10.2: Measured power consumption for various simulated flow rates using either valve or pump speeds control.

10.2 SCADA

10.2.1 Data Acquisition

The capability of the data acquisition system to accurately capture and faithfully reproduce the physical properties measured throughout the tool was crucial to being able to successfully deliver the educational curriculum (both current and future) as dictated by the Philosophy of Flexibility described in section 6.1.3. The following tests were undertaken during the hot commissioning of the data acquisition system to confirm it could capture and display the required physical properties of the system:

1. confirmation that the Current and Voltage LEM transducers had enough bandwidth and accuracy to make the physical phenomena in the system visible as expected by the detailed design. The transducers were checked both on a test bench, and when installed in the panels
2. confirmation that the physical current and voltage signals throughout the system were as expected with various configurations of drives and loadings.
3. investigations into the electromagnetic (EM) noise introduced to sensors by the switching of the power electronics within the drives.
4. confirmation that the data acquisition system could capture the signals from the transducers at adequate frequency from the transducers to present to the users

Due to the extent of this testing, only selected parts of this process are provided here.

10.2.1.1 Checks of LEM Transducers within the EMDET Panel

Bench testing had established that the current and voltage LEM transducers worked with sufficient accuracy, so they were then used to check the physical performance of the system to confirm that it operated as expected. A large number of tests were carried out with the system in various configurations at a various levels of loading; of which a small sample is included here. The final configuration of the LEM transducers as installed is shown in figure 10.3.

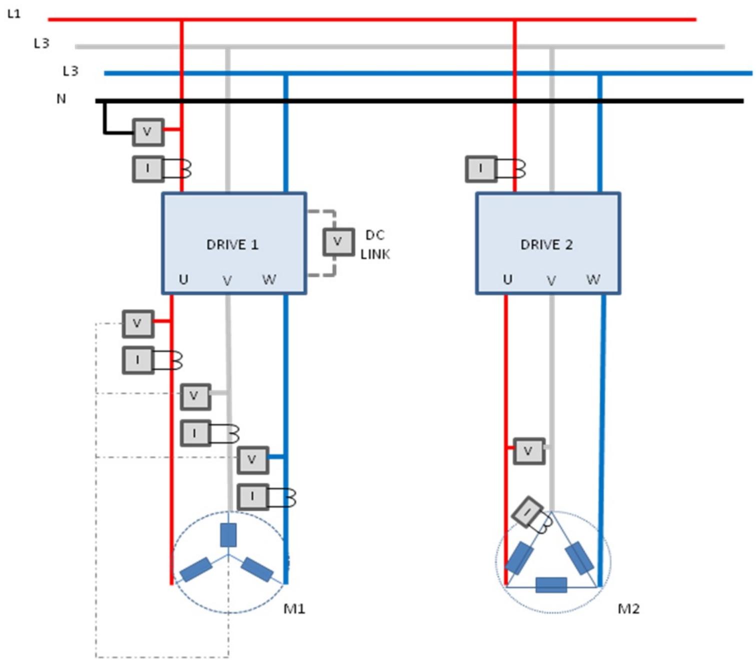


Figure 10.3: Configuration of the LEM transducers as installed.

Checks of Motor 1 Currents As an example of the checks made to current transducers the current signals tested around drive 1 are shown in figure 10.4. The PWM inverter is selected as drive 1; it is operating at 30 Hz with the regenerative drive applying 50% torque to motor 2. One phase of the current supply to the inverter is shown (channel 1) and all three phases of current to motor 1 are shown.

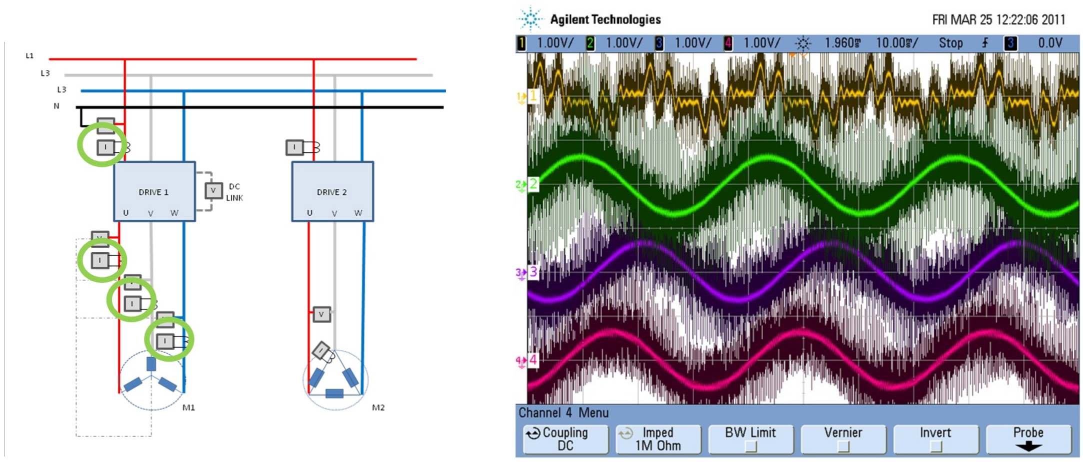
The supply current to the inverter shows the short pulses of high current that are characteristic of the capacitor DC link used in the Siemens inverter, this is one of the Power Quality issues nominated for teaching in the preliminary curriculum (Section 5.1.3). The motor phase currents are clearly visible at 30 Hz on channels 2-4. The check identified that currents do not have the expected phase relationship, which risks student confusion during laboratories. The motor phase 1 current (channel 2) appears to be 180 degrees out of phase, and in this case it was found that the wiring was run in the wrong direction through the LEM.

10.2.1.2 Instrument noise

While testing the transducers with various configurations of drives a significant amount of EMC noise was observed. This noise was investigated by observing the

CH	Colour	Quantity	Phase	Scale (CRO- Circuit)
1	Yellow	Drive 1 Phase L1 Current	L1	1 V = 12.5 A
2	Green	M1 Phase U Line Current	U	
3	Purple	M1 Phase V Line Current	V	
4	Red	M1 Phase W Line Current	W	

(a) CRO channel assignment during in situ checks of LEM signals around motor 1

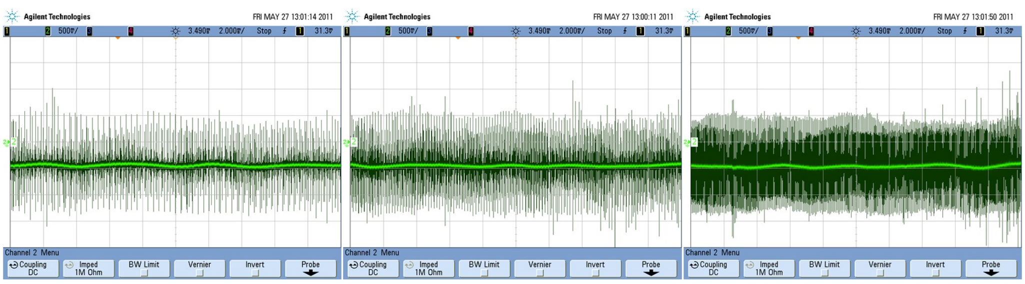


(b) LEM transducers under test

(c) Current signals from LEM transducers under test

Figure 10.4: Test of current signals from motor 1 LEM transducers

effects of activating the various devices containing switching power electronics, altering the switching frequency, the location of sensor connections and routing of the sensor cables. The torque transducer was very sensitive to EMC noise and tests of the torque signal at different drive switching frequencies (shown in figure 10.5) and routing of the sensor cable were carried out to address the noise issue.



(a) Noise visible on torque transducer signal at 3kHz drive switching frequency

(b) Noise visible on torque transducer signal at 6kHz frequency

(c) Noise visible on torque transducer signal at 16kHz frequency

Figure 10.5: Test of noise on torque transducer signal at various drive switching frequencies after cabling changes

The noise on the torque signal was considerably reduced by the new routing and low switching frequency, especially in view of the fact that the PWM inverter was in operation during the testing of the new route. While noise on the torque signal reamined with the new routing at low switching frequency, it was judged to be suitable for use in teaching for two reasons; firstly, it was judged the noise would not form an unnecessarily obstructive cognitive leap for students as the signal was still qualitatively evident through the noise. Secondly, that dealing with noise on a signal was a real world task and would add fidelity to the student learning experience.

10.2.2 Tests of NI DAQ

With the transducers in the system successfully tested it remained to confirm that they would work together with the acquisition system, and it could successfully acquire the signals correctly at sufficiently high frequency to deliver the curriculum. The National Instruments data acquisition system was tested by acquiring currents and voltages around the inverter (figure 10.6) while operating at 40 Hz. One phase of voltage supply to the inverter was acquired for a baseline and one phase of voltage output and two phases of current were acquired to check if the switching frequency effect was evident in the acquired data.

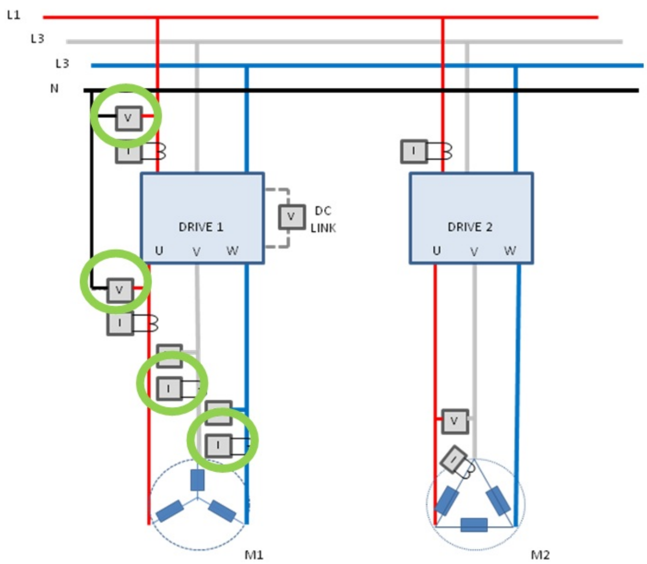
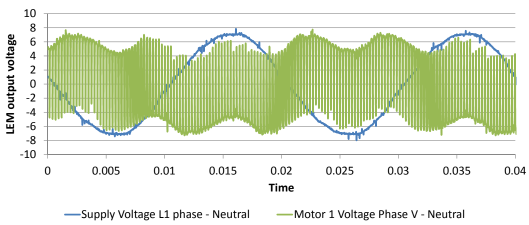


Figure 10.6: In situ check of LEM transducers and National Instruments Data Acquisition system on signals around Siemens Inverter.

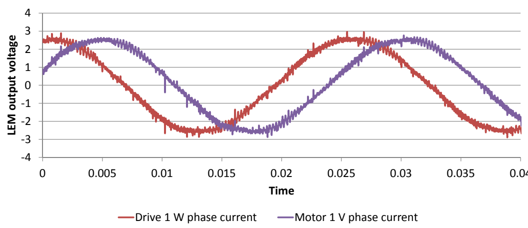
A sample of the data acquired is shown in figure 10.7. Figure 10.7a shows the line to neutral supply and the motor voltages captured. The supply voltage is as expected, while the motor line to neutral voltage has an unusual shape due to the inappropriate selection of the mains neutral as a reference further discussed in Section 10.5.1 . Figure 10.7c shows the voltage signals acquired over a smaller time scale, the switching effects in the motor voltage from the PWM inverter are clearly evident in the acquired data.

Figure 10.7b shows the V and W phase line currents supplied to the motor, these are sinusoidal as expected at a frequency of 40 Hz. Figure 10.7d shows the current signals over a smaller time scale, the sawtooth switching effects from the PWM inverter are clearly visible in the current traces.

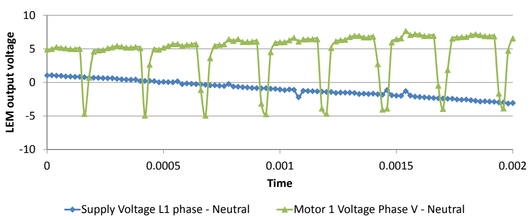
The data displayed in figure 10.7 clearly demonstrated the ability of the NI data acquisition system to acquire the data from the transducers in the system accurately and at a sufficiently high sampling frequency. The quality of data acquisition is suitable to deliver the revised course or any of the extended material; in particular the clarity of acquisition keeps cognitive leaps for students low and facilitates future teaching with the existing acquisition system.



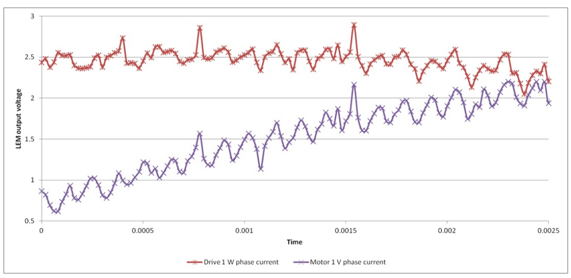
(a) Data acquired from supply voltage and motor line to neutral voltage



(b) Data acquired from motor phase currents



(c) Close up of voltage data, showing high frequency PWM switching effects.



(d) Close up of curent data, showing high frequency sawtooth switching effects

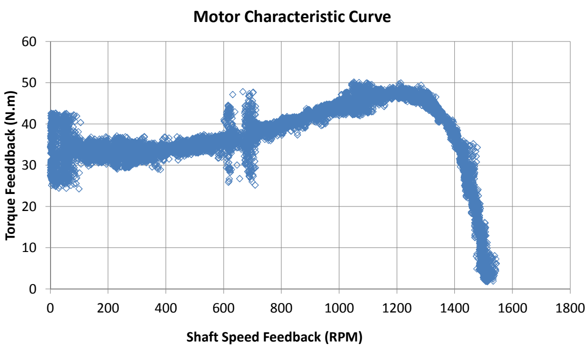
Figure 10.7: Data acquired from in situ check of LEM transducers and National Instruments Data Acquisition system on signals around Siemens Inverter.

10.3 Summative Testing of the system

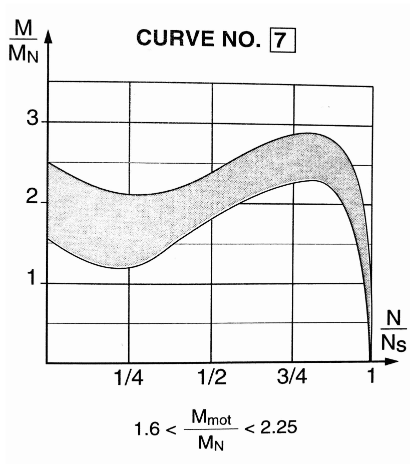
After hot commissioning of the motors, drives PLC, HMI and data acquisition system individually, a summative test was carried out to test that all of these components could operate in concert. This was to map the torque speed characteristic of motor 1.

A specific HMI screen and an automatic loading sequence in the PLC were used along with the cut down data acquisition screen described in Section 9.3.3. The intent of the automatic sequence and cut down VI was twofold; firstly to help students focus on the desired learning outcome by avoiding unnecessary cognitive leaps involved in manually running the equipment through a complex loading sequence, secondly to avoid running the equipment unnecessarily at stressful loading conditions for long periods of time.

The sequence was run, the torque data analysed and filtered to remove EMC noise (via an averaging filter), and then appropriately scaled and plotted against the shaft speed. The resulting motor curve is shown in figure 10.8a and the manufacturers expected curve is presented in figure 10.8b ("LS 3-phase TEFV cage induction motors Technical Catalogue", 2005). The curve measured is an excellent match to both the manufactures curve and the classical induction motor curve presented in engineering literature, providing the experience desired to prepare students for industrial practice. There are two interesting features in the curve; an oscillation of torque around zero speed and some torque pulsations at around 650RPM. The pulsations at 650RPM due to the resonance discussed in section 10.1.2.1; the resonance in the production models was at a lower speed than that observed in the prototype. This was attributed to differences in the mounting arrangement of the torque transducer.



(a) Recorded torque speed data after analysis



(b) Manufacturer's published motor characteristic (Rated torque (MN) for the 2.2kW Motor 1 is 14.7 N.m)

Figure 10.8: Mapping of torque speed characteristics of motor 1 as part of hot commissioning.

The successful generation of the induction motor torque speed curve marked a major milestone in the development of the tool; experimental measurement of this curve was a key educational objective that required all of the hardware and software in the system to operate correctly in concert to produce the result required to deliver the curriculum.

10.4 Educational

Educational component testing was a relatively straightforward exercise with the draft laboratory exercises being reviewed by the PED course subject coordinator prior to compilation into a lab manual. The review identified a number of relatively minor issues including:

- missing material, either in the exercises themselves, or the need for some additional supporting material
- incomplete or unclear instructions requiring more explanation, typically including direction on which part of the equipment to locate the required data
- re-sequencing some instructions to improve clarity
- addition of extra steps in instruction, including spaces in the notes requiring

users to record results or confirm that particular equipment operations had properly occurred. These were used to prevent students from skipping over important intermediate steps in their work
- poorly laid out portions for results were revised; typically tables for results were added rather than blank spaces being left in the text
- a number of the review questions were redrafted for clarity
- some review questions were added where an educational objective was not properly assessed

10.5 Project

10.5.1 Risk management Iterative approach

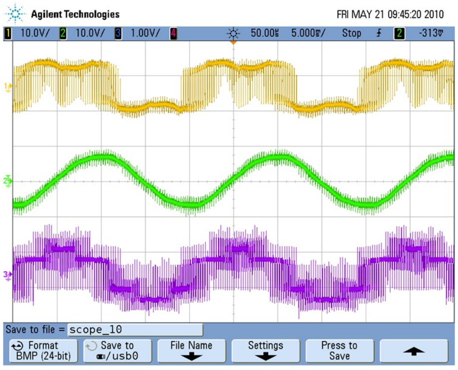
Placement of the current transducers and selection of transducer voltage references were the result of a number of iterations of design and testing. The prototype with two star connected motors initially used the mains neutral as a voltage reference, but when the PWM inverter was tested, nonsensical voltages were measured due to the DC link in the inverter disconnecting the motor output from the mains neutral. It was then that the possibility of using the motor star point as an alternative reference was shown.

Testing of this is shown in Figure 10.9, the expected line to line and line to star point voltages for a PWM inverter are shown in figure 10.9c from Drury (2009). The tests clearly showed line to star point voltages were the measurements needed to align with student pre-requisite knowledge and avoid unnecessary cognitive leaps. Due to the perceived value of this learning, the facility to switch the voltage reference between the motor star point and mains neutral was incorporated into the design.

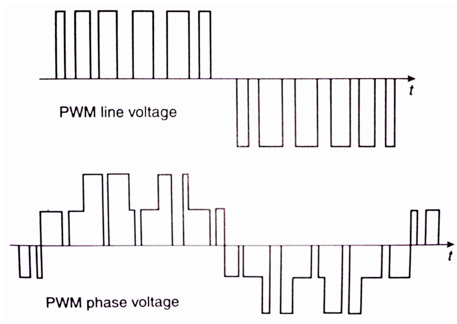
Motor 2 had similar issues with disconnection of the output from the mains neutral, the initial nonsense voltage measurements using the mains neutral are shown in figure 10.7a. Motor 2 had the added complication that the production models were delta connected, this removed the possibility of using the star point as a voltage reference. The delta connection determined that the only sensible voltage reference available was a line to line voltage; this then needed a corresponding current

Channel 1	Yellow	line to neutral motor 1 phase W volatge
Channel 2	Green	Mains W phase
Channel 3	Purple	line to starpoint motor 1 phase W voltage.

(a) CRO channel assignment during checks of motor 1 voltage reference



(b) Voltages measured during checks of motor 1 voltage reference



(c) Expected line to line and line to star point voltages for a PWM inverter

Figure 10.9: Iterative checks of motor 1 voltage reference

measurement that could be used to calculate electrical power using a single phase equivalent circuit model. This was necessarily the winding current resulting from application of the line to line voltage measured; measuring this current required that the transducer be placed within the motor terminal box after the phase connection branched to the two motor windings. The facility to switch the voltage reference between the motor star point and mains neutral was incorporated into the design for the same reasons as motor 1. The final successful configuration of transducers included:

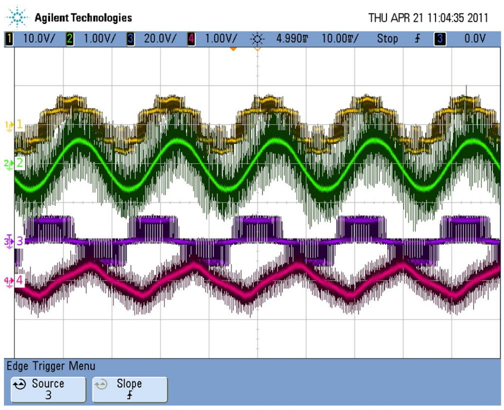
- measuring line current and line to star point voltages for motor 1
- measuring line to line voltage and winding current for motor 2

One of the first successful tests of this configuration is shown in table figure 10.10, with the PWM inverter operating at 50 HZ and motor 2 applying 50% torque sensible currents and voltages are observed. Motor 1 shows the expected line voltage from figure 10.9c and the corresponding sinusoidal line current. Motor 2 shows the expected line to line voltage from 10.9c with a winding current demonstrating the generator operation of the motor.

Selecting the correct current and voltages references was crucial to the ability of the

CH	Colour	Quantity	Phase
1	Yellow	M1 Line-Starpoint Voltage	L3 – starpoint
2	Green	M1 Line Current	L3 current
3	Purple	M2 L-L Voltage	U-W
4	Red	M2 Winding Current	U-W

(a) CRO channel assignment during checks final measurement references for motor 1 and 2



(b) Measured currents and volatges during checks final measurement references for motor 1 and 2

Figure 10.10: Outputs from final current and voltage transducers references selected for motor 1 and 2

tool to operate successfully as an educational tool. Correct selection meant that the power flow in the system could be analysed using single phase equivalent from student pre-requite learning, removing unnecessary cognitive leaps of converting currents and voltages from unfamiliar quantities. Without the iterative approach taken this issue may not have been identified much less successfully resolved.

10.5.2 Prototype EMDET

The development of the prototype terminated at this phase of the first major iteration through the WiSE approach. The prototype allowed for much of the hot commissioning to be successfully completed, apart from generating the motor torque speed curve described in section 10.3. Although there were issues with the prototype it functioned well enough during testing to gain support from stakeholders for the full production model EMDET to be funded.

Chapter 11

Case Study: Integration Test

During the integration test the EMDET equipment and curriculum, previously tested separately, were tested together to ensure they worked in concert. During this phase the designers tested (recomposed) the output of the component testing to ensure that it fulfilled the system design phase. A primary component of integration testing was to undertake all the laboratory exercises using the equipment, and then produce a set of instructor's solutions from the results. Instructors solutions successfully produced from equipment results meant that the equipment curriculum worked together and would confirm proper integration. Moreover, the successful production of the solutions would also confirm that most of the system design phase had been fulfilled.

The integration test phase included all the testing that could be carried out by the designers alone, and the divide between integration and the subsequent system test phase was when the ultimate users of the equipment needed to become involved in testing to make further progress.

11.1 Educational

The final edition of the student's laboratory workbook was used to produce the solutions which consisted of the five exercises delivered in the two laboratory sessions described in section 7.1 including:

- industrial Safety
- introduction to EMD systems and the Laboratory equipment
- the torque-speed behaviour of a squirrel cage induction motor
- characteristics of a squirrel cage induction motor
- behaviour of loads, motor, and drive in combination

11.1.1 Industrial Safety Exercise

This exercise introduces students to hazards, risks, controls and a safe system of work. Here students are given briefing materials, a short presentation within the laboratory and are then assigned a small hypothetical exercise (e.g. check motor coupling bolts, replace a circuit breaker) for which they were to write a safe work procedure using one of a number of formats contained in the briefing materials.

Integrating the equipment and curriculum required that the system physically include the components involved in the hypothetical tasks, and that it was safe for students to work around. Reflecting on the production of solutions for this laboratory identified that a presentation of industrial safety had not been prepared, so it was combined with an introduction to the equipment.

11.1.2 Introduction to EMD Systems and the Laboratory Equipment

This exercise introduces students to the various components of the equipment, and consequently, to typical industrial EMD systems and SCADA. The exercise requires students to identify the key components of the system, start a motor cooling fan using the HMI, use the emergency stop button to shut the equipment down, reset the emergency stop and confirm that the equipment restarts, energise an inverter to observe the input current waveform and frequency spectrum on the data acquisition system.

The integration of equipment and curriculum required that equipment was constructed as a typical EMD system; furthermore, that it was capable of demonstrating the emergency stop appropriately and generate relatively complex waveforms to view with the data acquisition system. To reduce risk, the exercise did not require Motor 1 or Motor 2 before the students had proved they could use the emergency stop because the exercise was introductory and could potentially be a students' first exposure to an EMD system. This was why the motor cooling fans were used to test the emergency stop and the DC bus of the PWM inverter was energised which drew a distorted current waveform visible to the acquisition system (shown in Figure 10.4); both of which precluded the possibility of students inadvertently operating a motor without being able to stop it again.

As the instructors solutions were produced a number of issues were identified that could create unnecessary or obstructive cognitive leaps for students and impair student learning. Solutions for these issues were subsequently formulated and implemented:

- this exercise did not require students to check the motor nameplate details of critical importance to the operation of the system, and which are used in later exercises. The exercise was updated to require students to record the nameplate details
- to help prevent students inadvertently skipping important steps check boxes were introduced next to these stages of the laboratory procedure. This was done in all of the exercises
- a number of steps were judged to be unnecessarily long and complex, these were broken down into a number of smaller steps
- labelling on a number of HMI screens was updated and expanded, and the laboratory notes were updated to use the correct labels as displayed on the HMI
- key files used to run the HMI and data acquisition system were placed on the PC desktop to allow easy access to them

11.1.3 The torque-speed behaviour of a squirrel cage induction motor

During this exercise students map out the torque speed curve of a squirrel cage induction motor; they also map out current, mechanical power and power factor against motor speed. To do this the students use a specific HMI screen and a special virtual instrument.

Integration of the equipment and curriculum required that:

- motor 1 was taken through the full envelope of its operation with sufficient time to gather appropriate data
- the relevant data was gathered while Motor 1 operated through its speed range
- motor 1 should not be held under high loadings for too long because the test places a great deal of strain on all components within the system mechanically and electrically. Ideally students would only run this test once, so precautions were taken to help students to gather the correct data during the first operation of the sequence

As a reflective change the automatic loading sequence was programmed into the PLC to address a number of the integration issues:

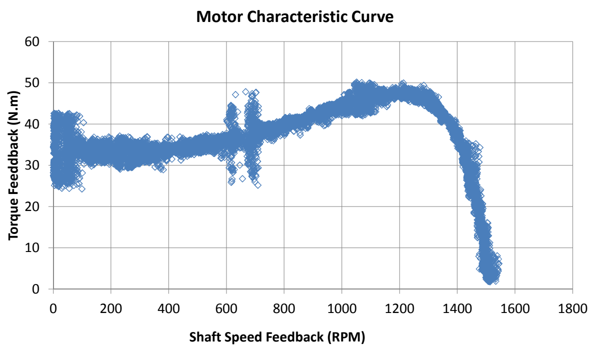
- simultaneously loading Motor 1 and acquiring the relevant data was a complex operation which did not address any of the educational objectives for the laboratory, and therefore formed an unnecessary obstructive cognitive leap for students. Moreover, it was anticipated that the complexity could cause confuse students, and result in the equipment operating for long periods of time under high loads. The automated sequence would remove most of the complexity and assist students with the simultaneous tasks
- the automatic sequence would ensure that the full operating range of Motor 1 was investigated
- the length of the sequence was carefully selected to strike a balance between minimising the amount of time the equipment is highly stressed, while still allowing enough time to gather sufficient data on the motor's performance

While producing the demonstrators solutions a number of issues were identified that could impair student learning, so the follwoing changes were implemented:

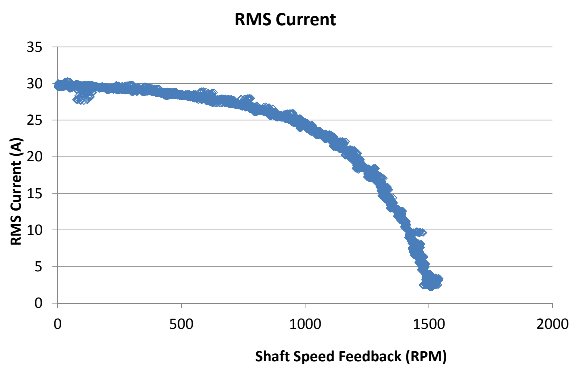
- a preliminary step was introduced in the procedure to test the data acquisition while the motors were running at no load before running the loading sequence. This was to ensure that the data acquisition was working and students could locate the logged data. Students were asked to record data, locate the supply voltage, and check the amplitude to ensure they had logged the data correctly. This effectively provided some educational scaffolding to the students to ensure they could operate the data acquisition system before attempting to measure the motor torque speed behaviour
- additional steps were introduced to assist students in selecting the correct data to log to their file

- the naming of the data logged was altered from a generic title (voltage 1, etc) to a specific, meaningful label (speed, torque, etc)
- the name of the VI was altered to clearly identify it

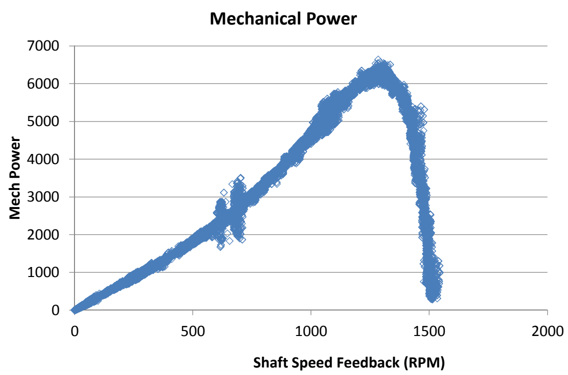
The motor torque speed curve, current, mechanical power and power factor were measured, high frequency noise was filtered from the signals and the results were plotted and provided in the instructors solutions as shown in Figure 11.1. Importantly there results were the results expected, and furthermore those required to deliver the curriculum.



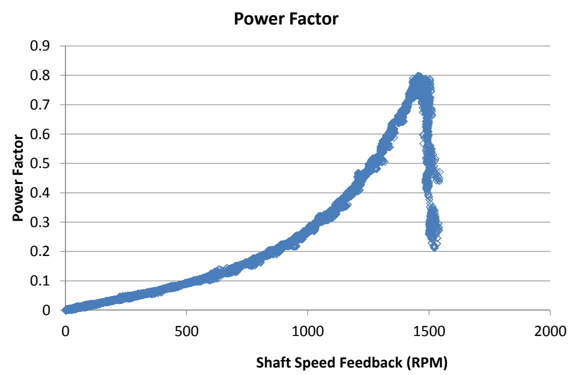
(a) Motor torque speed behaviour



(b) Motor current consumption with speed



(c) Motor mechanical power output



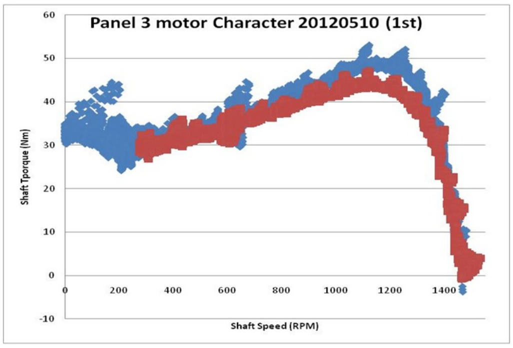
(d) Motor power factor

Figure 11.1: Motor characteristic behaviours found from torque speed testing

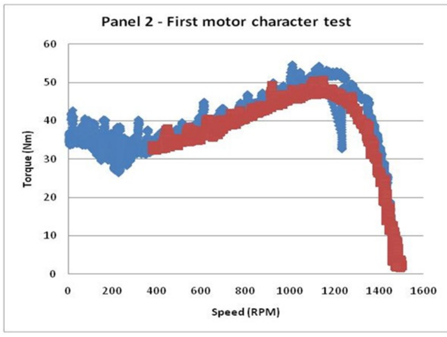
Several salient features within the curves differed from the archetypal curve due to the real world behaviour of the equipment. These unusual features were explained within the solutions to enable instructors to recognise them in student solutions and explain their cause if students taking a deep learning approach enquired about them. These features include:

- there may be some hysteresis apparent in the torque speed curve, the decelerating torque curve may be slightly different to the accelerating curve. This is highlighted in Figure 11.2a where the decelerating data in blue is at a higher torque level than the accelerating data in red. This result is attributed to the behaviour of the torque control algorithm in Drive 2
- there is scatter in the torque measured over a range of approximately between 100 RPM, typically between 500-600 RPM, as can be seen in Figure 11.1a. This result is attributed to torsional oscillation of torque transducer & flexible couplings
- there is scatter in the torque readings around stall as can be seen in Figure 11.1a. This is due to the 200 Hz torque oscillation possibly due to the induction motor stall characteristics or the torque control algorithm in drive 2

The potential issue of a coupling mechanically slipping, as encountered in testing, was outlined to enable a laboratory demonstrator to diagnose the issue and deal with it if it is encountered. Figure 11.2b shows the sharp and distinctive dip in the torque speed curve that results from coupling slippage during plots of the torque speed curve.



(a) Motor torque speed curve showing hysteresis



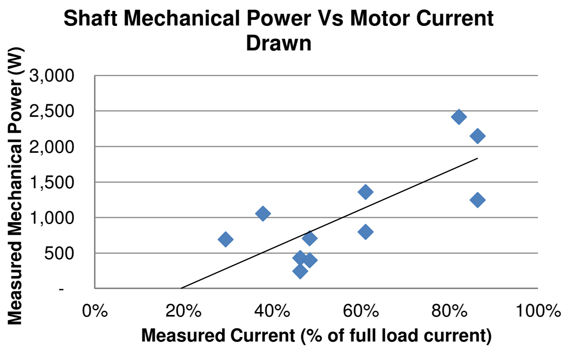
(b) Motor torque speed curve showing hysteresis and coupling slippage

Figure 11.2: Significant motor toque speed curves found during integration testing

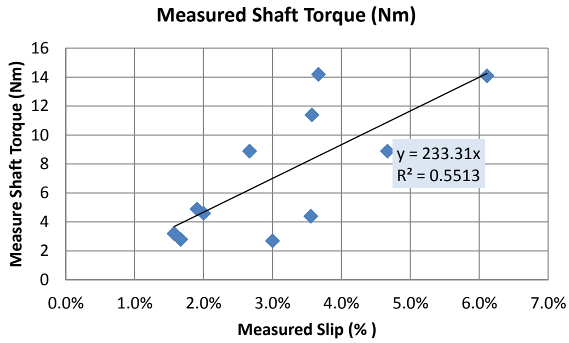
11.1.4 Characteristics of a Squirrel Cage Induction Motor

During this exercise students further investigate the characteristics of an induction motor under various combinations of electrical supply and mechanical loading. The exercise required students to gather data and analyse it to determine a number of quantities including motor slip and power. The integration of equipment and curriculum required that the electrical supply (voltage and frequency) to Motor 1 could be varied, that Motor 2 could apply varying levels of load and that the relevant parameters were available via the data acquisition system (current, voltage, speed, torque).

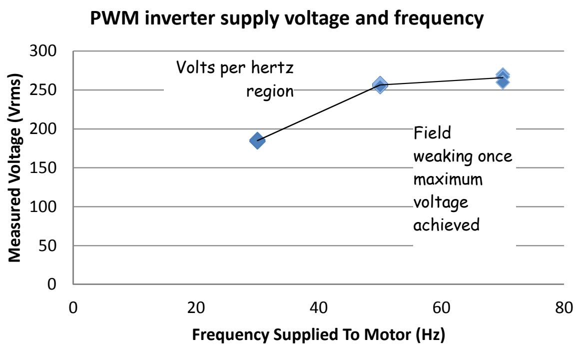
The motor characteristics were measured and found to be visible, and were as expected in this exercise. Figure 11.3 shows a sample of the relationships determined for Motor 1 including: supply voltage, frequency, mechanical power, torque and motor slip.



(a) Measured motor mechanical power against speed



(b) Measured motor mechanical torque against slip



(c) Motor voltage at various PWM Inverter supply frequencies

Figure 11.3: Measured characteristics of motor 1

In producing the demonstrators solutions several issues were identified that could impair student learning, to which the following solutions were implemented:

- the maximum frequency applied was increased from 60 Hz to 70 Hz to ensure that the inverter output voltage was limited and could not to apply a constant v/f strategy; this meant that the motor was definitively in the field weakening zone allowing students to observe this effect (shown in Figure 11.3c). At the original 60Hz setting, the inverter was not fully voltage limited and was not displaying the field weakening behaviour

- a number of labels in the notes did not match the HMI or VI
- some differences were found in the applied mechanical torque for a given torque set point between the five production model tools. The differences in the applied torque were compensated for by the scale factor discussed in Section 10.1.1
- a step was introduced to record voltages and currents on both panel meters and VI as a cross check that both systems were working; this also served to familiarise students with panel meters that are commonly employed in industry
- students were directed to use the VI to record a number of values rather than the HMI; the VI was more accurate due to a number of issues with the HMI, including the update rate and lower resolution available in the torque measurement due to the comparatively low resolution of the PLC analogue inputs used to transfer the data from the sensors to the HMI
- the table to record data and calculate derived values was rearranged to put data and derived values adjacent to each other
- a loading case included at 70 Hz supply and 50% torque was found to be above the motor power rating, so rather than removing the loading case it was used to prompt students to recognise that this was beyond the power limit of the motor. The load case was blanked out in the results table, instructing students not to make the measurement and asked why it was not to be measured
- the first draft of the student review questions overlooked the relationship between motor slip and torque, so a review question was introduced to examine it

11.1.5 Behaviour of Loads, Motor and Drive in Combination

This exercise requires students to test various combinations of drive and simple load types commonly encountered in industry. The students utilised DOL, soft start and inverter drives; they were used with constant torque, linear toque with speed and squared torque with speed loads. Students were asked to investigate the starting and running behaviour of each of the load and drive combinations.

Integrating the equipment and curriculum required that:

- the equipment could be configured to easily allow the combinations of three load and drive types to be tested
- the supply frequency could be altered when using the inverter
- the shaft speed could be observed during starting and running
- the current drawn by the motors could be seen during starting and running
- in producing the instructors solutions a number of issues were identified that could impair student learning, so solutions were implemented:

The behaviour of the motor and drive combinations were visible and as expected in this exercise. Table 11.1 summarises the behaviours observed which match those observed during testing the transient behaviour of the EMDET in in Figure 10.1 from the component testing phase.

Table 11.1: Observed behaviours of drive and load types.

Load/Drive	DOL	Soft Start	PWM Inverter
Constant Torque	Sudden violent start. Runs at fixed speed near synchronous speed	Struggled to move initially - then suddenly up to speed. Runs at fixed speed near synchronous speed	Smooth start up. Runs at speed set by inverter frequency (controllable)
Linear Torque	↓	Smooth start up. Runs at fixed speed near synchronous speed	↓
Squared Torque	↓	↓	↓

In producing the demonstrators solutions Several issues were identified that could impair student learning, to which the following solutions were implemented:

- the initial linear and squared torque with speed loads reached 50% of motor torque at full speed. It was difficult to differentiate the between these loads due to the relatively small difference in torque absorbed between them, so the loading was increased to 75% at full speed to make the difference between the two loads more apparent
- the mechanical couplings were painted with stripes to improve the visibility of the shaft rotation
- the experimental procedure to try each of the nine combinations of load and drive types was not clearly expressed in the initial laboratory notes, so the

procedure was redrafted and expanded

- the types of behaviour to be observed in both starting and steady state operation were not clear in the initial laboratory notes, so the procedure was expanded to clarify this point

11.2 Fulfilment of System Design Phase

Successful production of the instructors' solutions manual from data derived from the production model tools confirmed that the tool produced from the assembly and component testing phases fulfilled every aspect of the system design. This is summarised in Table 11.2.

11.3 Project - Risk Management

The iterative adjustments made to the equipment and curriculum to achieve the required educational outcomes were addressed in relation to each of the laboratory exercises undertaken to produce the instructors laboratory solutions.

Table 11.2: Summary of EMDET performance against system design phase.

System Design Aspect	Confirming Test
Educational System Design	Instructors' solutions were successfully produced for exercises conforming to the revised course structure described in section [ref – system design] including war stories and solutions.
Contextual issues	The equipment utilised the equipment provided by the Industrial partners.
Power Side Design	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the power side design work successfully. Specifically motor 1 could be supplied by three different drive types and motor and drive 2 regenerated mechanical power into the mains.
SCADA	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the SCADA design to work successfully. The SCADA successfully integrated a PLC, transducers, panel controls and a HMI.
Control Side Design	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the control side design to work successfully. The control side design successfully integrated the drives, PLC and transducers in the system.
Data Acquisition	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the Data Acquisition design to work successfully. The acquisition system sampled the data at sufficient frequency; all signals were converted to ELV prior to acquisition.
HMI & Overall system	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the HMI & Overall system design to work successfully The system used conformed to the system design of the HMI and Overall system; so much so that Figure 8.9 was used in the briefing introducing students to the laboratory equipment.
Load Control	Completion of the laboratory exercises to produce the instructors' solutions necessarily required the Load Control to work successfully. In particular a variety of real world loads were successfully simulated by controlling the torque applied by motor 2. The torque applied was based on the measured shaft speed and torque speed curve representation of a real world load.
Project Resources	The equipment complied with the system design comprising the electrical panel, motor assembly and personal computer. These fit within the allowances made in the system design.

Chapter 12

Case Study: System Test

During the system test phase the users became involved with testing the EMDET for the first time. In this phase the users and designers collaboratively tested (re-composed) the output of the system test phase to ensure it fulfilled the specifications phase. Testing in this phase had two main aspects; a test of equipment and curriculum by representatives of the users and a confirmation by the designers that the equipment and curriculum met the specification described in Section 6.

The equipment and curriculum were tested for the first time by representatives of the users in the context in which they would ultimately be used. The laboratory demonstrators for the PED course carried out the laboratory exercises, both to test the equipment and curriculum, and prepare the demonstrators for teaching with the equipment. Testing in this phase differed from the previous component testing phase in that it tested the suitability of the equipment and curriculum in context; both for the users and the teaching laboratory.

12.1 Testing by Laboratory Demonstrators

Testing in this phase was carried out by handing over the laboratory workbooks to the laboratory demonstrators for the ECTE 412/912 course who then attempted to carry out the experiments. Afterwards they were given the instructors solutions manual prepared in the integration test phase and they provided feedback. The demonstrators successfully completed the exercises within the laboratory with only very minor issues. These minor issues included:

- some labelling within the HMI and laboratory workbooks did not match
- shortcuts to the required software were placed on the PC desktop
- of the five EMDET assemblies provided, some did not have the latest version of the HMI software installed; these were updated
- some incorrect resistors installed in the data acquisition system of some of the EMDET assemblies were identified and replaced

All of these issues were rapidly addressed after they were identified. The success of this testing indicated that the both the equipment and curriculum within the EMDET was ready for the acceptance testing phase of teaching the PED course cohort.

12.2 Fulfilment of Specification

During this stage the designers made a comparative check of the equipment and curriculum against the outcome of the specification stage. This involved a qualitative assessment of the final system against the philosophies and organisational schema developed in Section 6, and an itemised check against the details of the specification.

12.2.1 Adherence to Design Philosophies

The equipment and curriculum assembled and tested were assessed against the philosophies of equipment constitution, fidelity, and flexibility as described in Section 6.1. The equipment constitution philosophy dictated that the EMDET must necessarily consist of hardware, software, procedures, and a curriculum; all of which are mutually compatible and function together to allow the curriculum to be delivered. The final tool complied with this philosophy because it consisted of hardware, software, and curriculum. The successful production of the instructors' solutions in Section 11 confirmed that they functioned together.

The philosophy of fidelity stemmed from the desired educational approach of authentic assessment described in Section 3.2.3. The components used within the EMDET are real industrial components in a typical industrial configuration. The electric motors, drives and panel equipment and configuration are all commonly used industrial components, so training with this equipment would expose students to typical industrial conditions. Motor 1 was rated at 2.2kW and by using this equipment, students would become familiar with industrial levels of mechanical and electrical power. The EMDET used a typical industrial SCADA system including a PLC, HMI, panel meters, safety relay and emergency stop. In the course of their experimental work students would become familiar with how such equipment typically operates, the kinds of data that are typically available, and where to find it.

In addition to the SCADA system, the tool included a laboratory grade data acquisition system overlaying the SCADA to fulfill another aspect of the fidelity philosophy. This system measured the mechanical and electrical energy throughout the tool allowing students to view the physical phenomena within the tool at a far greater level of detail than allowed by the SCADA. Students used and comparatively assessed the data available from both the SCADA and data acquisition system, thus familiarising them with the capabilities and application of the two systems.

In light of the mandatory design criteria for the tool, the simulation within the tool was minimised and confined to the mechanical loading of motor 1. This complied as far as practicable with the third aspect of the fidelity philosophy. The selection of an induction motor and regenerative drive as a load was driven by mandatory design criteria arising from the philosophy of flexibility and the contextual requirements described in Section 6.7.1. While the mechanical power absorbed by Motor 2 was not physically manifested, typical industrial levels of shaft torque and speeds are present between Motors 1 and 2. Overall the use of a motor and regenerating drive as a load is viewed as a known and deliberate reflective compromise between authenticity, flexibility for teaching and appropriateness to the context.

The philosophy of flexibility stemmed from the large quantity and variety of the knowledge and skills described in Section 5.1.3 to be taught to students. The philosophy of flexibility had two aspects: firstly that there should be flexibility and modularity in the equipment and control systems, and secondly that the equipment should be flexible and future proofed.

The EMDET provided fully complied with the philosophy of flexibility. Addressing the first aspect of modularity, the tool included three different drive types available for Motor 1 (DOL, soft start and inverter), and the simulated load types from Motor 2 that can be selected in a modular fashion by software request. Motor and Drive 2 are capable of simulating a large variety of mechanical loads including both simple, and complex torque speed characteristics that can be fixed or variable. The PLC has inbuilt programming for over 15 different simulated load types for Motor 2, including the option of a user defined torque speed characteristic derived from a lookup table of values provided by the user. Changing the load type is carried out in the software and no mechanical changes to the equipment are required.

The approach taken to programming the PLC was deliberately modular and enables many new laboratory exercises to be created simply by authoring new screens in the existing HMI. The three drive types and fifteen inbuilt load types can be utilised in permutations and combinations by simply requesting the relevant types from within the HMI programming. Many additional laboratory exercises could be created by simply writing new exercises and authoring new HMI screens that employ the inbuilt load and drive options. In particular, the torque speed characteristic defined by a lookup table could be exploited to create numerous exercises where each exercise would simply define a new load via an appropriate lookup table of values to simulate the load required. The coding of the PLC is written to protect the equipment and will ignore requests for unsafe operation of the equipment from the HMI.

The modular design of the PLC code, particularly the simulation of loads is structured with the express purpose of simplifying creation of new load types. The load type simulation is contained within one task of the PLC program, so a laboratory exercise could be created by introducing a new load into the PLC code, authoring a new HMI screen and appropriate laboratory workbook. The new simulated load would also add to the permutations and combinations of potential educational exercises available within the tool.

The tool strongly complied with the philosophy of flexibility whereby the tool be flexible and future proofed. The important physical phenomena of both electrical and mechanical power flow throughout the system were present and visible via the data acquisition system or SCADA. This includes being able to trace at least one phase of electrical power throughout the system as well as the mechanical shaft power.

The configuration of the hardware, software, and data acquisition means to create many of the new laboratory sessions needed to address the desired curriculum stated in the requirements stage (Section 5.1.3) would only require that new laboratory workbook exercises be authored with little or no changes required to the tool. The capability of the data acquisition system to examine electrical and mechanical phenomena (currents, voltages, harmonics and power factor) throughout the system with the load and drive combinations available represents a wealth of potential laboratory exercises. Their creation only requires new workbook exercises that will utilise the existing HMI and data acquisition systems. The educational potential of the tool as delivered, should be considered as the product of the many possible drive and load combinations multiplied by the capability of the data acquisition system.

In addition to the permutations and combinations of load and drive types, the tool also includes a number of hardware features enabling additional educational exercises. These include:

- a controllable contactor on one phase of Motor 1 to allow simulation of a common industrial fault where one phase of the three supplying a motor is lost. The motor can still operate under certain circumstances; however its performance characteristics are greatly changed and are often difficult to understand. Experimentation and experience with this fault can prepare students to deal with it in practice
- two sets of inductors and contactors are connected to one phase of Motor 1; these inductors can be switched into the motor circuit and will unbalance the voltage supplied to the motor. This is a common problem in the quality of the power supplied to an induction motor. The motor characteristics are changed from normal and can be difficult to understand. Experimentation and experience with this issue can prepare students to deal with it in practice
- thermistors are included in Motors 1 and 2 and both motors have controllable cooling fans so that the thermal behaviour and characteristics of the motors can be examined within the context of motor duty cycles

Mechanical allowance has also been made for the inclusion of a DC motor into the tool. The inclusion of a second motor type would virtually double the potential number of educational exercises available.

12.2.2 Organisational Schema

The high level design decisions manifested within the four organisational schema detailed in Section 6.2 were complied with; they included the configuration of the power flow in the equipment, the configuration of the control system, the linkage between educational and operational concerns to the power and control system, and the curriculum design methodology

12.2.3 Power Flow

The power flow organisational schema was formulated to comply with the design philosophies and address a number of design issues centred on how the power from the electric motor would be dealt with, culminating in selecting the load. A number of mandatory and desirable design criteria for the load were defined in Section 6.2.1 and used to select an electrical load as part of a power flow schema shown in Figure 6.1. The selection criteria were further refined to determine the specific type of electrical load to be used, in this case an induction motor with a regenerative drive. The final tool met all the mandatory design criteria and most of the desirable criteria using the load and power flow selected. Specifically the load met the following mandatory criteria:

- Motor2, Drive 2, and the PLC form a flexible and controllable load which can simulate a variety of real mechanical loads. Loads are defined by a torque speed-characteristic programmed within the PLC. A variety of loads had been successfully implemented in the PLC, ranging from simple fixed characteristics to a complex pumping simulation
- The use of induction motors and comparatively common drive system lowered the cost of equipment cost and enabled the load to fit within budgetary constraints
- The electrical load regenerating power into the mains supply did not introduce fluids, undue heat, or noise to the laboratory. This was appropriate to both the context of the Power Electronics and Drives Laboratory and to the SMART building which housed the laboratory

The load also met most of the desirable criteria: the motors and drives were typical industrial equipment, the load was at relatively low cost compared to the alternatives and power used in running the EMDET was regenerated, minimising wastage.

The major drawback was that the electrical load did not physically manifest power in an appreciable way, such as a mechanical load may have (e.g a pump, conveyor belt, etc.). In practice, the manifestation of power in the electrical load was somewhat better than anticipated for a variety of reasons: firstly movement of the motor coupling was visible, the sounds of the motor under load could be heard, and motor currents, particularly staring currents, were distinctly visible in panel meters. This arrangement also had some unanticipated advantages in fidelity, because in in many industrial situations the only appreciable effects of the motor power, are noise from the motor, shaft movement, current drawn, and sensor feedback from a HMI.

12.2.3.1 Configuration of the Control System

The control system organisational schema was formulated according to the design philosophies to deal with issues such as, how users would interact with equipment, where control decisions were made and the kind of hardware used in the control system.

- the control system was flexible and modular, and programming of the PLC code was modular allowing simple reconfiguration of the system to use different drives or simulated load types as required
- the data acquisition system measured and displayed both mechanical and electrical power flow around the entire system from the mains to Drive 1, through Motor 1, Motor 2, Drive 2, and returning to the mains. These constituted the critical physical phenomena required to be present and visible to students to allow teaching according to constructivist principles
  - the philosophy of flexibility would dictate that, all three phases of current and voltage should ideally have been measured, however the cost was beyond the available budget. The approach taken was to measure a single phase of power where a balanced system could realistically be expected, and where unbalance could occur all three phases were measured. All three phases of current and voltage were measured in the supply to Motor 1 due to the switchable inductors installed to examine the effects of supply unbalance on a motor. This approach balanced budgetary constraints and the requirements for the relevant phenomena to be visible
  - the mechanical power transmitted between motor 1 and motor 2 was

measured by a torque transducer and shaft speed measurement

- additional thermal and mechanical phenomena were also made visible to complement the visibility of the power flow. Thermistors installed in Motor 1 and 2 allow the temperature of the electric motors to be monitored
- A laboratory grade data acquisition system that overlaid the industrial SCADA was used. Juxtaposing the two provided an opportunity for students to appreciate the strengths and weaknesses of each

12.2.3.2 Linkage Between Educational Concerns, and the Power and Control System

The linkage matrix (described in Section 6.2.3 was created to ensure that the equipment within the EMDET fulfilled both the operational and educational functionality required to deliver the laboratory curriculum. This matrix explicitly stated the role that each of the major components of the EMDET would perform in a function or lesson. This explicit statement of the linkage between equipment, operational and educational concerns provided a comprehensive specification of the equipment. The specification developed around the linkage matrix allowed the subsequent design, construction and testing phases to be successfully executed.

The requirements presented within the matrix were broken down into three parts. Firstly the basic operational functionality required to safely start, stop and run the equipment. Secondly, the functionality required to deliver the revised curriculum for the PED course, and lastly the functionality required for the course material that the equipment should be capable of beyond the revised PED course. The EMDET completely fulfilled all of the requirements for basic functionality and for delivery of the revised curriculum.

The EMDET also met most of the needs for future teaching, with only relatively minor software changes required; the significant exception being teaching with key motor types other than squirrel cage induction motors. The design of the EMDET realistically allows for an additional motor, as described in section 7.7.2, however this needs significantly more than minor software and hardware changes.

Figure 12.1 summarises the performance of the EMDET against the linkage matrix created in Section 6.2.3. The table is colour coded to show the degree to which each of the requirements were met.

12.2.4 Curriculum Design Methodology

The curriculum design methodology was formulated to link the educational requirements to the creation of the curriculum materials in the system and detail design phases. Three major aspects of the methodology fostered the successful development of the laboratory curriculum: firstly, broad educational requirements were translated into useful educational objectives; secondly, the objectives were assigned to a practicable series of lessons; and lastly, the individual lessons were developed to meet the objectives. Of particular value in this process were the statements of educational objectives in content-behaviour form developed in Section 6.5.3 and the tabular representation of the Tyler Rationale developed in Section 8.4.

This methodology was used to successfully develop the revised curriculum consisting of laboratory workbooks and associated assessment. This curriculum was ready to be used to teach students in an attempt to prepare them for successful practice with EMD systems.

12.3 Specification Detail

The detailed specifications developed in Section 6.4 addressed educational, contextual, technical, and project concerns.

Educational requirement or Function	Motor 1 & Drive 1	Motor 2 & Drive 2	HMI	SCADA
Basic Operation				
Monitoring and reporting of equipment health	Drive 1 health reported to PLC.	Drive 2 health reported to PLC.	Equipment health displayed via HMI mimic screens	Equipment health monitored by PLC and displayed on panel lamps and via HMI
Protection	All required functions met.			
- Indication of Power	Equipment power status visible by verification lamps and panel meter on panel front			
- Positive Isolation	Equipment isolated via main power switch at panel and verified by verification lamps and panel meter on panel front.			
- Emergency Power disconnection	Emergency stop functionality compliant with AS4024 realised via safety relay and emergency stop buttons.			
- Protection of wiring and equipment from electrical fault	All devices protected with circuit breakers as per AS3000. Wiring and circuit enclosures compliant with AS3000.			
- Protection from overheating	Motors fitted with independent forced cooling and Thermistors connected to PLC.		HMI diagnostic screens available to diagnose thermal trips of equipment.	PLC executes staged thermal protection of motors.
Operation of motors (start, direction, speed, etc.)	Drives selected using remote relays. Start, stop and direction from HMI Via PLC.	Drive torque character controlled by PLC based on mode request from HMI.	HMI screen authored for lesson determines torque characteristic for motor and drive 2. It also allows motor start, stop and direction.	PLC operates all equipment based on requests from HMI screen. Unsafe equipment requests are ignored. Unsafe equipment conditions cause shutdown with diagnostic indication.
Feedback of key operation parameters	A single phase of Drive 1 current and voltage measured and visible via DAQ. Three phases of current and voltage to Motor 1 measured. Motor shaft speed and torque measured.	A single phase of Drive 1 current and voltage measured and visible via DAQ. Three phases of current and voltage toMmotor 1 measured.	Shaft speed and torque visible on HMI screen. All transducer data visible on LabView GUI. Data can be viewed in real time as a value, a trend or a frequency spectrum. Data can be logged and downloaded.	Voltage, current, shaft speed and torque measured. Panel meters and data acquisition system employed for power measurement.
Revised Curriculum				
Industrial Safety	EMDET exemplifies how industrial equipment should be mechanically guarded and electrically protected. Equipment can be easily and positively isolated as required by the lesson.			
Introduction to EMD systems	Emergency stop system present for equipment shut down. This is demonstrated to students		HMI screens allow operation of equipment, diagnosis of emergency stop and reset.	
Torque speed behaviour of an induction motor	Motor 1 able to be run at torque limit via DOL start.	Motor 2 able to load Motor 1 to its torque limit throughout speed range.	HMI screen authored to access automated loading sequence.	PLC contains automated sequence to map motor characteristic. DAQ system logs all relevant parameters.

(a) Operational and curriculum performance of the EMDET within the context of the linkage table

Characteristics of a squirrel cage induction motor	Inverter allows motor 1 to be run at various voltages and frequencies.	Motor and Drive 2 can provide various levels of torque to investigate motor parameters.	HMI screen signals PLC for appropriate drive 1 and 2 configuration. Allows user to start, stop and adjust operating parameters.	PLC selects and operates Drive 1 and 2 as required based on signalling from HMI screen.
Characteristics of Loads, Drives and EMD systems	Inverter, Soft Start or DOL can be selected for Drive 1.	Motor and drive 2 assume various load characteristics.		
Allowance for Future				
Loads: Simulation of a variety of torque speed behaviours	Three different drive types available for experimentation.	Torque controlled by PLC as required for load to be simulated.	May need to author new screens to demonstrate loads	17 load types pre-programmed including table input for torque speed character
Key Parameters to Size and induction motor	All physical Parameters available	All physical Parameters available	May need to author new screens to suit.	May need a new load type programmed depending on lesson
Induction Motor with power supply issues	Imbalance inductors and two phasing contactor included	No change required to apply various torque loadings.	May need to author new screens to suit.	✓
Operation of key motor types	Allowed for DC motor in Future. Need new electrical hardware.		Would need to author new HMI screens	Would need revise all significant portions of code to accommodate additional motor and drive
Temperature changes with motor loading	Motor Thermistors allow temperature to be monitored.		May need to author new screens to suit.	All functionality required present.
Effect of drive switching on voltage	Drive 1 inverter and Drive 2 able to alter their switching frequency.		May need to author new screens to suit.	
Effect of motor on power supply system	All functionality required present.		May need to author new screens to suit.	
Effect of unbalanced load on supply system	Imbalance inductors and two phasing contactor included	All functionality required present.	May need to author new screens to suit.	
Simulation of a motor in a sophisticated system (e.g. pumping system)	All functionality required present.		Screen for pump simulation included. New screens would be needed for new loads.	Pump simulation included. New loads can be programmed in a similar manner.
Demonstrated advantages of variable speed drives in system design			May need to author new screens to suit.	May need a new load type programmed depending on lesson
Closed Loop control strategies			May need to author new screens to suit.	Would need new software programming to accommodate loop control teaching

Colour coding to show if linkage matrix specs met.	Functional	Allowed for with minor software changes	Requires Additional Hardware or significant software update	Not Included or viable

(b) Curriculum performance and allowance for future work of the EMDET within the context of the linkage table

Figure 12.1: Performance of the EMDET within the context of the linkage table

12.3.1 Educational

The detailed educational specifications addressed issues of audience, learning limitations, material to be taught, the teaching approach to be taken, the required constitution of equipment, the assessment of learning quality and the target level of skill set to be achieved by students completing the revised teaching curriculum.

A decision was made to focus the development of the EMDET on teaching students in the ECTE 412/912 course within the specification phase. This was done for reasons of pragmatism and the representative nature of the student cohort in ECTE 412/912. The equipment and curriculum delivered in the EMDET addressed the audience as defined in the specification stage.

The curriculum within the EMDET was developed with due consideration of the learning limitations of the student audience, including the time available, student prior learning and the need for the lessons to consist of a series of cognitive leaps the student audience could achieve. The success of the curriculum development would be assessed by the acceptance testing phase of the WiSE project approach, specifically looking for students achieving the desired competency for industrial practice.

The material to be taught was initially identified within the specification stage and finalised over the succeeding system design and detail design phases. This material was selected with the aim of providing graduates with the desired wisdom regarding EMD systems. The revised curriculum developed within the EMDET addressed all of the material identified.

The teaching approach utilising concepts of authentic assessment, constructivism, constructive alignment and the Tyler rationale outlined in the section 5.1.2 were complied with in development of the curriculum.

The specifications for constitution of the equipment were captured within the linkage matrix, and importantly all of the physical phenomena required to deliver the PED course and the majority of future teaching needs were included within the EMDET.

The assessment of learning quality specified included scenario assessment to detect the requisite wisdom with EMD systems, the laboratory workbooks, and direct observation of students during the laboratory courses. All of these were prepared in readiness for use during the acceptance test phase.

The target level of skill defined in the specifications stage was addressed by the curriculum within the EMDET. In particular the teaching included the material required for students to be able to attain the wisdom required to successfully negotiate the four war story scenarios described in Section 6.5.7.

12.3.2 Contextual

The detailed contextual specifications addressed the ability of students to work with hazardous voltages, the constraints placed on the equipment due to its location in the SMART building and the industrial partners involved with the project.

Due to the potential lack of significant electrical safety training, the EMDET would not potentially expose students to anything above extra low voltage, as defined by Australian Standard ("AS/NZS 3000:2007 Wiring Rules", 2007). This was achieved by two major means: using relays remotely operated by the PLC to carry out any electrical reconfiguration of equipment, and using transducers to reduce dangerous circuit voltages to ELV before to connection to the data acquisition system and any potential interaction with the students.

The electrical load utilised by the EMDET ensured that it fulfilled the contextual requirements of the SMART building of minimising power wastage, avoided water or other fluid movement within the laboratory and unacceptable levels of noise.

12.3.3 Technical

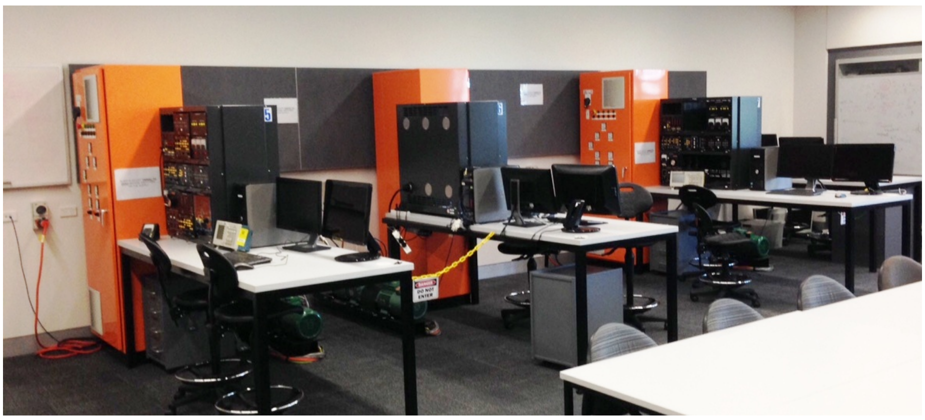
The detailed technical specifications, including the combined power flow and SCADA linkage and preliminary circuit diagram were fulfilled, with minor variations by the equipment delivered. The full technical requirements for the equipment were captured in the linkage matrix, and the performance of the EMDET against this is summarised in Figure 12.1.

12.3.4 Project

The project management specifications included the resources available to the project, the quality required and the method used to address risks to the project. The project resource specifications included the budget, timeline and physical space. The project was completed within the financial constraints available, and within the required timeframe. The equipment fit well into the available laboratory space as shown in Figure 12.2. The quality of the project would be primarily judged on the outcome of the acceptance testing, however the EMDET fulfilled the particulars of the specification phase. The project risk management approach was built into the WiSE Approach used to develop the equipment, this was particularly evident in the four testing phases.

(a) Individual laboratory bench arrangement

(b) Motor assemblies



(c) Overall laboratory layout

Figure 12.2: Final laboratory Layout within the SMART building

Chapter 13

Case Study: Acceptance Test

During the acceptance test phase the Users alone tested the EMDET to ensure it fulfilled their needs. As the final stage of the recomposition process this testing had two important aspects: firstly, that what was delivered by the project team met the users stated requirements; secondly, that the User's statement of requirements encapsulated their needs.

If the product of the preceding phases did not meet the users need the distinction between a deficient product, or a deficient definition of requirements had to be made because this would identify who is responsible for the remedial iteration of the project, and potentially what has to be done. If the stated requirements are not met, the designers would revisit the specification phase with the existing requirement and begin working through the project phases again. Whereas if the requirement was inadequate the users would revisit the requirements phase and pass this on to the designers for iteration through the project.

The users tested the equipment and curriculum within the EMDET by delivering the revised laboratory curriculum agreed to in the specification phase to three cohorts of the PED course in 2012, 2013 and 2015. The 2015 cohort also included students in a new post graduate program ECTE812 studying at a less advanced level that the ECTE912 students. Testing was undertaken to determine whether the equipment and curriculum worked, and if the students being taught using the EMDET were developing the desired wisdom of engineers who can successfully practice with EMD systems, as measured by war stories, student lab books and direct observation.

A cyclical approach was used where the course was delivered, results of teaching were analysed, deficiencies in performance identified, remedial action proposed and implemented ready for delivery of the next course. This approach was applied to the 2012 and 2013 cohorts of ECTE 412/912, allowing for implementation and analysis of two cycles of remedial action. The EMDET was deemed acceptable by the users at the conclusion of the 2013 course; however the opportunity for an additional iteration using the 2015 course was taken.

13.1 Testing by the User of Educational Outcomes and Equipment

The user tested the effectiveness of the EMDET in student teaching in both general and specific terms. The general assessment was based upon student completion of the revised curriculum, equipment capability and addressing the Engineers Australia accreditation audit Engineers Australia (2013). The specific assessment focussed on the generation of the motor characteristic torque speed curve and completion of the war stories, as these were representative of high levels of student achievement.

13.1.1 General Assessment of EMDET

The general assessment of the EMDET was based on three criteria: satisfactory overall completion of the revised curriculum presented in the laboratory workbooks by students, the capability of the EMDET to teach those areas of the preliminary curriculum not addressed in the PED course and how well the EMDET addressed the previous concerns raised by the accreditation audit.

Table 13.1 summarises student performance in areas relevant to the acceptance testing, including their performance in previous subjects, the PED course as a whole and their performance in the two laboratory exercises using the EMDET. The Users accepted the average 2012, 2013 and 2015 student marks in the laboratory as satisfying the first criteria.

Table 13.1: Student academic performance in the PED course.

Student Year	Overall Average % Student Mark in ECTE 412/912	Average % Marks in Lab 4	Average % Marks in Lab 5	Overall Average% Lab Mark
2012	60.6	67.6	69.2	68.2
2013	63.0	84.6	79.9	82.2
2015*	54.7	83.2	79.8	81.5

			Average% Student Mark in ECTE 412/912		Average % Lab Mark	
Student Year	% of students with prior marks available	Average % Mark Students in subjects prior to ECTE 412/912	Students with prior UOW marks available	Students without prior UOW marks available	Students with prior UOW marks available	Students without prior marks available
2012	86.2	64.0	61.4	55.3	69.9	57.9
2013	82.4	70.1	63.5	59.5	82.5	80.2
2015*	83.0	69.0	57.4	41.6	80.8	85.2

* includes students at 812 level

The following observations were drawn from the results in table 13.1:

- an improvement in laboratory marks between 2012 and 2013 with the 2015 results being similar to 2013. Consideration was given to whether the improvements in marks stemmed from the impact of reflective changes to the curriculum or student ability
- students with prior study at UOW performed better in the overall subject by 6.1% (2012), 4% (2013) and 15.8% (2015). The difference in their performance in 2015 was significant, with the average overall subject mark for students without prior experience at 41.6% which is a failing grade. This would indicate that students without prior UOW study in the 2015 cohort had significantly less ability than other students in the study
- if student marks in prior subjects (where they had previously studied at UOW) and overall subject marks are used to infer student ability it would appear that the 2013 cohort was the most able, followed by the 2012 then 2015 as least able; significantly the 2015 cohort included a subset of students with significantly less ability than their fellows - the students studying at the 812 level
- if student ability is taken into account when considering laboratory marks it appears that the reflective changes made to the curriculum have resulted in improvements in student marks in workbooks. If the improvement between 2012 and 2013 is due to student ability, this does not explain how the least able cohort (2015) achieved similar marks to the most able cohort (2013). It is therefore concluded that reflective changes have caused at least some improvement in student attainment

The EMDET capability to teach within the preliminary curriculum areas outside of the PED course is presented in Table 13.2. The EMDET met the User's expectations of curriculum delivery, because the topics in the original preliminary curriculum outlined in the requirements phase in Section 5.1.2 were either successfully delivered in the revised curriculum, or were within the capability of the EMDET to deliver according to the philosophy of flexibility described in Section 6.1.3, needing at most software changes and additional laboratory exercises to be written.

Table 13.2: EMDET capability to teach the preliminary curriculum.

Area of Preliminary Currriculum	EMDET capability
1. A Safety Introduction to Rotating Equipment	Addressed in revised curriculum
2. Introduction to the Induction Motor and Variable Speed Drive	
i. What characteristics can you expect from an induction motor	Addressed in revised curriculum
ii. How do I size a motor?	Equipment capability allows for teaching with appropriate additional curriculum.
iii. What can the variable speed drive offer?	Majority of items addressed in revised curriculum, for those not addressed equipment capability allows for future teaching with software programming and new laboratory
3. What does the variable speed drive offer to different systems	
i. Theory of loads (if not already covered, constant torque, linear torque, speed squared torque)	Addressed in revised curriculum
ii. Energy efficiency in centrifugally driven pump systems	Pump simulation produced that allows for teaching , only requires a new laboratory exercise to be written.
iii. Energy efficiency in positive displacement pump systems	Equipment capability allows for future teaching with software programming and new laboratory exercises.
iv. Energy efficiency in systems with motors driving and braking at the same time	Equipment capability allows for future teaching with software programming and new laboratory exercises.
v. Reduce the risk of uncertainty in design	Pump simulation produced that allows for teaching , only requires a new laboratory exercise to be written.
4. Drive Control	Equipment capability allows for future teaching in control (expecting mechanical transmission concerns) with software programming and new laboratory exercises.

The original motivation for the EMDET stemmed from the outcome of the 2008 EA course accreditation audit, the next scheduled audit was carried out in 2013. As an integral part of the new Power Electronics and Drives Laboratory, the EMDET made a significant contribution to the excellent review given by EA of the capability possessed by UOW to teach in the area of EMD systems and address the concerns raised by the 2008 audit, as shown in in Table 13.3 (Engineers Australia, 2013). While not used as part of the explicit assessment criteria established during the requirements phase, this weighed heavily in the assessment of the EMDET because it addressed much of the original motivation for the EMDET project.

Table 13.3: EA Accreditation Panel Recommendations

2008 Recommendation	2013 Assessment against previous review Review
R8 Current laboratory facilities which support the teaching of electrical machines drives and power systems are considered inadequate.	.... two new laboratories to support undergraduate and postgraduate electrical engineering have been brought into operation: a Power Electronics and Drives Laboratory and Power Systems Laboratory .... The facilities, as viewed, are probably amongst the best in any Australian university.

13.1.2 Specific Assessment: Production of motor Characteristic Curve and War stories

The production of the motor torque speed curves and successful completion of the war stories were used as detailed instruments to judge the success of the EMDET due to their summative nature and requirement for high levels of knowledge and understanding in terms of the SOLO taxonomy, including the desired wisdom. Attaining these goals would demand a very high level of performance from both equipment and curriculum, individually, and together would be compelling evidence of the worth of the EMDET. Table 13.4 summarises student performance in producing the motor characteristic curve, the war stories (before and after teaching) and the sections of the laboratory workbooks directly associated with the war story scenarios from a sample of student submissions.

An assessment of the 2012 course identified four major problems with acceptance of the EMDET by the users; a high proportion of students were unable to:

- map the induction motor characteristics during the laboratory exercise, particularly the torque speed curve
- identify the magnetising current of an induction motor and its consequences in a war story
- understand the typical torque and slip behaviour of an induction motor and apply this to a real world design problem in a war story scenario
- recognise the inappropriateness of using a soft starter drive with a constant high torque load in a real world scenario described in a war story

Table 13.4: Student performance in war story scenario assessment.

	Assessment	Motor Torque - Speed Curve	Motor Magnetising Current	Motor operataing torque slip	Capability of VSD	Motor - Drive Combination	Sample Size (n)
		% of Sample Correctly Completed					
2012	War Story - Pre	19%	0%	0%	100%	11%	10
	Theory		59%	31%	50%	36%	26
	War Story - Post		11%	17%	78%	11%	9
2013	War Story - Pre	49%	0%	7%	43%	7%	28
	Theory		71%	53%	65%	29%	34
	War Story - Post		39%	5%	58%	47%	19
2015	War Story - Pre	28%	0%	12%	38%	3%	29
	Theory		47%	49%	56%	31%	45
	War Story - Post		19%	6%	31%	16%	16

The cyclical reflective action research approach built into the WiSE approach was used to deal with each issue: the problem was identified by reflecting on student performance in assessment; the problem was analysed using the closed loop model of education and solutions were proposed; solutions were selected and implemented, thus starting the cycle over again.

Three underlying issues were identified during the cyclical approach, in addition to issues specific to each learning exercise. The key issues were that:

- some students did not appear to be building the individual laboratory exercises together into a high level of understanding in terms of the SOLO taxonomy
- students had difficulty completing tasks that required a summation of knowledge and skill from various parts of their prior learning
- students had difficulty making a connection between the laboratory exercises and their application to real world scenarios

The specific issues addressed with the cyclical WiSE approach are described in sections 13.1.3 to 13.1.7.

13.1.3 Map Torque Speed Curve

As described in Section 11.1.3 students would plot key induction motor characteristics using experimental data. During the 2012 course a large proportion of students were unable to produce the expected plots - in particular the torque speed curve. The lack of success was surprising, and a variety of outcomes were observed, other than the desired curves achieved ranging in success. Direct observation during the laboratory confirmed that all the equipment operated correctly and students were able to gather valid sets of data, however students were then unable to analyse it correctly. With reference to the closed loop model of education there was an issue with how the EMDET curriculum affected the student, or with the student themselves. To analyse the problem in terms of the limitations on student learning (particularly the achievable cognitive leap) the exercise was mapped as a sequence of steps that the student must perform, along with the knowledge required to achieve step. The 2012 student results were then compared with the mapping to identify the issues encountered by students and the potential solutions, this is represented graphically in Figure 13.1.

The lowest levels of student achievement were to either submit nothing at all or plots similar to 1 in Figure 13.1, which is the result of simply plotting all of the logged data in time without any processing. This shows a lack of understanding of what was required from the exercise; the data is not processed, and the elements of current, torque, and motor power were not extracted and plotted as a function of motor speed (rather than time). These were elementary mistakes, so it was surmised that these students were completely lost, and in desperation plotted their data in the hope that some marks would be awarded. It is presumed that this is the result of not understanding the data logged or not being able to plan how to analyse the data.

The next level of achievement observed were plots similar to 2 in Figure 13.1, students have neglected to convert logged peak values into the root mean square (RMS) values needed to provide meaningful data. It is assumed that this issue is mainly due to a lack of recognition that the logged values were not RMS values - despite the laboratory notes reminding students of this. The calculation of RMS

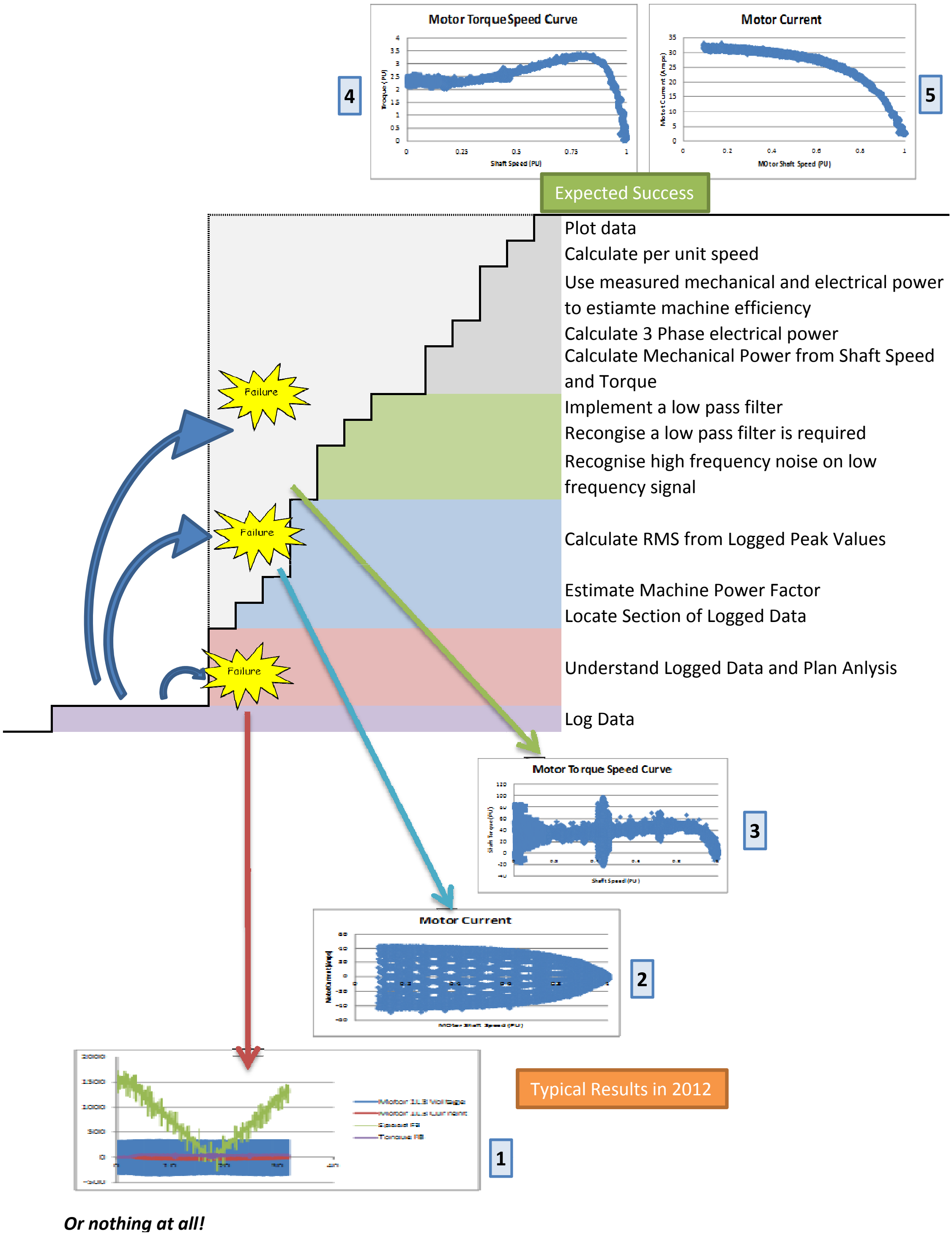


Figure 13.1: Instructional scaffolding mode of motor curve exercise, showing levels of success and failed cognitive leaps.

values is elementary, and integral to completing the first year of undergraduate engineering courses and was part of the assumed prior academic knowledge. It was therefore decided to proceed on the basis that this was an issue of overlooking the conversion of peak values to RMS, rather than an inability of the students to make the required calculation.

The next level of achievement observed were plots that resembled 3 in Figure 13.1, where students had not adequately filtered electromagnetic noise (described in Section 10.2.1.2) from the signals logged prior to plotting them. It was uncertain whether this issue was due to students not identifying the noise, or not being capable of the signal processing operations required. As with with calculation of RMS values, signal processing was part of the assumed knowledge and the laboratory workbooks caution students that they may need to filter electronic noise from the data. The difference here is that the signal processing knowledge required is a more advanced skill than calculating RMS values and is typically taught in the second and third years of engineering courses. In this case, whether was uncertain if students had simply overlooked the need to process the signals or genuinely did not possess the ability to carry out the necessary signal processing.

While students experienced a variety of problems in producing the required plots, there appeared to be some common underlying cause. Therefore, based upon the varying levels of student achievement, it was hypothesised that combining the multiple subject areas together and applying them to the novel exercise of experimentally measuring the motor performance was beyond the ability of many of the students. If this was true, it was it was further proposed that instructional scaffolding could break down the single insurmountable cognitive leap into a series of achievable leaps for students.

While trying to identify appropriate scaffolding, some imperatives of teaching were in conflict, based upon their stated pre-requisites the students within the PED course were final year engineering students or postgraduates who should possess all the skills needed to successfully analyse the logged data. The overall process of this analysis was viewed by the subject coordinator and designers during the requirements phase as one that a capable engineer should be able to complete without assistance. Consequently there was the belief that simplifying the task would diminish its value because the analysis should be within the capability of students who already had, or were about to graduate with a bachelor's degree in engineering. This was balanced against the high number of students unable to complete the task, not learning anything, and rendering the training ineffective.

It was therefore postulated that the summative nature of the analysis was a major issue for students, rather than a problem with their prior knowledge. This meant that for a variety of reasons students could not recognise all of the steps in the analysis and call on their previous knowledge to complete the task. For this reason, it was decided to provide some guidance on the overall process of the analysis by breaking it into a series of manageable leaps for students as instructional scaffolding. In order to retain educational value, each stage of the analysis was not enumerated in detail, rather some information was given to students about what sort of operation was required so they could carry it out or looki for a relevant reference in their earlier courses. It was hoped that enough guidance could be given without unduly diminishing the value of the task as a summative assessment for final year engineering students. The guidance implemented during the 2013 cohort was given as a description of the process required to successfully create the required plots.

A revised instructional scaffolding model in Figure 13.2 shows the anticipated impact of the process guide and places some of the actual results achieved in 2013 in the context of the model. A far greater proportion of the 2013 cohort were able to successfully produce the desired motor curve and produce the results shown in the figure.

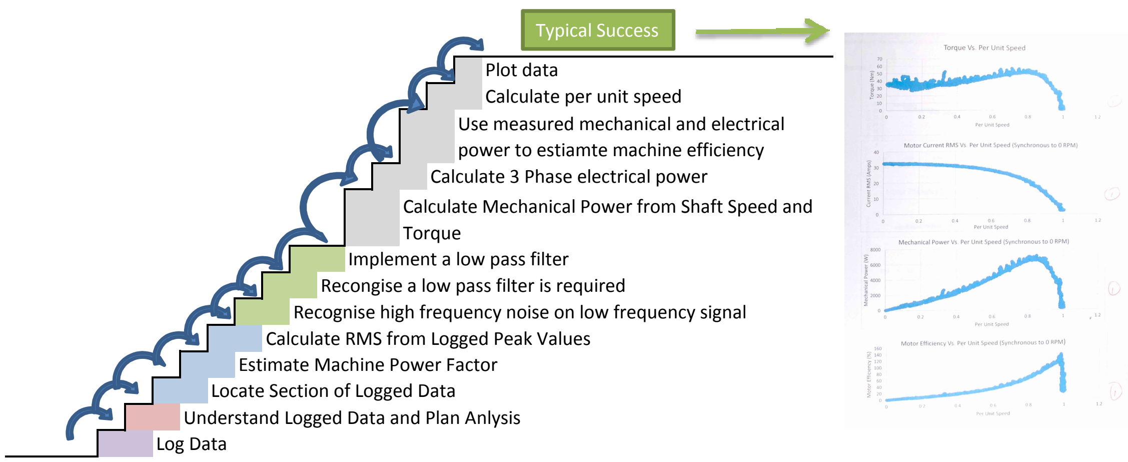


Figure 13.2: Instructional scaffolding model of motor curve exercise, showing successful cognitive leaps

It was concluded from the improved results in 2013, that the hypothesised issue that students had with combining various areas of knowledge was true and that the instructional scaffolding provided (process description for the analysis) worked well along with the additional time allowed for the exercise. Due to this marked improvement in performance, no further changes were judged necessary for the 2015 cohort. The drop in results in the 2015 cohort was unexpected with many students submitting work without filtering or calculating RMS values and 36% of students submitted work at the lowest level of understanding (1 in Figure 13.1) in spite of the process guide and an example of the desired goal of analysis (Figure 11.1) being displayed throughout the laboratory session. During the 2015 laboratory sessions, it appeared to the laboratory demonstrators that a higher proportion of students had difficulty with English and the expected pre-requisite knowledge than in previous years, difficulties which could prevent them completing this summative task and which may explain the drop in results. At the conclusion of the 2015 classes, two potential options were proposed to address the drop in results, providing more detailed scaffolding in the curriculum, or a review of student pre-requisites.

13.1.4 Apply the Concept of Motor Slip

Most students within the 2012 cohort were unable to successfully negotiate the war story scenario assessment addressing the torque - slip behaviour of an induction motor at its operating condition. For students to successfully negotiate these scenarios they had to be able make a series of cognitive leaps as shown in Figure 13.3. The desired response from students was to recognise that the required speeds and loads were within the normal operating range of an induction motor with a simple direct on line drive, in particular, avoiding an expensive over-engineered response of using a sophisticated motor and variable speed drive feedback system.

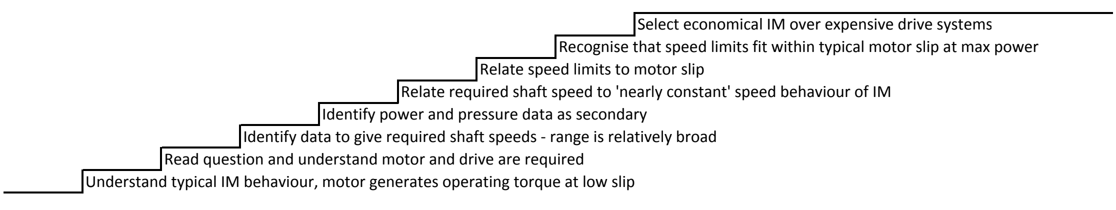


Figure 13.3: Instructional scaffolding model of the motor slip war story.

Most of the answers from the 2012 cohort were to use expensive feedback controlled solutions including DC motors, synchronous motors and variable speed drives. It was therefore hypothesised that the 2012 cohort could not recognise the 'nearly constant' speed behaviour of an induction motor (high amounts of torque being supplied at low slip) and the practical implications of this. The curriculum contained two opportunities for students to learn this relationship constructively; plotting the motor torque speed curve in Laboratory Session 1, and when investigating the behaviour of a squirrel cage induction motor under different conditions of supply and load in laboratory session 2 described in Section 8.4.

After assessing the 2012 results for this war story and associated theory in the lab workbook it was proposed that three issues were potentially preventing students from successfully negotiating the war story; firstly an inability to identify where to apply their knowledge in context to a scenario type situation while ignoring irrelevant data. Secondly, that students were not building individual experimental activities into a comprehensive understanding, and finally, students did not gain the expected learnings from the failed motor curve exercise. While very relevant to the torque-slip war story, the first two issues appeared to apply to all of the war story scenario assessments. Therefore, the reflective changes described in section 9.1 to add introductory scenarios and key questions to the workbook were made to help students in applying their knowledge in a context and building understanding. It was believed that the final issue could be resolved by addressing student problems with the motor curve exercise and that successfully plotting the motor torque speed curve would help students to appreciate the near constant speed behaviour of an induction motor.

Student performance in 2013 was worse than 2012, but after reviewing the hypothesised linkage of the motor torque speed curve generation, this was deemed to be false. It was expected that with an improved performance in generating the motor curve in comparison to the 2012 cohort, the 2013 cohort would also improve in the torque slip war story, but this was not the case. A closer examination of Laboratory Session 1 showed there was no component of the motor curve generation that specifically addressed the relationship of torque and speed around the rated motor operating parameters, and so there was little opportunity for students to identify the 'near constant' speed behaviour of the IM. This was only meaningfully addressed in

Laboratory Session 2, and therefore the solution to the lack of student performance had to be included within this exercise.

Laboratory Session 2 required students to plot the motor mechanical torque output against motor slip within the rated operating range of the motors at various supply frequencies. The review questions at the end of the exercise asked students to comment on the observed relationship between torque and slip and then to estimate motor speed at two levels of load torque given supply frequency. The expectation was that the students would use their experimental results to deal with this question, but some did however a number did not, assuming the motor would operate at synchronous speed. It appeared that students were not making a linkage between their experimental work and the review question, so to address this, an explicit instruction was placed with the review questions asking students to answer the review questions based on their experimental work and graphs.

The results for the 2015 cohort were similar to those of the 2013 cohort. In the laboratory assessment, a number of students ignored slip when estimating the speed of the loaded motor despite identifying that motor slip increased with torque in the question immediately prior. Within the war stories many students recommended an expensive feedback control loop system. Upon further review it was hypothesised that that students were:

- still failing to link experimental results with the review questions
- do not appreciate the near constant speed behaviour of the induction motor
- continuing to have issues using the knowledge of torque slip behaviour in the context of war stories
- not considering economy when suggesting expensive and unnecessary feedback control systems

It is difficult to suggest how to help students link experimental results to the review questions in ways that would be more effective than the current explicit directive to answer the questions in relation to student experimental results; it may be that outside factors are an issue. The solutions suggested to the remaining three issues are to include either a review (or key) questions addressing the near constant speed behaviour of an induction motor in a context, and to consider altering the war story scenario to force consideration of a DOL induction motor for reasons of economy.

13.1.5 Identify the Magnetising Current of an Induction Motor

Most students within the 2012 cohort could not successfully negotiate the war story scenario assessment addressing the current consumption behaviour of an induction motor before or after training; to successfully negotiate these scenarios students had to be able make a series of cognitive leaps as shown in Figure 13.4.

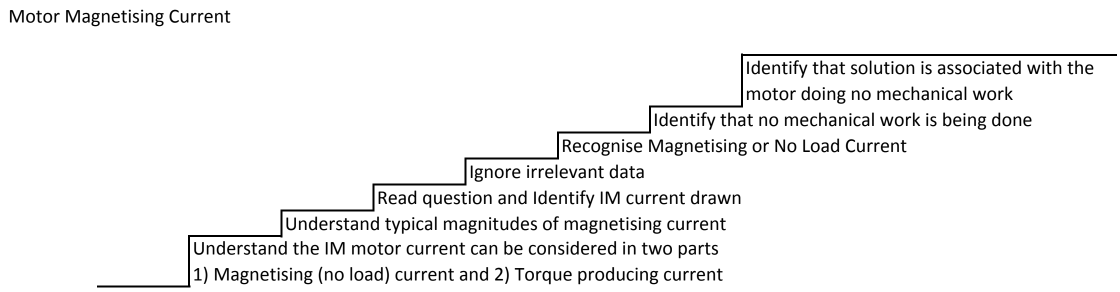


Figure 13.4: Instructional scaffolding model of the magnetising current war story

The responses from most of the 2012 cohort indicated they have a variety of issues, most importantly, an inability to appreciate the significance of no load current, identify the no load (or magnetising) current, and ignore irrelevant data in the scenario.

The students' completed workbooks indicate that the majority of students had successfully completed an exercise where they investigated and plotted the motor current at various levels of mechanical power output. This exercise asked students to:

1. Comment on the shape of the plot
2. Identify how much current is being drawn at no load
3. Identify what the no load current is doing
4. Derive a relationship to estimate mechanical power from the current drawn.

It was believed that the steps within this exercise should lead students to be able to understand the implications of an induction motor current and be able to identify the motor no load current. Initially, it was surmised that students were unable to identify the induction motor current within the scenario and ignore irrelevant data, so the introductory scenarios and key questions described in Section 9.1 were added to the 2013 workbook. However, during the 2013 laboratory sessions it appeared that students were unable to *combine* the individual components of this exercise into a comprehensive understanding. While most students could plot the data and find a linear relation of the form y= mx + b, many could not explain the physical significance of the gradient (m) and offset (b), these being the proportionality of current drawn to power delivered and the motor magnetising current respectively.

During the 2013 laboratory classes, the laboratory demonstrators employed some coaching of students, students were specifically asked 'what is the physical significance of the offset in your relation?', 'what is the physical significance of the gradient?' and ' How do these things relate to your understanding of how an induction motor operates?' As students answered these questions it appeared that the physical interpretation of their data and analysis began to crystallise. In terms of the instructional scaffolding model this coaching added extra steps to the base of the instructional scaffolding by refreshing students on their prior learning and prompting them to relate this to their experimental observations; this is shown in Figure 13.5. The 2013 performance in this scenario was significantly improved from 2012, and consequently the laboratory workbook was re-written for the 2015 cohort with additional background material and review questions which emulated the 2013 coaching.

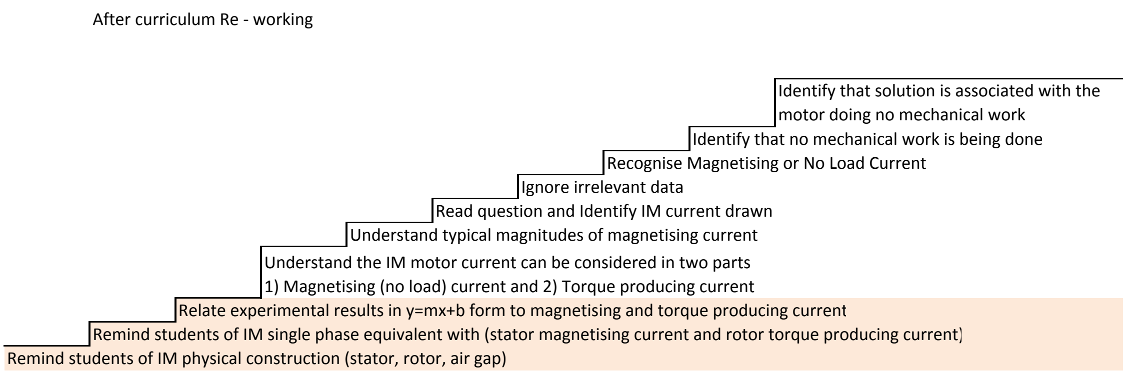


Figure 13.5: Instructional scaffolding model of the magnetising current war story including coaching

The result of the 2015 cohort was surprising because they achieved significantly lower results than the 2013 cohort in terms of both their attainment in the war stories, and in the associated lab book exercises. Three explanations for the superior performance of the 2013 cohort were posited: firstly the coaching delivered in 2013 was essentially investigator bias, or the 'experimenter effect' (Yin, 2009, p. 141) coaching students to answer the assessment; secondly, that the changes to the curriculum were inferior to the direct coaching by demonstrators; and thirdly, that the 2013 cohort had superior abilities. The experimenter effect was deemed unlikely because coaching did not directly address review questions or scenario assessment. The potential inferiority of written exercises in compared to direct coaching was dismissed due to the care with which the coaching was emulated in the written exercises and the impractical demands that widespread intense one-on-one teaching places on staffing. The hypothesised superior ability of the 2013 cohort is plausible given the observed issues with pre-requisite knowledge in the 2015 cohort and their overall attainment in the laboratory exercise and subject as shown in table 13.1. At the conclusion of the 2015 course this was unresolved; two potential options from this stage are to build more detailed scaffolding into the curriculum or review the pre-requisites for the course.

13.1.6 Capability of Variable Speed Drive

Most students within the 2012 cohort successfully negotiated the war story scenario addressing the capability of variable speed drives. Students appeared to have a high level of prior knowledge in this area and due to their success in this scenario, and it was considered that no further action was required. While the 2013 cohort had a lower success rate than the 2012 cohort, the performance of the 2013 cohort did not warrant additional work. However, the performance of the 2015 cohort was worse still and appears to require attention. In order for students to successfully negotiate these scenarios they had to be able make a series of cognitive leaps as shown in figure 13.6.

In reviewing the curriculum, there is no exercise or review question that makes an explicit linkage between the motor speed, power used, and the economic cost.

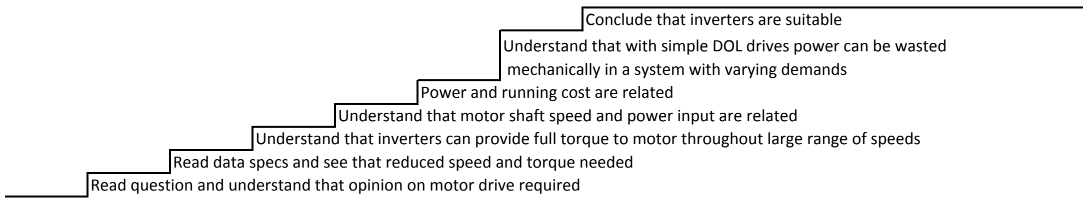


Figure 13.6: Instructional scaffolding model of theVSD capability war story.

There is no exercise in the laboratory informing students that systems with variable demand that use a constant speed motor often waste power. However, this was judged of less importance because the war story scenario provided this information explicitly, and only requires students to recognise that variable torque and speed was required, and furthermore that a VSD could achieve this. It was hypothesised that a review question linking power and economy be added to Laboratory Session 2 to address motor speed, power consumption and economic cost in a context.

13.1.7 Soft Starter with a High Torque Load

Most students within the 2012 cohort could not negotiate the war story scenario assessment addressing the appropriate motor drive combination before or after training. In particular, students could not identify that a soft starter is not suitable for use with constant, high torque loads. For students to successfully negotiate these scenarios they had to be able make a series of cognitive leaps as shown in figure 13.7.

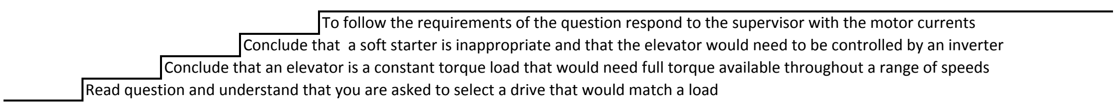


Figure 13.7: Instructional scaffolding model of the soft starter war story.

While assessing the student workbooks, three potential problems were identified; students appeared to be having issues with the kinds of observations they should be making of motor and drive combinations during start up, that they were having trouble using knowledge in context and were not matching nominal load types (constant torque with speed, linear, etc.) with real world loads. Changes were made to address these issues, including guidance on the potential observations to be made, introductory scenarios and key questions were added (as described in Section 13.1.4), and modifications were made to the laboratory workbooks and HMI to include pictures of real world loads, the torque speed curves of the loads, and the different drives, as shown in Figures 13.8 and 13.9.

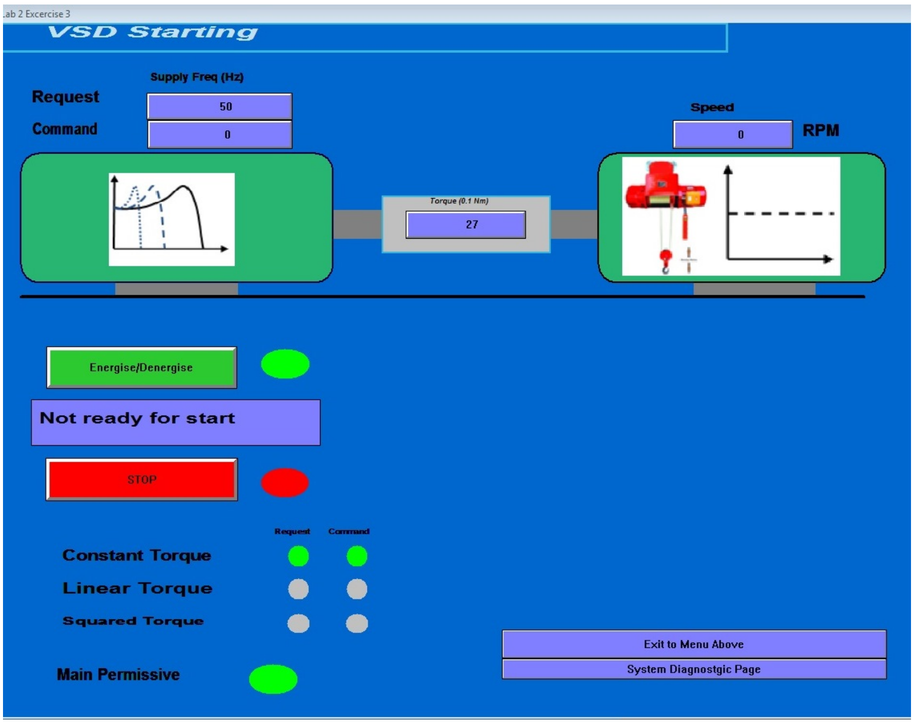


Figure 13.8: Screen shot of HMI modifications.

The performance of the 2013 cohort was similar to the 2012 cohort and further review highlighted a another issue. During the laboratory, students would test 3 different drive types (Direct On Line, Soft Start, Inverter) with three different load types (constant, linear, squared torque loads) and make observations. It was hypothesised that the order of these laboratory exercises would influence student's opinions of the drives, perhaps misleadingly so. During the exercise students would first test DOL, followed by soft start, and finish with the inverter, trying each drive with the three different load types. It was believed that the first drive tested would establish a base expectation for students and that a contrast would be drawn from the baseline. In this way the baseline would be the sudden violent start of the DOL and that both soft starting and the inverter would appear far superior in all cases. Moreover, students could not contrast two critical load and drive combinations directly due to the ordering of the exercise - constant torque loads with inverters or soft starters.

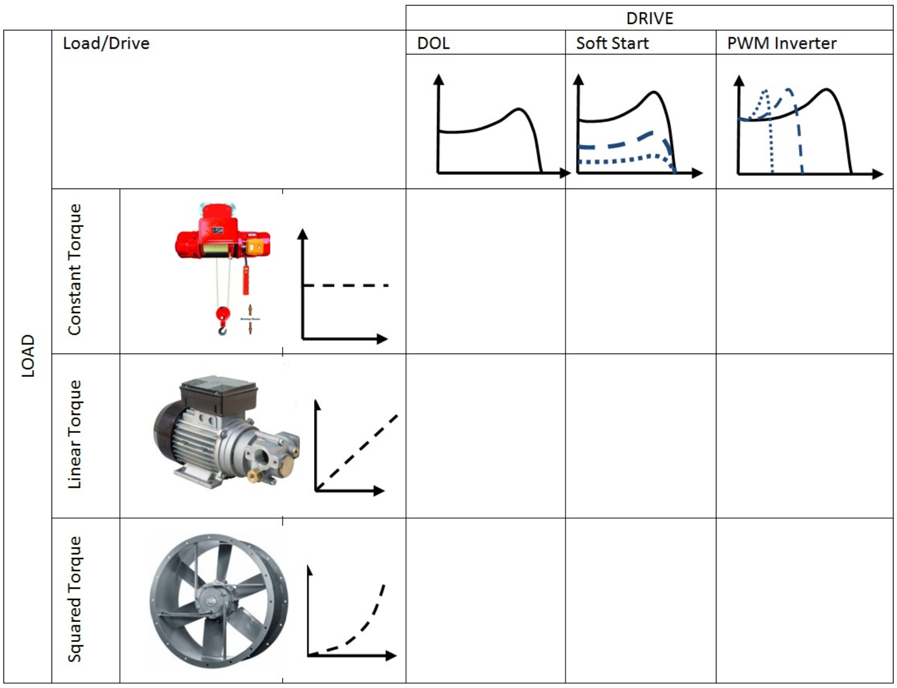


Figure 13.9: Modified results section of laboratory workbook showing pictures of real world load.

While soft starters are appropriate for squared and linear torque loads they are not suited to high constant torque loads, only as inverter is truly appropriate to start these loads. The distinction however, is only clear if these are directly compared, but the original ordering of the exercise did not contrast them in this way. To remedy these issues the laboratory exercise was re-sequenced to assist students to make appropriate comparisons.

The results achieved by the 2015 cohort in the war story assessment were worse than the 2013 cohort which was surprising, given there was a high degree of similarity between the war story and a review question in the laboratory workbook and a number of students were directly observed in the laboratory classes identifying the poor performance of a soft start drive with a high constant torque load. Possible issues were difficult to identify, but based on the information available, it is posited that either the additional scaffolding added for the 2015 cohort is still not sufficient, or there are problems with student pre-requisite knowledge preventing them from performing well in this scenario assessment. It should be noted however, that evidence in support of these two propositions is not very strong. Addressing these issues would involve either further augmentation of the instructional scaffolding for the exercise, or reviewing student pre-requisites to see if there are underlying issues with the 2015 cohort of students.

13.2 Reflections on war story performance and acceptance

In attempting to assess student attainment of wisdom using the war story scenarios and to determine if the performance of the EMDET was sufficient for user acceptance, a number of issues and impacts have become apparent.

On reflection the goal of achieving student competency to practice (desired wisdom) as assessed by the war story scenarios was judged to be a highly aspirational target. Successfully dealing with a war story scenario requires a student to accomplish a number of tasks and synthesise an overall solution, it requires:

- understanding a real world situation
- identifying valid and invalid data to properly identify the problem or at least recognise valid hypothetical issues
- bringing together knowledge from a variety of subjects from throughout the undergraduate curriculum (including pre-requisite and the subject being studied)
- applying the knowledge from the subjects in concert to the problems identified

This process of completing these tasks, and the overall synthesis was termed an *ensemble performance*; a problem with any of the component tasks of the *ensemble performance* will prevent success within the scenario, or indeed in real world practice. The word ensemble is deliberate choice because it emphasises the the concept of many individual parts of a whole that must act together in concert to reach a single goal. While implicitly understood as a requirement for students to successfully complete the laboratory exercises at the outset of the EMDET project, it was not until the student issues with completion of the exercises were analysed that an explicit definition was arrived at.

When considered in terms of the closed loop conception of teaching and learning defined in Section 3.2.9, it appeared that the model developed did not adequately address the student ability to deliver an ensemble performance in the definition of student competency sought. In order to successfully practice with EMD systems students will not only have to apply knowledge from a single area at the level of Zeleney's wisdom (Zeleny, 2006) as identified previously, they must also combine and apply knowledge from many discrete areas of the undergraduate curriculum, or as Balog, Sorchini, Kimball, Chapman, & Krein (2005, p. 538) stated perform a 'synthesis, requiring them to use knowledge across their full curriculum with close attention to detail' .

If student knowledge of a subject (e.g. induction motor theory) and its immediate pre-requites (e.g. 3 phase power, electromagnetic theory) are considered the 'depth' of knowledge required, the experience with the EMDET and Balog, Sorchini, Kimball, Chapman, & Krein (2005) indicate that a 'breadth' of knowledge is also required. For example to predict the speed of an induction motor under varying load conditions an engineer must not only have wisdom in relation to the motor, they also must understand the concept of dynamic equilibrium from engineering mechanics to successfully solve the problem. There are many other examples where a 'breadth' of knowledge in other areas is required (e.g. power distributions systems, signal processing, power electronics, digital control systems) to address an issue with EMD systems. In order to succeed in war story scenarios - or in engineering practice - students need to draw on both a depth and breadth of knowledge that is then used at Zeleny's level of wisdom. It appears that many student issues lie in utilising a breadth of knowledge; possibly because:

- the student may lack the knowledge from other 'breadth' subjects entirely entirely
- they may not recognise the need to utilise other knowledge
- they may recognise the need for using breadth knowledge but are unable to perform the combination of the knowledge areas to find an overall solution

When considering student ability (or lack thereof) to deliver an ensemble performance a potential mismatch was observed between the project target for EMDET, the subject being used for an acceptance test, and potentially the degree course within which the course is sited. The required ensemble performance draws on many subjects throughout the undergraduate curriculum, whereas the assessment within the PED course is predominantly concerned with the material that it delivers, a much narrower focus. Reflecting upon the fundamental structure of undergraduate (and postgraduate) degrees it appears that during assessment, most subjects are mainly concerned with the material that the subject delivers; little attention is paid to the linking and application of material from throughout a degree course that is required by an ensemble performance. It appears therefore that the war story assessment differs from the typical subject (or degree) assessment, being perhaps broader and arguably more rigorous. Given that students have had little or no exposure to or training in the linkage and contextual application aspects of the ensemble performance it is perhaps unsurprising that many students have difficulty with such a novel assessment exercise.

The mismatch between the EMDET and PED course goals was not viewed as a mistake in retrospect, on the contrary the selection of the PED course as an acceptance test is judged prudent and was driven by pragmatic concerns involving a number of issues that most educational intuitions executing this kind of project would need to address. From a stakeholder perspective, the PED course was the only pragmatic entry point for the EMDET into a Bachelors degree course at the time, in particular the EMDET needed to win support from the University prior to taking the risk (and expenditure) of altering more than one subject within an established degree course to include teaching with as yet untested equipment (the EMDET).This recognition of the mismatch should be used to temper the expectation of the extent to which students being trained on the EMDET will attain the desired wisdom and ability to deliver an ensemble performance. The expectation should be built on the presumption that delivering an ensemble performance is novel, and that students have had little previous exposure to it in their training. On this basis a modest number of students showing relative improvement between before and after assessment is proposed as a more appropriate measure of success.

Two issues related to the mismatch identified within the PED course were the time available in the course for teaching with the EMDET and student mastery of agreed prerequisites. The time available for using the EMDET in the teaching curriculum was limited to two laboratory sessions within the PED course, so in assessing students for an ensemble performance, the EMDET was actually attempting to do something that the remainder of an undergraduate degree course did not. The time limitation also meant that the EMDET curriculum was predicated on the assumption that students had a strong foundation of prerequisite skills agreed upon in the specifications stage. The educational scaffolding within the curriculum started at this foundation of assumed knowledge and began to present new knowledge on EMD systems targeting higher levels of knowledge within the SOLO taxonomy and ultimately the wisdom required for successful industrial practice. Direct observation by laboratory demonstrators identified that a number of students did not have the foundation of knowledge specified, the lack of which formed additional cognitive leaps that were not allowed for in the curriculum. These additional leaps have likely prevented some of these students from achieving the desired wisdom and contributed to their performance in the war story assessments.

Related to prerequisites there were some issues with the format and delivery of the war story scenario assessments that have likely impacted on student performance. Firstly, the war story scenario format is based on a literary description of a technical situation, so if either the prose is confusing or, student English abilities are lacking, this form of the assessment will be a barrier to its purpose. There is some evidence of both of these issues because the 2012 and 2015 cohort achieved lower scores on the post testing dealing with the capability of the VSD as compared to pre-testing. In particular, the 2012 cohort achieved 100% on the pre-test, indicating that they already had a good knowledge in this area but their performance declined in the post test.

The purposes of the war story assessment requires that the underlying technical issue be tested in seemingly different scenarios before and after training. In the case of the test for the VSD capability, a comparison of the pre-test and post test supplied additional information and used a slightly more complex situation, so it may have been this attempt to obfuscate the underlying technical issue has detracted from this scenario detecting student understanding. Within the 2015 cohort there was a perception among laboratory demonstrators that a higher number of students had English language difficulties than in previous years. If true, the translation of the scenario for the student would have formed an additional and unintended cognitive leap. This additional leap may have made the ensemble performance required by the scenarios too difficult for students without the requisite English skill to complete.

The impact of excluding the war story assessment from student grades on their effectiveness as an assessment instrument is unclear. In making this decision there were a number of factors in tension. In favour of exclusion was the desire to have candid answers from students to assess the knowledge and potential wisdom that an individual had gained. In particular, it was judged important to avoid student collusion and potential plagiarism because this would not assess individual attainment. Against exclusion was the issue that not all students submitted war story assessments, which also raises the possibility that students may have been dismissive of the assessment and did not give it their full attention as desired by the examiners. On balance, the decision to exclude the scenarios would probably allow a number of students who have attained the desired wisdom to go undetected, whereas including them in student grades may be more likely to falsely detect student wisdom due to student collusion or plagiarism.

Notwithstanding poor student performance in the scenarios and the mismatch between project goals and acceptance testing, there appear to be two important corollary benefits of using war story scenarios and wisdom as a project target. Firstly the broad and rigorous target of wisdom should ensure that the EMDET can deliver educational outcomes for a number of subjects beyond the individual subject requirements of the PED course. Wisdom could therefore be considered as a target, that if reached, will result in a conservative over-delivery of capability in the equipment and curriculum. Furthermore this is compatible with the approach taken by the university to ensure that the EMDET can deliver on the outcomes for one elective before considering a broader utilisation within the degree course.

Secondly the use of these assessments appeared to be a motivator in the development of the EMDET, in particular ensuring the equipment and curriculum were well integrated with a focus on delivering student outcomes. In the case of the EMDET a complex physical system consisting of hardware, software and curriculum was delivered and functioned as a coherent whole with only minor issues and has now become an entrenched component in the electrical engineering curriculum. It appears that the aspirational nature of the war story scenario assessment and desired wisdom has implications not only for student learning and teaching but to the equipment and curriculum development as well

13.3 Rationale for User Acceptance

The purpose of the Acceptance Testing Phase is to judge project delivery against requirements. The EMDET was effectively accepted by users at the conclusion of the 2013 PED course on the basis of:

- delivery of equipment and curriculum on time and within budget
- student success in the PED course laboratory workbook assessment and by direct observation of the laboratory classes
- success of some students in some war story scenarios and attaining the desired wisdom
- contribution to the Engineers Australia accreditation assessment addressing concerns that were part of the motivation for EMDET
- the readily apparent capability of the EMDET to teach both the revised PED course curriculum and the potential to deliver all of preliminary curriculum described in section 5.1.3

Reflection on the goal of wisdom and war story scenario assessment has identified that student delivery of the required ensemble performance is an aspirational target and one that few, if any, engineering subjects (or degree courses) train students in. This has tempered the expected student completion rates within the war stories and altered the original expectations in the requirements stage to a more pragmatic goal of a modest proportion of students showing relative improvement in before and after assessment.

In terms of acceptance testing, the issues observed during laboratory exercises of students lacking prerequisite English and technical skills specified in Section 6.5.2, was a case of the users not adhering to the agreed specifications. Whether this was actually an inadequate statement of requirement from the users or simply not complying with what was agreed, the burden of resolving this lies with the user, not the project team.

Unexpectedly, the war story scenarios were found to provide valuable motivation throughout the project execution, inspiring the delivery of high quality integrated equipment and curriculum capable of delivering high quality educational outcomes in the field of applied EMD systems.

Part III

Analysis and Discussion

Chapter 14

Analysis: Outcome Analysis

The first key question of the study was to determine what were the significant success or failures of the project leading to the overall success or failure. This was addressed using a project evaluation analysis and is the first step in the overall synthesis methodology as shown in Figure 14.1.

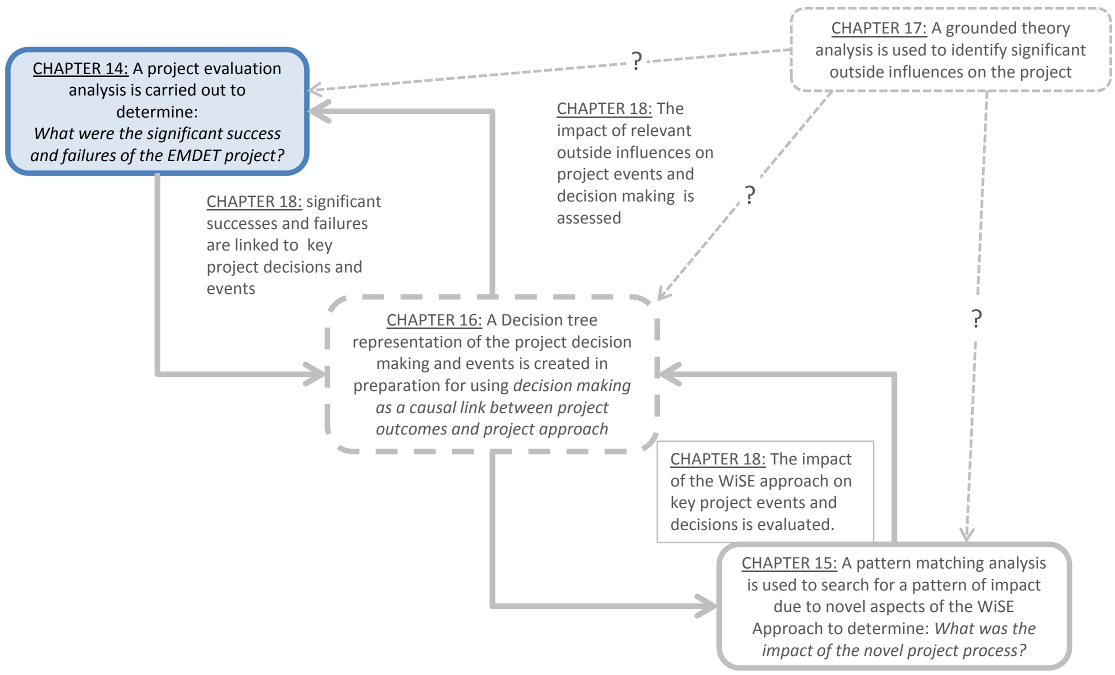


Figure 14.1: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

This question has two components which determine the overall project success, and then identify the subsidiary significant successes or failures which contributed to the overall result. Three different evaluation processes were used to address the questions: an outcome evaluation, a component evaluation and a lessons learned evaluation, as described in Section 4.4.1.

The outcome evaluation applied the fundamental definition of a project to judge in absolute terms of whether or not the project succeeded or not. The component evaluation applied the definition of the project process to judge in absolute terms the success of the individual stages of the project process that form the overall project. The lessons learned evaluation reflectively reviewed the project to determine what actions should be replicated in future, what actions should be avoided in future, and what possible improvements could be made to a similar project in future.

Executing the EMDET project involved construction and evaluation of a prototype as a proof of concept, the approval for construction of the production model EMDET depended on the successful performance of the prototype. Given that the prototype and production model were funded separately, and that the project may have terminated with the prototype, the outcome evaluation and the component evaluation separately addressed the prototype and production model EMDET to account for the two different financial constraints and to help identify subsidiary success or failures in the EMDET project.

14.1 Outcome Evaluation

The outcome evaluation was based on the fundamental definition of a project project (described in section 4), and asked:

1. What were project the deliverables for the project? Where they met?
2. What were the resources assigned to the project? How many did it utilise?
3. What was the time allowed for the project? Did it work within it?
4. Was their acceptance of the project from the stakeholders?

The deliverables evaluated include the curriculum, hardware, software (PLC, HMI and DAQ) and support information to operate and maintain the equipment. Project timing was evaluated given target start and completion dates. Resources were evaluated in terms of financial cost, paid and unpaid labour, and space in the laboratory. Finally, stakeholder acceptance is addressed. The outcome evaluation for the prototype was conducted using project documentation and correspondence, the outcome of which is summarised in Figure 14.1.

The prototype overall was successful as its operation was sufficient to gain acceptance for the construction of the production model EMDET, significantly:

- in terms of deliverables all the hardware and physical assets required were delivered. Although the software was only partially developed, extensive work was completed and it enabled sufficient commissioning of the prototype EMDET to prove the concept. Only preliminary work on curriculum had been undertaken but it was enough to guide the design of the prototype through the agency of the linkage matrix developed, which proved to extremely valuable through development of both the prototype and production model EMDET
- key issues requiring iterative changes were identified, importantly including the symmetrical motor sizing, and layout of panel meters
- the prototype was originally planned to be fully completed in 8 months, it was partially completed in 9 months and was of a sufficient standard to gain stakeholder acceptance. In review this timeline was optimistic, but it did not adversely impact the timeline for the subsequent production model
- in terms of resources the project was delivered within the financial and space constraints, although a large amount of unpaid expert labour was utilised by the project that was used as credit towards an undergraduate degree, if this labour was financially supported the cost of the project would have dramatically increased
- the prototype gained enough acceptance by stakeholders to fund the production model

Following the success of the prototype, the production model EMDET was initiated and the result of the outcome evaluation for the production model EMDET is summarised in table 14.2.

Table 14.1: Outcome evaluation of the EMDET prototype.

Project Outcomes

Legend
Outcome Successfully met
Outcome partially met or had significant issues complications
Outcome not met
An issue of likely importance for projects operating under other circumstances (e.g. Purely commercial project)

Prototype			
		Target	**Actual**
Deliverables	Hardware	Electrical, mechanical and SCADA design completed.	All completed
		Motors, drive equipment and SCADA construction completed.	All completed
		Commissioning completed.	Hot commissioning completed one month late. Major issues to be addressed by iteration include symmetrical motor sizing, allowance for a future DC motor of motor sizing, the panel meter layout, the motor voltage references and panel sizing were all identified.
	Software		
	PLC Code	Fully operational code ready for laboratory delivery	Two code versions: Reduced code used for hardware and DAQ testing completed. Operational code half complete
	HMI	Fully operational code ready for laboratory delivery	Two code versions: Reduced code used for hardware and DAQ testing completed. Operational code half complete
	DAQ	Fully operational code ready for laboratory delivery	Custom software not started. Functionality tested with example code provided my manufacturer.
	Curriculum	Laboratory Exercises developed	Preliminary curriculum developed Preliminary laboratory outlines developed Linkage Matrix developed
	Support information	Engineering drawings, operating and commissioning procedures	Drawings provided, no manuals delivered.
Project Timing	Start	Mar-09 Project Inception for prototype	Mar-09 Project Inception for prototype
	Completion	Oct-09	Nov-09 All hardware had undergone commissioning. Software ready for further development as part of production equipment
Resources	Cost	$35,000 for a single prototype	$35,973 for a single prototype
	Paid Labour	Electrical design and construction labour incorporated into quote for each tools.	Target reached
	Unpaid Labour	Design commentary, Software and SCADA assistance from the Industrial Partner	Target reached
		Project management, mechanical and electrical design, SCADA programming, commissioning and curriculum by the researcher	A very large amount of time was spent on this project by a student with relevant industry experience in mechanical and electrical engineering as part of a undergraduate thesis in electrical engineering If this project was not an industry/University collaboration and labour and expertise had to be paid for it would have added significantly top the project cost.
	Space	Fit within SMART Floor plan provided	Target reached
Acceptance		Proof of concept and organisational support for commencement of production rigs.	Target reached

The production model EMDET was successful overall and was accepted on the basis of the performance of the hardware, software and student results in the laboratory workbooks, significantly:

- in terms of deliverables all the hardware and software required were delivered and the curriculum was fully developed and delivered. The EMDET was accepted in 2013 on the basis of hardware, software, and student performance in the workbooks (average laboratory marks 68% or higher- Section 13.1.1), and a revised expectation of student success in the war story scenario assessment
- student performance in the war story scenario assessment was poor so project iterations were initiated to address this with varying success. During these iterations the value, weight and place of war stories in assessment was reconsidered along with the match between the goals of elective subject used for acceptance testing and the comprehensive nature of the war story
- the project was completed and on time, and the equipment delivered to the SMART building on schedule where it successfully taught the first cohort of PED course in 2012. Iterations to address the shortfall in war story performance were carried out in 2013 and 2015
- the time available to teach with the EMDET was restricted to two laboratory sessions within the PED course
- in terms of resources the project was delivered within the financial and space constraints. However, the overall project budget was reduced during the execution due to a reduction in funding supplied by the new research facility for equipment within the power electronics laboratory. The number of EMDET units to be delivered was reduced in proportion to the budget, and the unit cost remaining the same. A large amount of unpaid expert time was spent on the project by a researcher that was used as credit towards a postgraduate degree; however, if this labour was financially supported then the cost of the project would have increased dramatically. The amount of in-kind labour provided by the industry partner became an issue towards the end of the project, so additional work had to be taken on by the researcher
- the production model was accepted and is now an entrenched part of the electrical engineering laboratory curriculum; expanding the use of the EMDET into other courses has aslo been posited
- the EMDET was a key part of addressing past criticism in the latest accreditation review by the institute of Engineers Australia, criticism which was the original motivation for the EMDET. When reviewed as part of an accreditation audit Engineers Australia (2013) deemed it ‘probably amongst the best in any Australian University’

Table 14.2: Outcome evaluation of the production EMDET.

Production			
		Target	**Actual**
Deliverables	Hardware	Electrical, mechanical and SCADA design completed.	All completed including changes from prototype
		Motors, drive equipment and SCADA construction completed.	All completed including changes from prototype
		Commissioning completed.	Hot commissioning completed on all instances
	Software		
	PLC Code	Fully operational code ready for laboratory delivery	Fully completed
	HMI	Fully operational code ready for laboratory delivery	Fully completed
	DAQ	Fully operational code ready for laboratory delivery	Fully completed
	Curriculum	Rough Curriculum developed	Full curriculum developed and delivered
	Support information	Engineering drawings, operating and commissioning procedures	Drawings provided along with on-site introduction to technical staff. Manuals incomplete.
Project Timing	Start	Feb-10	Mar-10
			Slight delays to production model commencement due to student re-enrolment
	Completion	Dec-11	Aug-11
		Installation of equipment in new SMART building prior to ECTE412/912	Target reached
		May-12	May-12
		Satisfactory equipment operation for first cohort of ECTE412	EMDET was provisionally accepted at this time. Equipment function was good and accepted with some minor issues to be addressed.
		May-12	May-12
		Satisfactory performance of the curriculum for first cohort of ECTE412	EMDET was provisionally accepted at this time. Laboratory workbooks were good student performance in lab books was sufficient to warrant acceptance of these - further changes undertaken due to war story performance.
		May-12	Oct-15
		Satisfactory performance of students in war stories - attain desired wisdom	Student performance in war story scenarios were poor, elected to undertake iterations of improvement, however these may have been more appropriately refereed to as curriculum development. Iterations were undertaken in 2 following cohorts in 2013 and 2015
Resources	Cost	$35,000	$35,709
		Per instance, original budget was for 7 tools in total. Revision of funding from SMART project this was reduced to 5 tools.	Per instance for 5 tools. Less than 3% over spend that was due to an additional data acquisition card which was deemed acceptable and approved out of project contingency funding.
	Paid Labour	Electrical design and construction labour incorporated into quote for each tools.	The paid labour allowed for was exceeded by the industry partner.
	Unpaid Labour	Design commentary, Software and SCADA assistance from the Industrial Partner	The labour allowed for by the industry partner was exceeded - the became a burden for the industrial partner.
		Project management, mechanical and electrical design, SCADA programming, commissioning and curriculum by the researcher	A very large amount of time was spent on this project by a researcher with degrees and relevant industry experience in mechanical and electrical engineering as part of a Masters degree in engineering later that was subsequently upgraded to a Doctor of Philosophy. If this project was not an industry/University collaboration and this labour and expertise had to be paid for it would have added significantly top the project cost.
	Space	Fit within SMART Floor plan provided	Target reached
Acceptance		Equipment functioning and accepted as part of undergraduate teaching labs	Accepted as integral part of ECTE412/812/912 laboratory curricula; potential for use in further subjects posited.
			Value of war stories recognised as goal for curriculum development

- student feedback on the laboratory experience via regular faculty course evaluation surveys has been positive

14.2 Component Evaluation

Both the prototype and production model EMDET were evaluated in terms of completing the stages of the WiSE approach. The prototype was originally planned to commence at the requirement phase and complete the component testing phase to prove the EMDET concept prior to approval of the production model EMDET, which should have completed all phases of the WiSE approach. The results of the component evaluation are summarised in Table: 14.3

During the creation of the prototype the requirements, specifications, system, and detail design phases were all successfully completed. The assembly and component test phases were partially completed because the PLC and HMI code needed for final operation were only partially completed, and the laboratory curriculum was not fully drafted within the time allowed for the prototype. The partially completed code was adequate to operate the EMDET and to demonstrate sufficient capabilities within the prototype for the production model to be approved. In retrospect the original timeline established was judged to be optimistic, and the prototype was used to continue developing the PLC and HMI code in parallel to the design and construction of the production model EMDET.

During the creation of the production model EMDET all phases apart from the acceptance test were successfully completed without issue. Although the acceptance test phase was completed, there was a change in the weighting and expectation of student performance in the war story scenario assessment to gain acceptance in 2013 from the original requirements. As part of acceptance testing a number of iterations were initiated to address the issues encountered in 2012 and 2013 which, judging by the performance of the 2015 cohort, still had not been fully addressed. These iterations prompted a revaluation of the role of the war story in acceptance testing, particularly in view of the aspirational nature of the measure and potential mismatch with the goals of the course.

Table 14.3: Component evaluation of the prototype and production model EMDET.

		Prototype	Production
	Should	Actual	Actual
Requirements	User requirements stated in their own terms to designers	Customer Requirement Specification and Outline drafted	Iteratively modified requirements from prototype. Educational requirements codified in terms of closed loop model. CRS from Prototype still valid.
Specifications	User requirements translated into design brief that designers can progress without user involvement	Laboratory Requirement Specification, load options and signals list drafted. Preliminary circuit diagram drafted	Iteratively modified specifications developed for prototype. Equipment and curriculum philosophy formalised. Fidelity philosophy and flexibility philosophy codified. Curriculum design methodology formalised in terms of closed loop model including use of the Tyler rationale. Goal of providing wisdom to practice established measured using war stories, lab work books and observation established. Educational objectives stated in content behaviour form. Audience defined as ECTE412 class. Preliminary curriculum reduced for delivery to ECTE412/912.
System Design	High level system design completed until all detail design tasks identified and constructors involvement required	Load type decided, preliminary space layout drafted, SCADA Layout drafted. Power side circuit diagram drafted and control side circuit diagram drafted. Conceptual DAQ, HMI and overall system drafted. Load control drafted	System Design modified with design changes identified from prototype testing. Breakup of revised curriculum decided upon.
Detail Design	Design completed so that it can be handed over from designers to constructors and assembled	Power and control side construction drawings created. Lem transducers and DAQ selected. HMI screens designed and pump simulation designed.	Power and control side construction created for iterated design. Panel front and DAQ layout drafted. Code flow design completed. Frame mounting modifications completed.
Assembly	components purchased and assembled. First stage of design realisation	Panel and motor assembly constructed. Simple PLC and HMI code authored allowing testing to progress. Sophisticated code under development - completed as part of production model	5 new panel and motor assemblies built. PLC, HMI and DAQ code completed. Laboratory work book and war story assessments completed.
Components Test	Component function tested individually by constructors and designers until designers can progress on their own. "White box testing" all details are known	Cold warm and hot commissioning undertaken with simplified PLC and HMI. Issues identified requiring iterations to address in production model. DAQ system tested with manufacturer's sample code.	Cold warm and hot commissioning completed. Sophisticated load type simulation tested. Motor torque speed curves produced as summative testing. Minor editing of laboratory work books completed.
Integration Test	Groups of components tested by designers. Individual; components are treated as black boxes and groups of components and their interactions are tested.	Iterated to Production model	Instructors solution manual produced by designers using completed work book on fully commissioned EMDET. First time the equipment and curriculum had been fully tested together. A number of issues resolved integrating equipment and curriculum. Full check of EMDET against specifications was successful.
System Test	All components of system are tested together under controlled conditions by designers and User representatives.		User representatives (laboratory demonstrators) used lab work books on EMDET and successfully completed work books with only minor issues. Full check of EMDET against specifications stage was successfully.
Acceptance Test	Full system is tested under conditions of final use (or at least sufficiently representative) by Users		Equipment used for teaching ECTE412/912, effectively accepted after first cohort on basis of equipment and student lab work book completion. War story performance was poor. Iterations were pursued to improve war story performance firstly and lab book performance secondly.

14.3 Lessons Learned Evaluation

The relative lessons learned (Thomas, 2012, p. 20, 29-40) evaluation used a 'Keep, Stop Start' (Vilasini & Neitzert, 2012)approach to identify success, failures and potential future improvements within the project that may not have otherwise been captured by the outcome or component evaluations

The lessons learned evaluation was a reflective review of the project to determine which actions where successful and should be replicated in future, which actions were unsuccessful and should be avoided in future, and what possible improvements could be made to a similar project in future.

14.3.1 Keep

The following actions, issues or features of the EMDET or project process were seen as valuable by the project stakeholders contributing to the success of the EMDET project.

- the concurrent equipment and curriculum design reduced the risk of delivering equipment for an engineering teaching laboratory that could not deliver the desired curriculum
- the iterative approach of design and construction addressed a number of potential design flaws and issues; particularly the creation of a prototype as proof of concept as a first step towards the production EMDET; this was important to gaining financial support from project stakeholders.
- the design philosophies developed (equipment constitution, fidelity, flexibility) positively contributed to the quality of the equipment produced and led to acceptance by the project User's
- the linkage matrix organisational schema proved to be a valuable tool for linking equipment and curriculum development
- the flexibility and adaptability of the hardware and software provided within the EMDET facilitated the delivery of the revised curriculum, allowed for iterative changes, and offers great potential for teaching the entire proposed curriculum from the requirements phase in section 5.1.3
- the real world applied nature of equipment and curriculum as evidenced by verbal feedback from students within laboratory classes, and addressing concerns of previous accreditation reviews of the undergraduate engineering curriculum

- the close cooperation of the University and primary industry partners Emerson Control Techniques was crucial to project success, this facilitated rapid development of design, construction of the EMDET, and iterative improvements during the component testing phases
- the closed loop model of education proved valuable for design and development of both equipment, and the curriculum. This model had two particular strengths: firstly, it placed complex educational issues within a conception familiar to engineers; secondly, it brought the subtlety and depth of understanding encapsulated with the engineering conception of a closed loop feedback model to the educational setting
- reflective changes to equipment, reflective compromises in equipment design, and removing unnecessary cognitive leaps from the equipment and curriculum during design due to the interaction between the closed loop model of education, the closed loop reflective approach of Wise and the deliverable of student competency
- the important role of the laboratory demonstrator in execution of the laboratory teaching; this role was examined in detail during the grounded theory analysis presented in section 17
- the value of the war story scenarios as motivation for equipment and curriculum development. The war stories provided tangible measures of the desired wisdom that could be used to guide detailed equipment and curriculum design
- the availability of expert labour at no cost to the project under the auspices of a postgraduate degree was vital to completing the project within budget
- the cooperation of the industry partner control techniques which provided in-kind expertise at no financial cost and making readily available expert construction labour with appropriate skills to complete construction within a small budget

14.3.2 Stop

The following actions, issues or features of the EMDET or project process were seen as detrimental by the project stakeholders either making the project more difficult, or risking failure of the EMDET project.

- there was a fundamental mismatch between the goals of the EMDET project to provide the desired competency to practice with EMD systems as measured by war story scenarios and the educational goals of the PED course used as an acceptance test. The focus of the desired competency requires students to draw on skills and knowledge from throughout the entire undergraduate engineering curriculum, these must be combined and applied in the ensemble performance required by the war story scenarios. The objectives of the PED course solely focus on the knowledge within the specific component of the curriculum, not on the summative understanding needed to successfully practice with EMD systems. This means a student can learn enough to pass the PED course but not reach the standard desired by the EMDET. The pragmatic restriction of the acceptance testing was that the PED course was the only realistic entry point for the EMDET into the undergraduate or postgraduate curriculum, and while this could not be helped the relative weighting of the war stories in acceptance testing may have been different

- during laboratory teaching a number of students appeared to lack the specified pre-requisite knowledge for the laboratory exercises, both in terms of English literacy and technical knowledge. The length and content delivered within the laboratory classes building towards the war story scenario assessment was based upon the specified pre-requisites, so either more class time is required to cover additional material, or the pre-requisites should be applied more stringently to class enrolment
- multiple reflective iterations of the project over a period of years to address poor performance in the war story scenarios as part of the project. These iterations come close to violating the fundamental definition of a project as a temporary activity [ref Nicholas and Steyn, p xxvi] and may more properly be viewed as ongoing teaching development of a laboratory teaching subject as opposed to acceptance testing of a project to provide equipment and curriculum
- using an unrealistic target of a high proportion of students achieving success in all the war story scenarios. Successful completion of war story scenarios is aspirational and depends upon many factors, some of which are outside the control of the project team and Users

14.3.3 Start

The following are suggested improvements for any future projects similar to the EMDET project using the WiSE approach based on issues that were not anticipated or properly dealt with during the execution of the EMDET project.

- the amount of unpaid labour put into project (postgraduate researcher and industry partner in-kind support) was not quantified, so accounting for this time in future projects would allow a better evaluation of the human effort needed to use the WiSE approach in circumstances where all labour is financially supported by the project budget
- finding a more realistic benchmark for war story performance rather than a 100% success rate, in particular looking for a relative improvement in student performance on the war story performance may be a more appropriate starting point. The fit of the comprehensive nature of the war story scenario assessment should be reviewed in the context of the broader under-graduate and post graduate curriculum. If the broader curriculum does not support this level of learning it is doubtful if two laboratory sessions within an isolated elective is enough to instil the desired wisdom for practice with EMD systems. Simply put, a more pragmatic view of what success in teaching should look like in needed as the project deliverable for acceptance testing, taking into account the broader curriculum
- the assessment weight of the war stories should be reviewed to improve student participation rates. The decision to not assign any weight in assessment may have caused the relatively low participation rates seen in the war stories.
- A number of issues were encountered with software licensing on the personal computers provided in the Power Electronics and Drives Laboratory. The EMDET equipment was developed on typical stand alone computers with full software administrator rights, while the equipment provided in the laboratory used complex networked based 'images' of computers which caused numerous issues with the software that were not evident with stand alone model
- a number of issues were encountered with nuisance tripping of the domestic Earth Leakage Circuit Breaker (ELCB) protection of the power supplies used by the EMDET equipment. The ELCB's fitted to the supplies were incompatible with PWM inverter equipment and should be replaced with compatible industrial ELCB's
- the laboratory demonstrators should be used to provide more input into the development process because a number of useful insights were provide by the grounded theory analysis employed in 2015. Using a formal (but possibly less onerous than the grounded theory method) feedback process with the laboratory demonstrators may have provided these useful insights earlier in the iterative process
- producing better operating documents and references for the EMDET as the project only provided drawings and copies of the final software packages.

- during the laboratory classes students were not focused on the physical behaviour of the motor shaft and were often fixating on consumption of current. Electric motors exist to drive mechanical loads and this should be the focus, possibly the movement of the motor shaft should be made more visible, and the laboratory exercises direct more attention to it.
- the use of short videos to introduce the equipment to students should be investigated; they could be made available to students prior to the laboratory and help introduce them to the equipment more quickly
- investigate making laboratory pre-work assessable. As a number of students seemed to lack pre-requisite knowledge that was presented as introductory materials in laboratory exercises
- during the development of the EMDET issues arose in a number of circumstances that can be formulated as questions for project teams to guide them during the design process, these include:
  - what proportion of students having a specific difficulty with the curriculum materials would prompt a reflective iteration to the curriculum? Is this a minority of students or a majority? A common occurrence is that students lack or cannot recall some component of their prerequisite knowledge, so is the curriculum to be increased at each and every instance of a student having difficulty with prerequisites?
  - what is the expected role of the laboratory demonstrator in supporting the curriculum? Will the project deliverables be accepted by the users if issues experienced by a minority of students are dealt with by the laboratory demonstrators?
  - an explicit listing of the infrastructure that the User must supply during acceptance testing, e.g. Personal computers, power supplies, etc. These should be viewed as project resources
  - what does success in teaching look like? How many students can realistically be expected to attain the desired wisdom?
- an outline during the requirements and specifications stage of what would trigger a reflective iteration during the system testing and acceptance testing phase and who is responsible for providing the resources for this? For example, if students are not achieving the desired competency due to malfunction of equipment provided by the project, the project team would be expected to provide the resources for the iteration, but if the issue was due to students not possessing the specified prerequisite knowledge the Users would be expected to provide the resources to address this issue. The circumstances considered should include:
  - if the deliverables do not meet the agreed specifications or requirements

- typically the project team would be exited to address this
  - if the requirements do not accurately reflect the Users actual need (a user issue)
  - if the specifications do not accurately reflect the Users actual need (project team)
  - conditions of use for the project deliverables do not conform to the agreed specifications (Users)
- while operating the equipment, support and licensing for the ASTRA HMI software became difficult due to poor manufacturer support. Alternative software should be investigated

14.4 Significant project Success and Failures

Based upon the outcome evaluation, the EMDET project was judged as an overall success due to delivering equipment that was accepted by the users within the specified time and budgetary constraints. The following were identified as significant subsidiary successes and failures by collectivity reviewing the outcome evaluation, component evaluation, and lessons learned reflective evaluations.

- the success of the prototype in gaining sufficient acceptance from the stakeholders to fund the development and construction of the production model EMDET was identified as a significant success
- the acceptance of the production model EMDDET on the basis of the performance of the equipment and student performance in the laboratory workbooks was identified as a significant success
- the completion of both prototype and production model within acceptable budget limitations was identified as a significant success
- a key reason for the budgetary success of the EMDET is the amount of expert labour utilised at no financial cost to the project. If this free labour (industry partner and researcher) had to be financially supported by the project it would have exceeded its budget significantly. While it could be considered part of the budgetary success it is explicitly assessed becuase it poses a significant risk of failure to future projects

- the poor student performance in the war story assessment, and the failure to improve this to the desired levels in spite of repeated iterations was identified as a significant project failure

The impact of the novel project process on these successes and failures will be examined during the overall synthesis in section 18.

Chapter 15

Analysis: Pattern Matching

The second key question of the study was to determine what the impact of the novel project process was on the project successes and failures. As a step towards addressing this a pattern matching analysis was used in the overall synthesis methodology, as shown in Figure 15.1 to establish what the impact of the WiSE approach was on the EMDET project.

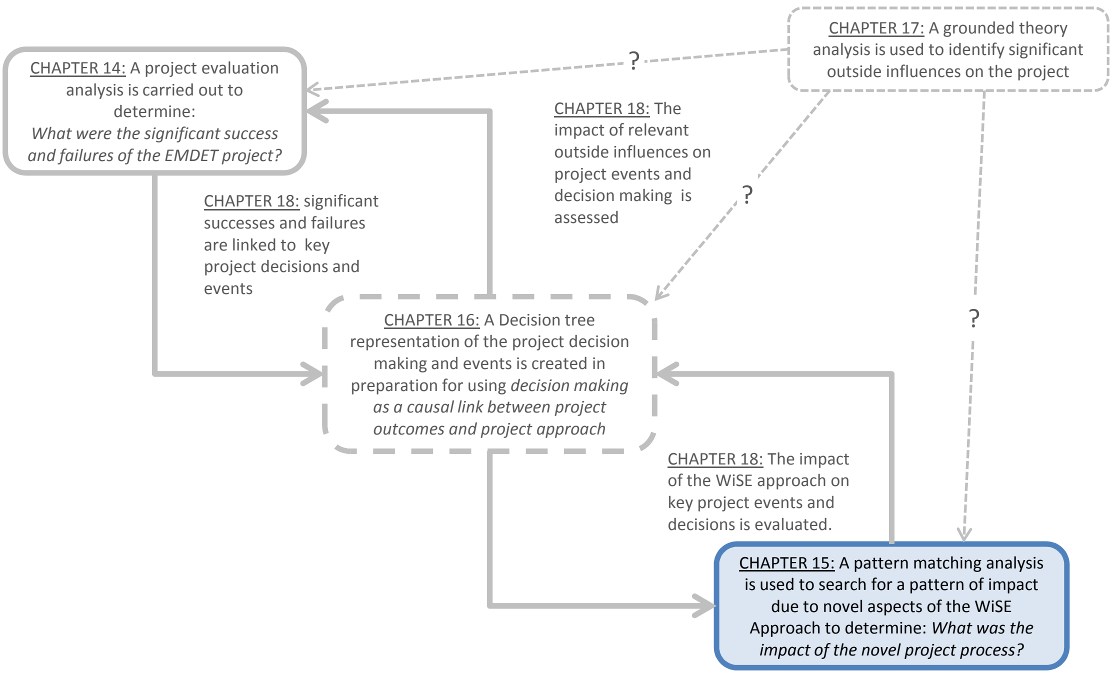


Figure 15.1: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

The pattern matching analysis was used to determine both if there was an impact from the novel aspects of the WiSE approach on the EMDET project, and how these impacted the project.

The first proposition within the methodology (Section 4.2) posits that there is a predictable pattern of impacts (direct and indirect) on the project as a result of using the WiSE approach; furthermore, that these are related to the WiSE augmentations. The individual augmentations were considered and their potential *direct* impacts (positive and negative) on the project were predicted, and are presented in Table 15.1 for comparison with the empirical data from the case study.

WiSE Augmentation	When reviewing the project process, decision making or the products of the project the following should be evident if:	
	If the augmentation is effective and beneficial:	If the aspect is not effective or is detrimental:
Measure of student competency	There is a measurable definition of competency and it is used in curriculum and equipment design	There is no definition or there is no evidence of its use in design
Deliverable of project is student competency	Project success has been assessed using the measure of student competency; potentially leading to iterative changes on the basis of testing	The competency measure has not been used, or it has not been used to gauge success.
Scope of delivery is integrated equipment and curriculum	Both equipment and a complete curriculum are delivered.	Either no curriculum or a partially complete curriculum is delivered with the equipment.
	There should be no unexpected limitations placed on the curriculum by the equipment.	The curriculum finds unexpected limits imposed on it by the equipment.
	There should not be unresolved conflicts between laboratory equipment and curriculum - there may however be known and deliberate design compromises. There have potentially been project iterations due to conflict between equipment and curriculum.	There are unresolved conflicts between equipment and curriculum.
Reflective closed loop project methodology	There is evidence of closed loop reflection; it has affected the project. Student performance against a standard has resulted in changes to equipment and curriculum; potentially including project iterations.	There are no changes in equipment or curriculum based upon observed student outcomes.
	In the expectation that reflective changes would be necessary equipment and curriculum delivered allowed for these.	The equipment and curriculum are rigid and not easily adapted.
Closed Loop model of education	Interactions between equipment, students, assessment and teaching either predicted by the model or interpreted with the model have impacted the project. Potentially initiating project iterations.	There is no evidence of these interactions affecting the project or other models of education have been used.

Table 15.1: Predicted pattern of direct impact on the project as a result of using the WiSE approach

The individual augmentations of the WiSE approach were also considered for their potential to indirectly affect the project, whereby the augmentation interacted with the parent vee model process to affect outcomes. Table 15.2 presents the predicted pattern of indirect impact for comparison with the empirical data from the case study

	When reviewing the project process, decision making or the products of the project the following should be evident if the WiSE augmentations have interacted with the Parent Vee model	
	In a beneficial manner	In a detrimental manner
Applicable to all five augmentations	Outcomes from augmentations gained strong or widespread acceptance by the users	Augmentation poorly accepted
	Outcomes from augmentations have gained strong acceptance (important to the user) were incorporated into the project form an early stage potentially with gains in efficiency	The level of acceptance by the end users did not justify the expenditure of time and resources, particularly if project iterations were initiated
	Time and cost implications may not be apparent.	Blending equipment delivery with curriculum development and delivery was not worth the time and cost; for example in comparison to equipment delivery being separate from curriculum development and teaching
	Additional requirements for expertise may not be apparent.	The combination of educational and technical expertise required by the project was not worth the expenditure; either in having extra staff or finding staff capable in both areas
Measure of student competency	The measure has received acceptance from the end user.	The measure is not accepted, for example it is not used or its effectiveness is disputed.
Deliverable of project is student competency	The closed loop approach has led to curriculum and equipment accepted by the user.	Equipment milestones were not reached and there is a perception that this was due to time spent on competency related work.
	No specific project over-runs are identified in relation to the project deliverable of student competency.	The project has over-run as the distinction between the project delivering equipment and curriculum and ongoing teaching activities into the future is not clear.
Scope of delivery is integrated equipment and curriculum	No conflicts between equipment and curriculum integration and project progress were noted.	Equipment time and cost targets were not met and there is a perception that this is due to conflicts with curriculum development.
Reflective closed loop project methodology	Holistic project and educational view allowed for requirements to be amended for overall project economy, e.g. A failure to meet early equipment specifications later found not to impact on educational outcomes did not lead to unnecessary re-work.	No amendment of requirements was allowed.
	The project team involvement in teaching has resulted in ready acceptance from The users or equipment and curriculum.	Unnecessary time and money was spent having the project team involved with teaching. Little or no interaction between project team and teaching - no substantive action resulted from their involvement
Closed Loop model of education	Equipment development concerns requiring solutions with educational foundations were resolved efficiency using the model.	Time lost and resources expended due to staff unnecessarily working outside their field of expertise (technical staff working on education).

Table 15.2: Predicted pattern of indirect impact on the project as a result of using the WiSE approach

The predicted impacts were correlated with the empirical evidence from the EMDET case study and the results were compiled quantitatively and qualitatively in readiness to map to the decision tree described in section 16.

15.1 Assessment of Direct Impact

The novel aspects had a clear and beneficial *direct* impact on the conduct of the EMDET project; Table 15.3 is an overall count of the positive instances of direct impact predicted in Table 15.1 that were observed during the review of the case study presented in Part II. All the direct impacts were beneficial, and no instances of predicted detrimental direct impact were observed during the review. All phases of the project were directly impacted, and all five augmentations impacted the conduct of the project.

Table 15.3: Direct impacts of the project process on the EMDET.

	Requirements (Chapter 5)	Specifications (Chapter 6)	System Design (Chapter 7)	Detail Design (Chapter 8)	Assembly (Chapter 9)	Component Test (Chapter 10)	Integration Test (Chapter 11)	System Test (Chapter 12)	Acceptance Test (Chapter 13)	TOTALS
Measure of student competency	2	3	1	3	4	1	1	1	4	20
Deliverable of project is student competency	3	6	4	4	10	5	2	7	6	47
Scope of delivery is integrated equipment and curriculum	3	10	5	19	13	14	10	13	7	94
Reflective closed loop project methodology	1	4	4	16	7	10	10	7	7	66
Closed Loop model of education	4	3	3	10	11	8	4	5	5	53
	13	26	17	52	45	38	27	33	29	

For each augmentation, observations of its direct impact were taken from throughout the project, due to the large number of observed direct impacts they were assessed for key themes and exemplary instances of these themes were selected from within the EMDET case study. These are detailed in sections 15.1.1 to 15.1.5 and summarised in figure 15.2.

15.1.1 Measure of Student Competency

This augmentation had a direct beneficial impact on the EMDET project. A measurable definition of competency was established within the initial stages of the project, this was defined as students who could practice with wisdom in the field of EMD systems in the requirement phase (evidenced in Section 5.1.7 of the EMDET Case study presented in Section II). A measure for this competency was the war story scenario that was initiated in the Requirement phase (section 5.1.7) and was developed sequentially in the Specifications (sections 6.5.6, 6.5.7), Assembly (Section 9.1.1) and System Test phases (section 12.3.1). During the design phases the war stories and wisdom inspired reflective design of equipment and curriculum, particularly asymmetrical sizing of the EMDET motors described in section 7.7.2). During testing with students the war stories prompted reflective iterative changes to address shortfalls in student performance.

15.1.2 Deliverable of Project is Student Competency

This augmentation had an evident direct beneficial impact on the EMDET project, both in terms of the assessment of project success and on the development of equipment and curriculum. The project success was measured at the acceptance testing phase using war story scenarios, laboratory work books and direct observation acting together as a composite assessment instrument. A number of iterative reflective changes were made to the equipment and curriculum based on the outcomes of this assessment.

In reviewing the EMDET project it is evident that the aim of providing the desired competency had numerous observable impacts on the equipment and curriculum development throughout all phases of the project. The observed impacts can be usefully grouped together under two main themes: wisdom as a project goal and fidelity in the laboratory experience.

The goal of wisdom shaped the curriculum development throughout the EMDET project. This was particularly evident in the statement of objectives in content behaviour form developed in the Specifications phase (section 6.5.3), the lesson development using the Tyler Rationale in the Detailed Design (section 8.4), and the creation of the laboratory workbooks during the Assembly phase (section 9.1). Representative examples of how the goal of wisdom affected curriculum development include the reflective changes made to add introductory scenarios to each laboratory to help students make connections between laboratory work and engineering practice and therefore provide motivation for learning in section 9.1 and placement of relevant key questions throughout the laboratory exercises to promote higher levels of learning as defined by the SOLO Taxonomy that build towards the desired wisdom.

The motivation behind the provision of fidelity was to make the cognitive leap between learning in the lab and industrial practice achievable for students. From an equipment and curriculum perspective fidelity in these terms means making the experiences within the teaching laboratory sufficiently close to industrial practice. There are numerous instances of where the provision of fidelity has impacted both the equipment, and the curriculum developed. Significant examples include:

- the philosophy of fidelity was established to guide equipment design during the Specifications phase (section 6.1.2)
- the use of real industrial equipment in a typical industrial configuration
- the extensive efforts put into the torque control and simulation of real world loads
- the creation of laboratory exercises that included common real world industrial tasks
- the investigation and reduction of EMC noise on sensor inputs

The philosophy of fidelity was established to guide the design of equipment during the Specifications phase (section 6.1.2); it significantly affected the design of equipment in the subsequent System Design (Sections 7.1 7.7.2) and Detail Design Phases, along with the corresponding verification in the System Test phase (Section 12.2.1).

The use of real industrial equipment in a typical industrial configuration was motivated by the need to provide fidelity, this included the mechanical equipment, electrical equipment and software. This decision was made early in the project (in the Specification phase Section 6.1.2) and was carried through the design, construction and testing phases to the finished product.

The extensive efforts put into the torque control and simulation of real world loads to provide fidelity was evident throughout the system design (section 7.6), detail design (section 8.2.2), assembly (section 9.3.1) and component testing (section 10.1.2.1). The development of the pumping system simulation (Sections 8.2.3, 9.3.1 and 9.3.1) was an exemplar of this effort.

The creation of laboratory exercises that included common real world industrial tasks for fidelity including using a standard industrial safety process to identify hazards, risks, and controls for a simple industrial task. Significantly this included the use of a real emergency stop system and the reset process to re-start the system afterwards, as described in the Integration Test phase (section 11.1.1).

The investigation and reduction of EMC noise, in particular on the torque signal, during Component Testing (section 10.2.1.2) was motivated by the provision of fidelity. Here the value of providing students with the experience of noise on a real world signal was recognised, this was balanced against the potential for the noise to be an unnecessary and obstructive cognitive leap for students. In this case the noise was reduced by shielding and altering drive switching frequencies; however, no attempts were made to eliminate it entirely such as by software filtering in the data acquisition system. This was left as an instructive exercise for students.

15.1.3 Scope of Delivery is Integrated Equipment and Curriculum

This augmentation had an evident direct beneficial impact on the EMDET project in terms of the pattern of predicted impact, including delivery of complete equipment and curriculum, the integration of the equipment and curriculum, limitations imposed on the curriculum by the equipment, and conflicts between equipment and curriculum.

15.1.3.1 Both Equipment and Curriculum

The observations on the impact of this augmentation can usefully be grouped into three key themes: the curriculum design methodology, integration of equipment and curriculum and the delivery of functioning equipment and curriculum. Within the EMDET project an in depth curriculum design methodology was formulated and executed throughout all phases of the project. This methodology was established during the specification phase (section 6.3) and implemented in the succeeding System Design (section 7.1), Detailed Design (section 8.4), and Assembly (section 9.1) phases. This methodology started with generating the educational objectives, developing them into content behaviour format, using the Tyler rational to break them into a curriculum, and culminated in the production of the war story assessment scenarios and laboratory work books. These were then tested throughout the Component Test (section 10.4), Integration Test (section 11.1), System Test (section 12.1) and Acceptance Test (section 13.1) phases.

During the early stages of the EMDET project explicit methods were established to link the development of the equipment and the curriculum, which were then used throughout the entire project. In particular, during the Specification phase the philosophy of equipment constitution was formulated in section 6.1.1 stating that the EMDET must necessarily consist of hardware, software and curriculum, and all of these elements must be mutually compatible and function together to allow the curriculum to be delivered. During the specifications stage a linkage matrix was established as described in section 6.2.3 that created a link between the operational and educational concerns and the design of the major groups of equipment identified at that stage. The linkage matrix was used during the system test to verify that the equipment could deliver on the specified operational and educational needs.

The linkage between equipment and curriculum development was active throughout the entire project with a continual symbiotic interaction between equipment and curriculum development. There are numerous instances of the equipment development being driven by the requirements of the curriculum, this is exemplified by the design, selection, construction and testing of the data acquisition system described in the System Design (section 7.4), Detailed Design (section 8.1.3), Assembly (section 9.3.3) and Component Test (section 10.2.1) phases. While the curriculum typically to drive the equipment design, the converse also occurred, such as the deliberate inclusion of EMC noise on the torque signal used in the motor curve generation exercise described in the Integration Test (section 11.1.3) and Acceptance

Test (section 13.1.3) phases.

The EMDET project delivered fully functioning equipment and curriculum that was used successfully to teach within three PED courses from 2012-2015. The integration test, system test, and acceptance test phases all concentrated on delivering equipment and curriculum that worked together for the end user (demonstrators and students); during these phases a number of iterative changes were made in both equipment and curriculum to properly integrate them. The acceptance of the EMDET was based on student submissions using the final curriculum executed on the equipment (Section 13.3). The equipment also demonstrated the capabilities needed to teach all the material to be addressed by the EMDET which would not fit within the PED course curriculum described in section 6.5.3 during the components testing and integration testing phases.

15.1.3.2 Limitations on Curriculum

A review of the EMDET project for any unexpected limitations placed on the curriculum by the equipment revealed several beneficial impacts made by the augmentation. These can be grouped under four key themes: visibility of relevant physical phenomena, equipment suitable for student use, torque simulation, and testing for integration of equipment and curriculum.

Throughout the EMDET project extensive efforts went into ensuring that all the physical phenomena required for the curriculum were present, visible to the students, and of suitable quality to deliver the teaching. During the specification phase, the design philosophy of flexibility was established, including an aspect stating that the current and future teaching needs can be met by ensuring that the important physical phenomena within the system is present and visible (section 6.1.3). The effects of this philosophy were evident in the subsequent design, assembly and testing of the data acquisition system. During the design phases the type, location, and measurement references of all the sensors were carefully considered to ensure that the required currents and voltages were visible and enabled the measurement of power flow throughout the system. Particular examples of this include providing a selectable reference for voltage measurements on the motors and the placement of the current sensor in the delta connected motor 2 described in the Detail Design phase (section 8.6.1) facilitating the students use of a single phase equivalent circuit analysis, which was important to curriculum delivery. Significant attention was paid to the quality and visibility of the physical phenomena, the transient response of transducers, and sampling frequencies of the associated data acquisition systems were carefully considered in the design phases to ensure that the impacts of PWM inverter switching frequencies were visible to students to enable teaching in this area. Throughout the component phase in particular (section 10.2), the quality and visibility of the signals and the performance of the installed data acquisition system were checked to ensure they met the requirements of curriculum developed. These efforts aimed to ensure that the curriculum would not be limited by the availability and visibility of relevant phenomena.

Throughout the design and construction of the EMDET decisions were made to ensure that the equipment would be suitable for student use and not put unnecessary limits on curriculum delivery. Specific examples include the selection of voltage transducers, the method of reconfiguring equipment, and the role of the PLC. The contextual specification (section 6.6) stating that students should not be required to interact with dangerous voltages beyond their ability to work with safely resulted in the selection and installation of appropriate voltage transducers to reduce dangerous LV signals to safe LV signals before connection to data acquisition systems and any potential student interaction. The design of the EMDET means that any reconfiguration of drive or load is carried out remotely by the PLC without direct human intervention as per the specifications (section 6.6) to avoid risks to students. The PLC also plays a protective role on all requests to stop and start equipment and change the configuration, as determined by the Detailed Design (section 8.2.1) which avoids risks to equipment from inadvertent operation by students. Consequently the curriculum is not restricted by concerns that reconfiguration of loads or drives might pose risks to students and equipment.

Throughout the design, construction and testing of the EMDET significant efforts were put to controlling the torque of motor 2 so it could simulate a variety of real world loads as required by the specified curriculum and potential future teaching. These included the design of the load simulation during the System Design (section

7.6) and Detail Design (section 8.2.2) phases, the execution of the load simulation during Assembly (section 9.3.1), and extensive testing and tuning as during Component Testing (section 10.1.2.1) and Integration Testing (11.1.5). The ability of the system to simulate various real world loads such as the pumping system (described in section 10.1.2.3) means that no restrictions were placed on the current curriculum by the load performance; moreover, this reduces the potential that any future curriculum would be similarly restricted.

In reviewing the EMDET project it is clear that extensive testing was undertaken to ensure that the equipment and curriculum were properly integrated during the component, integration, system and acceptance testing phases. The extensive testing carried out during these phases resolved many issues that could have restricted curriculum delivery due to equipment issues.

15.1.3.3 Conflicts Between Equipment and Curriculum

The EMDET project was reviewed for evidence of conflicts between equipment and curriculum and whether these were resolved. Three significant conflicts were found, all of which were resolved. The first was the addition of a switchable reference for voltage transducers during the Detail Design phase (Section 8.6.1); the second conflict was revision of the motor sizing to allow the EMDET to plot the motor torque speed curve with symmetrical motors (Section 7.7.2); the third was using an induction motor and regenerative drive as a load rather than a real mechanical load as determined in the Specifications phase (section 6.7.1), this was a known, deliberate, and accepted design compromise

15.1.4 Reflective Closed Loop Project methodology

This augmentation had a direct beneficial impact on the conduct of the EMDET project both in terms of reflective changes, and in capacity for future reflective changes built into the equipment and curriculum delivered. It became clear while reviewing the EMDET project for the impact of the reflection augmentation it became clear that the concept of reflection needed to be expanded beyond its common usage in reflective teaching which is defined as 'making changes to teaching after reviewing the impact of teaching on students using a theory of teaching' J. Biggs (2003)(p 7). While many changes in equipment and curriculum were indeed prompted by reflecting on student performance, many changes made to improve student outcomes in the project prior to any teaching with students. These changes were made by reviewing the design produced, the equipment assembled, or the result of verification testing and reflecting on the potential impact (of the design, equipment or equipment performance) on student performance using the closed loop model of education and finding changes were needed to improve likely student outcomes . These changes could be variously termed as educationally: *reflective design*, *reflective construction* or *reflective verification testing*, however the important point is that they are all **reflective** changes. The EMDET project was reviewed in its entirety for reflective changes regardless of whether they were prompted by student performance, or by an anticipated potential impact on student performance.

Many reflective changes were observed while reviewing the EMDET project to assess the impact of the augmentation; these changes could be usefully grouped according to what prompted the reflective change and what was affected by the change (hardware, software or curriculum). Prior to any student involvement in the EMDET project changes were prompted by three key motivators: the result of verification checks against earlier stages (requirements, specifications, system design or detail design), resolving a problem with integration between equipment and curriculum or solving equipment design problems that needed educational input to the solution. There were many observed instances of reflective changes made because a verification stage check identified a shortfall in performance. These shortfalls including equipment unable to deliver the results required by the curriculum, unclear experimental procedures, experimental processes that did not produce a sufficiently distinct physical phenomena, and assessment questions that were not properly aligned to the educational outcomes.

Among the many examples of equipment shortfalls identified during verification checks important examples include the asymmetrical sizing of motors to enable generation of the motor curve during the System Design phase (section 7.7.2) and placement of current transducers on the motors to enable the use of single phase equivalent analysis during the System Test phase (section 10.5.1). Examples of changes to experimental process and procedure include additional steps introduced in the motor characteristic tests and increasing the operating frequencies tests were conducted at to make the impact of motor field weakening clear during the Integration Test phase (section 11.1.4). An example of assessment not properly aligned to the educational outcomes was addressed during the Integration Test phase (section 11.1.4) where it was found that none of the student review questions in the motor characteristic lab exercise dealt with the key educational objective of relating motor slip and torque.

With the advent of student involvement in the EMDET project during the acceptance testing phase, reflective changes were prompted by student performance in the written assessment materials (lab books and war story scenarios) or direct observation of the students. Student performances within the war stories in particular prompted reflective changes to the curriculum over a number of cohorts including an extensive re-working of the laboratory exercise investigating induction motor magnetising current during Integration Testing (section 11.1.4) and the inclusion of introductory scenarios to the lab work books and key questions through the text of the lab exercise to promote the deeper student learning described during the Assembly phase (sections 9.1 and 9.5.1). Student performance in the laboratory work books also prompted changes during the Acceptance Test phase including the addition of the process guide to create a motor characteristic curve (section 13.1.3) and rearranging the motor, drive and load experiments to better contrast the performance of a soft starter against a PWM inverter in driving a constant torque load (section 13.1.7).

Throughout the EMDET project extensive allowances for future reflective changes were built into the equipment and curriculum. Notably, the design philosophy of flexibility was established during the Specifications phase to guide the design phases, one element of which stated that equipment should be flexible and future proofed (section 6.1.3). As a result of this philosophy the design of the EMDET included three drives and a large number of simulated load types that could be combined and used in many different permutations and combinations for different educational purposes. To complement this the code within the PLC controlling the equipment was modular and flexible enough to allow the different loads and drives to be easily utilised.

The philosophy of flexibility also required that all important physical phenomena were present and visible (section 6.1.3); this motivated the design and commissioning of the data acquisition system, including placement to monitor power flow throughout the entire EMDET in the Detailed Design phase (section 8.1.3), the selection of the sensors, and testing to ensure that the signals acquired were good enough to deliver the curriculum during the Component test phase (section 10.2.1).

Elements of the philosophy of flexibility also interacted beneficially with each other to provide important outcomes in the EMDET system such as the number of potential lessons that could be taught with the EMDET, all the possible permutations and combinations of simulated loads, drive combinations and sensor outputs from the data acquisition system yield potential future lessons. In particular, the user defined load torque speed characteristic (sections7.6 and 8.2.2) potentially enables many different lessons on load behaviours to be taught. These lessons can easily be realised due to the modular coding within the PLC, so new laboratory exercises only need new HMI screens to suit the lessons being delivered.

15.1.5 Closed Loop Model of Education

This augmentation had an evident direct beneficial impact on the EMDET project in that it was used extensively in developing both equipment and curriculum throughout the project, including the design, construction, and commissioning phases. This model was used to deal with issues involving equipment or curriculum in isolation, however, it also proved effective in addressing issues where interactions between the equipment and curriculum could (or did) impact on student educational outcomes. During the early stages of the project the model was used in a predictive fashion to guide design and development, whereas in the later stages it was used in a diagnostic role during the commissioning and testing phases.

The curriculum was extensively influenced by the closed loop model of education during both the design and assembly phases; it began during the requirements phase (section 5.1) where the educational requirements explicitly used the closed loop model in their development. These requirements, together with continued use of the closed loop model influenced the curriculum throughout the remainder of the project. The requirements and model drove the curriculum design methodology during the Specifications phase (section 6.3) and underpinned the subsequent detailed educational specifications (section in 6.5). The model was again used explicitly during the detailed design phase, resulting in the creation of the Tyler Tables for each lesson in section 8.4. The model continued to be used during the Assembly phase when creating the laboratory work books (section 9.1).

The design and construction of the equipment was also informed by the closed loop model of education, particularly where a technical design issue needed educational input into its solution. Significant examples of this include the decision to establish the measurement of a single phase of power flow around the EMDET within the data acquisition system to match student teaching during Detailed Design (section 8.1.3); selection of voltage transducer references and placement of current transducers to avoid unnecessary and obstructive cognitive leaps for students during the Detailed Design and Component Test phases (sections 8.1.3); and 10.5.1) and to reduce but not eliminate electromagnetic noise on the torque signal during the Component Test phase (section 10.2.1.2).

The closed loop model was very useful in resolving issues where the interaction of equipment and curriculum impacted on student learning throughout the design, construction, and commissioning of the EMDET. Typically, some adjustment was required to eliminate unnecessary cognitive leaps from the laboratory exercise, either equipment was adjusted to suit the curriculum, or the curriculum materials were altered to suit the equipment operation.

Compelling examples of adjustments to the equipment include the work to ensure that signals were recognisable to students during the Detailed Design Phase (section 8.1.3), implementation of an automated loading sequence in the Integration Test phase for measurement of the motor torque speed characteristic (section 11.1.3), and creation of a specific virtual instrument that only logged the relevant system parameters for students during the Assembly phase (section 9.3.3). Examples of adjustment to the curriculum materials include creating a tabular format for the laboratory instructions described during the Assembly phase (section 9.1) so that students could use unfamiliar industrial equipment, and introducing an extra step as educational scaffolding in the laboratory procedure for measuring the motor torque speed characteristics where students tested the data acquisition system before measuring the motor character during the Integration Test phase (section 11.1.3).

Finally the closed loop model was extensively to address issues with student performance during the project test phases; examples include addressing student issues with generation of the induction motor torque speed curve, being able to identify the significance of induction motor magnetising current, and recognising the importance of appropriate load and motor drive combinations. During Acceptance Testing especially, the closed loop model was used to address issues with student performance, identifying cognitive leaps and assisting in developing changes to address the leaps. This led to the development of the process guide to address issues with motor curve generation (section 13.1.3). The model facilitated analysis of coaching given by demonstrators to assist with student performance in war stories recognising the current consumption behaviour of an induction motor and magnetising current (section 13.1.5). After analysis, the coaching was incorporated into the written lab books. The model led to changes to the laboratory work books and HMI as educational scaffolding to make the differences in drive performance with different loads stark for students (section 13.1.7).

15.1.6 Summary of Observed Qualitative Direct Impact

Figure 15.2 summarises the observations of direct impact from throughout the project detailed in sections 15.1.1 to 15.1.5.

WiSE Augmentation	If the augmentation is effective and beneficial:	Empirical evidence
Measure of student competency	There is a measurable definition of competency and it is used in curriculum and equipment design	The measure of student competency was established as students that could practice with wisdom in the field of EMD systems. A composite measure was developed for acceptance testing including student laboratory work books, war story scenario assessment and direct observation. War stories prompted iterative changes to equipment and curriculum before and after student teaching.
Deliverable of project is student competency	Project success has been assessed using the measure of student competency; potentially leading to iterative changes on the basis of testing	Empirical evidence of: - Assessment of project success based upon student competency - Development of curriculum and equipment motivated by the deliverable of student competency - A number of iterative improvements in equipment and curriculum based upon student assessment outcomes.
Scope of delivery is integrated equipment and curriculum	Both equipment and a complete curriculum are delivered.	- In depth curriculum design methodology formulated and implemented - Explicit methodologies and significant efforts to link equipment and curriculum development - Fully functioning equipment integrated with curriculum delivered.
	There should be no unexpected limitations placed on the curriculum by the equipment.	- Significant effort expended to ensure physical phenomena relevant to the curricula was present and visible. - Design of equipment and its operated driven by the need to be suitable for student use. - Significant effort expended to ensure that load torque simulation is accurate and flexible to suit current and future teaching needs. Equipment design and operation

(a) Qualitative correlation of direct impact of the project process part 1

	There should not be unresolved conflicts between laboratory equipment and curriculum - there may however be known and deliberate design compromises. There have potentially been project iterations due to conflict between equipment and curriculum.	Evidence of significant potential conflicts between curriculum and equipment operation identified and iteratively rectified including known and deliberate design compromises.
Reflective closed loop project methodology	There is evidence of closed loop reflection; it has affected the project. Student performance against a standard has resulted in changes to equipment and curriculum; potentially including project iterations.	Reflective changes to equipment (hardware and software) and curriculum prior to student involvement prompted y: - Verification checks against design stages - Resolving an integration problem between equipment and curriculum - Solving an equipment design problem requiring educational input Reflective changes to equipment and curriculum post student involvement prompted by: - Student performance in written assessment - Direct observation of students
	In the expectation that reflective changes would be necessary equipment and curriculum delivered allowed for these.	Design philosophy of flexibility established that significantly impacted the EMDET design, prompting a variety of equipment to be included in the EMDET that can be combined in a modular fashion.
Closed Loop model of education	Interactions between equipment, students, assessment and teaching either predicted by the model or interpreted with the model have impacted the project. Potentially initiating project iterations.	The closed loop model of education was used extensively in developing both equipment and curriculum and in the testing and commissioning phases. The model proved particularly useful in solving technical equipment design issues that required educational input.

(b) Qualitative correlation of direct impact of the project process part 2.

Figure 15.2: Qualitative correlation of direct impact of the novel aspects of the project process on the EMDET

15.2 Assessment of Indirect Impact

Throughout the EMDET project the novel aspects had a mixture of beneficial, detrimental and potentially detrimental *indirect* impacts on the conduct of the EMDET project. Table 15.4 is an overall count of the instances of indirect impact (both beneficial and detrimental) observed during the review of the case study presented in Part II. The indirect impacts were less frequently observed than the direct impacts, many predicted indirect impacts involve user acceptance and will therefore only be present in the phases of the project including user involvement: System Test (section 12) and Acceptance Test (Section 13).

Table 15.4: Indirect impacts of the project process on the EMDET.

	Requirements (Chapter 5)	Specifications (Chapter 6)	System Design (Chapter 7)	Detail Design (Chapter 8)	Assembly (Chapter 9)	Component Test (Chapter 10)	Integration Test (Chapter 11)	System Test (Chapter 12)	Acceptance Test (Chapter 13)	TOTALS
Measure of student competency	1	3	0	1	3	0	0	0	3	11
Deliverable of project is student competency	1	3	0	1	3	1	0	0	3	12
Scope of delivery is integrated equipment and curriculum	1	0	2	4	0	0	1	1	1	10
Reflective closed loop project methodology	0	1	0	0	0	0	0	1	0	2
Closed Loop model of education	1	1	1	3	1	2	0	0	0	9
	4	8	3	9	7	3	1	2	7	

The EMDET case study was reviewed to identify the direct impact of each of the augmentations of the WiSE approach. For each augmentation observations of its impact were taken from throughout the project, due to the large number of observed direct impacts they were assessed for key themes and exemplary instances of these themes were selected from within the EMDET case study. These are detailed in sections 15.2.1 to 15.2.6:

15.2.1 Observed Impact

The predicted indirect impacts on the project due to the interaction between the WiSE augmentations and the parent Vee model are presented in the Methodology in

Table 15.2. Some of these predicted indirect impacts may apply to all the augmentations and some are specific to individual augmentations. The concerns relevant to all augmentations included concerns around the User's acceptance of the outcomes of the augmentation, whether the expenditure due to the augmentation was worthwhile, the time and cost implications of implementing the augmentation, and the requirement for both technical and educational expertise on the project. The specific concerns for each augmentation are addressed below.

15.2.2 Measure of student competency

There were clear interactions between this augmentation and the parent vee model with beneficial effects, detrimental effects, and effects that would be detrimental under different project circumstances. The specific concern for this augmentation was the potential that the User would dispute the effectiveness of the augmentation (war story as a measure of competency) or not use it at all. The final usage of the war story as an acceptance test changed from what was anticipated in the Requirements phase (Section 13.2), due to the unexpectedly aspirational nature of the assessment and the mismatch between the goals of the course and the goals of the war story assessment. During Acceptance testing the original expectations were altered from a high proportion of students succeeding in the assessment to a more pragmatic goal of a modest proportion of students showing relative improvement in the before and after assessment. The difficulty encountered with the war story scenarios tempered User's expectations of this as an assessment tool; while it was accepted, it did not perform as well as hoped. In spite of student performance, the value of the war story to teaching as a diagnostic of high levels of student understanding was accepted, and the value of the war story as an inspiration and motivation for equipment and curriculum development was recognised.

The time and cost implications of this augmentation were not apparent and the development of the war story was incorporated into the project from the requirements phase. However the labour expended developing these was not financially supported by the project, if the labour was financially supported by the project it would likely have caused issues with the project budget. The war stories themselves did not require additional educational expertise to generate because they came from industry survey, however, educational theory was needed to use them to diagnose student understanding.

15.2.3 Deliverable of Project is Student Competency

There were clear interactions between this augmentation and the parent Vee model with beneficial effects, detrimental effects and effects that would have been detrimental under different project circumstances. The specific indirect impacts predicated for this augmentation were that a deliverable of competency may delay or prevent equipment development meeting project milestones and that the project may overrun due to the distinction between a discrete project and ongoing teaching activities becoming ambiguous due to this augmentation.

The equipment was developed and delivered on time to teach the PED course cohort and was accepted on the basis of the equipment performance, student results in the laboratory workbooks, and a reduced expectation of student performance in the war story scenarios. This initial delivery was not unduly delayed by the intended deliverable being student competency. However, the project did engage in two reflective iterations during 2013 and 2015 to address the poor student performance in the war story scenarios with only moderate success. These iterations would conform to the predicted detrimental indirect impact where the approach could make the endpoint of the project ambiguous. This issue relates to the unrealistic expectations of student success in war stories and the need to adjust this expectation that was raised in the outcome analysis in section 14.3.2.

The use of the desired competency to practice was accepted by the User from an early stage and was viewed as an inspirational element throughout development of the EMDET. The time and cost implications of focussing on delivering student competency were not immediately apparent, however caution is due for two reasons: firstly the project could afford to undergo a number of reflective iterations in an attempt to deliver the desired levels of performance in the war story scenarios without incurring financial cost. Secondly, the assessment materials were developed and implemented by labour that was not financially supported by the project. If the labour had been supported financially the outcome would likely have been different. The burden of technical staff gaining educational skills was borne by the researcher without financial cost to the project. This time was used in developing the closed loop model that may help alleviate these concerns in future similar projects.

15.2.4 Scope of Delivery is Integrated Equipment and Curriculum

There were clear interactions between this augmentation and the parent vee model with beneficial effects and effects that may have been detrimental under different project circumstances. The specific indirect impacts predicted for this augmentation were that the time and cost milestones for equipment development were not met due to perceived conflicts with curriculum development. There were no significant conflicts between equipment and curriculum development, and in many instances equipment development depended on concurrent equipment development to allowed designs to be completed.

Setting the scope of the project as the delivery of equipment and curriculum gained strong User support from an early stage and the equipment and curriculum ultimately achieved strong acceptance from the Users (Section 13.3). These were instrumental in passing recent course accreditation for the undergraduate degree (section 13.1) and are an entrenched part of the laboratory curriculum with hopes to expand their usage. Equipment development milestones were not adversely impacted by curriculum development and in some cases relied on curriculum development to allow design to be completed. The goal and outcome of integrated equipment and curriculum was strongly accepted by the Users from an early stage in the project. The laboratory work books and assessment has gained strong acceptance from the Users and justifies the level of expenditure, but due to the unexpected difficulties the war story scenarios were not as strongly accepted.

The time and cost implications were not immediately apparent, however a caution is due as these were developed by labour that was not financially supported by the project, had it been financially supported the outcome would likely have been different. The burden of technical staff gaining educational skills was borne by the researcher without financial cost to the project, and may be an issue under different circumstances.

15.2.5 Reflective Closed Loop Project Methodology

There were clear interactions between this augmentation and the parent Vee model with beneficial effects, detrimental effects and effects that would have detrimental under different project circumstances. The predicted impacts specific to these augmentations were that a holistic project and educational view may allow the requirements to be amended for overall project economy and that involving of the project team in teaching may be a waste of time and resources. There were several significant instances where this augmentation enabled balanced compromises in equipment design between performance and cost, taking into account the educational outcomes that the equipment would deliver. Possibly the most important example of this was the the decision to monitor a single phase of power flow in balanced parts of the EMDET power flow circuit during the Detailed Design phase (section 8.1.3), this was crucial in keeping the unit cost of EMDET within the permissible budget. The involvement of the project team in teaching has allowed for many small technical issues to be quickly identified and resolved during verification tests. While it is difficult to gauge the exact effect, it appears likely that this involvement may have given teaching activities with the EMDET a 'running start'.

The reflective approach gained early acceptance from the User and was used from the initial stages in the project has been vital in the development of some of the most significant features of the EMDET including the decision to include asymmetrical motors and the criteria for circuit waveforms to be recognisable described during the Detailed Design phase (Section 8.6.1). There were detrimental impacts due to this augmentation on the time taken for the project in the form of iterations attempting to address the poor war story performance. These did not cause budget issues due to the staff time used not being financially supported by the project; however, under other circumstances this would likely have been a significant issue. The burden of technical staff gaining educational skills was borne by the researcher, again without financial cost to the project, but in other circumstances this additional cost may have been an issue. However throughout the project the closed loop model was used extensively in reflective iterations and enabled technical staff to dealt with equipment design issues that needed educational input.

15.2.6 Closed Loop Model of Education

There were clear interactions between this augmentation and the parent Vee model with effects both beneficial, and potentially detrimental under different project circumstances. The specific indirect impact predicted for this augmentation was that equipment development concerns requiring solutions with educational foundations could be resolved efficiently using the model. There are numerous significant examples, including the single phase of power monitoring, criteria of recognisable waveforms, motor voltage transducers references, and many more.

The Closed Loop Model of education was accepted by the User, and project team and used it extensively throughout the project from an early stage, and consequently it is viewed as worthwhile. The uptake of the augmentation has been efficient in this regard, facilitating the resolution of equipment to curriculum interface issues, particularly when a compromise is required between equipment performance and cost.

The time and cost implications of the closed loop model are not apparent, however the burden of technical staff gaining educational skills was borne by the researcher without financial cost to the project. However, had this time was financially supported it may have caused issues for the project. There are arguments that the time saved time due the model enabling technical staff to deal with educational issues in equipment design and building without needing recourse to specialist educators may possibly counteract the time taken to develop it.

15.3 Impact of the WiSE Approach on the EMDET project

The pattern matching analysis has clearly identified that the novel aspects of the WiSE approach impacted the EMDET project both directly and indirectly. The direct impacts from all five augmentations were frequent, beneficial (often highly so) and affected all phases of the project. The indirect impact resulting from the WiSE augmentations interacting with the project process were a mixture of beneficial, detrimental, and potentially detrimental under other project circumstances. The main indirect impacts observed were: the additional time spent on iterations to address poor war story performance, the issue of making the project end point ambiguous and the amount of labour used at no financial cost to the project. The amount of labour consumed is a potential issue under different project circumstances where the project was financially liable for this labour.

15.3.1 Match to Decision Making

The empirical evidence gathered for the qualitative impact of the novel aspects of the WiSE approach on the EMDET project was correlated with the significant events and decisions identified in preparation of the decision tree. The results of this correlation were incorporated into the decision tree presented in section 16.

Chapter 16

Analysis: Decision Tree

The second key question of the study was to determine what the impact of the novel project process was on the project successes and failures; this was developed further by the proposition that decision making could form a causal linkage between the impact of the project process (determined by pattern matching analysis) and the final project outcomes (determined by outcome evaluation). Representing this project as a series of decisions on a decision tree is an intermediate stage within the overall synthesis shown in Figure 16.1 to facilitate the linkage .

This section of the analysis presents the decision tree created from a review of the case study in Part II and the subsequent correlation to the outcomes of the pattern matching analysis (from Section 15). The linkage between the project outcomes (from Section 14), decision making, and project process will be established in the synthesis presented in section 18.

16.1 Creation of the Decision Tree

To create the decision tree, the EMDET case study was reviewed and important events and decisions were identified and recorded.Each decision was the further analysed to make subjective judgements on the possible alternatives at that point, and the anticipated relative performance of the option selected against the potential alternatives.

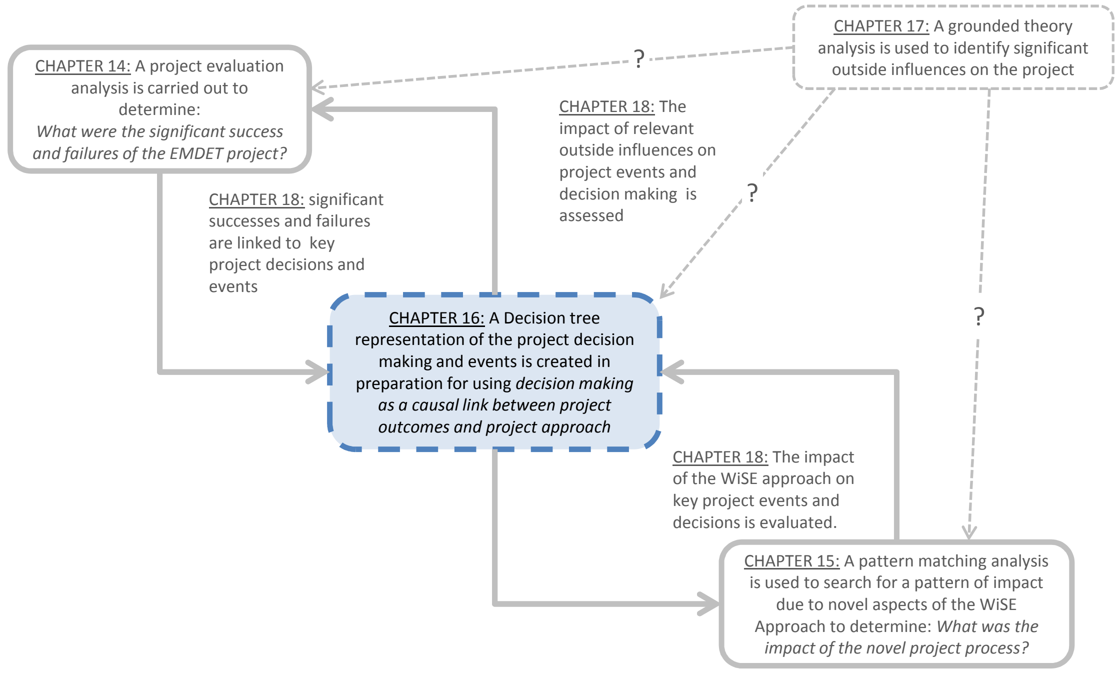


Figure 16.1: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

The decisions and events on the tree were subsequently correlated with the findings of the pattern matching analysis, and the augmentations that had impacted on each decision or event (directly or indirectly) were identified. Prior decisions that significantly impacted an event were also identified to examine the potential for any significant flow on effects of decisions made early in the project due to WiSE augmentations.

Many of the decisions made within the project are the result of iteration, but only the major iterations that have a bearing on the analysis are depicted. In reality, the project was a constantly iterating non-linear process and representing it in the relatively linear presentation of a decision tree necessarily simplifies the real conduct of the process. Additionally representing all of these processes would be both unnecessary and confusing in terms of addressing the questions of this study. The final decision tree produced was composed of:

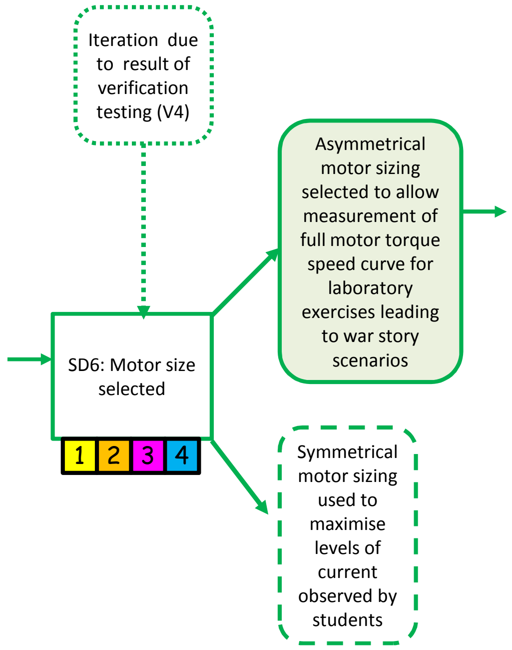
- *events* which are defined as a necessary action that had to be performed to complete the project where no plausible alternatives were available or applicable
- *Decisions* where one of a number of courses of action was selected that was

significant in determining the final form of the EMDET, including
  - The selected alternative taken within the EMDET project
  - The potential alternative(s) rejected
- *Iteration* - where a *verification* check has identified an issue that required a decision to be re-visited and altered
- the *impact* (if any) of WiSE Augmentations on the decision or event correlated from the pattern matching analysis.

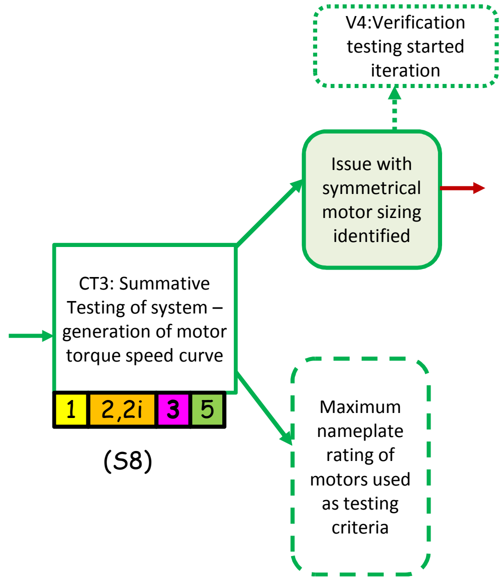
To illustrate this process Figure 16.2 shows how the tree was constructed around two key decisions which determine the size of the motors within the EMDET from the System Design and Component Test Phase. Within the prototype, Motor 1 and Motor 2 were the same size (3 kW, see Section 7.2). During the Component Testing phase the prototype EMDET could not generate a motor curve (Section 10.3); so the motor size decision within the System Design phase was reviewed and the motors were asymmetrically sized to allow Motor 2 to stall Motor 1 (Section 7.7.2).

Figure 16.2a represents the selection of the motor size (labelled SD6 as it was the sixth decision in the System Design Phase). The options at this decision point were to have symmetrical or asymmetrical motors. Symmetrical motor sizing would maximise the levels of current drawn when the Motor 1 was within its normal operating limits; whereas, asymmetrical motor sizing would allow Motor 1 to be stalled and its full torque sped curve measured. The issue with symmetrical motor sizing was identified due to a verification check (labelled V4 as it was the fourth major project verification made).

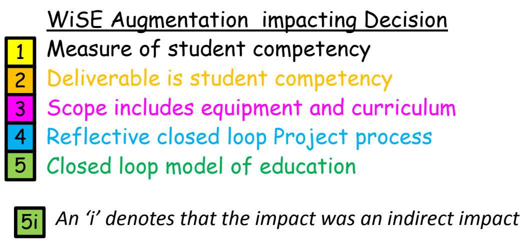
Decision SD6 was directly impacted by four of the WiSE augmentations; the curriculum included an exercise to plot the torque speed curve of Motor 1, so the augmentation of *integrated equipment and curriculum* was in favour of asymmetrical sizing (Section 15.1.3). Plotting the torque speed curve was seen as a valuable exercise to build student understanding of induction motor operation in practice, which was important to the project deliverable of *student competency.* The exercise was seen as important preparation for attempting one of the war story scenarios that was used as the *measure of student competency* (Section 15.1.1). Therefore, both the measure and deliverable of student competency WiSE augmentations weighed in favour of asymmetrical motor sizing. This decision was revisited due to the *reflective closed loop methodology* to address educational problems caused by the equipment



(a) A decision iteratively revised due to a verification check



(b) Verification of a decision leading to iteration.



(c) WiSE Augmentations impacting on a decision or event.

Figure 16.2: An example decision explained

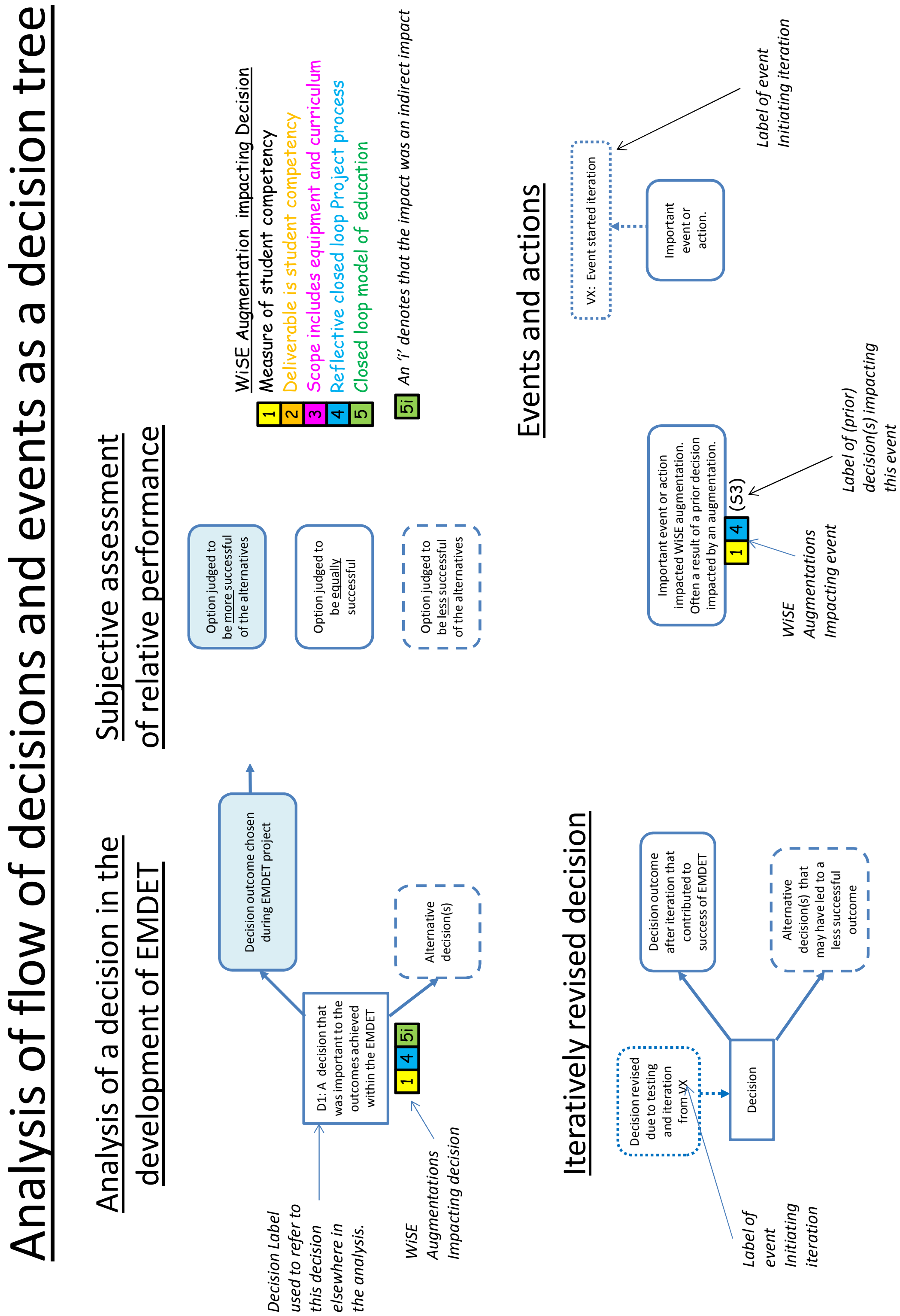
performance (Section 15.1.4). The impact of the augmentations determined by pattern matching was captured on the decision tree in Figure 16.2a by colour coded numerical labels with the explanatory key presented in Figure 16.2c.

Figure 16.2b shows the decision on what summative test of the EMDET would be conducted to determine if the motor sizes were satisfactory (labelled CT3 as it was the third decision in the Component Testing phase). The options at this point were that the motors would be tested to determine whether they delivered their name-plate rated power, or if could meet the most demanding exercise within the curriculum, in this case to produce the torque speed curve.

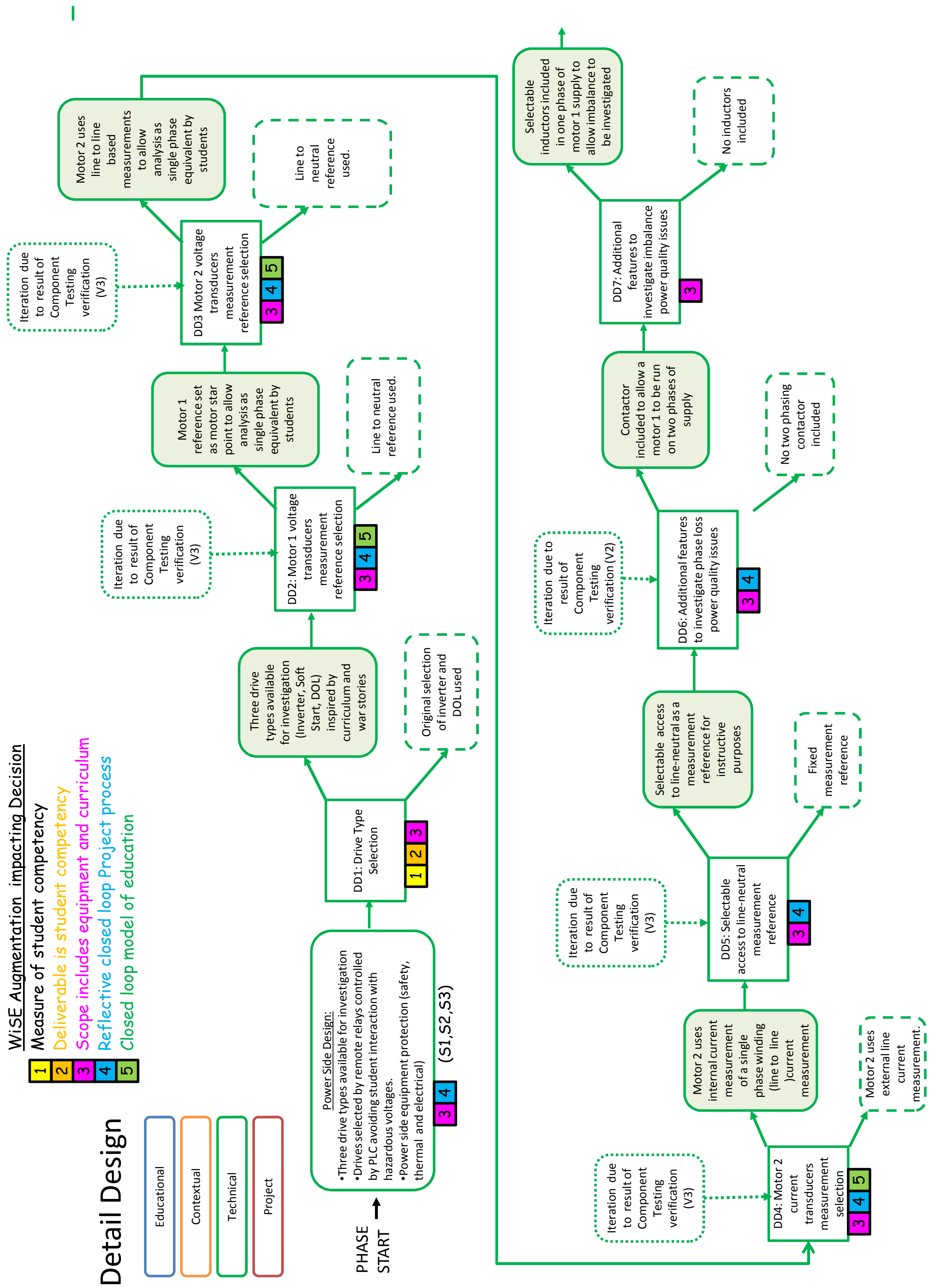
This decision was directly impacted by four of the WiSE augmentations; the test selected was the most demanding exercise required by the curriculum, as prompted by the augmentation of *integrated equipment and curriculum*. When the motor curve could not be plotted on the prototype EMDET, priority was given to addressing this issue due to the importance of the exercise to the deliverable of *student competency* and *measure of student competency*. During testing, the complexity of manually operating the equipment to generate the torque speed curve was identified as an issue that may cause (what would be according to the *closed loop model of teaching and leanring*) unnecessary and obstructive cognitive leaps for students. This prompted the introduction of an automatic loading sequence to simplify the exercise (Section 15.1.5) and allow students to concentrate on the educationally valuable parts of the exercise.

This decision showed one indirect impact of the WiSE Approach; it was made to initiate an iterative change largely due to the importance of the exercise to the deliverable of *student competency*. This decision extended the project due to the time required to re-engineer the system to accommodate asymmetrical motor sizes. In this case the indirect impact resulted in a better result in the EMDET equipment delivered, it did however come at the cost of time.

The full decision tree includes includes sections for each of the nine stages of the WiSE approach (Requirements, Specifications, etc.) and includes over fifty individual decisions and eight significant events. Due to its size the full decision tree is presented in Appendix B and an extract is presented here in Figure 16.3, including an explanation of the format and some of the Detailed Design phase. The full decision tree, including data correlated from the pattern matching analysis, was used during the synthesis presented in Section 18 to establish a linkage between the project outcomes (from Section 14) and the impact of the project process.



(a) Explanation of the decision tree format



(b) Decision tree for part of the Detail Design Phase.

Figure 16.3: Extracts from decision tree

Chapter 17

Analysis: Grounded Theory

The two major propositions of the study presume causal effects between the project process and project outcome, but it is important to recognise that other factors can affect the project outcome and include these in the overall synthesis. The methodology of this study (Section 4.4.4) considered the outside factors in two categories; *prior* to student involvement and *after* student involvement. A grounded theory approach as described by Case & Light (2011) was used based on observations by laboratory demonstrators conducting the lessons. The outside factors identified were used in the overall synthesis assessing the impact of the WiSE Approach on the EDMET project as shown in in Figure 17.1

The grounded theory approach was based on observations made by two laboratory demonstrators given during interviews and a reflective journal kept by the researcher acting as a laboratory demonstrator during the 2015 cohort. The laboratory demonstrators were postgraduate Electrical Engineering students who had completed the PED course previously. The demonstrators were interviewed, and both written notes and an audio recording made were made; The interview was guided by the following questions that were presented to the interviewee within a participation information sheet that was part of the research ethics approval for the work (included in Appendix G).

- Where there any issues with the student interaction with equipment (hardware/ software) that may have impacted on performance?

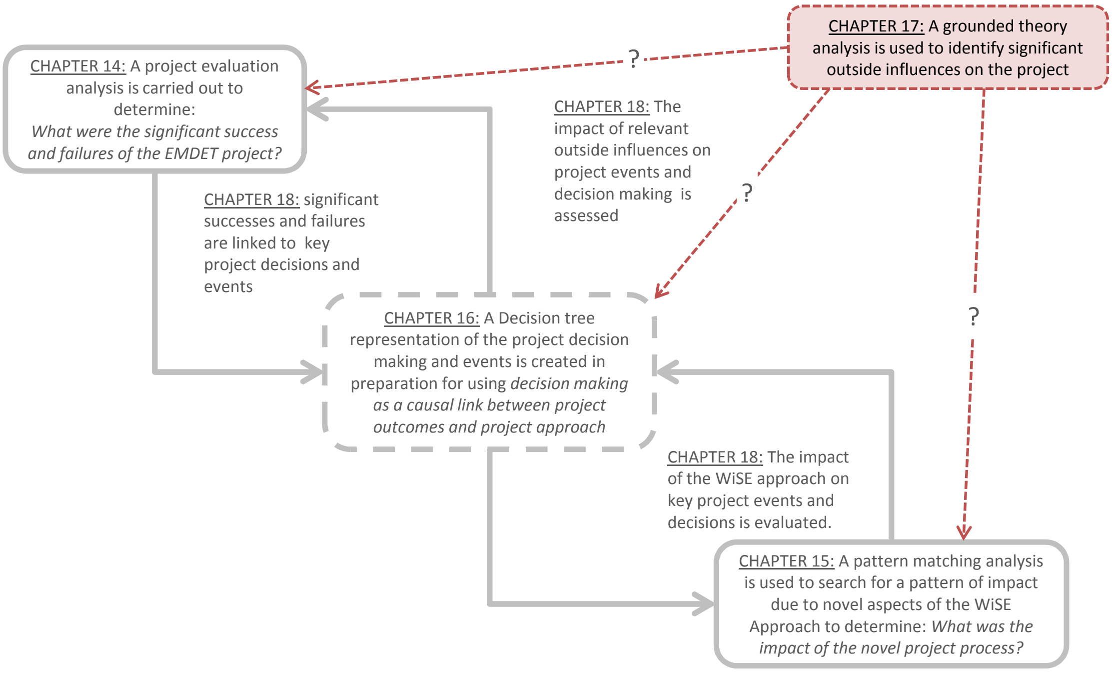


Figure 17.1: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

- Where there any logistical or curriculum delivery issues (insufficient time, curriculum materials not available) that may have impacted on student performance?
- Where there any student issues within the class that would not be evident from a students workbook (e.g student punctuality, linguistic ability, apparent motivation, etc.)
- Did you have to provide additional coaching or teaching to students beyond what is in the curriculum materials to allow them to complete the laboratory?
- Is there anything else you think the researchers should be aware of about student interaction with PED course equipment and lab workbooks?

The reflective journal kept by the researcher was a series of notes based on observations in the laboratory such as: issues with equipment and curriculum, assistance rendered to students in the role of a laboratory demonstrator or issues raised by other demonstrators during the laboratory sessions and prior to the interviews.

The notes from interviews, the audio recording and reflective journal were reviewed, and then individual observations were extracted from them and entered into a Microsoft Excel spreadsheet for the grounded theory analysis process. The sources of the data points were not included in the spreadsheet to de-identify the data as required by the Ethics approval.

These observations were subjected to the 'constant comparative method' described by Case & Light (2011). Only the 2015 cohort was subjected to grounded theory analysis as part of the case study assessment of the effect of the WiSE approach on the EMDET project. While the grounded theory analysis was not initially part of the WiSE approach itself, it may be valuable to include it in future usage of the WiSE Approach because of the insights it provided. The comparative method consisted of:

1. initially, a set of possible content of categories was presumed before starting the iterative process of the analysis including student, teaching, equipment and curriculum. The full list of categories initially considered was the sixteen possible combinations of one or more of these
2. a stage of open coding was then carried out by assigning the data available to the initial categories and progressively analysing and comparing them to identify new categories inside or outside of the initial presumptions
3. a stage of axial coding that re-evaluated all the data against the new categories determined and also investigated the initial categories for potential sub-themes either beyond or within the initial presumptive categories
4. the categories were then checked for potential overlap or relationships between them. Within this first iteration of this stage many of the original presumptive categories were removed because none of the observations fell within those categories.
5. further data was collected until input from all 3 laboratory demonstrators who delivered the 2015 EMDET lessons were included. Open and axial coding continued until all the data was categorised, overlap was eliminated from the categories, and no additional themes were identified

The final outcome of the analysis was a three tier categorisation, where:

- the first tier consisted of the initially presumed combinations of students, teaching, equipment or curriculum, with only seven of the original sixteen possible combinations was finally used

- the second tier was key themes identified in the data associated with each of the top level themes
- the third tier consisted of specific issues encountered within the observations, typically used when the same (or fundamentally similar) observations were recorded multiple times

The results are summarised in two tables, Table 17.1 provides the breakdown of the first and second tier of categorisation and Table 17.2 provides further details of the second and third tier. The frequency with which observations fell into each category is shown in percentage terms, in all 386 individual observations were recorded and categorised. Importantly, aspects of many observations contained issues from multiple categories; frequently this was because the individual issues were interacting. When evaluating how significant an issue was to teaching and learning the frequency of occurrence is one metric, but the consequences should also be considered because a minor issue that occurs frequently may have less overall consequence to teaching than an infrequent, but major issue. The relative consequence of the issues identified is discussed for each of the themes identified.

Table 17.1: Grounded theory first and second tiers of categorisation.

First Tier	Second Tier	
Student	Inherent Characteristics	24%
	Cognitive behaviour that can be influenced	28%
	Desired Knowledge and Cognitive Behaviours	10%
	Factors difficult to influence	13%
	Factors that cannot be influenced	3%
Equipment	User responsibility	3%
	Project Responsibility	2%
Curriculum	User Responsibility	11%
	Project Responsibility	2%
Curriculum & Student	Curriculum and student cognition interaction	23%
	WiSE Iterations (potential and results of past)	13%
	Information reception	5%
Student & Teahcing	Linguistic Cognitive Q&A	9%
Student, Teaching & Curriculu	Tailored Scaffolding	16%
	Coaching & mentoring	6%
Student, equipment & Curriculum	Equipment/curriculum interaction	2%
	Lab experience	2%

Table 17.2: Grounded theory second and third tiers of categorisation.

Second Tier		Third Tier	
Inherent Characteristics	24.1%	English Language Proficiency	11.7%
		Student Pre-Req Knowledge & prior learning	11.7%
		Student Individual Capabilities	0.8%
Cognitive behaviour that can be influenced	28.0%	Deep Vs Shallow learning	13.0%
		Learning Approach in Lab (Passive/active)	6.5%
		Student Motivation	8.5%
Desired Knowledge and Cognitive Behaviours	9.8%	Ensemble combination and/or application of concepts	6.0%
		Critical Thinking	2.3%
		Knowledge Retention (couresework delivered)	1.6%
Factors difficult to influence	13.0%	Student Behaviour - Individual	6.0%
		Student Behaviour - Group	7.0%
Factors that cannot be influenced	3.4%	Physiological	1.3%
		Psychological	1.0%
		Human Error	1.0%
User responsibility	2.6%	Infrastructure - Power Supply	1.3%
		Infrastructure - IT	1.3%
Project Responsibility	2.3%	Project Equipment Issue	2.3%
User Responsibility	10.6%	Pre-requisites required for student enrolment	7.8%
		Plagiarism issues	0.3%
		relationship of Lectures to Laboratories	0.5%
		Logistical Issues (Time allowed for exercise)	1.0%
		Resources available to student/teachers	1.0%
Project Responsibility	1.8%	Improvements to written materials (clarify, mis-prints, mistakes in materials provided)	1.8%
Curriculum and student cognition interaction	22.8%	Cognitive Leaps required	11.7%
		Disconnect with Lab approach - Theory, test, analyse	6.7%
		Curriculum promotion of deepl active learning	4.4%
WiSE Iterations (potential and results of past)	12.7%	Potential WiSE iteration	11.4%
		Result of previous WiSE iteration	1.3%
Information reception	5.2%	Student information reception (format OR inattention) to backgound info or experimental procedure	5.2%
Linguistic Cognitive Q&A	9.3%	Linguistic/Cognitive model of Q&A	9.3%
Tailored Scaffolding	15.8%	Demonstrator - tailored scaffolding	15.8%
Coaching & mentoring	6.0%	Demonstrator - Coaching for Motivation Mentoring on student learning approach (deep/shallow, active/passive)	6.0%
Equipment/curriculum interaction	1.6%	Issue faced by students with equipment/curriculum interaction	1.6%
Lab experience	1.6%	Students (engagement with) enjoyed lab experience	1.6%

17.1 Outcome of Grounded Theory Analysis

Five first tier categorisations were identified and are addressed within this analysis; they are primarily related to students, equipment, curriculum, curriculum and student interaction, interaction between student, teaching and curriculum, and the interaction between equipment, curriculum and student.

17.1.1 Student factors

The first tier category consisting of factors related primarily to students had five second tier themes within it: inherent student characteristics to be avoided, cognitive behaviour that can be influenced by teaching, the desired knowledge and cognitive behaviours, student factors difficult to influence and lastly factors that cannot be influenced.

17.1.1.1 Student Inherent Characteristics

Inherent characteristics refers to issues which prevent students from achieving the desired competency which cannot be remedied by teaching with the EMDET within the time allowed, When viewed from the project perspective some of these issues were due to the students lacking the specified level of pre-requisite knowledge and ability (Section 6.5.2), and once the Acceptance Testing (teaching) is under way it is likely too late to address these issues. To address them, either the current project specification should be complied with to avoid the issues, or it should be altered to include them in the scope of the project.

Within inherent characteristics category, three subsidiary third tier categories were identified; the first being students observed without enough English language proficiency (either written or spoken) to engage with the curriculum materials or the laboratory demonstrators who provided assistance. This was one of the most frequently occurring issues observed and made it difficult for laboratory demonstrators to render assistance to students; the demonstrators opined that these language difficulties likely had a significant impact on student attainment. It was observed that the students did not need native speaking English ability because a number of students from non-English speaking backgrounds did not experience this issue. The difficulties included students lacking conversational English, as well as technical English vocabulary.

The second of the inherent characteristic issues was student prerequisite knowledge and prior learning, this was again one of the most frequently observed issues. The majority of the observations within this category where that a lack of the necessary pre-requisite knowledge negatively impacted students performance, which then required demonstrator intervention. This occurred to varying degrees, some students 'just needed a reminder' of the relevant knowledge, while others had some exposure to the knowledge but needed teaching by demonstrators on the expected prerequisite knowledge, and some students so completely lacked any prerequisite knowledge that demonstrators were unable to teach the shortfall in the time available; this led to one demonstrator to comment that ‘students with no background in power engineering are painful’.

The first two inherent characteristics were frequently observed in association with the linguistic cognitive question and answer activities described in section 17.1.5. It was noted that the agreed Specification for the EMDET curriculum (Section 6.5.2) was based on the knowledge that fourth year undergraduate electrical engineering student must possess prior to enrolment. It was also noted that the most of the issues were experienced by post graduate students, whereas undergraduate students appeared to perform better by comparison.

The last inherent characteristic was individual capability of the student, particularly their aptitude for the material being taught and the necessary prerequisites. One demonstrator observed that ’some students can do the lab work, others are totally lost’ and consequently ’we cannot teach the entire undergraduate curriculum’. Another demonstrator observed they had insufficient time to train students whose lack of pre-requisite learning appeared so extensive that apart from the expected knowledge of three phase electrical systems they appeared to not grasp the concept of finding a line of best fit for data they had recorded and plotted. They appeared unable to achieve this graphically (by hand) or by using spreadsheet software. It was found that these issues of this depth could not be remedied by teaching within the time available.

17.1.1.2 Student Cognitive Behaviour That Can Be Influenced

Student cognitive behaviour that could be influenced referred to the way students approached learning activities within the laboratory that could or were influenced by the laboratory demonstrators. Within this category, three third tier sub-categories were identified that could appear singly, but were more often were interrelated; these included whether a student took a deep or shallow approach to learning (J. Biggs, 2003) (p12), whether the student was active or passive (Bonwell & Eison, 1991; Prince, 2004) during the laboratory exercise, and the students motivation. These were important because reaching the desired competency needed a student to be motivated enough to take a deep active approach to learning, and engineering teaching laboratories are fundamentally predicated on students taking an active approach to learning.

These three third tier categories were grouped as cognitive behaviour that can be influenced, because it appeared that demonstrators had some success in addressing them. While it appeared that students would naturally favour one approach or another, demonstrators could encourage students to take a deep active approach to attain the desired competency. This often took the form of coaching and mentoring, as described in section 17.1.6. The distinction between this second tier category and the previous inherent characteristics for avoidance is that issues within this category (preventing students from attaining the desired competency) can apparently be addressed with some success by teaching within the laboratory. When viewed from the project perspective these issues were not explicitly addressed within the project specification, but given the demonstrators success in this regard, these issues could reasonably be assigned to them in future as part of a revised project specification.

During the laboratory sessions both deep and shallow learning approaches were observed and were judged to be a significant factor is student attainment. The students who were characterised as taking a deep approach to learning were observed to have an genuine interest in the material being presented, and according to one Laboratory demonstrator appeared to generally 'know what they were doing' and could be seen to make efforts to truly understand the material, making comments such as 'ohh! I see what is going on!' when they had achieved an enlightenment. Typically, when these students asked questions of demonstrators they appeared to be with the intent of summarising their own understandings at higher levels of the SOLO taxonomy.

Conversely those students characterised as taking a shallow approach were described by demonstrators as 'doing the experiment on paper but not in their minds', and that they would not 'stop and think' during experimental work; rather they would follow a procedure by rote without attempting to comprehend what was occurring, appearing to be simply concerned with gathering data rather than deriving any knowledge from the analysis. It was noted that this approach was often detrimental to student performance particularly when the curriculum called for students to contrast the behaviour of equipment under different conditions, during data gathering the students had treated each measurement in isolation, and after gathering all of the data were could not relate the measurements to each other and were unable to answer the review questions. It appeared that these students were taking what would be described in the SOLO taxonomy as unistructural, or potentially multi-structural approach, to their learning. During interactions with demonstrators it was noted that these students seemed more concerned with answering the questions within the work books rather than the intended understanding, and would often ask demonstrators for the explicit answers to written review questions.

During the laboratory sessions the demonstrators discussed a speculative hypothesis in relation to the shallow learning approach, whether it was intrinsic or extrinsic to the student. If the shallow approach was intrinsic to the student it was proposed that these students may potentially leave the laboratory sessions when they had gained what the believed were enough marks to pass, therefore students may leave early without fully completing the laboratory. The observed behaviour from students was that the students who left early had usually fully completed the work, whereas those with an observed shallow learning approach would often stay till the last minute. This tended to point towards the shallow approach being extrinsically motivated, and it was hypothesised that it may be a coping mechanism, this however was not tested.

During the laboratory session students were observed to take both passive and active approaches to learning. Those identified as taking an active approach would work with the EMDET equipment, operate the HMI, run the equipment, and actively take readings from the data acquisition system. Whereas, students identified as taking a passive role would appear to 'sit back and let others do the work' noting results as they came.

The demonstrators observed that these students would not actively seek information for themselves; rather they preferred to simply ask the demonstrator. A common example of this was an exercise in the first lab session which asked students to find the induction motor characteristics off the nameplate (pole number, power factor, etc.). This information was needed in the second laboratory session and many students simply asked the laboratory demonstrator rather than finding it in their past work. The demonstrators also observed that ‘Passive students will usually get the results but not the group discussion that helps to build understanding - often students will get lost.’ and that ‘Passive members will miss out on discussion with group and will not understand’ whereas ’active members are able to answer questions’. It was noted that the student learning approach was impacted by group dynamics discussed in section 17.1.1.4

The last third tier category observed was student motivation, different students appeared to have different motivations for being in the class, with some students appearing to be genuinely motivated to learn, while others gave the impression they were motivated to just ‘complete the lab and get the marks’. It was speculated that motivation was linked with learning approach because the students with apparent high levels of motivation would appear to take a deep active approach, and when questioned displayed high levels of thinking in terms of the SOLO taxonomy. It was hypothesised by the demonstrators that motivation also derived from the perceived value of the learning exercise.

17.1.1.3 Desired Knowledge and Cognitive Behaviours

Desired Knowledge and cognitive behaviour refers to what the EMDET was trying to instil in students, and the apparent patterns of mental behaviour presumed to lead to it. Demonstrating the desired wisdom requires students to execute an ensemble performance, students must display critical thinking and be able to retain the knowledge that comprises an ensemble performance. These were three themes identified in observations.

The aim of the WiSE approach in creating the EMDET was to instil in students the ability to practice with Wisdom in the field of EMD systems. Actually performing this requires an ‘ensemble performance’ where students have to display critical thinking, combine knowledge from different parts of undergraduate teaching and apply them in context. Many students were unable to complete tasks involving as ensemble performance prompting a demonstrator to say that ‘Students were having trouble relating something symbolic, to the physical, into the context it will be encountered in '. This applied especially to reviewing experimental results, deriving an understanding from them and applying this to another (real world) context. The exercises aimed at addressing the motor magnetising current war story was a good example of this, students were required to: measure the motor current and torque, relate this to a single phase equivalent circuit representation of the motor, and then relate that to the physical construction of the motor. Many students had difficulty with this during the laboratory exercises.

Critical thinking and the retention of knowledge are necessary for the desired wisdom, students were observed to display what was judged to be both good and bad critical thinking skills. A common example of critical thinking was a students response to calculating a motor efficiency of over 100% due to a mistake in their calculations. Some students critically evaluated this as being impossible and actively tried to address the issue, while others saw no problem. It was also observed that some students were not retaining knowledge from the previous laboratory session, which was seen as a potential indicator of shallow learning.

Observations of students unable to execute the desired ensemble performance or not displaying the appropriate levels of critical thinking and knowledge retention usually triggered an intervention from the laboratory demonstrator, as discussed in section 17.1.6.

17.1.1.4 Student Factors Difficult to Influence

This category consisted of student behaviours that appeared to affect learning and could prevent them from attaining the desired competency; furthermore these behaviours were difficult to remedy by teaching with the EMDET within the time allowed. When viewed from the project perspective these issues were not addressed within the project specification and would require (possibly extensive) alteration of the curriculum to address. If the EMDET were expected to address these issues, the project specification should be altered to include them. This category included behaviour that students exhibited individually, and behaviour resulting from group dynamics between students working on a single EMDET apparatus. The individual behaviour observed included how a student would approach the laboratory exercises, their approach to the analysis and the time they would physically spend in the teaching laboratory.

Students were observed to take different approaches to laboratory sessions, some would gather all of the data for multiple individual exercises and then go back and attempt an analysis, while others would gather data and concurrently analyse it; the former approach appeared to be associated with a shallow learning approach and the latter with a deep approach. At this level the choice of how the laboratory was approached was entirely up to the student. Students also had a variety of approaches to planning and analysing their data which could impact the achievement and learning within the laboratory. The most striking example was a set of repetitive calculations made on a series of measurements of motor, current, voltage, torque and speed under varying levels of load. Some students followed advice within the laboratory notes and used a spreadsheet to expedite the calculations and spend more time on analysis, while others would laboriously carry out these repetitive calculations on a hand calculator, sometimes in spite of the advice of demonstrators.

Student behaviour resulting from group dynamics was also observed to influence student attainment in the laboratory session. It appeared that group dynamics could impact on student approach to the laboratory exercise and analysis, as well as whether they took an active or passive approach. It appeared that sometimes 'strong' or dominant personalities would influence the approach taken by other students to the laboratory exercise and analysis, and whether they took an active or passive approach to the laboratory exercise.

A clear example was where a student appeared to be dominating the operation of equipment to the exclusion of the other students within the group, and when a series of measurements was complete the 'dominant' student was carrying out repetitive calculations on a calculator (as described above) while the other students were idle. After repeated questioning by a demonstrator as to why the student was not using a spreadsheet their response was that they were not familiar with spreadsheets, at this point one of their partners exclaimed 'why didn't you say! I can use Excel! [sic]'. By the time the demonstrator had resolved this issue a large proportion of the allotted time in the laboratory appeared to have been wasted and the group was unable to complete the exercises.

Group dynamics can promote or discourage active learning, both of which were observed. One Laboratory Demonstrator observed ‘One group of three friends - all keep changing who is holding the mouse (more active) and all are more engaged. [sic]’ . Another observation was that one student noted to be a passive participant in one group where ‘she did not fit with’ was moved to another for logistical reasons, the new group appeared to be actively encourage her involvement and her approach changed to a more active one.

It appeared that both student behaviour, both individual, and prompted by group dynamics impact student attainment. As well as dealing with issues of student understanding, influencing student approaches to the lab or analysis could require prohibitive amounts of time from laboratory demonstrators. These issues were also not explicitly included within the specification of the EMDET and if influencing student group dynamics was to be part of the curriculum it would require a significant revision.

The amount of time students spent within the lab and consequently their achievement was impacted by their attendance. This could have been poor punctuality or leaving the laboratory early with exercises partially completed (appearing to accept the academic penalty involved), due to other time commitments. While it is possible to influence student punctuality and choice of how long to spend in the laboratory, it is ultimately beyond the control of teaching or the project team.

17.1.1.5 Factors that Cannot be Influenced

There were a number of factors noted that negatively impacted student performance and could prevent them from attaining the desired competency, which cannot feasibly be influenced by the project stakeholders; these included physiological factors, psychological factors and human error. When viewed from the project perspective these issues were not addressed within the project specification and the curriculum could not feasibly be altered to to address them. The physiological factors observed included students coming to teh classes suffering illness, injury and fatigue. Another issue observed was two students who could answer most questions verbally, but despite demonstrator prompting did not write any of these answers down, the only vaguely plausible explanation for this was some kind of psychological issue. Lastly human error was observed, the most common being students making silly mistakes such as using 50 seconds in a minute instead of 60 during calculations.

17.1.2 Equipment

Within the top tier category of factors primarily related to equipment, two second tier themes were identified based on the responsibility of addressing the issue: equipment issues outside the project scope for the User to address and issues within the project scope for the project team to address. The third tier categories identified within the User's responsibility were issues with the power supply infrastructure and with the Information technology infrastructure.

17.1.2.1 User's Responsibility

During the laboratory sessions the electrical power supply to individual EMDET laboratory benches would occasionally shut down due to the protective earth leakage circuit breakers (ELCB) tripping. This was due to the incorrect use of a grade ELCB's that were not properly compatible with power electronic switching devices, an issue that had been raised by the project team and agreed as a User responsibility. When an ELCB would trip, the EMDET unit would be without power until the laboratory demonstrator could contact a technician to reset the breaker within a building switch room. This disrupted student learning, waste time waiting for the breaker to be reset, and on one occasion students had to be relocated to other laboratory benches and groups to complete the lab.

The issues with the information technology infrastructure supplied revolved around how the software operating system was implemented. Rather than each computer using a common stand-alone software operating system, as agreed in the project specification, all the computers in the lab used an operating system based on a 'software image' held on the University's network. The network image approach was intermittently compatible with the software supplied by the project and caused delays in student work; on one particular PC some students were unable to open the required software, or only able to open old versions of software that prevented them from starting their work until an alternate login could be sourced. There would have been no issues with the software or licensing had stand alone computers with full administrative rights been used as per the specification instead of a complex network based operating system.

17.1.2.2 Project Team Responsibility

The issues identified within the responsibility of the project team were relatively minor. These included a PC with an old version of the HMI software that was quickly updated, a panel meter that had stopped working, a 1% offset in one current transducer and a small offset in the torque signal displayed on the HMI in comparison to the same torque recorded on the data acquisition system due to electromagnetic noise on the signal. The offset in the torque signal was only an issue because the students did not follow the directions in the laboratory manual to use the more accurate readings from the data acquisition system for their calculations. None of these issues caused any significant delays or barriers to student learning.

Overall equipment issues only occurred with a relatively small proportion (5%) of the observations made, and within this only half of these were due to project equipment. Issues with the equipment supplied by the EMDET project were also of less consequence that IT and power infrastructure issues that were relatively disruptive to student learning. The overall impression the laboratory demonstrators conveyed was that the 'Equipment worked almost perfectly'.

17.1.3 Curriculum Issues

Within the top tier category of factors primarily related to the curriculum, two second tier themes were identified, again based on the responsibility of addressing the issue: curriculum issues outside the project scope agreed in the specifications for the User to address, and issues within the project scope for the project team to address. The third tier categories identified were: prerequisites required for student enrolment, the relationship between Lectures and the Laboratories, Logistical Issues (Time allowed for exercise), and the resources available to students and teachers.

17.1.3.1 User Responsibility

The most significant and frequent issue within this category involved student pre-requisite knowledge required for enrolment into the PED course, including both technical and English literacy. When laboratory demonstrators observed students without the prerequisite knowledge, it was uncertain if the students received sufficient prior training to gain the pre-requisite knowledge and had not retained it, or if they were allowed to enrol without ever having attended previous training to provide the prerequisite knowledge. The general observation made by demonstrators were that the undergraduate students had fewer issues with pre-requisite knowledge; when the pre-requisite subjects for enrolment were checked (Univeristy of Wollogong, 2010a) it was found that undergraduates were required to complete at least one second year foundational subject in power engineering, whereas there were no specified pre-requisites for post graduate students.

A change in timetabling meant that PED course lectures were held after the laboratory sessions rather than before, as originally agreed in the project specifications. According to the subject coordinator this meant that during the second laboratory session students had not received the relevant lecture before the laboratory session been introduced to the voltage.

The amount of time available for students to complete the laboratory exercises was discussed. In general the laboratory demonstrators believed there was enough time to complete the exercises, but the lab was challenging. Within each session laboratory session it was observed that generally two of five groups would complete all the exercises, with the remainder completing the majority of the exercises.

It was suggested that a printer in the laboratory may have assisted students by giving them the option to print tabulated values and graphs rather than having to fill them out by hand. There were printing facilities available nearby on the campus, just not immediately in the laboratory.

17.1.3.2 Project Team Responsibility

The laboratory demonstrators only made minor suggestions to improve the laboratory notes as provided, these included small misprints, adding page numbers and clarifying some instructions. The instructions needing to be clarified were that students could not log to a file that they had open and that they could not have two virtual instruments running simultaneously. These issues were minor and quickly dealt with by verbal instructions from the laboratory demonstrators. Overall, the issues with curriculum materials provided by the project were relatively minor and infrequent.

17.1.4 Curriculum and Student

This category consists of issues where interactions between student and curriculum were observed, this was the second most frequently occurring first tier category. Within this category three second tier categories were identified: the interaction between curriculum and student cognition, WiSE Iterations, and student information reception. When considered from the project perspective these issues and their resolution were within the scope of the EMDET project.

17.1.4.1 Interaction Between Curriculum and Student Cognition

Within the category of interaction between curriculum and student cognition three themes were identified: an observed disconnect that students had with the fundamental laboratory approach, the cognitive leaps required within the curriculum, and the curriculum promoting deep and active learning. Importantly these three issues appeared to be related to each other in a triangular fashion, and could prevent students taking the deep active learning approach required to attain the desired wisdom.

It appeared that students engaged to varying degrees with what was viewed as a standard approach to a laboratory class. In this approach relevant background theory was presented, students would conduct related experimental tests, the experimental results would be analysed to derive relationships and finally review questions would require students to utilise the relationships derived to answer applied questions. Some students appeared to have fundamental difficulties engaging with this approach. A frequent observation by Laboratory Demonstrators was that students would gain the necessary experimental results, derive the expected relationships between parameters and would completely ignore them when asked a related review question which expected them to apply the experimental relationships already determined. A representative example of this was an exercise measuring the speed of an induction motor (expressed as slip - the % below theoretical synchronous speed) at varying levels of load torque, and then plotting the results to derive a relationship. A review question would ask them to predict motor speed at various loading levels. Many students simply gave the motor theoretical synchronous speed, completely ignoring the relationship they had just developed. In contrast to this, some students were able to carry out the measurement, analysis and application of results as expected.

There were many observations made that related to the cognitive leaps that the curriculum required of students, over 10% of all the observations made involved cognitive leaps. Many of the observations of student difficulties with the laboratory material can be explained in terms of the cognitive leaps required, for example the exercises aimed at giving students a proper understanding of induction motor magnetising current (as required by a war story) can be explained in these terms. During operation, the current flowing into the motor must first create a magnetic field, coupling stator to rotor, before being able to do mechanical work. The cognitive leaps during the laboratory exercise leading to this understanding were that students make the following leaps:

- derive a relationship between the measurements of motor current and torque in the form of a linear relationship $y = mx + b$
- link the relationship to a single phase equivalent circuit representation of the motor, and identify the magnetising and torque producing current
- link this to the physical construction of the motor and the need for the magnetising current to couple stator to rotor via a magnetic field to spin the rotor and do mechanical work

A high proportion of students having difficulty with this exercise appeared to fail at the second or third leap.

The observations involving cognitive leaps required by the curriculum also included recognition of the challenging nature of the laboratories due to the cognitive leaps involved, the extra cognitive leaps required by students who lacked the required prerequisite knowledge, and that a student executing an ensemble performance (and displaying the desired wisdom) is actually achieving a series of cognitive leaps.

The theme of the curriculum promoting deep and active learning was closely related to student learning approach (deep/shallow, active/passive) and whether the structure of the laboratory work book could influence this. A number of the observations were suggestions aimed at addressing problems with students following the laboratory procedure by rote and treating each measurement in isolation, rather than part of a larger picture. It was observed that after gathering all of the data these students were unable to contrast and relate measurements to answer the review questions. It was suggested by the Laboratory Demonstrators that possibly the analysis could be brought closer to experimental measurements, interspersing them to promote deeper learning. While there were key questions written into the experimental procedure it was suggested that as these do not actually require a student response and are being ignored. Requiring a simple answer from students (multiple choice, tick box, etc.) would would activate student attention causing them to 'stop and think', thus meeting the intent of the key question.

The three themes identified of the observed disconnect with the lab approach, cognitive leaps required and the curriculum promotion of deep active learning appeared to be interacting in a triangular fashion in the recorded observations. Some of the observed interactions include that:

- students who take a deep active approach understand the lab approach and are able to complete the cognitive leaps expected
- students who are 'shallow' learning do not engage with the laboratory approach and therefore find the required cognitive leaps too much
- if the cognitive leaps required are too much for a student they may respond by reverting to a shallow learning approach.
- the curriculum layout may promote a shallow approach (too detailed)
- the curriculum may promote a shallow learning approach by giving instructions that are too detailed

While the order of causation within these observations are supposition, the relationships between the three themes are clear and appear to be significant; the curriculum as written may possibly be altered to promote the deep active learning approach required to reach the desired competency. The alteration must consider the possible student disconnection from the fundamental laboratory approach and the cognitive leaps required by the curriculum.

17.1.4.2 WiSE Iterations

The observations relating to WiSE iterations involved the results of previous reflective changes to the curriculum, and by the WiSE approach and potential future WiSE iterations. It was noted that changes made to the ordering of an experimental exercise to help students appreciate the differences between two key load and drive combinations may have been successful, because a number of students were heard to make comments appreciating the differences between a PWM inverter of thyristor soft starter operating a constant torque load.

Some potential improvements were suggested by the laboratory demonstrators such as placing experimental work and relevant review questions closer together, reordering some assessment items that may provide students with the technical English vocabulary needed to answer subsequent questions, requiring students provide an answer to review questions to promote deep learning so they 'stop and think' rather than skipping the question, assigning some assessment weight to the background material for the laboratories so that students read it before the laboratory session, and providing short videos as background materials to introduce students to the equipment and its operation.

17.1.4.3 Student Information Reception

The theme of student information reception included observations where students were not reading the laboratory notes either before or during the laboratory session. The archetypal examples are students asking a laboratory demonstrator how to operate equipment that is clearly explained in the procedure that the student has not read for unknown reasons, and students asking questions that are covered within the background materials presented in the laboratory notes. The reasons for these issues suggested by the demonstrators include laziness on the part of the students, that a different format may assist (e.g. suggested videos), and that some students are more receptive to verbal information, as opposed to written, materials.

17.1.5 Student and Teaching

This category consists of issues where there were observed interactions between student and teaching and after axial coding had one sub theme identified that occurred in 9% of the observations made; to represent these interactions a visual model was formed during the research that was termed *linguistic cognitive question and answer* (LCQ&A). This became evident when a demonstrator asked a question of a student from non-English speaking background the process shown in figure 17.2 would need to occur:

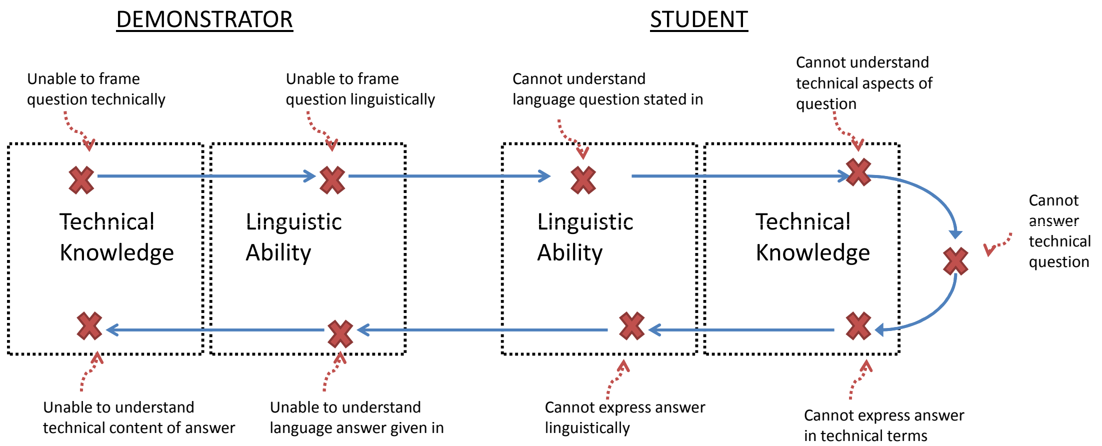


Figure 17.2: Linguistic cognitive question and answer model of teaching interaction with students.

This process would typically begin when a demonstrator would observe a student who appeared to have difficulty, and would ask the student a question about the work as a first step to identify and hopefully rectify the issue. In this process the demonstrator had to formulate a technical question, compose it into English, the student had to understand the English, understand the question technically, solve the question technically, compose a technical answer, formulate the answer into English, which the demonstrator had to understand firstly linguistically, then technically. If the process failed the demonstrator would then have to diagnose the process to work out where the problem arose in order to begin to address it. Can the student understand the language of the question? Can the student understand the question technically? Can they actually answer the question, but cannot express this answer in English? Once the issue was identified then a solution must be formulated and implemented by the demonstrator.

This process took up significant amounts of demonstrator time, and it was often coupled to the role the demonstrator had between student, teaching and curriculum. Carrying out this process as a preliminary to addressing student issues within the laboratory was judged to be both difficult and an extremely important function of the demonstrator. The process was unique to the student and situation, also in many cases it is difficult to predict.

17.1.6 Student, Teaching and Curriculum

This category consists of issues where the student, teachers and curriculum were seen to interact, and after axial coding two themes were identified within this category: tailored scaffolding and coaching & mentoring.

17.1.6.1 Tailored Scaffolding

Tailored scaffolding refers to educational scaffolding provided by a demonstrator to individual students who was unable to complete an exercise as it was presented in the curriculum. In terms of educational scaffolding the curriculum expected that a student had a given level of initial knowledge and an ability to make certain cognitive leaps, but if either of these conditions are not met a student could not complete the exercise. It was at this stage that a demonstrator would intervene to remedy the situation via tailored scaffolding, which was considered as a process consisting of the three steps summarised in Figure 17.3. The first step was to determine what was the actual level of student prior knowledge, the next to gauge the students ability to make leaps in understanding, and the last was to break down the step from their actual knowledge to the target knowledge into achievable series of leaps.

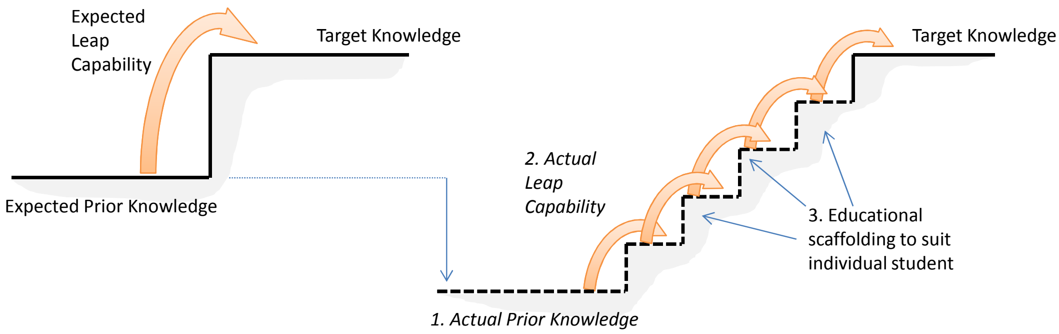


Figure 17.3: Tailored scaffolding within the instructional scaffolding model.

The underlying principle of scaffolding is that after rendering assistance for the first time, the student can make the leap by themselves without assistance in future. This is what differentiates scaffolding to allow students to achieve a higher level of understanding from simply providing the student the answer to the specific question. In the words of one demonstrator they would 'explain something, twist it and re-question [sic] to see if students understand' to determine whether the scaffolding was successful.

This process was extremely important to the conduct of the laboratory and the student outcomes achieved; it was also the most frequently observed appearing in over 15% of all observations. There were many potential issues that students could have which would require this kind of intervention to overcome, far too many to feasibly re-write the curriculum for. Many issues were unique to an individual student and their circumstance, usually consisting of permutations of a lack of prior knowledge and inadequate leap ability. It is the number of different issues encountered that means that adjusting the curriculum to suit all of them would likely be impractical.

During the scaffolding the amount of assistance that students required would vary, many needing little or no assistance of this kind, some students needing one or two interventions, while others would need many interventions of this kind to successfully complete a laboratory. This was judged a vital function of the laboratory demonstrator, and made significant contribution to the overall success of the laboratories.

17.1.6.2 Coaching and Mentoring

The difference between providing scaffolding, coaching and mentoring is possibly subtle but important. Coaching and mentoring in this context refers to when demonstrators intervene with students to assist their learning, but not necessarily dealing with the specific curriculum material. Coaching and mentoring were often intertwined when observed, but it is important to differentiate them. The theme of coaching included all the observations of laboratory demonstrators attempting to motivate students to use a deep active learning approach, often this would be to place the use of the learning into a real world context that was relevant to the student, and one not necessarily presented in the laboratory work book. One demonstrator would ask students 'If you were designing an elevator for your grandmother which EMD system would you want operating the winch?' This intervention focuses on student motivation and with the aim of a influencing the student to change their learning approach to better engage with the curriculum material rather than addressing a specific difficulty in understanding.

Mentoring also does not focus on specific knowledge, rather it addresses the process students use to engage with the curriculum material. Often this was discussion related to the way students approached the analysis or the laboratory exercise, as described in section 17.1.1.4, or an attempt to help students better appreciate the fundamental laboratory approach to gathering and analysing data for application in other contexts. This could occur after students had completed a laboratory exercise and the demonstrator would summarise what they had done and what they should take from the experience. There was also often a marked a change in the dynamic between the demonstrator and students, as mentoring was often delivered as advice from a senior colleague to a junior colleague rather than knowledge delivered from teacher to student.

Coaching and mentoring was judged to be an important function of the demonstrator, being both significant and relatively frequent, occurring in around 6% of observations. Importantly along with tailored scaffolding, coaching and mentoring is a function that could not be readily filled by adjustments to the EMDET curriculum.

17.1.7 Student, Equipment and Curriculum

The final category identified consists of interactions between equipment, curriculum and students. After axial coding two themes were identified within this category: issues faced by students due to equipment-curriculum interaction, and the overall laboratory experience had by students.

Equipment and curriculum interactions included some suggestions to improve the graphical layout of the HMI including colour coding and additional labelling to some parts of the mimic screens. This issue pointed to their being an unrecognised cognitive leap between the HMI layout, the data acquisition screen layout, and the equipment.

The observations related to overall laboratory experience include comments by the demonstrators that they themselves like the lab, that students had expressed enjoyment in doing the lab, and that motivation and engagement was positively affected by the laboratory experience, as 'Some students not engaged or motivated at beginning of lab but once they start the experiment they begin to see what is happening get more engaged and start asking questions of demonstrator [sic]'.

17.2 Summary Analysis of Grounded Theory

The purpose of the grounded theory analysis was to identify factors outside the control of the project team that would impact on the acceptance of the EDMDET equipment and curriculum. Several issues can be drawn from the categories and themes identified within the grounded theory analysis.

The first issue is determining a realistic expectation of success in delivering the desired competency across the cohort of students within the laboratory class.

An expectation that all students will gain the desired wisdom to practice with EMD systems appears to be unrealistic, due to the number of factors that can affect this that our outside of the control of the project team and teaching. In order to achieve the desired competency a student must be motivated to take a deep active learning approach, but the project team cannot ensure this will happen in all cases, as there are many things outside their control that can prevent the deep active approach from being taken. If these issues taken together would indicate that success in acceptance testing should be based on a proportion of the students achieving the desired wisdom.

This then begs the question, what does successful acceptance testing look like and how how can it be quantified? It does seem reasonable to expect a relative improvement in students measured by assessment before and after teaching, but the quantum of students reaching the absolute measure of achievement (wisdom) is still in question.

The nature of the ensemble performance that students need to execute to successfully gain the requisite wisdom to complete the war story scenarios should also be considered. To gain the requisite wisdom is a difficult task; students must master perquisite subjects from throughout an undergraduate engineering curriculum, they must be sufficiently motivated, and be able to engage in a deep active learning approach in spite of possible barriers. Ultimately expecting that all, or possibly even a majority of, students will attain this level of knowledge seems highly aspirational; particularly given the students are only trained with the EMDET for two laboratory sessions.

The apparent need for students to take a deep active learning approach to reach the desired competency combined with the frequently observed issues involving cognitive leaps indicates that these are important issues that should be explicitly considered during curriculum design. Particularly if the curriculum is targeting the ensemble performance needed to practice with wisdom in the field of EMD systems (or any other applied technical field). Moreover, this may also require broadening the scope of the design of the laboratory curriculum materials to a more holistic view that considers the course of education that the laboratory exercises reside in.

In relation to the judgement of acceptance another aspect to consider comes from a reviewing the significance and frequency of issues with the equipment or curriculum that are within the project teams' responsibility. There are only a small number of relatively insignificant issues within these two categories. Even if this consideration is expanded to categories that include equipment and curriculum in combination with student and teaching, the issues identified are arguably are of the kind that could be expected of ongoing curriculum development appropriate to any course of teaching, not specifically for an engineering teaching laboratory. This offers the possibility of the acceptance test is based on the equipment and curriculum operating sufficiently well, both individually and together, such that the issues identified in student learning are typical of any course of teaching and learning. Therefore the equipment and curriculum are transparent, and allow teaching staff to focus on the complex and difficult issues of student teaching without equipment or curriculum faults getting in the way. Potentially the measure of an acceptance test lies in the answer to the question: *when does a project stop and ongoing teaching begin?*.

Another consideration related to project acceptance is when should iterative reflective changes to a curriculum under the auspices of the project stop? Should every issue encountered with student learning result in a change to the curriculum materials? Given the number of issues observed with shortfalls in pre-requisite learning this approach may result in the laboratory workbook being expanded to include a large part of an undergraduate engineering degree, which is plainly not feasible. It therefore seems that another measure is required to determine whether a curriculum change is warranted, such as considering the proportion of students encountering a specific issue. If a laboratory is delivered with a demonstrator in attendance, a potential approach is that if a majority (or significant proportion) of students encounter an issue, an improvement to the curriculum materials is warranted; for issues experienced by a minority of students, the laboratory demonstrator is expected to deal with them. This is particularly relevant to a curriculum requiring students to execute an ensemble performance that draws on many prerequisite subjects, this may help to avoid the curriculum materials growing to encompass an entire undergraduate degree. This expectation of minority vs. majority issues could be built into the acceptance testing criteria.

The key role of the laboratory demonstrator in the student learning observed needs to be recognised and its ramifications considered for both acceptance testing and potentially curriculum design. The demonstrator provision of tailored scaffolding to students and engaging in linguistic cognitive question and answer, often in tandem, was crucial to student learning. These roles would be difficult and potentially impractical to expect any written curriculum to deal with entirely. It seems reasonable that the expectation of how the LCQ&A and tailored scaffolding, particularly for minority student issues, is to be addressed should be discussed and agreed within the project specification stage in an effort to set a realistic expectation during the acceptance testing phase. The role of the demonstrator in coaching and mentoring was also a valuable one that deserves recognition.

A frequent and significant issue encountered was a lack of student prerequisites, both English and technical which prevented students from achieving the desired educational outcomes. The inherent student characteristics for avoidance were the most frequently observed second tier category and the review of entry requirements for post graduate students into the PED course indicates that many students did not have the pre-requisite knowledge agreed for the EDMET curriculum agreed to in the Specifications phase (Section 6.5.2) ,and furthermore this lack was likely a reason that many were unable to successfully complete the war story scenario assessment. This issues was due to the User not complying with the agreed conditions for the project and the project team would argue that the remedy of issues stemming from this is a User responsibility. Due to the significance of this issues future projects should consider exploring the depths of student pre-requisite knowledge either at the early stages of the project or at least prior to acceptance testing, such as a knowledge quiz to ascertain the base level of student knowledge.

It could be argued that the project team was responsible for educating the User's on how to set realistic project goals, but the did not discharge this responsibility. At the outset of the EMDET project the Users possessed more educational expertise than the project team and their judgement was replied upon; however, in future projects using the WiSE Approach the learnings from the EMDET suggest the project team can and should advocate clear, realistic levels of prerequisite knowledge that are agreed on and adhered to during acceptance testing.

The issues identified here together point towards the importance of answering the question: *what does success look like?* during the requirements and specifications phase, this is necessary for proper execution of the acceptance testing phase later in the project. This should include what a realistic proportion of students achieving wisdom is, whether issues with the curriculum are experienced by a minority or majority of students trigger iteration, are the laboratory demonstrators fulfilling their intended role or dealing with shortcomings in equipment and curriculum, and finally if the issues encountered in teaching are due to the inherent complexities of teaching or failures within the equipment and curriculum provided by the project.

A deeper understanding was gained during interview of Laboratory demonstrators and the subsequent grounded theory analysis, so it may be worth incorporating parts of this into the WiSE Approach. The time involved in the grounded theory analysis was significant and must be considered, however many useful suggestions emerged from the interview process alone, which suggests that this would be a useful augmentation to the reflections already within WiSE.

Chapter 18

Discussion

This chapter presents the final synthesis which links the successes and failures of the EMDET project to the impact made by the WiSE Approach using decision making as a causal linkage; as shown in Figure 18.1.

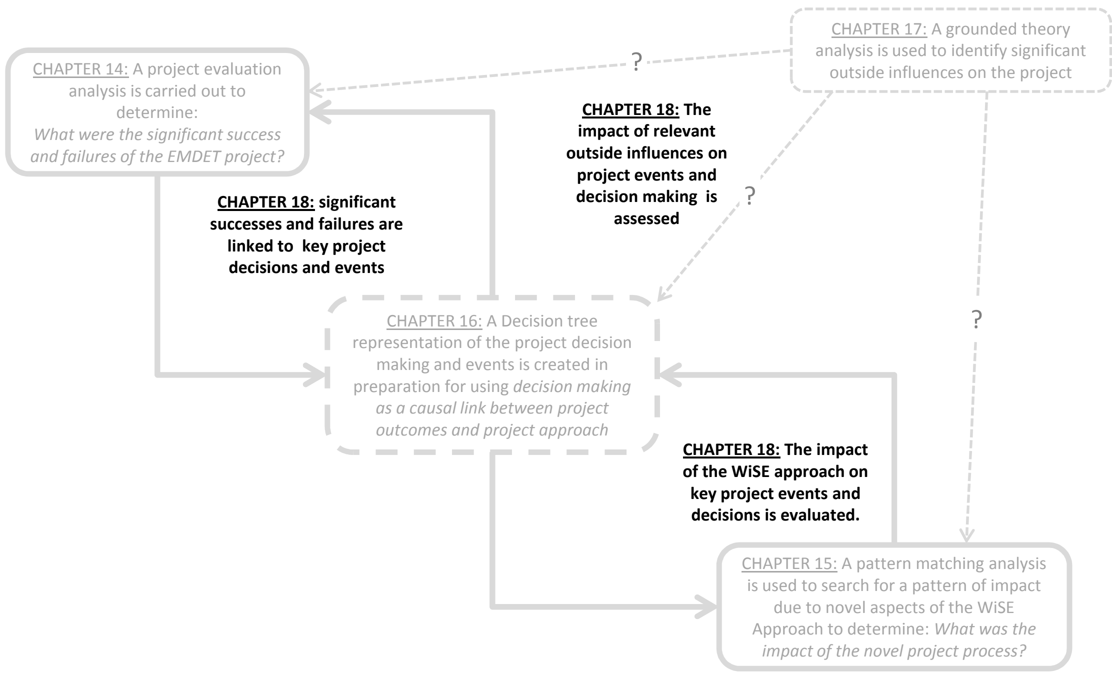


Figure 18.1: Schematic representation of the synthesis of the four analytical tools used to address the hypothesis

Significant success and failures identified in the outcome analysis (Chapter 14) are linked to significant project decisions in the decision tree (Chapter 16) which has the impact of the novel aspects of WiSE mapped to it from the pattern matching analysis (Chapter 15). The final synthesis considers the linkage of success, to decisions, to impact in light of outside influences identified in by the grounded theory analysis (Chapter 17). Exemplary instances of the synthesised linkages between the impact of the novel aspects and each success or failure are discussed in sections 18.1 to 18.5. There were however typically many more instances of impact than the exemplary instances alone, a summary of all observed impacts is presented in Section 18.6.

The success of the prototype and subsequent production model EMDET were due to the either fulfilling the project requirements or at least demonstrating their evident potential to project stakeholders. Delivering both the prototype and production model EMDET within budget is an aspect of the users acceptance, however it is singled out for further analysis due to the risk that the EMDET project may have failed in different circumstances where free labour was not available. Finally the performance of students in the war story scenarios was worse than originally anticipated requiring a re-adjustment of expectations. Each of these success and failures are considered individually and the results summarised into a matrix in Section 18.7 to allow conclusions to be reached about the individual novel aspects of the WiSE Approach.

18.1 Prototype Success

The overall goal of the EMDET was to provide the University with a tool to assist in preparing students to properly utilise EMD systems in practice and addressing the observed knowledge gap; this goal was refined to providing students with the wisdom needed to practice in the field of EMD systems. The prototype was a risk control measure enacted to ensure that the EMDET could deliver the desired outcomes before committing larger resources. The prototype successfully recruited stakeholder support for the production EMDET because it demonstrated the ability (or displaying the evident potential to) fulfil the User's requirements. To achieve the goal of student outcomes the EMDET had to consist of equipment and curriculum that worked together to deliver the desired student outcomes, the summative nature of this achievement is shown conceptually in Figure 18.2.

The prototype performance in achieving the goal included:

- delivering an agreed preliminary curriculum and associated teaching approach
- sufficient evidence within the equipment that the physical phenomena were present and visible, thereby giving stakeholders confidence that the equipment could deliver the curriculum with the desired authentic teaching approach
- demonstration that the prototype fit within resource requirements and contextual constraints

In analysing the component parts of the success for relevant decisions (to ultimately link to the WiSE approach), only the most significant and representative decisions that were found are presented here. There were typically more decisions associated with the success, however they were not needed to argue for a causal linkage between the project outcomes and project process, so they are omitted for clarity.

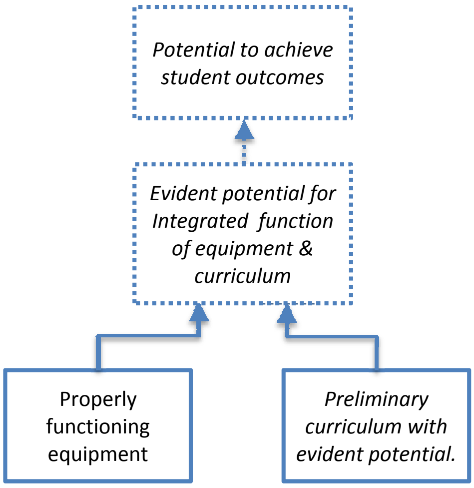


Figure 18.2: Conceptual representation of prototype success.

18.1.1 Prototype Equipment

Fully operational hardware was delivered in the prototype with the software development of the SCADA system being only partially complete; this enabled a significant amount of hot commissioning to be completed while demonstrating the capability (or evident potential) of properly functioning equipment. The prototype equipment showed that all phenomena relevant to the curriculum were present in the hardware and visible via the SCADA during hot commissioning. The significant decisions relevant to this component of prototype success were identified from the decision tree in section 16 (including the label) and are summarised in Table 18.1. All the novel aspects of the WiSE approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Table 18.1: Decisions related to prototype equipment success and WiSE impacts.

	Requirements	Decisions →			Component Testing	Prototype acceptance
Physical phenomena present	R7: Equipment must match curriculum [3]	S1: Philosophy of fidelity [2]	SD5: Load control methodology [2][4]	DD1: Drive Type selection [1][2][3]	Hot Commissioning motor steady state [2][3]	*Required physical phenomena are present. Three common industrial drive types and ability to simulate many real world loads*
		S2: Philosophy of flexibility [3][4]	System (and Detailed) Power side circuit design [2][3][4]	DD11 Torque simulation [2][4]	Hot Commissioning motor starting [3][4]	
		S3: Equipment constitution [3]	System and Detailed SCADA and control side design [2][3][4]	DD12: Pump Simulation [4]	Hot Commissioning sophisticated load [2][3][4]	
Phenomena visible	Equipment will include a motor, load, drive and	S4: Organisational Schema included linkage matrix of educational concerns to equipment design. [3]	S13 - Data acquisition system for power flow [3][4][4i][5][5i]	DD2 Motor voltage transducer reference [3][4][5]	Hot Commissioning - SCADA Data Acquisition [2][3][4][5][5i]	*Required phenomena are visible and can be captured through laboratory grade data acquisition system*
			SD 4 DAQ sampling rate and DAQ layout [3][3i][5][5i]	DD9 DAQ transducer selection [3][3i][5][5i]		

Many decisions impacted this outcome, of particular importance were decisions made within the requirements and specifications stages whose effects propagated throughout the rest of the project. These included the requirement of equipment matching curriculum (decision R7 in table 18.1), design philosophies (fidelity (S1), flexibility (S2) and equipment constitution (S3), and the organisational schema (S4) developed in the specifications phase. All of these were motivated by novel aspects of WiSE, either the *deliverable of student competency*, scope of *integrated equipment* *and curriculum* or the closed loop *reflective project process.*

Specific examples of decisions and events are the hot commissioning checks which addressed motor starting (section 10.1.2.2), the data acquisition system(section 10.2.2) and testing of a sophisticated load (section 10.1.2.3). The motor starting checks tested that all three drives in the system (DOL, soft starter and PWM Inverter) against three simple simulated load types (constant, linear and squared torque with speed) demonstrating much of the important physical phenomena. This test was inspired by industrial war stories (WiSE *measure of student competency*) and the intent was to train students in appropriately matching drives to load types in industrial practice (WiSE *deliverable of student competency*). The flexibility and ease of mixing load and drive types was inspired by the flexibility demanded of the WiSE *reflective project approach* and *integration of equipment and curriculum.*

The successful test of the data acquisition system (section 10.2.2) clearly demonstrated that the physical phenomena required was present, could be viewed, and importantly captured for subsequent display and student analysis. This event was driven by four of the WISE aspects, *deliverable of student competency* for industrial practice and *integration of equipment and curriculum* required so that students could interact with these physical phenomena. The *reflective project approach* motivated inclusion of a comprehensive data acquisition system to allow flexibility in future teaching. The *closed loop model of education* stipulated that understanding the content of the signals was an achievable cognitive leap and gave the qualitative requirement that signal waveforms could be recognised from the DAQ (section 7.4).

The prototype demonstrated the evident potential for delivering the curriculum during the successful simulation of a complex pumping system (section 10.1.2.3). This simulation was part of the agreed curriculum and its development was instigated by the scope of the project, including *integrated equipment and curriculum.* The fidelity built into the simulation required to train students on realistic systems was motivated by the *deliverable of student competency* and the flexibility of the load simulation was motivated by the *reflective project approach.*

18.1.2 Prototype Curriculum

Within the prototype preliminary curriculum and laboratory outlines were produced in consultation with stakeholders in the requirements and specification phases; these satisfied the stakeholders that the correct topics could be covered with an appropriate teaching approach. The stakeholders were also satisfied with the evident potential of the equipment to deliver the curriculum using the desired approach. The significant decisions relevant to this outcome are summarised in table 18.2. All the novel aspects of the WiSE approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Table 18.2: Decisions related to prototype curriculum success and WiSE impacts.

<table>
<tr><th></th><th colspan="2">Decisions</th><th></th></tr>
<tr><td rowspan="2">Agreed Preliminary Curriculum</td><td>R1: Project scope: Tool will consist of equipment and associated curriculum
3 3i</td><td rowspan="4">Preliminary curriculum proposed
3

S3: Equipment constitution
3

S4: Organisational Schema included linkage matrix of educational concerns to equipment design.
3</td><td rowspan="2">Preliminary curriculum of agreed teaching topics created and there is sufficient evidence in the equipment that it can deliver teaching on them.</td></tr>
<tr><td>R4:Target level of student skill defined
1 2 5 5i</td></tr>
<tr><td rowspan="2">Teaching Approach</td><td>R2:Approach to teaching defined
2 5</td><td rowspan="2">Teaching approach agreed. There is sufficient evidence in the equipment produced that it can deliver the agreed authentic assessment approach.</td></tr>
<tr><td>R8: Closed loop deliverable set as student outcomes
2 2i 4</td></tr>
</table>

An important example of the impact of WiSE on decisions leading to the prototype curriculum success is the creation and use of the design philosophy of equipment constitution (decision S3 in table 18.2) and the organisational schema of the linkage matrix (S4) within the specification phase (sections 6.1 and 6.2). The design philosophy codified the WiSE aspect of *integrated equipment and curriculum* during the system and detailed design phases, and also led to the linkage matrix that provided the mechanism to ensure that all the significant groups of hardware and software within the EMDET could deliver the function required by the desired curriculum during the design process. The impact of the linkage matrix permeated the design and construction of the prototype EMDET and resulted in equipment with the evident potential to deliver the agreed curriculum.

18.1.3 Prototype Resource and Contextual Constraints

The equipment delivered fit with the resource limitations and contextual constrains within the requirements. The design was affordable, would fit with the new laboratories, and was suitable for undergraduate student use. The significant decisions relevant to this outcome are summarised in Table 18.3. All the novel aspects of the WiSE approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Table 18.3: Decisions related to prototype fulfilling resource and contextual constraints and WiSE impact.

	Decisions		
Fits within resource requirements	S5:Power flow organisational Schema selects load type 3, 4	DD9: Data Acquisition System: Selection of transducer 3, 3i, 5, 5i	*Equipment and curriculum fits within budgetary and space constraints.*
		Data Acquisition system detail design a reflective compromise 3, 3i, 4, 5, 5i	
Fits contextual requirements	R6: Student exposure to ELV signals 3	S12: Design requirement for students to interact with dangerous power levels 3	*Equipment suitable for use by students (safety and equipment risks)*
		DD10: SCADA: Programmable Logic Controller functions as a gatekeeper 3	

One example of the impact of WiSE was providing equipment suitable for student use; this was motivated by the WiSE aspect of providing *integrated equipment and* *curriculum*. The students were judged as not being able to interact with hazardous voltages on industrial equipment (decisions R6 and S12 in table 18.3), consequently the EMDET was designed to reduce all signals to extra low voltage before any potential student interaction (Section 6.6). Moreover, students should not have to physically interact with changing loads and drives, and the equipment should not allow itself to operate in a configuration that could damage itself; so the PLC was programmed as a gatekeeper (DD10), and when requested would only change load and drive types when safe (Section 8.2.1).

18.2 Production Model EMDET Success

The overall goal of the EMDET was to provide the University with a tool to assist in providing students with wisdom to practice in the field of EMD systems. The production model EMDET fulfilled the User's requirements within the acceptance testing phase by successfully teaching students and addressing some general assessment criteria (albeit with a changed expectation of success in scenario assessment). To achieve the goal of student outcomes the EMDET had to consist of equipment and curriculum that worked together to deliver the desired student outcomes, the summative nature of this achievement is shown conceptually in figure 18.3. The Production EMDET performance in achieving the goal included:

- providing properly functioning equipment
- providing of a working curriculum
- achieving integrated function of equipment and curriculum
- achievement of student outcomes in laboratory work books and (to a lesser extent) scenario assessment.

In analysing the component parts of the success for relevant decision for ultimate linkage to the WiSE approach only the most significant and representative decisions that were found are presented here. There were typically more decisions associated with the success, however they are omitted for clarity as they were not needed to argue for a causal linkage between the project outcomes and project process.

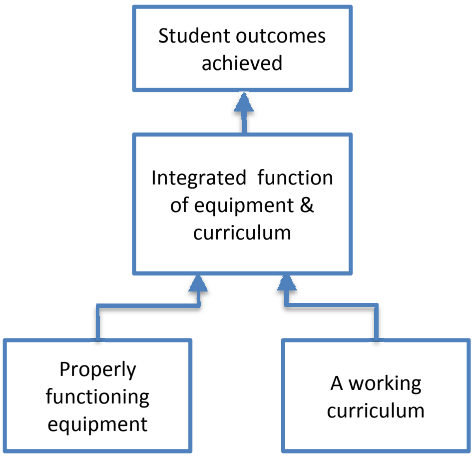


Figure 18.3: Conceptual representation of production EMDET success.

18.2.1 Properly Functioning Equipment

Providing properly functioning equipment was a significant outcome in its own right, requiring a number of components and sub-systems and systems to be successfully designed, built, integrated and commissioned as a coherent whole. The resulting EMDET is a complex system including mechanical and electrical hardware, as well as software within the PLC, HMI and data acquisition system. When reviewed as part of an accreditation audit (in Section 13.1.1), Engineers Australia (2013) deemed it 'probably amongst the best in any Australian University'.

Throughout the development process many major and minor issues were identified and resolved. The proper function of the EMDET equipment was first demonstrated in the integration test phase where the equipment was able to deliver the curriculum and enabled an instructors solutions manual to be produced. The significant decisions relevant to this outcome are summarised in table 18.4. All the novel aspects of the WiSE approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Generating the motor torque speed curve within the component testing phase (Section 10.3) is a representative example of the impacts of WiSE on the EMDET. This event was impacted by the *deliverable of student competency* and *measure of student competency*, the scope of *integrated equipment and curriculum* and the *reflective project approach*.

Table 18.4: Decisions related to production EMDET equipment Success..

	Decisions			
	Requirements →		Integration Testing	
Functional sub-systems	*All decisions identified within the prototype equipment contributed to the success of the production model*	Hot Commissioning – PLC & HMI: 3 5	Test of all five lab exercises during integration test phase 2 3 4	*All sub systems functional and operate as on overall system.*
		CT2:Operation of equipment for motor curve generation 3 4 5		
Functioning systems of sub-systems	1 2 3 3i 4 4i 5 5i	CT3: Summative Testing of system – generation of motor torque speed curve 1 2 2i 3 5	Reflective Changes to Laboratory Equipment and all five Exercise during integration test phase 2 3 4 5	
	SD6: Motor Asymmetrical size selected 1 2 3 4	CT1: Electromagnetic Noise on sensors 2 3 4 5 5i		

The motivation for the exercise was to prepare students for industrial practice, particularly to understand the torque-slip behaviour of the induction motor which frequently arose within industrial war stories. The proposition was that by plotting the torque speed curve for themselves students would appreciate the relationship between slip and torque around rated motor conditions; this would also build student confidence in the utility of manufactures motor torque speed curves.

Plotting the motor torque speed curve was a key exercise within the revised curriculum, but during testing the symmetrical motors of the prototype could not complete this exercise. A decision was therefore made (SD6 in Table 18.4) to initiate a reflective change between the prototype and production EMDET to use asymmetrically sized motors (described in Section 7.7.2) to ensure that the equipment could execute the curriculum. Apart from its value in assessment, the war story proved to be an inspiration during design and development activities, as shown by these iterative changes. The first successful motor curve was produced during Component Testing (Sections 10.3 and 17.1.3.2) and during acceptance testing students have successfully produced this curve (section 13.1.3).

During the grounded theory analysis of the EMDET looking for outside influences it was found that there was only a very low incidence of equipment issues during student teaching, and few of these were the responsibility of the project team to address (Section 17.1.2.2). This would support the conclusion that properly functioning equipment was delivered.

18.2.2 Working Curriculum

Creation of a working curriculum consisting of two laboratory sessions meant addressing learning objectives, student capabilities, creating learning experiences, and assessments appropriate to the predetermined educational objectives; This was a significant achievement in itself. The working curriculum materials were first demonstrated during the Integration Test phase where the instructor's solutions manual was produced (Section 11), and further confirmed during the subsequent System Test phase (section 12.1) where the laboratory demonstrators completed the laboratory work books before teaching students. The significant decisions relevant to this outcome are summarised in Table 18.5. All novel aspects of the WiSE Approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

The creation of the instructor's solutions manual is an important example of the impact of the WiSE approach. The creation of the manual was initiated as a confirmation that *integrated equipment and curriculum* would be provided that could *deliver student competency* to practice with EMD systems.

While the solutions were being created several issues emerged which were dealt with by the *reflective project approach* using the *closed loop model of education* to diagnose issues and posit solutions. Tests and reflective changes were made on all five laboratory exercises during the Integration Test Phase (section 11). An example of this is the automated loading sequence to generate the torque speed curve that was

Table 18.5: Decisions related to production EMDET curriculum Success and WiSE impact.

	Decisions: Requirements →				→ Integration Testing	
Working curriculum addressing learning objectives, approach and assessment.	*All decisions identified within the prototype preliminary curriculum contributed to the success of the revised curriculum* 1 2 3 3i 4 5 5i	S6: Organisational Schema included curriculum design 3	DD16: Learning Quality Assessment 1 1i 2 2i 3 5	A7:Production of Motor Characteristic Curves (including reflective iterations) 2 3 4 5		*Laboratory work books and war story scenarios assessments produced and instructors solutions manuals produced.*
		S8:Limitations of student learning addressed 5	A1: Laboratory book format –depth of learning 2 3 4	A8:Motor Magnetising current war story and associated theory (including reflective iterations) 1 1i 2 2i 4 3 5	Tests of all five lab exercises during integration test phase 2 3 4	
	R3: Limitations of student learning addressed 5 5i	S10: Definition of educational objectives. 1 1i 2	A2: Laboratory work books format addresses student motivation and context for learning 2 4 5	A9:Induction Motor Slip war story and associated theory (including reflective iterations) 1 1i 2 2i 4 3 5	Reflective Changes to Laboratory Equipment and all five Exercises during integration test phase 2 3 4 5	
	R4:Target level of student skill defined 1 2 5 5i	S11: Methods of assessing quality of student learning further developed 1 1i 2	A3: Laboratory book Alignment of exercises and assessment 3 5	A10:Motor drive and load combinations war story and associated theory (including reflective iterations) 1 1i 2 2i 4 3 5		
	R5: Assessment of student learning addressed 1 1i 5	S12: Definition of target level of skill refined as practice with wisdom in field of EMD systems 1 1i 2 2i	A5:Student data collection (collection proximate to analysis) 3 5	War story scenarios written to assess student learning quality looking for competency for industrial practice (including reflective iterations) 1 2		

created during this process (Section 11.1.3). The complex nature of simultaneously loading the motors and logging data was recognised as an unnecessary and obstructive cognitive leap for students, so an automated sequence was added to remove the complexity to enable students to focus on the operations relevant to the exercise.

The grounded theory analysis of the EMDET revealed that there very few issues with the curriculum materials provided during student teaching, few of these were the responsibility of the project team to address (section 17.1.3.2); this supports the conclusion that working curriculum materials were delivered.

18.2.3 Integrated Function of Equipment and Curriculum

Providing equipment and curriculum that functioned together in a integrated fashion was important, because otherwise worthy equipment and curriculum created independently of each other may not be compatible. This integrated function was confirmed while producing the instructors solutions (Section 11) and during initial testing of the curriculum by the laboratory demonstrators before teaching students (section 12.1). It is important to focus on the integrated nature because both equipment and curriculum must work together in an engineering teaching laboratory for it to achieve its fundamental purpose of student outcomes. The inherent flexibility of the EMDET was also important because it facilitated resolution of conflicts between equipment and curriculum. The significant decisions relevant to this outcome are summarised in table 18.6. All novel aspects of the WiSE approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Table 18.6: Decisions related to success of production EMDET equipment and curriculum integration and WiSE impact.

	Decisions				
	Detail Design →			System Testing	
Integrated Function of Equipment and curriculum	DD14: Layout of electrical panel meters 3 3i 4 5 5i	Tests of all five lab exercises during integration test phase 2 3 4	Checks for adherence to Philosophy of Equipment Constitution: 3	Checks for adherence to the Schema of Linkage between educational concerns, and the power and control system 2 3 4 5	*Instructors solutions created by designers using curriculum developed on equipment*
	DD13: Data Acquisition System interface layout 3 3i 4 5 5i	Reflective Changes to Laboratory Equipment and all five Exercises during integration test phase 2 3 4 5	Checks for adherence to Philosophy of Fidelity: 2 3 5	Checks for adherence to the Schema of the Curriculum Design Methodology 2 3 5	
	DD3 & DD4: Motor 2 voltage transducers measurement reference and current selection 3 4 5	Testing by laboratory demonstrators acting as User representatives and reflective changes 3 4	Checks for adherence to Adherence to Philosophy of Flexibility: 2 3 4	Checks for adherence to detailed educational specifications 1 2 3 5	*Laboratory demonstrators successfully completed curriculum as representatives of future students.*

Representative examples of the impact of WiSE in prompting development of properly integrated equipment and curriculum are the selection of current and voltage transducers and the layout of panel meters on the EMDET. The WiSE aspects of *integrated equipment and curriculum*, *reflective project approach* and the *closed loop model of education* all interacted to make positive changes to the production model

EMDET. While testing the EMDET issues emerged with the voltage reference used by the transducers (Section 8.6.1). Using an unusual (or irrelevant) voltage reference was recognised (using the closed loop model of education) as an unnecessary and obstructive cognitive leap. Furthermore, that voltage and current measurements should be provided so students could analyse them within the familiar conception of the single phase equivalent circuit model of the induction motor. Therefore, reflective changes (DD3 and DD4 in Table 18.6) were undertaken in the placement of current and voltage transducers to ensure that the measurements were compatible with the curriculum.

Similarly, it was noted while testing the prototype that by using the panel meters to understand system operation, their arbitrary layout was often translated to the power flow schema to understand system operation. This was also recognised as an unnecessary and obstructive cognitive leap (section 8.6.1), in order to match with the curriculum materials being presented a reflective change (DD14 in Table 18.6) was made to lay out the panel meters and DAQ interface on the production model EMDET using the power flow schema.

18.2.4 Student Outcomes Achieved

The achievement of student learning outcomes is as a significant project success that leads towards the overall project goal of the EMDET - providing students with wisdom to practice in the field of EMD systems. Achieving learning outcomes is a summative achievement built upon working equipment, working curriculum, and then integrated function of the equipment and curriculum (Figure 18.3) but signifies something more; it means that the equipment and curriculum has been effective *within the context* in fulfilling its purpose. Effectiveness encompasses several separate issues, it means that goals have been set, measures established, and the result of the project have been assessed to confirm that the purpose has been met. Moreover, effective *within the context* means that what has been provided is suitable for students, teachers and the (university) environment in which it operates. Assessment at this level is important because it addresses the possibility that while integrated equipment and curriculum may be produced, they may not work within the context, or still fail to achieve the desired outcome for a variety of reasons.

The summative nature of achieving student learning outcomes can be illustrated within the context of the 3-P model of teaching and learning in Figure 18.4. The first three attributes of the success occur within the learning focused activity where equipment and curriculum are both needed as part of the activity, and must function individually, and together to enable the learning activity to occur. Achieving the student learning outcome expands the scope from just the learning focussed activity to include the outcome, and all of the *interactions* between student, teaching, the learning activity, and the outcome. These interactions are part of the summative nature, as they can prevent the desired outcome from being reached regardless of the quality of equipment or curriculum in isolation.

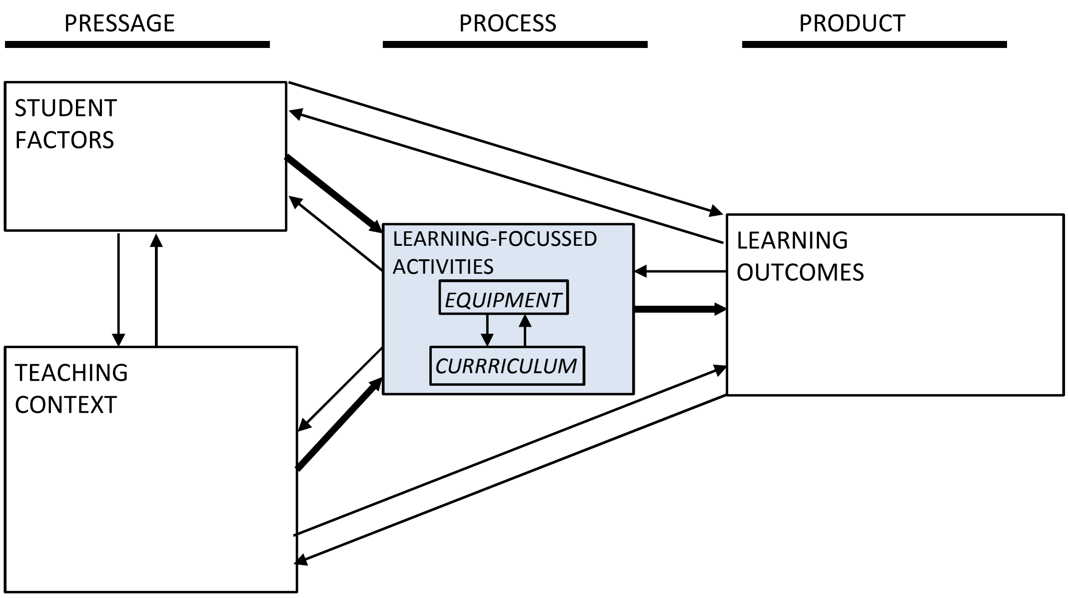


Figure 18.4: Summative success in context of the 3P model of teaching and learning.

The equipment and curriculum within the EMDET passed acceptance testing, and were used to teach students in 2012, 2013 and 2015. In each year the laboratory workbooks were successfully completed with passing marks (Section 13.1.1) and student performance was assessed before and after teaching with war story scenarios (sections 13.1.4 to 13.1.7); student performance in the scenarios were lower than anticipated (and hoped) but it was accepted after the war story was re-evaluated as a performance measure (Section 13.3). The significant decisions relevant to this outcome are summarised in Table 18.7. All novel aspects of the WiSE Approach had a beneficial impact, with each of the decisions identified being affected by at least one aspect.

Table 18.7: Decisions related to successful student outcomes with production EMDET and WiSE impact.

	Decisions				
	Acceptance Testing				
Student goals have been set, measures established and the result of the project have been assessed to confirm that the purpose has been met	User Testing - General Assessment - Student completions of lab books 2 3 4	User Testing - Specific Assessment and reflective changes Production of Motor Characteristic Curves 2 3 4 5	User Testing - Specific Assessment and reflective changes War Story: Capability of VSD 1 2 3 4 5	A1 Adherence to acceptance testing criteria from requirements phase - revaluation of war story acceptance criteria 3 4 4i	*Student lab books completed satisfactorily.* *After revaluation of war story assessment student improvement grounds for acceptance.* *Equipment judged capable of meting future teaching needs* *Equipment helped to gain excellent accreditation review - addressing original motivation for EMDET.*
	User Testing - General Assessment - capability for future teaching 2 3 4	User Testing - Specific Assessment and reflective changes War Story: Magnetising Current 1 1i 2 2i 3 4 5	User Testing - Specific Assessment and reflective changes War Story: Capability of VSD 1 1i 2 2i 3 4 5		
	User Testing - General Assessment - addressed IEAust accreditation 2 3 4	User Testing - Specific Assessment and reflective changes War Story: Induction Motor Slip 1 1i 2 2i 3 4 5	User Testing - Specific Assessment and reflective changes War Story: Drive and load types 1 1i 2 2i 3 4 5		

Important examples of the impact the WiSE approach had on student outcomes are seen in the completed student laboratory work books (section 13.1.1), the motor torque speed curve exercise (Section 13.1.3), and work around the war story scenario addressing motor, load, and drive combinations (Section 13.1.7).

Successful completion of student laboratory workbooks showed that integrated equipment and curriculum had been delivered as part of the EMDET. The laboratory work books had been developed using the *closed loop model of education* and a *reflective approach*. For example, in the first cohort of teaching student difficulties with the motor curve generation (Section 13.1.3) were noticed and assessed with the *closed loop model of education* (User Testing - Specific Assessment and reflective changes Production of Motor Characteristic Curves in Table 18.7). The importance of this exercise to delivering competent students was recognised and the *reflective project* *approach* was used to remedy the shortfall in the performance of the 2012 cohort resulting in a much improved performance in the 2013 cohort (Section 13.1.3). All novel aspects of the WiSE approach had a beneficial impact on these decisions, the impact is summarised in Table 18.7.

Similarly issues with student performance in the war story scenarios (*measure of student competency*) were diagnosed using the *closed loop model of education* and the *Reflective Project Approach* was used to implement a number of changes to address them. For example the poor 2012 student performance in the scenario addressing the proper selection of motor, loads and drives (User Testing - Specific Assessment and reflective changes War Story: Drive and load types in Table 18.7) resulted in several changes to laboratory work books, and the HMI described in Section 13.1.7.

Within the student outcomes achieved the Grounded Theory analysis (section 17.2) identified the important role of the demonstrator as a complement to the equipment and curriculum. The role of the demonstrator in providing tailored scaffolding to students, engaging in linguistic cognitive question and answer (LCQ&A), as well as coaching and mentoring was very important. In future it is recommended that the role of the demonstrator should be addressed explicitly in project specifications and requirements.

18.3 Completion within budget

Both the prototype and production model EMDET were delivered within project budgetary constraints; there were two types of decisions that contributed to the financial success of the EMDET: decisions that reduced the capital cost, and decisions made to carry out work because expert labour was available at no financial cost to the project (via the researcher and industry partner). The significant decisions relevant to this outcome are summarised in Table 18.8. All novel aspects of the WiSE approach had an impact, and each of the decisions identified was affected by at least one aspect.

Important examples of savings in the capital cost of equipment include the selection

Table 18.8: Decisions related to production EMDET meeting budget targets and WiSE impact.

	Decisions: Requirements →				Acceptance Testing	
Reduction of Capital Cost	S5:Power flow organisational Schema selects load type (low cost induction motor) 3 4	DD9: Data Acquisition System: Selection of transducer 3 3i 5 5i	SD4: Data acquisition system design – sampling rate 3 3i 5 5i			*Reflective compromises allowed a cost for educational performance compromise to be made in technical systems*
		S14: Data Acquisition system design to measure power flow 3 4 4i 5 5i	Detailed SCADA Design: HMI Software package 3 4			*Economical technical solutions found meeting educational requirements*
Decision made due to availability of labour at no cost	R1: Project scope: Tool will consist of equipment and associated curriculum 3 3i	S6: Organisational Schema included curriculum design 3	A8:Motor Magnetising current war story reflective iterations (V6,V7) 1 1i 2 2i 4 3 5	Hot Commissioning – SACDA Data Acquisition- significant efforts to ensure physical phenomena visible with adequate quality 2 3 4 5 5i	Tests of all five lab exercises during integration test phase	*Curriculum added to project scope as it was supported by no cost labour* *Educational models developed by no cost labour*
	R2:Approach to teaching defined 2 5	DD15: Laboratory lessons designed 2 3 5	A10:Motor drive and load combinations war story reflective iterations (V8) 1 1i 2 2i 4 3 5	CT1: Electromagnetic Noise on sensors 2 3 4 5 5i	Reflective Changes to Laboratory Equipment and all five Exercises during integration 2 3 4 5	*In depth testing and commissioning undertaken by no cost labour without economic concern*
	R8: Closed loop deliverable set as student outcomes 2 2i 4	A7:Production of Motor Characteristic Curves reflective iterations (V5) 2 3 4 5	Warm Commissioning - Significant efforts to ensure speed feedback and torque control suitable to deliver curriculum 3 4	Acceptance testing checks initiating reflective iterations to Assembly phase		*Due to availability of no cost labour reflective iterations undertaken without economic concern*

of voltage and current transducers and the design of the data acquisition system. An understanding of the educational outcomes due to the *integrated equipment and curriculum* along with the *closed loop model of education* allowed for the transducer selection criteria of recognition to be established (section 8.1.3). This enabled a reflective compromise to be made when selected the transducer balancing performance and cost (DD9 in Table 18.8); that had a large impact on the overall price of each EMDET. Similarly, another reflective compromise was made to log a single phase of electrical power flow in balanced parts of the EMDET circuit (S14 in Table 18.8), this compromise enables students to analyse the EMDET using the familiar single phase equivalent analysis while reducing overall cost(section 8.1.3). In both cases an understanding of the curriculum to be delivered allowed the *reflective project approach* informed by the closed loop model of education to significantly reduce the unit cost of EMDET while still delivering the equipment performance needed to deliver the curriculum.

Examples of decisions based on the availability of expert labour at no cost to the project include the testing and commissioning of the data acquisition system and reflective iterations to address shortfalls in war story scenario performance. while checking the data acquisition system (Hot Commissioning - SACDA Data Acquisition in Table 18.8), transducers were tested on the bench, in the panel (Section 10.2.1.1) and when connected to the data acquisition system itself (section 10.2.2). These extensive checks were undertaken to ensure that the physical phenomena was present, visible and of sufficient quality to deliver the required curriculum to enable students to achieve the desired outcomes. The Wise *deliverable of competency* and *integrated equipment and curriculum* drove testing of the data acquisition system using the *reflective project approach* to ensure that the right information was provided in achievable cognitive leaps to students.

Similarly, student performance in the war story scenario *measure of student competency* triggered analysis of the issues with the *closed loop model of education* and subsequent reflective changes to address the shortfall in performance with the aim of *delivering student competency.* Iterations were carried out for all the war stories, over the three years. In this case, and for the commissioning, no significant consideration was given to the labour expenditure on these tasks simply because it was available at no cost. If the labour was financially supported the amount of work undertaken may have been far less.

18.4 The Risk Posed by the Project Use of Free Labour

If all the labour used in the EMDET project were financially supported the project would have significantly overspent its budget and failed. This poses a risk for future projects in future, and the amount of expert labour required must be recognised and supported either by using in kind sources, or from the project finances. Significant examples of these have been described in section 18.3.

The novel aspects of the WiSE approach setting the project *deliverable as student competency* and the *reflective project approach* driving repeated iterations to achieve the deliverable as assessed by the war story scenario *measure of competency* (that was later deemed highly aspirational) were responsible for much of the free labour used. Given this interaction, it is important to set realistic targets of acceptance, otherwise this risks what should be a finite project becoming an ongoing commitment.

The grounded theory analysis also identified several issues related to the use of free labour in section 17.2, where (potentially) unnecessary iterations may be triggered using large amounts of labour. To avoid this risk it is important therefore to define in the requirements phase of a project when student issues should trigger reflective changes to a curriculum, and when should it be left to the laboratory demonstrators to deal with? A related issues is when should reflective iterations by the project team end and ongoing reflective teaching practice by the ultimate User's of equipment begin?

18.5 Poor Student Performance in War Story Assessment

Student performance in war story scenario *measure of student competency* was worse than had been anticipated and several iterations of the *reflective project process* were instigated to address this with limited success. Ultimately, the expectation of student success in this measure was revised based on two criteria: firstly, the measure being more aspirational than originally anticipated (requiring what was subsequently recognised as an ensemble performance); and secondly the mismatch between EMDET goals for competency, and the goals of the parent subject (and course) that the EMDET was used within (sections 13.2 and17.2). Additionally, issues with student prerequisites and the small amount of time available for training with the EMDET have prompted the revaluation of the success measure to look for a smaller number of students making a relative improvement during training. Four of the novel aspects of the WiSE approach had an impact, with each of the decisions identified being affected by at least one aspect.

The issues encountered around the war story addressing motor magnetising current

Table 18.9: Decisions related poor War Story Performance and and WiSE impact.

	Decisions		
Student performance in war story scenarios	R4:Target level of student skill defined as ability to practice with wisdom. Ensemble performance not fully appreciated 1 2 5 5i	S8:Limitations of student learning addressed. Specified pre-requisites English and technical knowledge not present in a proportion of post graduates 5	*Initial underestimation of aspirational nature of war story leading to an unrealistic target*
	R3: Limitations of student learning addressed - size of cognitive leap for desired competency not fully appreciated 5 5i	S12: Definition of target level of skill refined - aspirational nature was not initially recognised 1 1i 2 2i	*Student pre-requisites lacking*
		S9: ECTE412/912 chosen for acceptance testing during two laboratory sessions. Mismatch in assessment objectives and limited time to reach them. 2 2i 3	*Mismatch between war story goals and elective goal* *Time available in lab*

(Section 13.1.5) are representative of impact of WiSE on this issue. For students to address the magnetising current they have to execute an *ensemble performance*; which means they be able be exposed to a scenario in context, dismiss irrelevant (or inaccurate) information, recognise the magnetising current in context, and understand its significance. Gaining the required wisdom from the laboratory exercise requires students to assess measurements of motor mechanical power and current, derive a relationship and relate this to both the single phase equivalent circuit of at the motor and its physical construction. Viewed in terms of the SOLO taxonomy the ensemble performance could be considered as students possessing knowledge (at the unistructural level) which they can combine (a multistructural action) and use for analysis of, and application to, a situation (relational actions).

The assumed pre-requisite understanding of the equivalent circuit and motor construction was lacking, which prevented some students from understanding the significance of the scenario. The summative nature of the ensemble performance is not addressed within the PED course, or in many other places within a degree course (if at all). Herein lies the importance of the mismatch in expecting students to be able to deliver an ensemble performance that none of their prior training has prepared them for, particularly when only two laboratory sessions are used for training.

Lastly to attain the desired wisdom and the ability to deliver an ensemble performance, a student must engage in training with a deep active learning approach, but the grounded theory analysis has identified that there are many factors that can prevent students from taking this approach, and from there gaining the desired competency.

The unexpectedly aspirational nature of the war story scenario assessment was recognised on the basis of its reliance on mastery of prerequisites, the summative nature of the required ensemble performance, the novelty of this performance, and the number of factors that can prevent the deep active approach to learning needed to attain the ability to deliver the ensemble performance. The war story scenarios were part of the original motivation to develop the EMDET and formed the measure of competency to be used in training. The *reflective project approach* naturally engaged iterations to address this issue using the *closed loop model of education* to *deliver student competency* as assessed by the war story scenario *measure of student competency.* Given the now recognised aspirational nature of the war story scenario the importance of having a realistic measure of student performance for acceptance is paramount if a *reflective project approach* is to be used.

18.6 Typical impacts of WiSE on Decision Making

The WiSE Approach had a pervasive effect on the EMDET project. While mapping the impact determined by the pattern matching analysis (Section 15) to the Decision Tree (Section 16) many more impacts were linked to decisions overall than the examples discussed in sections 18.1 to 18.5. The most frequently recurring, or 'typical' impacts of the novel aspects of the WiSE approach on project decision making are summarised in Table 18.10; these represent the most common impact seen on the decision making process, but it is not an exhaustive listing.

Table 18.10: Typical impact of novel aspects of WiSE on decision making.

ID on decision tree	Novel Aspect	Recognising that a decision must be made	Defining the decision	Identifying the factors that impact upon the decision and their relative priority	Identifying the potential consequences of the alternatives	Selecting one of the alternatives
1 1i	***Measure of student competency***	decisions recognised and defined to address shortfalls in students achievement or where equipment and curriculum need alteration to allow for provision of competency.		Decisions impacting student attainment of competency given a high priority	Alternatives not providing desired student competency are discounted.	
				User acceptance of the measure weights selections.		
2 2i	**Project *deliverable of student competency***	decisions recognised and defined as providing students with authentic experiences with industrial EMD systems to deliver student competency.		Decisions impacting authenticity and fidelity are given a high priority.	Alternatives not providing required fidelity are discounted	
				User acceptance of the goal weights selections.		
3 3i	Scope of delivery is ***integrated equipment and curriculum***	Decisions recognised and defined as providing integrated equipment and curriculum		Priority is placed on providing equipment that can deliver the full curriculum and the integration of the two	Assists indentifying and avoiding decisions that have the consequences of equipment unable to deliver curriculum	
				User acceptance of the scope weights selections.		
4	Closed loop ***reflective project approach***	Decisions recognised and defined as providing equipment that is flexible flexible and future proofed.		Priority is placed on giving flexibility to allow for large curriculum and future reflective changes	Adverse consequences of alternatives without flexibility and enable to adapt to future teaching needs identified and avoided	
4i		Decisions recognised and defined as making changes to equipment or curriculum to address actual (or potential) shortfalls in student attainment		Priority placed on reflexively addressing issues with student attainment		
				User acceptance of the reflective approach weights selections.		
5	***Closed Loop model of education***	Allows for factors affecting teaching an learning to be recognised and consequent decisions defined.		Model facilitates an understanding of the factors within teaching and learning and the potential impacts of alternatives		Understanding of education can assist in deciding between alternatives
5i		Closed loop model allows reflective design, construction and commissioning,. I enables technical decisions requiring educational input to be recognised, defined and can facilitate a weighting of educational against technical imperatives.			Closed loop model allows better understanding of potentially competing educational and technical issues and allows decisions to be made with less risk.	

From the pattern matching [5] Represents a direct impact [5i] An 'i' denotes an indierct impact

18.7 Overall Synthesis

Impacts of the novel WiSE augmentations have been summarised in the matrix presented in Figure 18.5. The rows correspond to the WiSE impacts on each of the successes and failures identified; reading down the columns for each individual WiSE augmentations summarises its impact. A summary synthesis for each aspect is given in the final row that is used to address the last two research questions of this study in Section 19.

1. What was the impact of the novel project process on the significant success and failures? In particular:

(a) How does the novel process relate to the significant success and failures?

(b) What aspects of the novel process led to success and should be promoted?

(c) What aspects led to failure and should be avoided?

2. What is the scope of applicability of the aspects identified?

Contribution to overall success or failure	Measure of Student Competency	Deliverable of Closed Loop project is student competency	Scope of delivery included integrated equipment and curriculum	Reflective closed loop project methodology	Closed Loop model of education
Success of providing prototype as proof of concept to gain stakeholder support to fund development of production model	The war story was a valuable driver of equipment development and testing	Decisions leading to formulation of load control methodology to provide fidelity in load simulation crucial to prototype acceptance	Preliminary curriculum drove final physical form of prototype lading to the required physical phenomena (loads and drives) being present. And visible via the DAQ	The need to cater for reflective changes and future teaching drove the flexibility of the design which in turn led to required physical phenomena (variety of drive and load types) being present. This also drove the design of a comprehensive DAQ	The closed loop model of education allowed educationally reflective design decisions to be made particularly establishing required standards when cost for performance compromises needed to be made in the data acquisition system
		The deliverable of competency enlisted stakeholder support for prototype.			Definition of target competency as wisdom enlisted stakeholder support
Overall project success of EMDET - accepted on basis of ECTE412/912 students	The war story was a valuable driver of equipment development and testing	These decisions were recognised as one of the key decisions leading to the successful operation of the EMDET as mutually supporting equipment and curriculum and its acceptance		The concepts of reflective equipment design, reflective changes to equipment and curriculum and eliminating unnecessary cognitive leaps form curriculum and equipment inspired by the aspect of WiSE were judged important to the success of the EMDET	The use of an explicit strutted approach to education was recognised as one of the key decisions leading to the successful acceptance of the EMDET
	The role of the war story as an aspiration for curriculum development was important	The deliverable of competency is recognised as reducing the risk that the equipment and curriculum provided for teaching could not deliver on the educational objectives desired from teaching.	Working curriculum addressing learning objectives, approach and assessment.	The reflective approach led to a number of equipment changes judged crucial to the final success of the edit including asymmetrical motor sizing, design and implementation of the data acquisition system.	The value of the closed loop model in allowing technical staff to deal with educational issues was evident in many decisions that contributed to project success.
		The combined affect of these four aspects - particularly the reflective approach led - to extensive design efforts, testing and development resulting in improvements to torque control and data acquisition that was judged crucial to the success of the EMDET			
			The decision to include allowance for the areas of teaching outside of ECTE 412/912 was driven by these aspects		
			Due to the combined effect of these three aspects extensive efforts were invested in integration testing and acceptance testing, firstly ensuring equipment and curriculum was integrated and financially student outcomes were achieved which in turn was vital to project acceptance		
Success of providing prototype and production EMDET within financial budget			Extensive amounts of expert labour were applied at no financial cost to the project; in some instances the labour was applied due to this aspect in others simply because it was available at no cost and was otherwise compensated ()credit towards postgraduate degree).		
			Providing both equipment and curriculum, the closed loop model and the reflective approach allowed for reflective compromises in the design balancing equipment cost, performance and educational outcome. Without the linkage of these three elements a project supplying equipment only may have taken a risk averse and expensive approach resulting in the budget being exceeded and the project failing		

(a) Correlation matrix

Near failure of project - exceeding industry partner planned labour in-kind contribution and large amounts of expert labour provided at no financial cost by researcher	A large amount of labour was expended on iterations to reach the desired war story performance - see below	Setting the deliverable as student competency rather than equipment able to physically deliver the curriculum adds in the very significant complexities in teaching students	Setting project deliverables as equipment and curriculum rather than curriculum only is an increase in scope requiring more resources to deliver	The reflective closed loop process absorbed large amounts of time from the unpaid labour sources. If an unrealistic or unsuitable acceptance test is used the reflective approach risks a project iterating endlessly becoming an ongoing commitment	The closed loop model of education took a significant amount of labour to develop, however once developed it expedited resolution of technical issues requiring educational input and issues of equipment and curriculum interaction. This was due to the familiarity of the closed loop model to technical staff
					Once completed the closed loop model of education to some extent acts to mitigate the issues with including the complexities of student teaching.
Without the User's effectively altering the acceptance criteria to exclude the war stories this would have caused a project failure.	war story assessment was not properly appreciated at the outset of the project. Many things outside the control of student and teaching can prevent a student from undertaking the deep active approach needed to deliver	The fundamental mismatch between the EMDET looking to prepare for practice and the ECTE412/912 objectives of delivering only subject knowledge	The two laboratory sessions allowed in ECTE412 is a short amount of time to teach a student to deliver an ensemble performance.	The iterations to address the war story performance would not have occurred without the closed loop reflective approach.	The closed loop model of education was important in diagnosing issues evident from grounded theory analysis. In particular the issue with student lacking vital pre-requisite English and technical skills in 2015.
	The war story needs revision as an assessment instrument on a number of fronts to be realistic - including expectation of 100% success and aspirational nature of the measure				The pre-requisites' established in the specifications stage for English and technical ability were not complied with.
Summary synthesis of each WiSE Aspect	***Good driver of equipment and curriculum development. Assessment of performance and setting acceptance target must be adjusted. Not having a realistic acceptance target risks projects turning into ongoing commitments***	***This aspect was instrumental in the success of the EMDET. however It is crucial it is linked with a realistic acceptance test. This aspect exposes the project team to the complexities of teaching and learning in addition to equipment design and delivery, project teams should be prepared for this however the closed loop model can be of assistance in this regard..***	***This aspect was judged to be instrumental to the success of the EMDET, in particular responsible for providing equipment and curriculum that worked together and that were accepted during the first class of teaching. It was however an increase in scope above equipment delivery alone. This was allowed due to the expert labour available to the project at no financial cost***	***This aspect was crucial to the success of the EMDET in particular providing reflective design, reflective changes to equipment and curriculum and eliminating unnecessary cognitive leaps that contributed to the equipment function and its ultimate acceptance. This was allowed due to the expert labour available to the project at no financial cost . It is crucial it is linked with a realistic acceptance test***	***While this model took some time to set up it was instrumental to the design and testing of the EMDET and the ultimate success of the EMDET in acceptance. This was allowed due to the expert labour available to the project at no financial cost***

(b) Correlation matrix.

Figure 18.5: Matrix correlating EMDET successes (and failures) to impact of WiSE.

18.8 Addressing credible rival hypothesis

To test whether the conclusions of the synthesis are the most likely explanation requires that credible rival explanations have been identified and addressed. The rival explanations identified within the methodology (section 4.5) are addressed below:

- the same or better results could have been achieved delivering the EMDET project using a standard project process (e.g. vee model) followed by good reflective teaching. In other words the WiSE approach (or the augmentations) did not actually contribute in a meaningful way
  - the evidence does not support this hypothesis, in particular numerous hardware design changes (asymmetrical sizing of motors in section 7.7.2, selection of voltage transducer reference in section 8.6.1, etc.) to deliver the curriculum or remove unnecessary and obstructive cognitive leaps were instigated by aspects of the WiSE approach. These were crucial to the overall student performance and acceptance of the EMDET. The rival hypothesis of the Vee model implementation followed by reflective teaching has no credible mechanism to make this linkage, and is unlikely to have delivered a similar result
- the results achieved were due to the experimenter effect, the researcher inadvertently affected the results (e.g. students are taught to the assessment tool, rather than the desired competency).
  - the evidence does not strongly support this hypothesis because there was no overall trend of improving student results between cohorts. While it arguable that coaching delivered in 2013 by laboratory demonstrators around the magnetising current war story 13.1.5 may have been close to being the experimenter effect, it was limited because the coaching was confined to one of four scenarios in one cohort, so the likelihood of this being a continued effect was removed as the coaching was encapsulated into the written laboratory work book
- that positive student results could be due to the knowledge and ability of students prior to their training with the EMDT equipment; the equipment and curriculum did not positively affect the students
  - the evidence does not strongly support this hypothesis, in particular using war story scenarios to test students before and after training was designed to detect this, basing judgements of student attainment on the relative change in performance. Of the three cohorts and 4 scenarios there was only one instance of high student performance prior to training in the

acceptance testing phase (section 13.1.1)

- that improvements in student attainment could be due to work of students outside of the curriculum delivered as part of the EMDET project. A trend of improving results over the cohorts assessed could be due to students passing answers and information to successive cohorts
  - the evidence does not strongly support this hypothesis, there was no trend of improving results over successive cohorts. In fact the contrary was true between 2013 and 2015. Assigning no weight in marks and the method used to deliver the war story assessment (section 8.4.2) was designed to elicit candid answers from students avoiding collusion. Since the full cohort of students did not submit completed scenarios it would seem that there was not enough motivation for students to collude or work outside the curriculum to pass the scenario assessment

18.9 Learnings and Future Work

The EMDET project executed using the WiSE Approach successfully addressed the fundamental institutional motivations for UOW sponsoring the project. These motivations were the observed knowledge gap in EMD systems and the concerns raised by Engineers Australia in the 2008 course accreditation of inadequate facilities for teaching EMD systems (Section 1). These motivations were translated into a project requirement for a tool to assist in preparing students to properly utilise EMD systems in practice, with a particular focus on addressing the observed knowledge gap.

Using the WiSE Approach, the project the EMDET was delivered on time and within budget and resource allocations (Section 14.1); the EMDET included equipment that Engineers Australia (2013) described as ‘probably amongst the best in any Australian University’ during the 2013 course accreditation that ’worked almost perfectly’ according to feedback from laboratory demonstrators (Section 17.1.2). The EMDET included curriculum materials that were delivered with only a small number of minor faults (Section 17.1.3). Importantly, the equipment and curriculum within the EMDET were well integrated and students successfully completed laboratory workbooks using the equipment with average laboratory marks of 68% or higher (Section 13.1.1) from 2012 onwards.

The flexibility designed into the EMDET was valued and deemed important by the Users for two key reasons; firstly it facilitated resolution of conflicts between equipment and curriculum (Section18.2.3). Secondly, the flexibility allowed for iterative reflective changes (Section 14.3.1) based on issues that emerged from observing student performance in the laboratory classes, for example changes to the HMI as part of additional educational scaffolding (Section 13.1.7). In this respect the EMDET equipment could be considered as 'transparent' to reflective teaching practices in the laboratory.

The ultimate goal of the WiSE Approach - student outcomes - targeted by the EMDET project were found to be more aspirational than originally anticipated; while the EMDET did not achieve the original targets it was by no means unsuccessful. A proportion of the students showed a relative improvement in the war story assessments after training and demonstrated they possessed some of the wisdom required to successfully practice with EMD systems.

Reflecting upon the unexpectedly aspirational nature of the original targets this should be judged as a success given the factors that weigh against students gaining the desired wisdom including: the relatively short time available for training with the EMDET, the lack of support in the degree course for the ensemble performance, issues with a lack of student pre-requisites and the multiplicity of factors (within and outside the control of teaching) that can prevent students from taking the deep active learning approach needed to attain wisdom.

If the WiSE approach was used for similar projects in future, the knowledge and experience gained with the EMDET indicates that some refinements to the project execution are advised.

The project should pay more attention to the initial competency assumed of students to accurately establish the point at which educational scaffolding must begin, so that the subsequent design of the equipment and curriculum can proceed accordingly. Potentially students could be tested to determine their initial level of competency; the location of the testing in the project would depend on where the responsibility for addressing the shortfall in initial competency lies. If the project team is to deliver the target level of competency regardless of initial student competency, testing should occur in the requirements stage so as that equipment and curriculum can be designed accordingly. If the initial level of student competency is the Users responsibility testing could occur at the beginning of acceptance testing. From the perspective of the project team, testing for student initial competency is to either ensure there is an accurate statement of need from the Users during the Requirements phase, or during the Acceptance Testing phase the Users are complying with the stated requirements.

During the Requirements and Specifications phases the Users and Designers should conduct a more rigorous exploration of the target student competency. Firstly it should be determined whether the aspirational target of wisdom assessed via war story assessment and the necessary ensemble performances is appropriate. This decision should consider whether the parent undergraduate (or post graduate) course support students in gaining the skills required to deliver an ensemble performance, and if not is there sufficient time and resources allowed for the project to include these skills as project deliverables? In the case of the EMDET, the parent course did not to support the linking skills needed and the two lab sessions allowed for teaching with the EMDET were not enough to impart the linking skills as well as the EMD knowledge for many students. However, given the already extensive use of free and in-kind labour during the EMDET project including further laboratory sessions in the curriculum may have been problematic.

If wisdom is chosen as the target what is a realistic expectation of the proportion of students that could attain it? This decision must consider the deep active learning approach needed from students to attain wisdom, as well as all the factors that can prevent students from taking this approach. These factors can be are both within and outside the influence of teaching, the relative proportions of which will have a direct effect on what a realistic proportion of students gaining competency will be. Developing the expectation should answer a number of questions including: during assessment of the target wisdom what proportion of students are expected to complete successfully complete scenario assessments? What proportion of the scenarios should individual students complete to be deemed successful? Must all scenarios be successfully completed, or is a relative improvement appropriate?

The requirements and specifications developed should outline explicitly what a successful laboratory class looks like in progress. Importantly this would include what is the expected role(s) of the demonstrators during the conduct of the class? What issues are the demonstrators expected to deal with during a class that is accepted as successful (e.g. refreshing students on pre-requisites)? What issues are unacceptable for demonstrators to deal with will trigger project iterations to resolve (e.g. hardware faults)? Is the potential for demonstrators to provide tailored scaffolding, LCQ&A and coaching and mentoring appreciated? Should these be factored into curriculum design and acceptance testing?

During the requirements and specifications phases, a realistic expectation of potential project iterations should be developed, particularly those that would prompt a reflective iteration of the project. This should consider if there is threshold proportion of students having an issue with a component of the curriculum that triggers reflective project iteration to address the problem. This implies that where the proportion of students experiencing a problem is below the threshold, that the problem is left to the demonstrators to solve without triggering a project iteration.

Based on the experience of the EMDET project, it is suggested that a pragmatic threshold is a simple majority of students, to avoid unrealistic project iterations. To illustrate, if every issue with prerequisite knowledge resulted in a change to the curriculum, the laboratory work book would contain a significant proportion of the undergraduate electrical engineering curriculum. A more rigorous exploration of initial competency, target competency and what a successful laboratory class looks like may help to define what should trigger a reflective iteration of the project, and what would not.

Any discussion of project iteration must also recognise that at some point (reflective iterations of) the project must end and ongoing reflective teaching practice by the User's must begin. Where this point occurs should be discussed and ideally agreed during the early stages of the project.

Reflecting on the fundamentally modular structure of undergraduate (and postgraduate) degrees at UOW it appears that most subjects are mainly concerned with the material that the subject delivers; because apart from direct prerequisites little attention is paid to the linking of material *between subjects* which is vital to an ensemble performance. So the level of performance sought by the WiSE Approach is not held by the elective in which the EMDET was tested, or arguably the overall degree course. Therefore, delivering the ensemble performance needed by the war story scenario measure of competency is a novel experience to many students; and furthermore, expecting students to achieve a level of competency not supported by the surrounding elective (or degree course) after a short training period with the EMDET is unrealistic.

It could be argued therefore, that more attention should be paid to the process of linking knowledge from different subject areas needed for the ensemble performance, and ultimately for success in practice. Attempts to alter a degree course to include more linkage would need to consider the many pragmatic (and often competing) constraints on the structure of a degree that have led to the current modular structure, and that may make introducing more linkage activities difficult.

Chapter 19

Conclusions and Further Work

The purpose of this work was to critically evaluate the success of the EMDET project and the asserted contribution of the WiSE Approach to determine its worth for replication in future projects. A case study evaluation addressed the following questions:

1. What where the significant success and failures within the EMDET project leading to its overall success or failure?
2. What impact did this novel project process have on the significant success and failures?
3. What is the scope of applicability of the findings?

19.1 Methodology Conclusions

This research identified that the EMDET project was successful overall, and a project outcome evaluation identified five significant constituent successes and failures within the EMDET project:

- the prototype gained enough acceptance from the stakeholders to fund the development and construction of the production model EMDET was a significant success
- the acceptance of the production model EMDET was a significant success
- the completion of both prototype and production model within acceptable

budget limitations was a significant success

- the amount of free labour utilised in the EMDET project was a possible risk of failure to other similar projects
- the unexpectedly poor student performance in the war story assessment and the failure to improve it to the desired levels despite repeated iterations was a significant project failure.

A synthesis was used to link the outcome evaluation to the impact of the WiSE project approach, as determined by a pattern matching analysis using decision making as a causal linkage. The final output of the synthesis was an *evaluation of the impact that each novel aspect* of the WiSE approach had on the project.

19.1.1 WiSE Aspect: Measure of Student Competency

This proved to be an unexpectedly aspirational target for most students to attain; successfully completing the scenario and demonstrating the desired wisdom requires what was defined as an *ensemble performance* where students understand a real world situation, identify valid data and issues, combine knowledge from throughout the undergraduate curriculum and apply it in context.

The aspirational nature of this measure stems from both the learning approach needed from students, and the novelty of an ensemble performance. In order to attain this wisdom a student had to take a deep active learning approach; however, the number of things identified by grounded theory analysis (section 17) that can prevent this from happening that are *outside the control of* the project team (student motivation, group interaction, student pre-requisites, etc.) would infer that a proportion of students cannot reach this goal. Therefore the expectations for success should be based on only a proportion of the students achieving the desired wisdom, rather than expecting a large majority.

Moreover, the structure of the of undergraduate (and postgraduate) degree course at UOW paid little attention to the linking of material *between subjects* vital to an ensemble performance. This lack of support from the surrounding course made the delivery of an ensemble performance within the war story scenario measure of competency both novel, and unrealistic for students. This means that the support provided in a course for teaching students the skills needed for an ensemble performance should be considered before setting assessment targets based on them. It may be that delivering this level of student competency would entail some revision of a degree course, as well as provision of equipment and curriculum using the WiSE Approach.

When this measure as a target for acceptance testing it is crucial that the expectations of student performance are realistic, and take into account its aspirational nature. This is especially important when it is combined with a closed loop reflective project approach; as having realistic acceptance targets risk projects turning into ongoing commitments.

Apart from its use as a measure of student competency the war story scenario assessment also proved to be a good driver of equipment and curriculum development. The war story as an aspirational aim for student competency inspired many positive changes to the design of equipment and curriculum throughout the project from the early stages of design, through assembly, commissioning and testing that are unlikely to have happened without the war stories.

This approach of using the war story measure of competency as a guiding principle could be applied in future. The use would not be limited to projects developing equipment for teaching, the approach could used as a driver for curriculum development. The approach was not found in the literature reviewed and constitutes a contribution to new knowledge.

19.1.2 WiSE Aspect: Project Deliverable is Student Competency

This WiSE aspect was instrumental in the success of the EMDET because it made student competency (as judged by the measure) an outcome on which the project success was assessed, which ensured it was a fundamental part of the project from inception to completion. This also provided the *focus* for the development of compliementary equipment and curriculum development to provide the required student outcomes. The focus on student competency has led to identifying the importance of fidelity to give students realistic experiences, which are in turn needed to give real world competency.

This aspect has value for use in future projects, but crucially the competency to be delivered must be realistic. This aspect also exposes the project team to the significant complexities of teaching and learning in addition to equipment design and delivery. Project teams must be prepared for this because both technical *and* educational expertise are required, however the closed loop model can be of assistance in this regard.

19.1.3 WiSE Aspect: Scope of Delivery Includes Equipment and Curriculum

This aspect was judged to be instrumental to the success of the EMDET, in particular it was responsible for providing equipment and curriculum that worked together and was accepted by the User. In fact, the EMDET equipment was described by Engineers Australia (2013) during the 2013 course accreditation as 'probably amongst the best in any Australian University', and according to feedback from laboratory demonstrators 'worked almost perfectly' during teaching (Section 17.1.2). The equipment and curriculum within the EMDET were well integrated, and enabled students to successfully complete laboratory workbooks using the equipment with average marks 68% or higher (Section 13.1.1) from 2012 onwards.

The concurrent and complementary development meant that the physical design of hardware and software could be altered to improve or even permit the delivery of the desired curriculum. This also resulted in flexibility designed into the EMDET equipment that allowed for iterative reflective changes (Section 14.3.1) based on issues that emerged from observation of student performance in the laboratory classes. In this respect the EMDET equipment could be considered as 'transparent' to reflective teaching practices in the laboratory. A key learning worthy of recognition is that delivery of curriculum is a *significant* increase in project scope beyond equipment delivery alone. Within the EMDET project this was supported by the expert labour available to the project at no financial cost.

19.1.4 WiSE Aspect: Reflective Closed Loop Methodology

This aspect was crucial to the success of the EMDET, chiefly by providing the mechanism within the project to promote reflective design, reflective changes to equipment and curriculum and eliminating unnecessary cognitive leaps that contributed to the equipment function and its ultimate acceptance. It is crucial that a reflective closed loop methodology is linked with a realistic acceptance test because otherwise this aspect can risk a discrete project becoming and ongoing commitment; furthermore this aspect risks making the distinction between a project and ongoing teaching ambiguous. Within the EMDET project most of the reflective iteration was supported by the expert labour available at no financial cost, so projects where all labour is supported financially must carefully consider the risk of exceeding the project budget because of this aspect.

19.1.5 WiSE aspect: Closed Loop Model of Education

While this model took some time to develop, it was instrumental to the design and testing of the EMDET, and ultimately the success of the EMDET in acceptance. The power of this model was that it enabled technical engineering staff to solve complex educational issues involved with equipment development via a familiar analogy that is rich enough to deal with many educational complexities. This model can be used in future to help technical engineering staff address educational issues arising while developing curriculum, the teaching equipment, or both together.

While there are several closed loop models of education in the literature, the viewpoint used to create this model was novel because it started with an engineer's understanding of the important issues of a dynamic closed loop system and used these to link it to relevant educational theory. This model represents a contribution to new knowledge by both providing a rich model for technical rather than specialist educators, and allowing insights from engineering control system to contribute to teaching and learning.

19.1.6 Scope of Applicability

The WiSE approach was crucial in the success the EMDET project providing a tool consisting of integrated equipment and curriculum for teaching students to practice in applied technical fields. The novel aspects of WiSE individually or together could contribute to success of similar projects to establish engineering (or other applied technical) teaching laboratory equipment.

The successful use of the WiSE approach required both technical and educational expertise, which in the case of the EMDET project in a University environment was supported by labour without cost to the project from the researcher and industry partner. Outside of this context (e.g. a commercially contracted project) the risks of labour costs exceeding project budgets should be considered prior to using the WiSE approach, for example if a commercial contract was issued by the University to a company to provide equipment and curriculum using the WiSE Approach.

19.2 Future Use of the WiSE Approach

Establishing realistic acceptance testing is crucial to avoid unnecessary project iterations, so it is important to clearly define *what does success look like?* This should address the expected role (if any) of the laboratory demonstrators and how they fit into the desired picture of laboratory teaching. Demonstrators were observed addressing students issues via coaching & mentoring, linguistic cognitive question and answer (LCQ&A) and educational scaffolding tailored to individual problems. Is this (to some degree) acceptable in the project? If the expectation is that no demonstrator intervention should be required, does this mean that a reflective project iteration is needed to be alter the curriculum to address every student issue? This is probably unrealistic, and it is suggested that iterations are initiated to deal with problems experienced by a majority of students, while minority issues are dealt with by the demonstrators. Establishing the acceptance criteria for the project should also recognise that at some point the project (and iterative changes) must end, and normal ongoing reflective teaching practice by the User must begin.

The project should pay close attention to the initial competency assumed of students to establish the point where educational scaffolding must begin, so that the subsequent design of the equipment and curriculum can proceed accordingly. Potentially, students could be tested to determine their initial level of competency; where this testing is located in a project would depend on who carries the responsibility for addressing any shortfall in initial competency.

Many of the issues encountered in utilising the WiSE approach to develop the EMDET stemmed from an unrealistic target for acceptance testing, coupled with an unrealistic expectation of project iteration to reach the target. These could have been reduced or avoided by addressing several issues within the User definition of need in the requirements and specification phases. The following are a list of guiding questions to avoid issues encountered during the EDMET project by establishing a better project specification.

- What does a realistic target for success success look like?
  - Has student prior learning prepared them to delivering an ensemble performance, or is it a novel experience for students? Does the surrounding course support this?
  - Have students been assessed for wisdom previously or is this novel for students?
  - Given all the things that can prevent a deep active learning approach, what is a realistic proportion of students that could be expected to pass high level attainment measures such as the war stories?
- What is a realistic expectation of project iterations?
  - What would prompt a reflective iteration of equipment and curriculum?
  - What proportion of students having an issue would prompt a project iteration?
  - What issues are left to laboratory demonstrators to resolve in a successful implementation?
  - Where do project iterations end and ongoing reflective teaching begin?

Given the important role of demonstrators two other points are raised for future use of the WiSE Approach, firstly including a more structured debriefing of laboratory demonstrators within the reflective approach of WiSE may be a useful improvement. Secondly given the increasing popularity of virtual and remote learning the issues of delivering the functions of LCQ&A and tailored scaffolding for students could be problematic for these modes of teaching. Both LCQ&A and scaffolding are reliant on a rich communication between student and demonstrator, in this instance carried out face-to-face. Remote and virtual learning delivery modes may need to consider the need for LCQ&A and tailored scaffolding and how it can be provided to students, for example using virtual collaboration or meeting tools with video and audio capabilities.

19.3 Future Work

Based upon the literature review and case study examination of the EMDET projects several future avenues of research were identified. The fundamental motivation of WiSE was to take a closed loop approach to delivering student competency for successful industrial practice using the war story scenario at the conclusion of their training as the measure of success.

A natural extension of this approach is to expand the case study from final year students in the classroom to novice engineers in the workplace. This would test the success of the WiSE Approach in delivering competency by critically examining potential correlations between training with equipment and curriculum developed using WiSE, success in war story scenarios and subsequent success in practice. A longitudinal study investigating the experience of students trained with the EMDET in utilising EMD systems after their entry into industry would naturally extend the closed loop ideology of WiSE and would also give further insight into the effectiveness of the war story and the WiSE Approach.

Due to the important role that this study identified of motivation in taking the deep active learning approach required to attain the target student competency (wisdom); this study could also examine whether motivations change significantly after transition from student to employee. This could be an important factor in establishing a realistic expectation of the proportion of students expected to attain the desired competency and consequently project success when using the WiSE Approach in future.

Within this study 'war stories' were used as a summative assessment method, they could also be very useful in formative assessment and future work could investigate this.

Specifically the study could seek to answer if people are more likely to engage in a deep active learning approach when the learning applies to their employment as opposed to their studies? Does the change in commercial dynamic from paying student to paid employee make a significant difference? Does this difference place some bound on the proportion of students that could be expected to take the deep active learning approach required during training to achieve wisdom? Will the remainder of the students have to enter industry to find the motivation needed to take the required approach leading to wisdom?

Systems engineering design is often done using the assistance of comprehensive software management and design tools, e.g. to track requirements from requirements, through specifications and design. The EMDET project did not make use of these software tools and it has been suggested that the WiSE Approach could benefit from the use of them. Future work could investigate the suitability of these tools, although this may have significant implications for cost and resourcing depending on context.

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Appendix A

Preliminary Curriculum

Preliminary Course for Mechanical Engineering students:

- A Safety Introduction to Rotating Equipment
  - What are you planning to do and are you safe to do it?
    - Run the motor and drive?
    - Approach the motor?
  - Open the Panel
  - If it is not safe what can you do?
    - Are guards in place
    - Do you need to isolate to do your work?
- Introduction to the Induction Motor and Variable Speed Drive
  - What characteristics can you expect from an induction motor
    - Speed (poles, supply frequency etc)
    - Torque speed curves and the concept of slip
    - Effect of reducing voltage
  - How do I size a motor?
    - What are the key parameters I need to know?
    - What sort of motor do I need for the job?
  - What can the variable speed drive offer?
    - What sort of variable speed drives are there?
    - Change in speed (over speed and underspeed)
    - Breakdown torque available at a range of speeds
    - Electrical Parameters Vs Mechanical Parameters
      - Current vs. torque
      - Frequency vs. speed
    - What do you need to be careful of?
      - High torque loads and cooling
      - Old motor insulation may not be suitable for drives
      - EMC and harmonics can be an issue in re-using existing cables
- What does the variable speed drive offer to different systems
  - Theory of loads (if not already covered, constant torque, linear torque,

speed squared torque)
  - Energy efficiency in centrifugally driven pump systems
    * Simulate removing Throttling Loss
  - Energy efficiency in positive displacement pump systems
    * Simulate removing dumping loss
  - Energy efficiency in systems with motors driving and braking at the same time
    * For example metal strip transport systems use the energy from braking motors to supply the driving motors
  - Reduce the risk of uncertainty in design
    * Flexibility of a variable speed pump vs. fixed speed and control valve
    * For example do a valve sizing calculation and compare this to varying pump speed.
- Drive Control
  - Speed Control
    * Open Loop Control
    * Sensorless Control
    * Closed Loop Control
      · Steady State response
      · Transient response
      · Closed Loop Control (load & Drive disturbance)
      · Frequency response (bode plots)
  - Position Control
    * How accurate do I need to be?
    * How fast does my drive response need to be?
    * Can I achieve my goal?
  - Mechanical Transmission Concerns?
    * Backlash?
    * Power Loss?
    * Friction Estimation?

Preliminary Course for Electrical Engineering students:

- A Safety Introduction to Rotating Equipment
  - As above
  - Add electrical dimension to this?
    * Work inside a panel
    * Capacitor discharge?
    * Concept of isolation & verification
- Introduction to the Induction Motor and Variable Speed Drive
  - What characteristics can I expect from the induction motor?
    * Speed (poles, supply frequency etc)
    * Torque speed curves and the concept of slip
    * Effect of reducing voltage
    * Motor Power factor (at start & running)
    * Starting Current? How do I size a motor?

        - What are the key parameters I need to know?
        - What sort of motor do I need for the job?
    - What can the Variable speed drive offer?
        - What sort of VSD? are there?
        - Change in speed (over speed and under speed)
        - Breakdown torque provided at a range of speeds
        - Electrical parameters vs. mechanical parameters
            - Current vs. torque
            - Frequency vs. speed
        - What do you need to be careful of?
            - High Torque Loads and Cooling
            - Old Motor Insulation not suitable for drives
            - EMC and harmonics can be an issue re-using existing cables
            - Soft starters Vs Variable Speed Drives
- Looking at the VSD in more depth
    - set-up the VSD
        - input motor parameters
    - Drive VSD
        - Forward
        - Reverse
        - varying speeds
    - What happens if the set-up was wrong
        - incorrect nameplate
    - VSD electrical input & output
        - Current
        - Voltage
        - Input ?harmonics etc
        - Output ?see PWM waveform?
    - Electrical Parameters Vs Mechanical Parameters
        - Current vs. torque
        - Frequency vs. speed
    - VSD pitfalls?
        - High Torque Loads and Cooling
        - Insulation on old motors
        - EMC, unshielded cables and switching frequency
        - Switching frequency
        - EMC & switching frequency
        - Voltage Pulse reflection & cable capacitance
        - Effect of fast switching on DC voltage
- Variable Motor Speed to Save Power
    - Theory of loads - different types of torque characteristics and the possible loads [Ref ?Mohan]
        - Constant torque (power ?) ?Winches, hoists etc
        - Torque Varies in proportion to Speed squared (power ?3) ?centrifugal pumps, fans etc
        - Linear Torque Loads (power ?2) ?Positive displacement pumps

        - Constant Power Loads ?Torque and speed a constant product ?unwinders, reels etc.
            - Pump laws?
        - Loads with High Inertia
        - Brake & Motor sequencing?
    - How do these load characteristics impact the settings in the VSD?
        - What parameters can I change to cater for the different loads?
    - So how big does my motor need to be?
        - Get the student to make a calculation and then compare it to experimental results.
    - Possible Tests
        - Speed squared
            - simulate throttled power consumption
            - simulate VSD power consumption
- Variable Motor speed for improved system control when compared to traditional or ?echanical?means.
    - System that changes its operating point
    - A system that you don? really know the operating point ?a difficult problem of choosing the correct size of mechanical equipment made easy by the flexibility offered by a VSD.
    - Upgrading system performance ?improve upon what you already have.
- Vector Control
    - vector control demystified? What is this Vector Control and why would I want it?
    - See vectors in action as load & torque change?
    - What is torque current and what is magnetising current?
- Drive Control
    - Speed Control
    - Open Loop Control
    - Sensorless control
    - Closed Loop Control
        - Steady state response
        - Transient response (load & drive disturbance)
        - Frequency response (bode plots)
    - Position Control
        - How Accurate do I need to be?
        - How fast does my drive response need to be?
        - Can I achieve my goal
- Power Quality Issues
    - Input power issues (issues & remedies)
    - Series Reactor for VSD
    - Voltage and current unbalance
    - DC link when we have a voltage sag
    - Voltage and current Harmonics
    - Capacitor switching transient
    - What drives can cause on the AC mains
    - Tripping

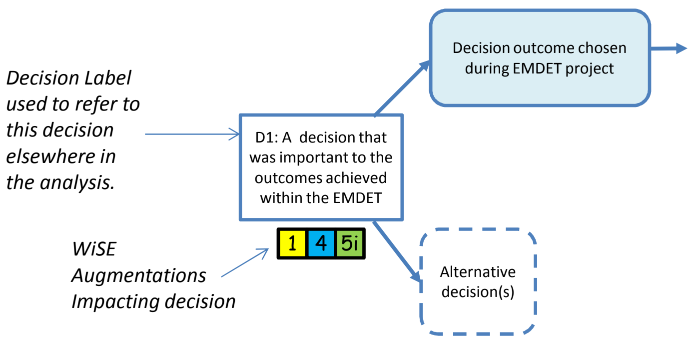
Appendix B

Decision Tree

Decision Tree

Analysis of flow of decisions and events as a decision tree

Analysis of a decision in the development of EMDET



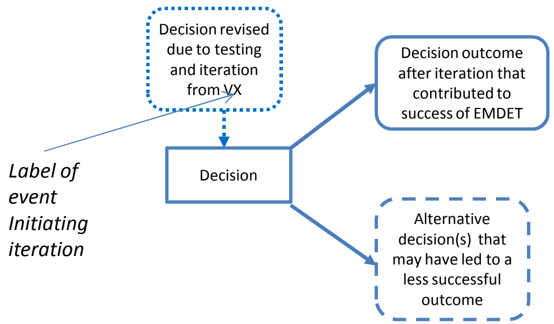
Subjective assessment of relative performance

WiSE Augmentation impacting Decision

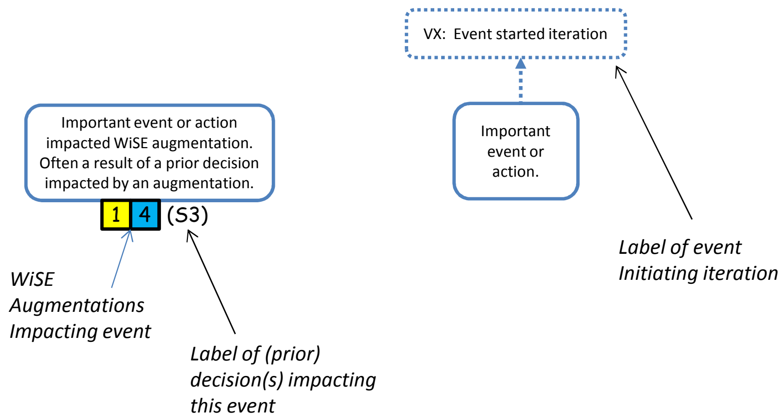
1 Measure of student competency
2 Deliverable is student competency
3 Scope includes equipment and curriculum
4 Reflective closed loop Project process
5 Closed loop model of education

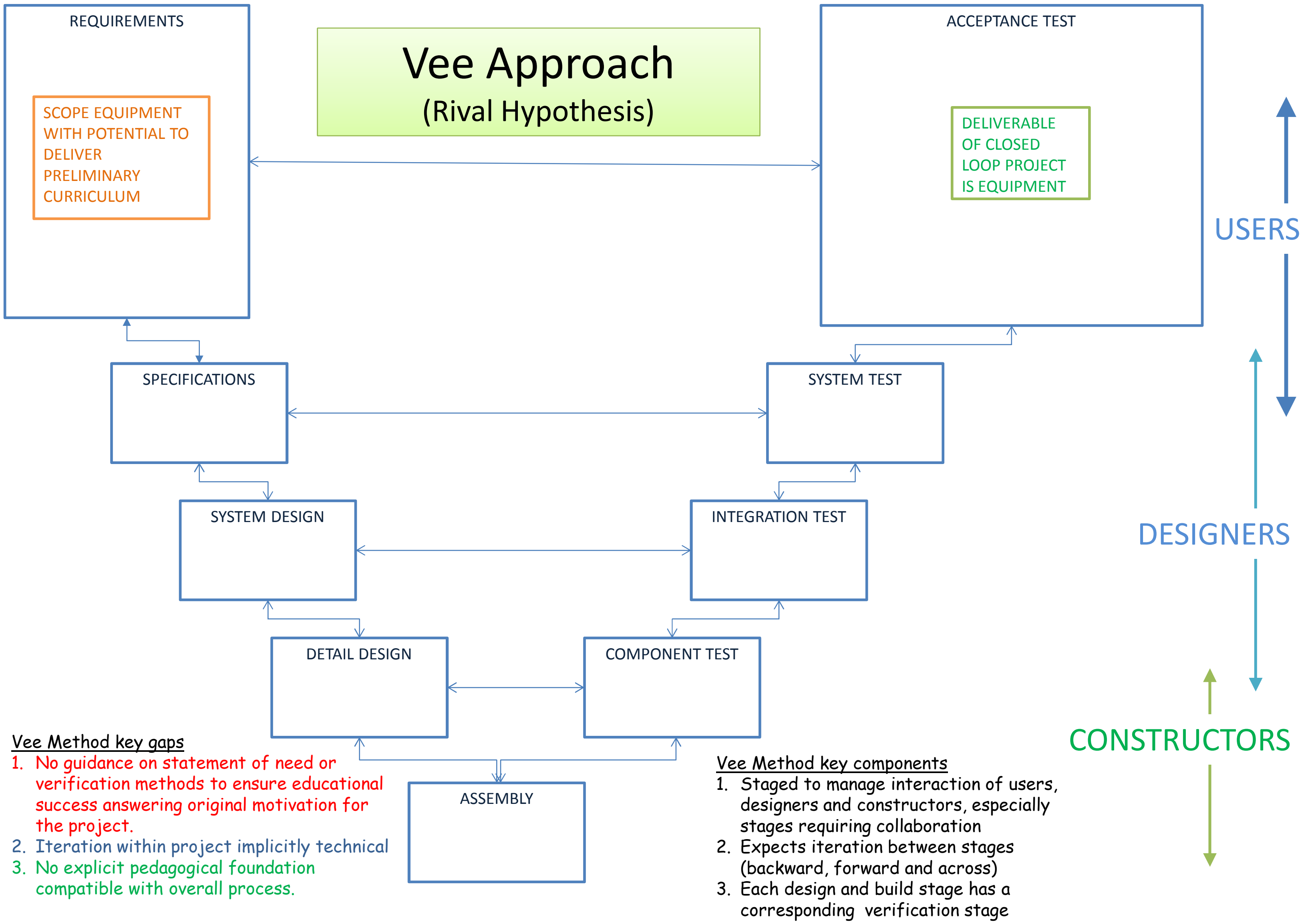
5i *An 'i' denotes that the impact was an indirect impact*

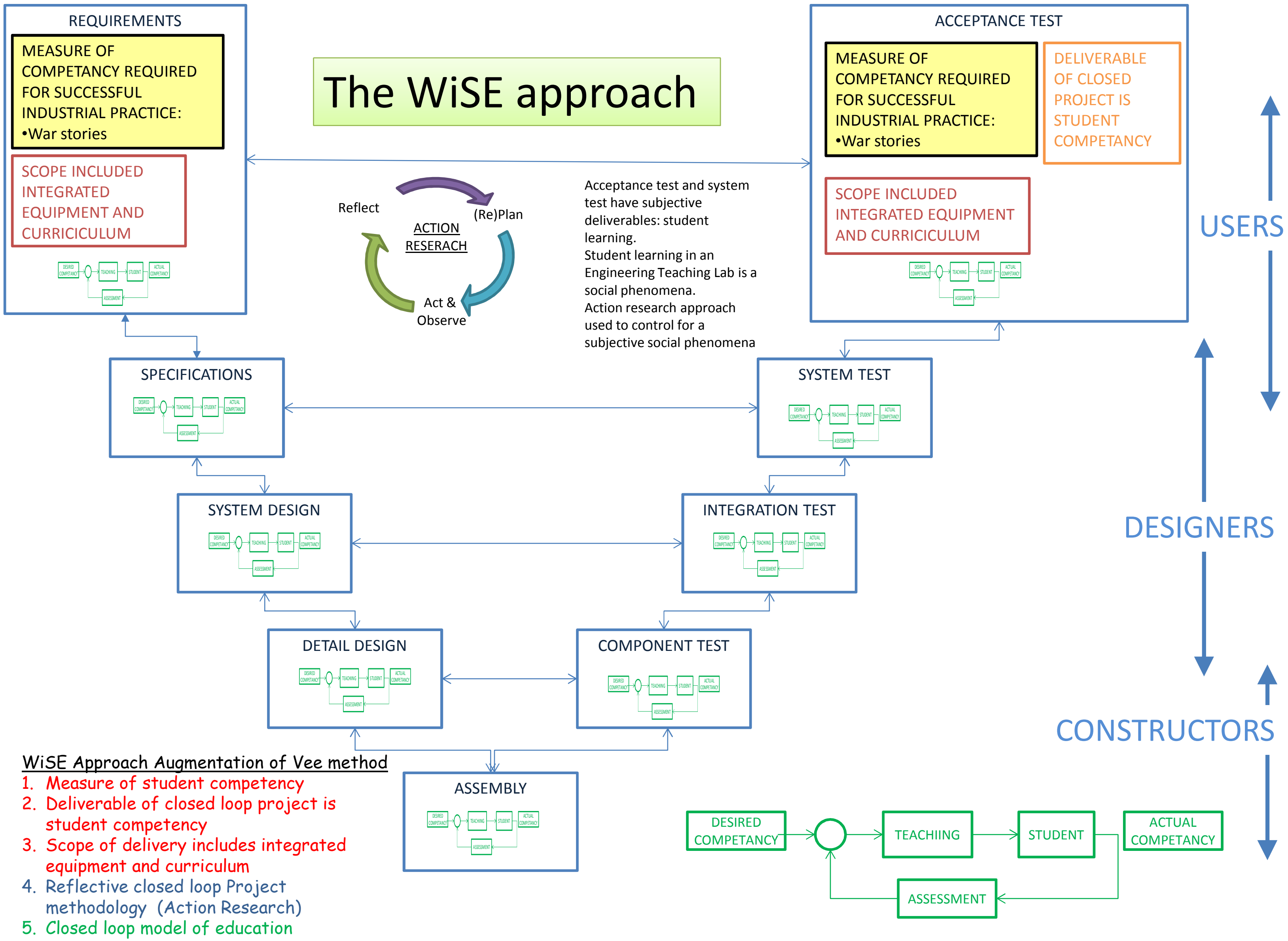
Iteratively revised decision



Events and actions




Vee Approach
(Rival Hypothesis)
REQUIREMENTS
SCOPE EQUIPMENT WITH POTENTIAL TO DELIVER PRELIMINARY CURRICULUM
ACCEPTANCE TEST
DELIVERABLE OF CLOSED LOOP PROJECT IS EQUIPMENT
USERS
SPECIFICATIONS
SYSTEM TEST
DESIGNERS
SYSTEM DESIGN
INTEGRATION TEST
DETAIL DESIGN
COMPONENT TEST
CONSTRUCTORS
ASSEMBLY
Vee Method key gaps
1. No guidance on statement of need or verification methods to ensure educational success answering original motivation for the project.
2. Iteration within project implicitly technical
3. No explicit pedagogical foundation compatible with overall process.
Vee Method key components
1. Staged to manage interaction of users, designers and constructors, especially stages requiring collaboration
2. Expects iteration between stages (backward, forward and across)
3. Each design and build stage has a corresponding verification stage


The WiSE approach
REQUIREMENTS
MEASURE OF COMPETANCY REQUIRED FOR SUCCESSFUL INDUSTRIAL PRACTICE:
•War stories
SCOPE INCLUDED INTEGRATED EQUIPMENT AND CURRICICULUM
ACCEPTANCE TEST
MEASURE OF COMPETANCY REQUIRED FOR SUCCESSFUL INDUSTRIAL PRACTICE:
•War stories
DELIVERABLE OF CLOSED PROJECT IS STUDENT COMPETANCY
SCOPE INCLUDED INTEGRATED EQUIPMENT AND CURRICICULUM
Reflect
(Re)Plan
ACTION RESERACH
Act & Observe
Acceptance test and system test have subjective deliverables: student learning.
Student learning in an Engineering Teaching Lab is a social phenomena.
Action research approach used to control for a subjective social phenomena
USERS
DESIGNERS
CONSTRUCTORS
SPECIFICATIONS
SYSTEM TEST
SYSTEM DESIGN
INTEGRATION TEST
DETAIL DESIGN
COMPONENT TEST
ASSEMBLY
DESIRED COMPETANCY
TEACHIING
STUDENT
ACTUAL COMPETANCY
ASSESSMENT
WiSE Approach Augmentation of Vee method
1. Measure of student competency
2. Deliverable of closed loop project is student competency
3. Scope of delivery includes integrated equipment and curriculum
4. Reflective closed loop Project methodology (Action Research)
5. Closed loop model of education

Predicted Pattern

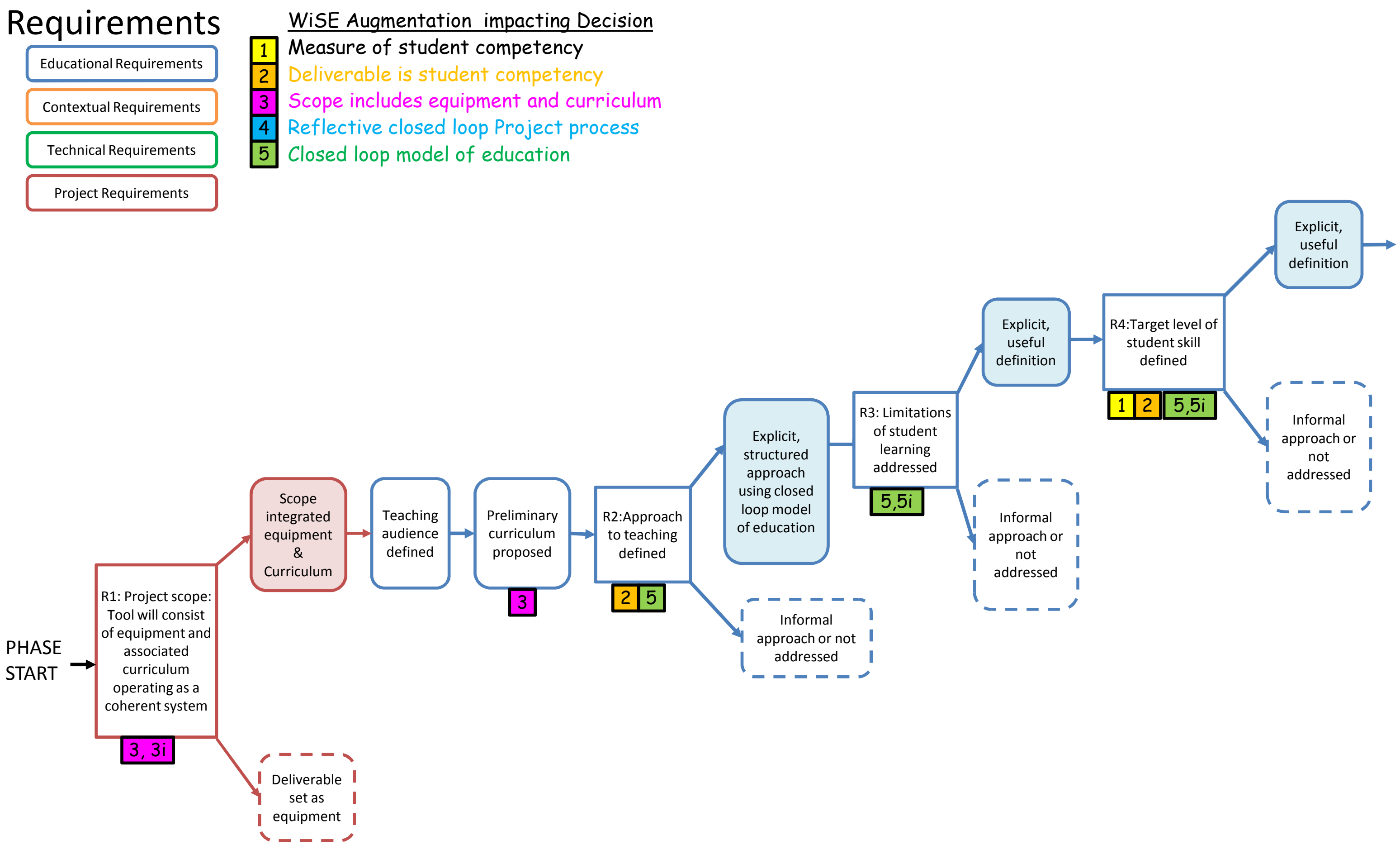
(From Methodology Chapter)

Predicted Direct Impacts

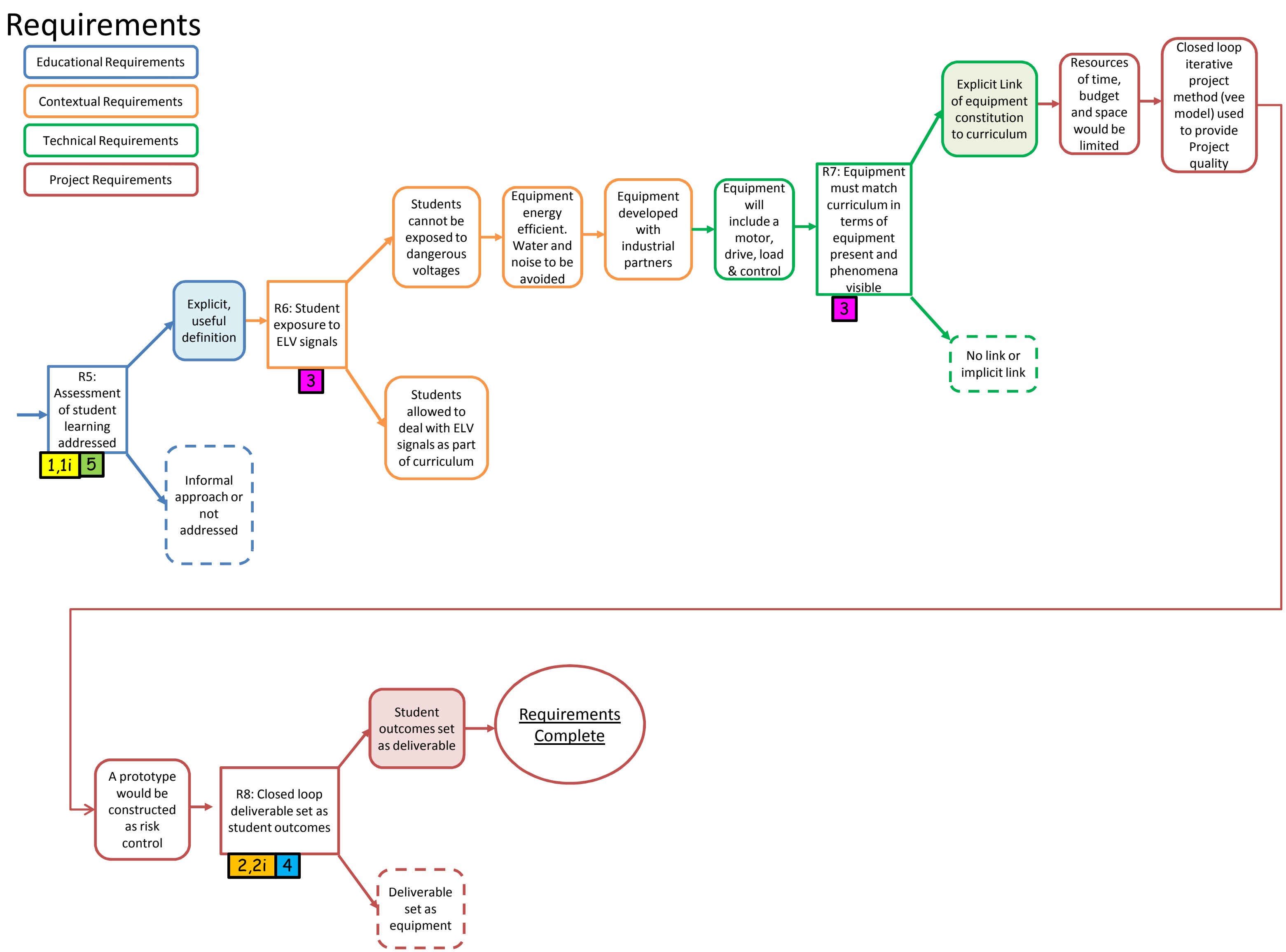
	WiSE Augmentation	When reviewing the project process, decision making or the products of the project the following should be evident if:	
		If the augmentation is effective and beneficial:	If the aspect is <u>not</u> effective or is deleterious:
1	Measure of student competency	There is a measurable definition of competency and it is used in curriculum and equipment design	There is no definition or there is no evidence of its use in design
2	Deliverable of project is student competency	Project success has been assessed using the measure of student competency; potentially leading to iterative changes on the basis of testing	The competency measure has not been used, or it has not been used to gauge success.
3	Scope of delivery is integrated equipment and curriculum	Both equipment and a complete curriculum are delivered.	Either no curriculum or a partially complete curriculum is delivered with the equipment.
		There should be no unexpected limitations placed on the curriculum by the equipment.	The curriculum finds unexpected limits imposed on it by the equipment.
		There should not be unresolved conflicts between laboratory equipment and curriculum - there may however be known and deliberate design compromises. There have potentially been project iterations due to conflict between equipment and curriculum.	There are unresolved conflicts between equipment and curriculum.
4	Reflective closed loop project methodology	There is evidence of closed loop reflection; it has affected the project. Student performance against a standard has resulted in changes to equipment and curriculum; potentially including project iterations.	There are no changes in equipment or curriculum based upon observed student outcomes.
		In the expectation that reflective changes would be necessary equipment and curriculum delivered allowed for these.	The equipment and curriculum are rigid and not easily adapted.
5	Closed Loop model of education	Interactions between equipment, students, assessment and teaching either predicted by the model or interpreted with the model have impacted the project. Potentially initiating project iterations.	There is no evidence of these interactions affecting the project or other models of education have been used.

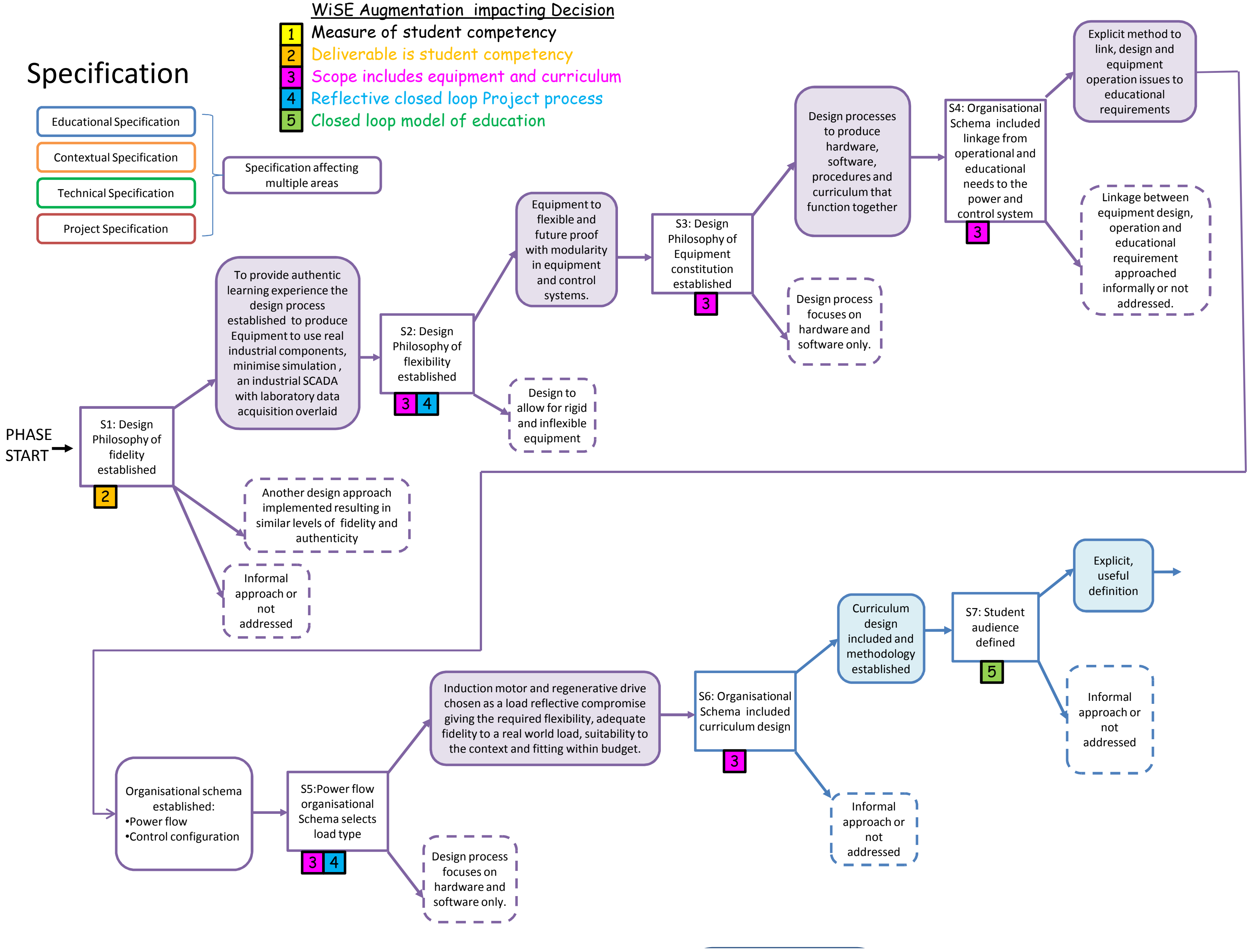
Predicted Indirect Impacts

		When reviewing the project process, decision making or the products of the project the following should be evident if the WiSE augmentations have interacted with the Parent Vee model	
		In a beneficial manner	In a deleterious manner
	Applicable to all five augmentations	Outcomes from augmentations have gained strong acceptance (important to the user) were incorporated into the project form an early stage potentially with gains in efficiency	The level of acceptance by the end users did not justify the expenditure of time and resources, particularly if project iterations were initiated
		Outcomes from augmentations gained strong or widespread acceptance by the users	Augmentation poorly accepted
		Time and cost implications may not be apparent.	Blending equipment delivery with curriculum development and delivery was not worth the time and cost; for example in comparison to equipment delivery being separate from curriculum development and teaching
		Additional requirements for expertise may not be apparent.	The combination of educational and technical expertise required by the project was not worth the expenditure; either in having extra staff or finding staff capable in both areas
1i	Measure of student competency	The measure has received acceptance from the end user.	The measure is not accepted, for example it is not used or its effectiveness is disputed.
2i	Deliverable of project is student competency	The closed loop approach has led to curriculum and equipment accepted by the user.	Equipment milestones were not reached and there is a perception that this was due to time spent on competency related work.
		No specific project over-runs are identified in relation to the project deliverable of student competency.	The project has over-run as the distinction between the project delivering equipment and curriculum and ongoing teaching activities into the future is not clear.
3i	Scope of delivery is integrated equipment and curriculum	No conflicts between equipment and curriculum integration and project progress were noted.	Equipment time and cost targets were not met and there is a perception that this is due to conflicts with curriculum development.
4i	Reflective closed loop project methodology	Holistic project and educational view allowed for requirements to be amended for overall project economy, e.g. A failure to meet early equipment specifications later found not to impact on educational outcomes did not lead to unnecessary re-work.	No amendment of requirements was allowed.
		The project team involvement in teaching has resulted in ready acceptance from The users or equipment and curriculum.	Unnecessary time and money was spent having the project team involved with teaching. Little or no interaction between project team and teaching - no substantive action resulted from their involvement
5i	Closed Loop model of education	Equipment development concerns requiring solutions with educational foundations were resolved efficiency using the model.	Time lost and resources expended due to staff unnecessarily working outside their field of expertise (technical staff working on education).

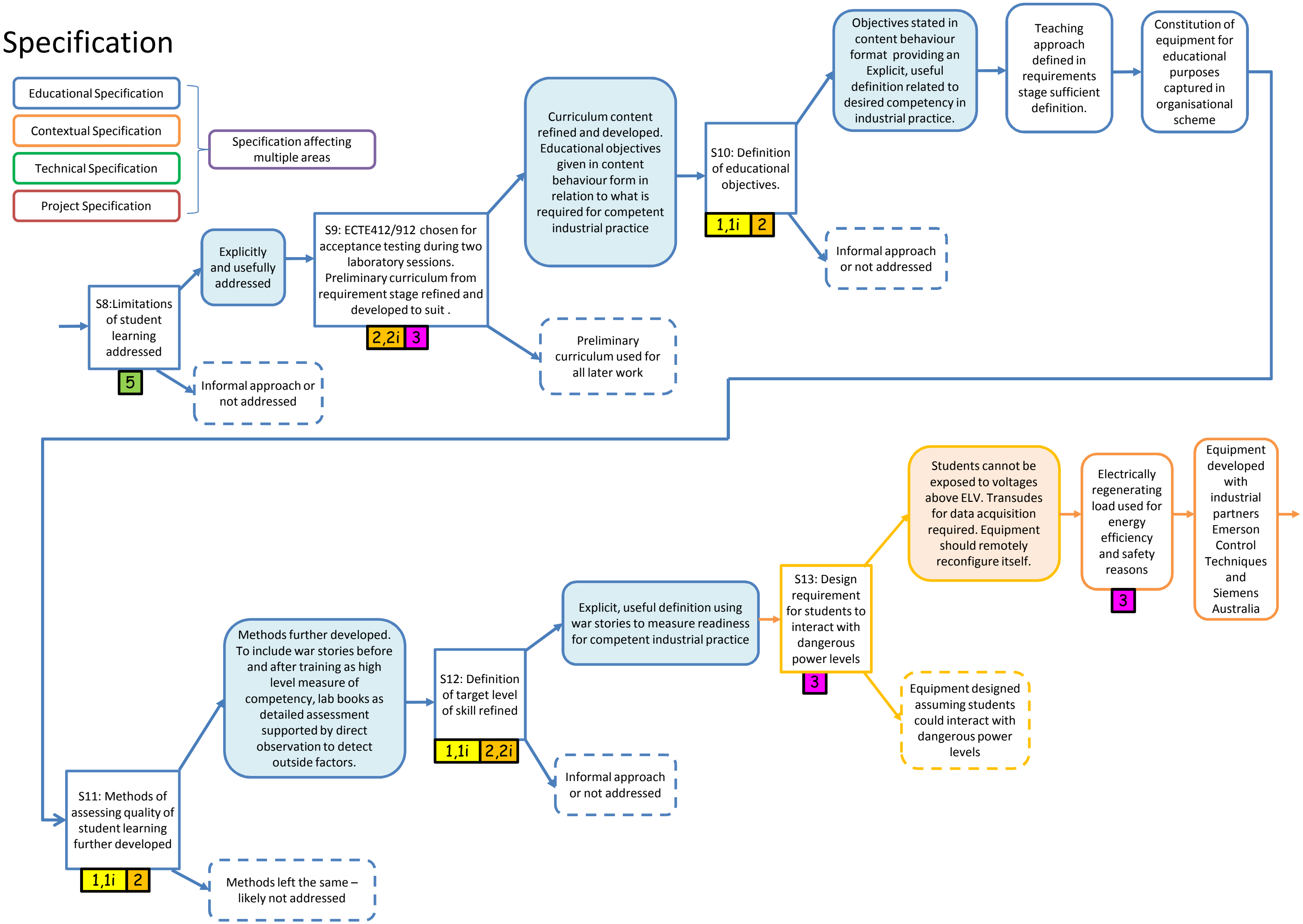


Requirements
Educational Requirements
Contextual Requirements
Technical Requirements
Project Requirements
WiSE Augmentation impacting Decision
1 Measure of student competency
2 Deliverable is student competency
3 Scope includes equipment and curriculum
4 Reflective closed loop Project process
5 Closed loop model of education
PHASE START
R1: Project scope: Tool will consist of equipment and associated curriculum operating as a coherent system
3, 3i
Deliverable set as equipment
Scope integrated equipment & Curriculum
Teaching audience defined
Preliminary curriculum proposed
3
R2:Approach to teaching defined
2 5
Informal approach or not addressed
Explicit, structured approach using closed loop model of education
R3: Limitations of student learning addressed
5,5i
Informal approach or not addressed
Explicit, useful definition
R4:Target level of student skill defined
1 2 5,5i
Informal approach or not addressed
Explicit, useful definition

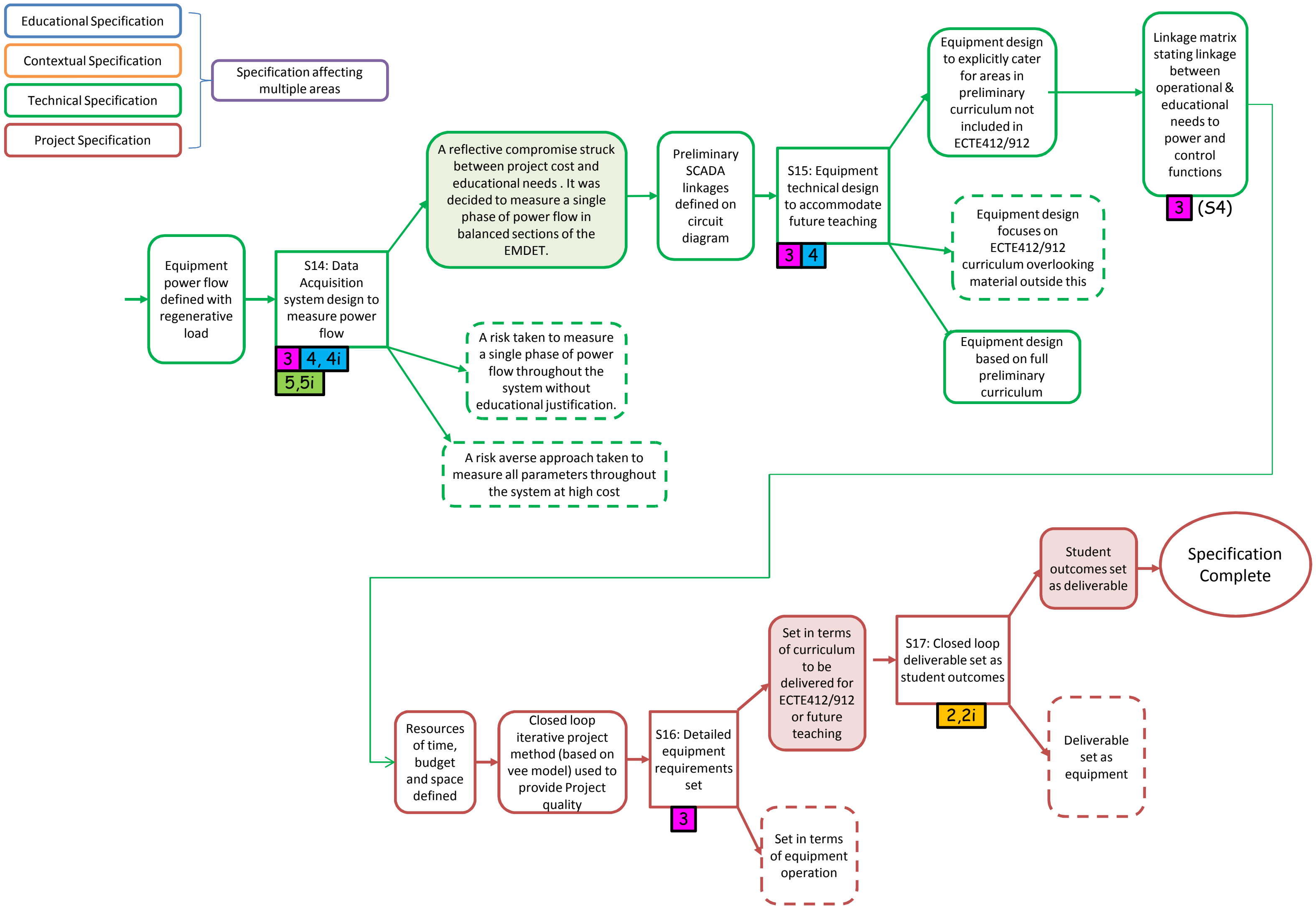

Requirements
Educational Requirements
Contextual Requirements
Technical Requirements
Project Requirements
R5: Assessment of student learning addressed
1,1i
5
Explicit, useful definition
Informal approach or not addressed
R6: Student exposure to ELV signals
3
Students cannot be exposed to dangerous voltages
Students allowed to deal with ELV signals as part of curriculum
Equipment energy efficient. Water and noise to be avoided
Equipment developed with industrial partners
Equipment will include a motor, drive, load & control
R7: Equipment must match curriculum in terms of equipment present and phenomena visible
3
Explicit Link of equipment constitution to curriculum
No link or implicit link
Resources of time, budget and space would be limited
Closed loop iterative project method (vee model) used to provide Project quality
A prototype would be constructed as risk control
R8: Closed loop deliverable set as student outcomes
2,2i
4
Student outcomes set as deliverable
Deliverable set as equipment
Requirements Complete

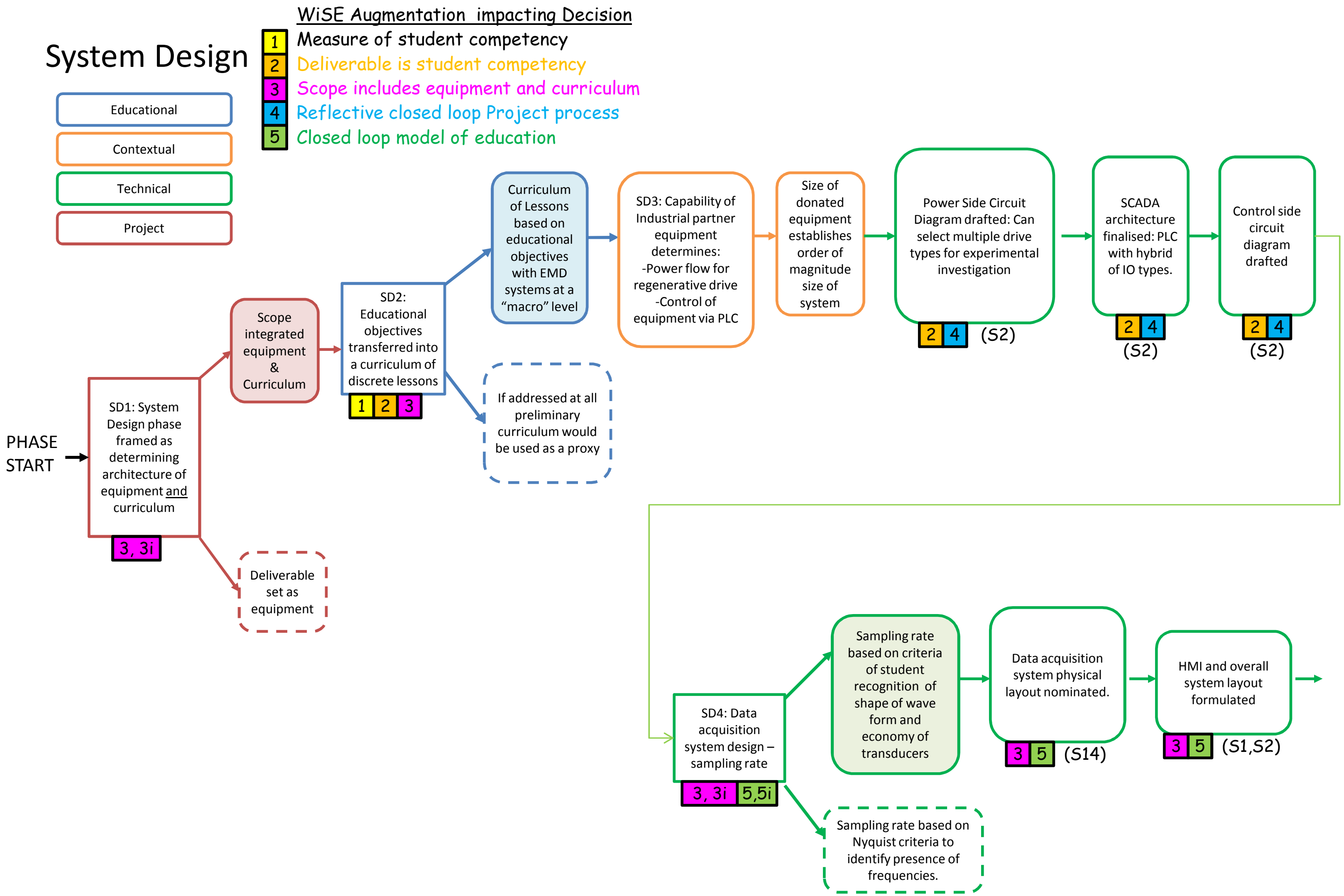

Specification
WiSE Augmentation impacting Decision
1 Measure of student competency
2 Deliverable is student competency
3 Scope includes equipment and curriculum
4 Reflective closed loop Project process
5 Closed loop model of education
Educational Specification
Contextual Specification
Technical Specification
Project Specification
Specification affecting multiple areas
PHASE START
S1: Design Philosophy of fidelity established
2
To provide authentic learning experience the design process established to produce Equipment to use real industrial components, minimise simulation , an industrial SCADA with laboratory data acquisition overlaid
Another design approach implemented resulting in similar levels of fidelity and authenticity
Informal approach or not addressed
S2: Design Philosophy of flexibility established
3 4
Equipment to flexible and future proof with modularity in equipment and control systems.
Design to allow for rigid and inflexible equipment
S3: Design Philosophy of Equipment constitution established
3
Design processes to produce hardware, software, procedures and curriculum that function together
Design process focuses on hardware and software only.
S4: Organisational Schema included linkage from operational and educational needs to the power and control system
3
Explicit method to link, design and equipment operation issues to educational requirements
Linkage between equipment design, operation and educational requirement approached informally or not addressed.
Organisational schema established:
•Power flow
•Control configuration
S5:Power flow organisational Schema selects load type
3 4
Induction motor and regenerative drive chosen as a load reflective compromise giving the required flexibility, adequate fidelity to a real world load, suitability to the context and fitting within budget.
Design process focuses on hardware and software only.
S6: Organisational Schema included curriculum design
3
Informal approach or not addressed
Curriculum design included and methodology established
S7: Student audience defined
5
Explicit, useful definition
Informal approach or not addressed

Specification



Specification




System Design
Educational
Contextual
Technical
Project
WiSE Augmentation impacting Decision
1 Measure of student competency
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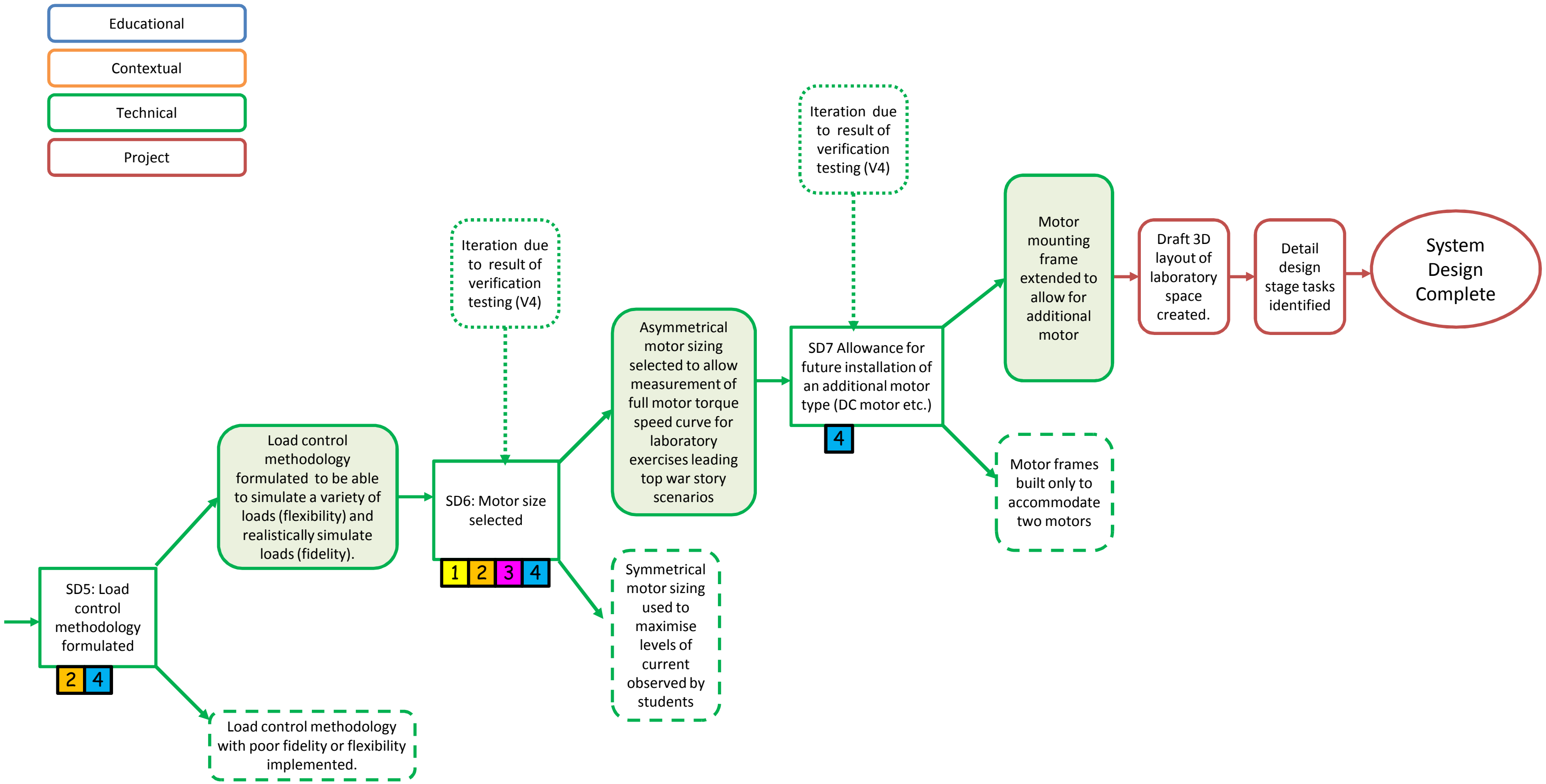
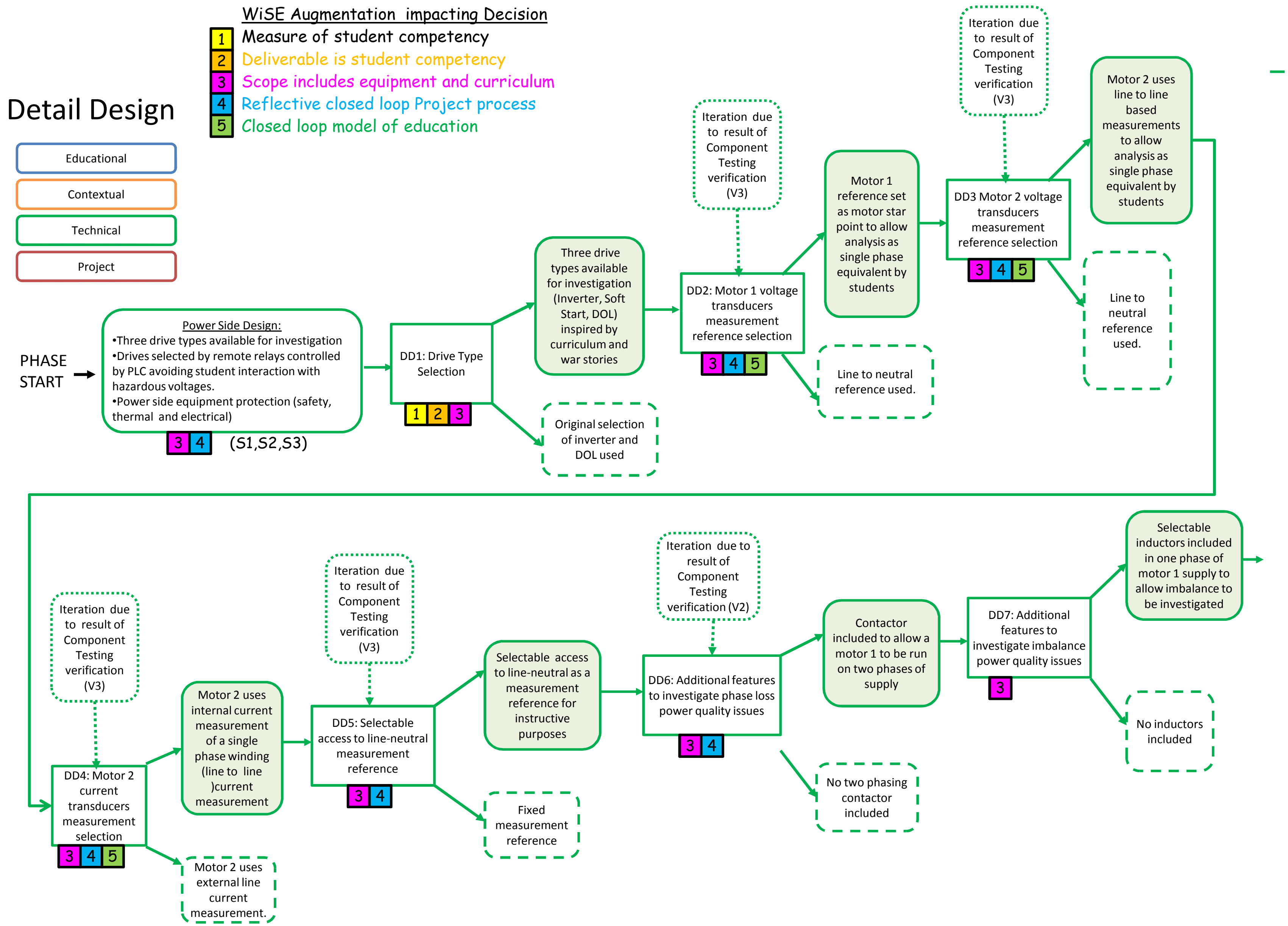
PHASE START
SD1: System Design phase framed as determining architecture of equipment and curriculum
3, 3i
Scope integrated equipment & Curriculum
Deliverable set as equipment
SD2: Educational objectives transferred into a curriculum of discrete lessons
1 2 3
Curriculum of Lessons based on educational objectives with EMD systems at a "macro" level
If addressed at all preliminary curriculum would be used as a proxy
SD3: Capability of Industrial partner equipment determines: -Power flow for regenerative drive -Control of equipment via PLC
Size of donated equipment establishes order of magnitude size of system
Power Side Circuit Diagram drafted: Can select multiple drive types for experimental investigation
2 4 (S2)
SCADA architecture finalised: PLC with hybrid of IO types.
2 4 (S2)
Control side circuit diagram drafted
2 4 (S2)
SD4: Data acquisition system design – sampling rate
3, 3i 5,5i
Sampling rate based on criteria of student recognition of shape of wave form and economy of transducers
Sampling rate based on Nyquist criteria to identify presence of frequencies.
Data acquisition system physical layout nominated.
3 5 (S14)
HMI and overall system layout formulated
3 5 (S1,S2)

System Design





Detail Design
WiSE Augmentation impacting Decision
1 Measure of student competency
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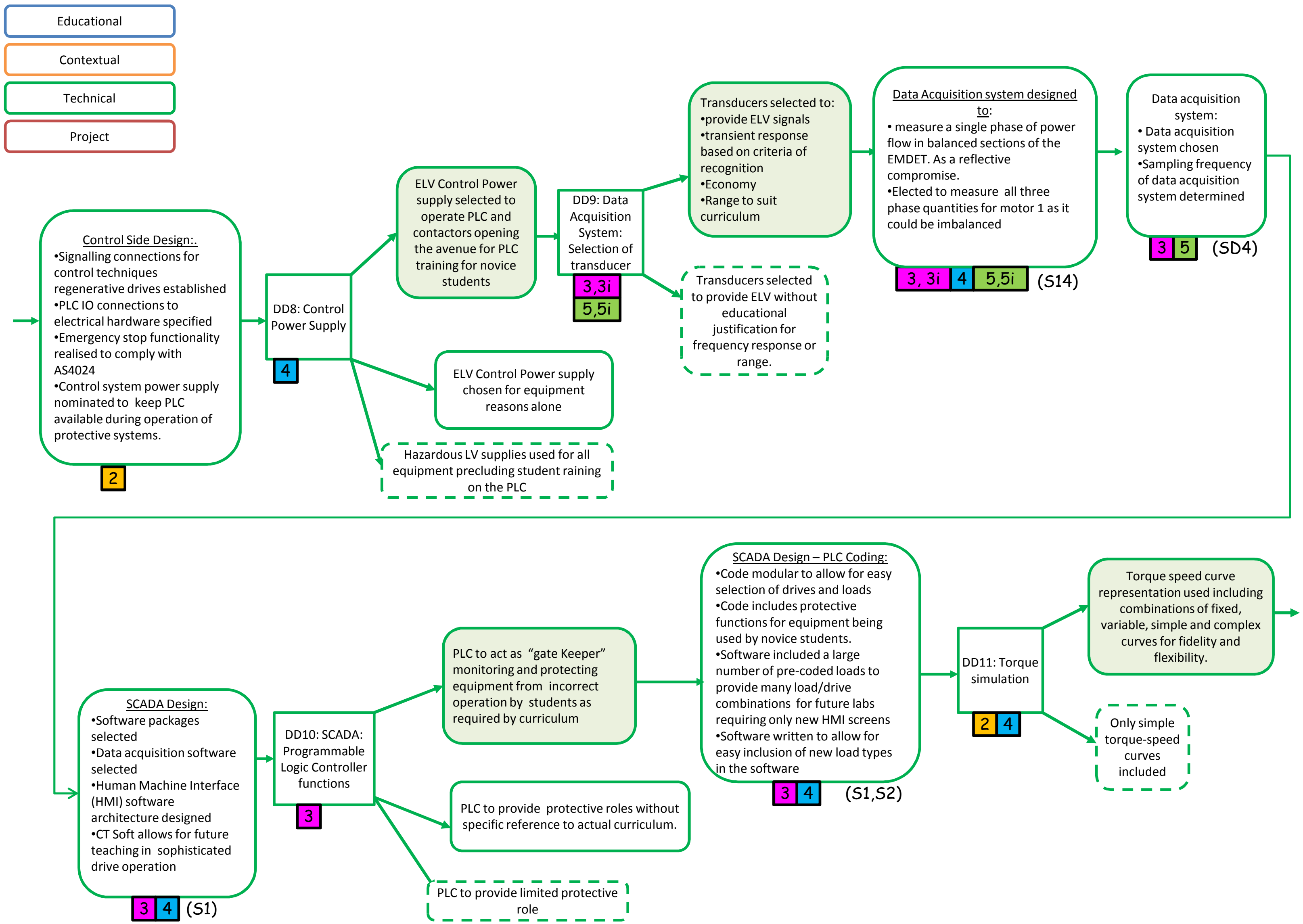
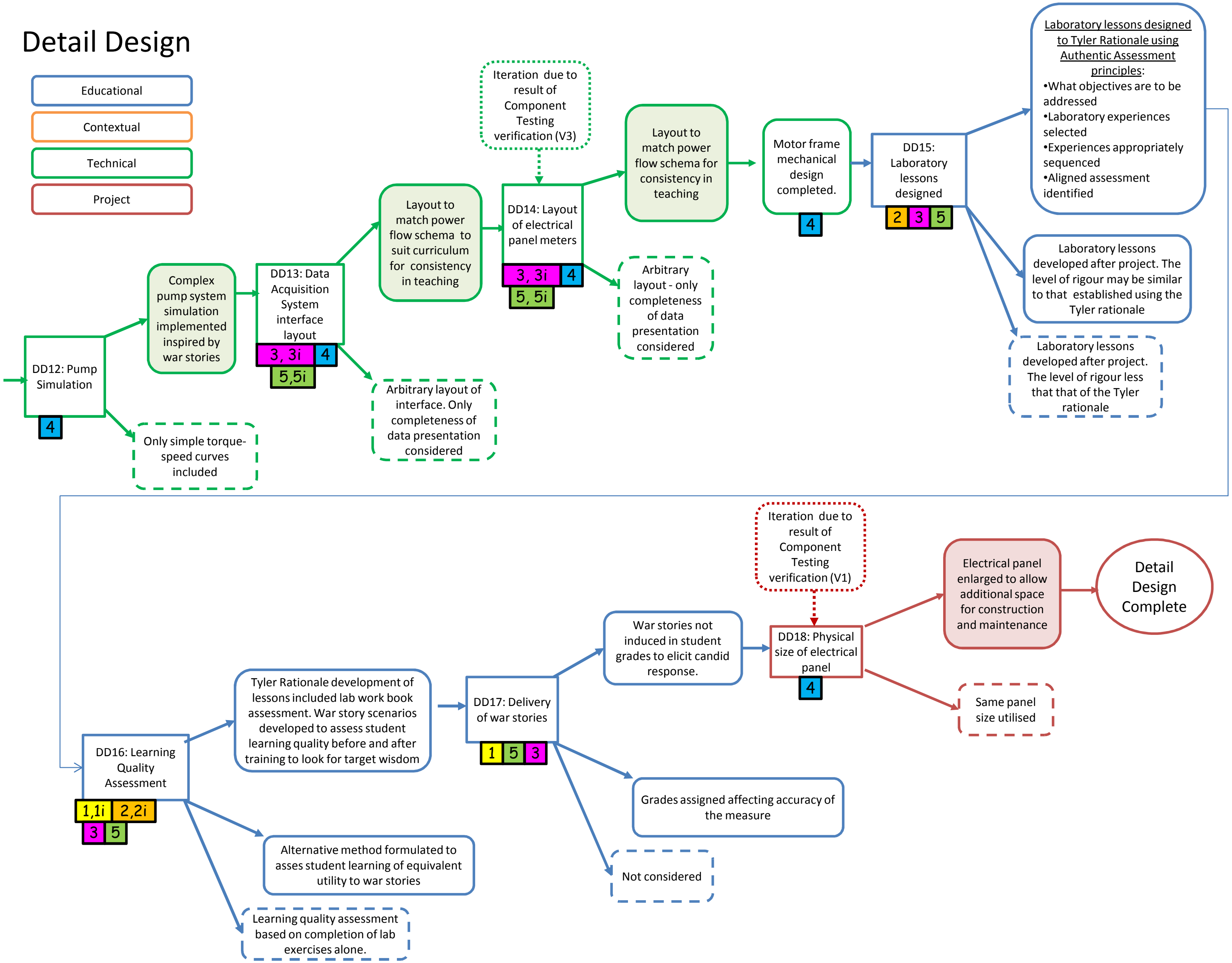
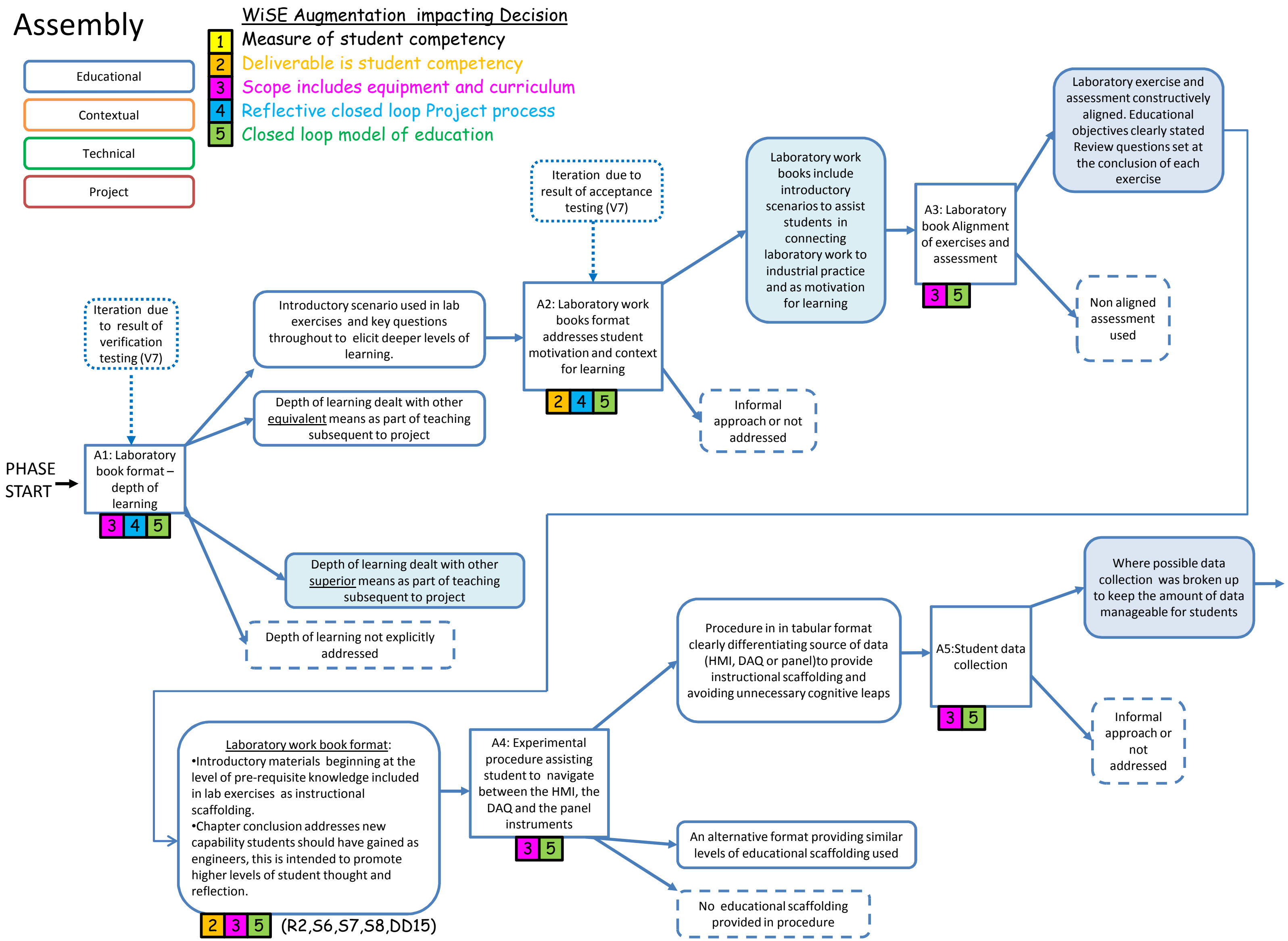
5 Closed loop model of education
Educational
Contextual
Technical
Project
PHASE START
Power Side Design:
•Three drive types available for investigation
•Drives selected by remote relays controlled by PLC avoiding student interaction with hazardous voltages.
•Power side equipment protection (safety, thermal and electrical)
3 4 (S1,S2,S3)
DD1: Drive Type Selection
1 2 3
Three drive types available for investigation (Inverter, Soft Start, DOL) inspired by curriculum and war stories
Original selection of inverter and DOL used
Iteration due to result of Component Testing verification (V3)
DD2: Motor 1 voltage transducers measurement reference selection
3 4 5
Line to neutral reference used.
Motor 1 reference set as motor star point to allow analysis as single phase equivalent by students
Iteration due to result of Component Testing verification (V3)
DD3 Motor 2 voltage transducers measurement reference selection
3 4 5
Motor 2 uses line to line based measurements to allow analysis as single phase equivalent by students
Line to neutral reference used.
Iteration due to result of Component Testing verification (V3)
DD4: Motor 2 current transducers measurement selection
3 4 5
Motor 2 uses internal current measurement of a single phase winding (line to line)current measurement
Motor 2 uses external line current measurement.
Iteration due to result of Component Testing verification (V3)
DD5: Selectable access to line-neutral measurement reference
3 4
Selectable access to line-neutral as a measurement reference for instructive purposes
Fixed measurement reference
Iteration due to result of Component Testing verification (V2)
DD6: Additional features to investigate phase loss power quality issues
3 4
Contactor included to allow a motor 1 to be run on two phases of supply
No two phasing contactor included
DD7: Additional features to investigate imbalance power quality issues
3
Selectable inductors included in one phase of motor 1 supply to allow imbalance to be investigated
No inductors included

Detail Design



Detail Design





Assembly
Educational
Contextual
Technical
Project
WiSE Augmentation impacting Decision
1 Measure of student competency
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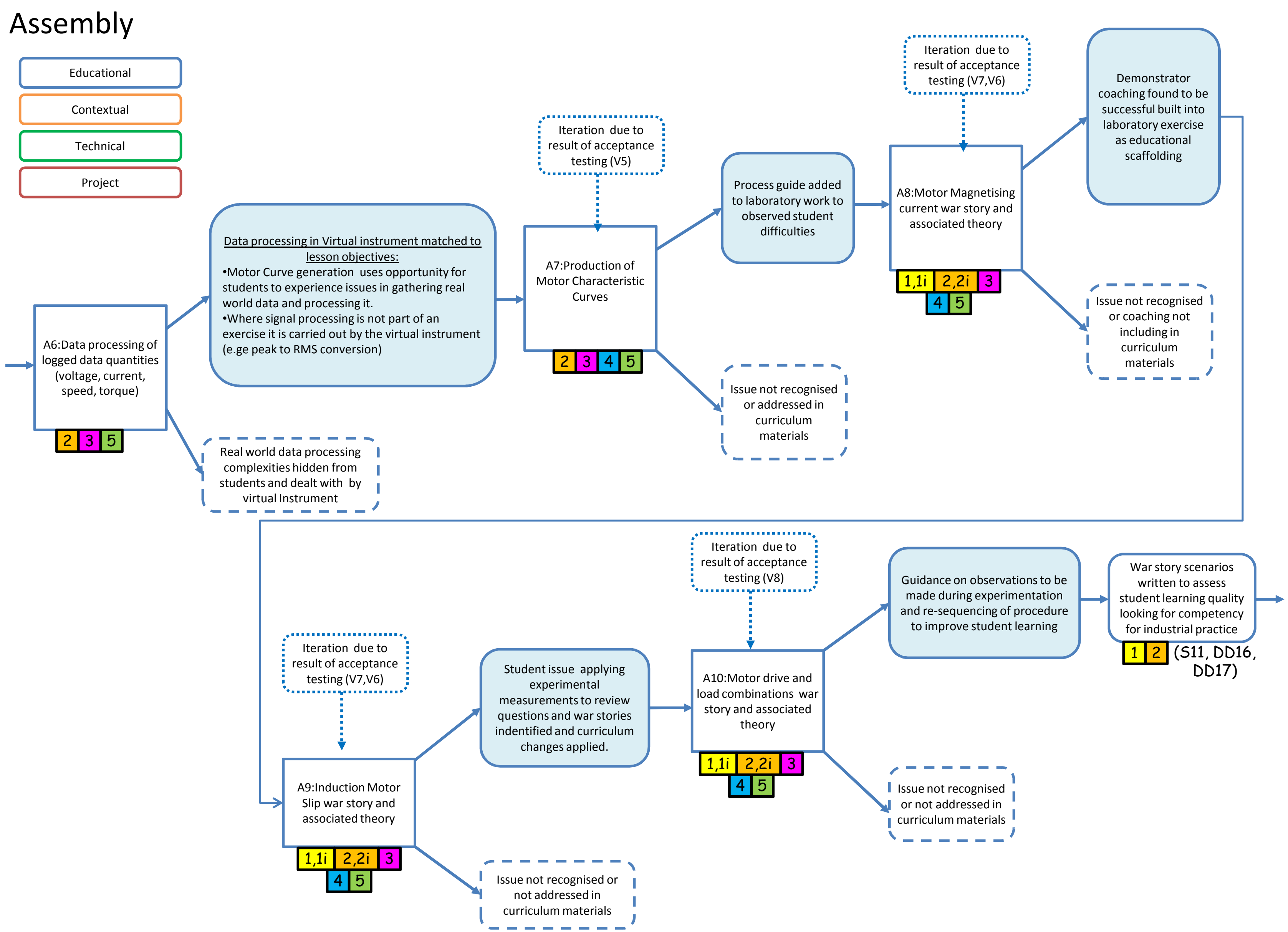
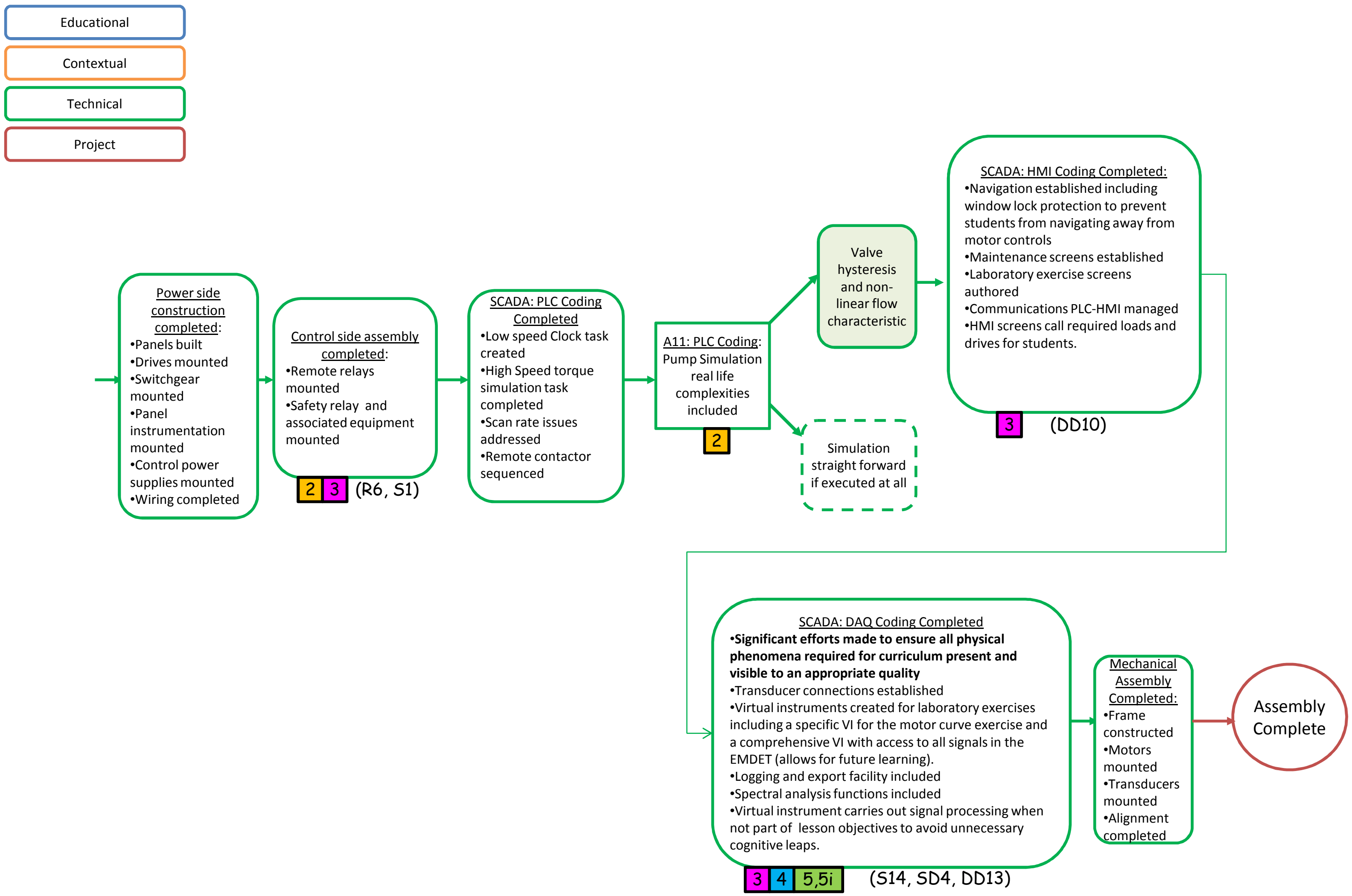
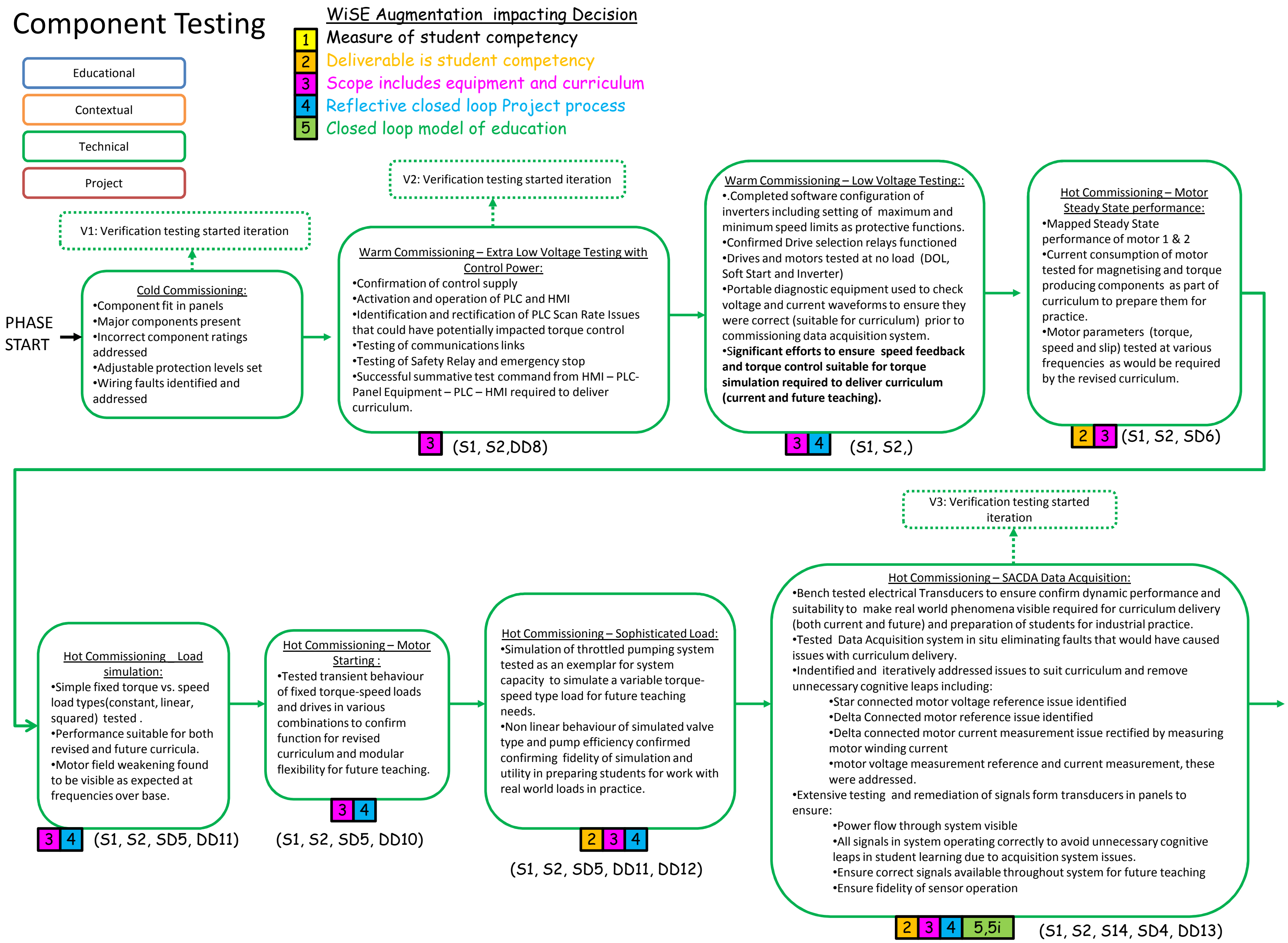
5 Closed loop model of education
PHASE START
A1: Laboratory book format – depth of learning
3 4 5
Iteration due to result of verification testing (V7)
Introductory scenario used in lab exercises and key questions throughout to elicit deeper levels of learning.
Depth of learning dealt with other equivalent means as part of teaching subsequent to project
Depth of learning dealt with other superior means as part of teaching subsequent to project
Depth of learning not explicitly addressed
Iteration due to result of acceptance testing (V7)
A2: Laboratory work books format addresses student motivation and context for learning
2 4 5
Informal approach or not addressed
Laboratory work books include introductory scenarios to assist students in connecting laboratory work to industrial practice and as motivation for learning
A3: Laboratory book Alignment of exercises and assessment
3 5
Laboratory exercise and assessment constructively aligned. Educational objectives clearly stated Review questions set at the conclusion of each exercise
Non aligned assessment used
Laboratory work book format:
•Introductory materials beginning at the level of pre-requisite knowledge included in lab exercises as instructional scaffolding.
•Chapter conclusion addresses new capability students should have gained as engineers, this is intended to promote higher levels of student thought and reflection.
2 3 5 (R2,S6,S7,S8,DD15)
A4: Experimental procedure assisting student to navigate between the HMI, the DAQ and the panel instruments
3 5
Procedure in in tabular format clearly differentiating source of data (HMI, DAQ or panel)to provide instructional scaffolding and avoiding unnecessary cognitive leaps
An alternative format providing similar levels of educational scaffolding used
No educational scaffolding provided in procedure
A5:Student data collection
3 5
Where possible data collection was broken up to keep the amount of data manageable for students
Informal approach or not addressed

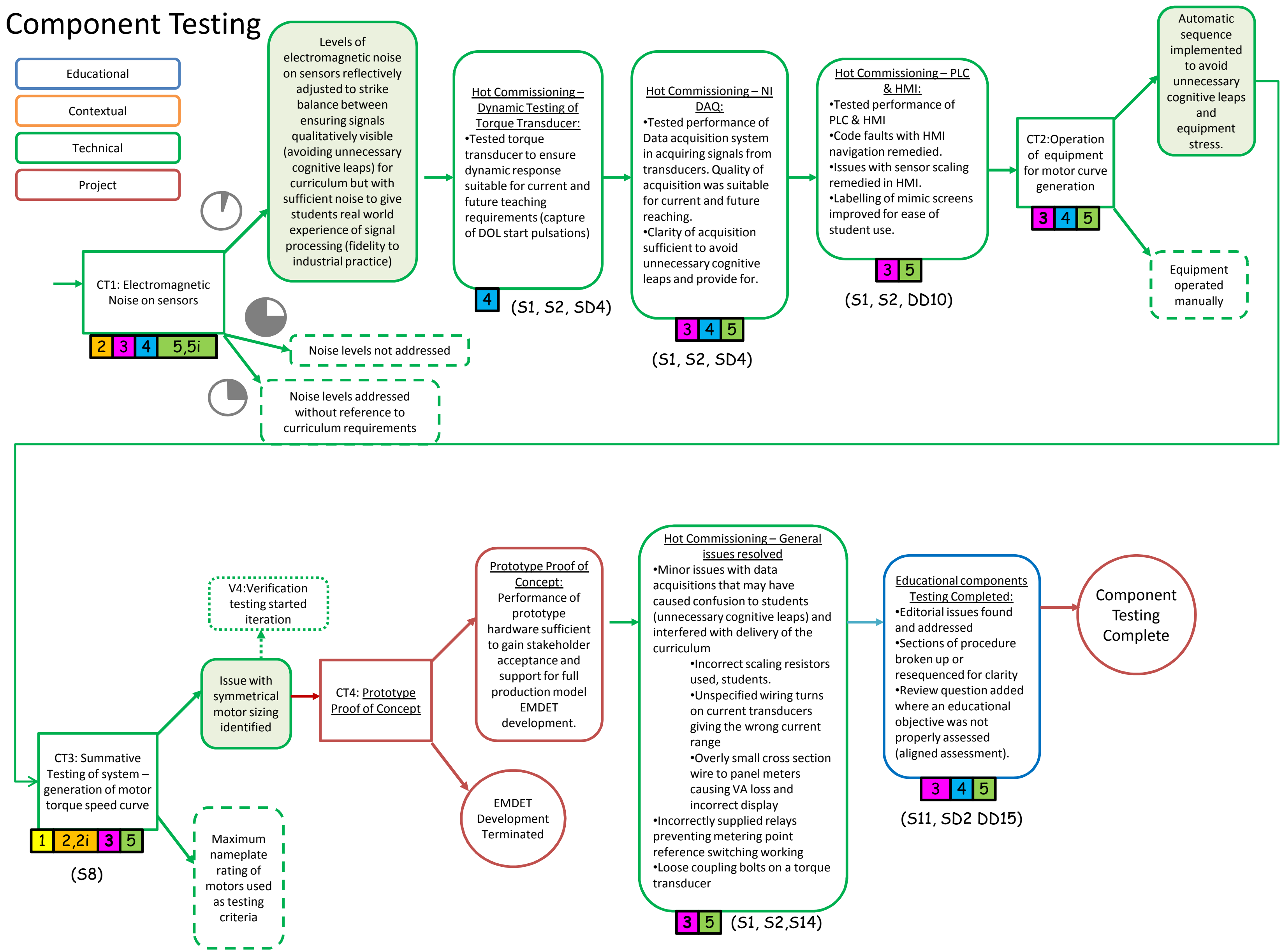


Assembly
Educational
Contextual
Technical
Project
A6:Data processing of logged data quantities (voltage, current, speed, torque)
2 3 5
Data processing in Virtual instrument matched to lesson objectives:
•Motor Curve generation uses opportunity for students to experience issues in gathering real world data and processing it.
•Where signal processing is not part of an exercise it is carried out by the virtual instrument (e.ge peak to RMS conversion)
Real world data processing complexities hidden from students and dealt with by virtual Instrument
Iteration due to result of acceptance testing (V5)
A7:Production of Motor Characteristic Curves
2 3 4 5
Issue not recognised or addressed in curriculum materials
Process guide added to laboratory work to observed student difficulties
Iteration due to result of acceptance testing (V7,V6)
A8:Motor Magnetising current war story and associated theory
1,1i 2,2i 3 4 5
Demonstrator coaching found to be successful built into laboratory exercise as educational scaffolding
Issue not recognised or coaching not including in curriculum materials
Iteration due to result of acceptance testing (V7,V6)
A9:Induction Motor Slip war story and associated theory
1,1i 2,2i 3 4 5
Issue not recognised or not addressed in curriculum materials
Student issue applying experimental measurements to review questions and war stories indentified and curriculum changes applied.
Iteration due to result of acceptance testing (V8)
A10:Motor drive and load combinations war story and associated theory
1,1i 2,2i 3 4 5
Issue not recognised or not addressed in curriculum materials
Guidance on observations to be made during experimentation and re-sequencing of procedure to improve student learning
War story scenarios written to assess student learning quality looking for competency for industrial practice
1 2 (S11, DD16, DD17)

Assembly


Educational
Contextual
Technical
Project
Power side construction completed:
•Panels built
•Drives mounted
•Switchgear mounted
•Panel instrumentation mounted
•Control power supplies mounted
•Wiring completed
Control side assembly completed:
•Remote relays mounted
•Safety relay and associated equipment mounted
2 3 (R6, S1)
SCADA: PLC Coding Completed
•Low speed Clock task created
•High Speed torque simulation task completed
•Scan rate issues addressed
•Remote contactor sequenced
A11: PLC Coding: Pump Simulation real life complexities included
2
Valve hysteresis and non-linear flow characteristic
Simulation straight forward if executed at all
SCADA: HMI Coding Completed:
•Navigation established including window lock protection to prevent students from navigating away from motor controls
•Maintenance screens established
•Laboratory exercise screens authored
•Communications PLC-HMI managed
•HMI screens call required loads and drives for students.
3 (DD10)
SCADA: DAQ Coding Completed
•Significant efforts made to ensure all physical phenomena required for curriculum present and visible to an appropriate quality
•Transducer connections established
•Virtual instruments created for laboratory exercises including a specific VI for the motor curve exercise and a comprehensive VI with access to all signals in the EMDET (allows for future learning).
•Logging and export facility included
•Spectral analysis functions included
•Virtual instrument carries out signal processing when not part of lesson objectives to avoid unnecessary cognitive leaps.
3 4 5,5i (S14, SD4, DD13)
Mechanical Assembly Completed:
•Frame constructed
•Motors mounted
•Transducers mounted
•Alignment completed
Assembly Complete


Component Testing
Educational
Contextual
Technical
Project
WiSE Augmentation impacting Decision
1 Measure of student competency
2 Deliverable is student competency
3 Scope includes equipment and curriculum
4 Reflective closed loop Project process
5 Closed loop model of education
PHASE START
V1: Verification testing started iteration
Cold Commissioning:
•Component fit in panels
•Major components present
•Incorrect component ratings addressed
•Adjustable protection levels set
•Wiring faults identified and addressed
V2: Verification testing started iteration
Warm Commissioning – Extra Low Voltage Testing with Control Power:
•Confirmation of control supply
•Activation and operation of PLC and HMI
•Identification and rectification of PLC Scan Rate Issues that could have potentially impacted torque control
•Testing of communications links
•Testing of Safety Relay and emergency stop
•Successful summative test command from HMI – PLC- Panel Equipment – PLC – HMI required to deliver curriculum.
3 (S1, S2,DD8)
Warm Commissioning – Low Voltage Testing::
•.Completed software configuration of inverters including setting of maximum and minimum speed limits as protective functions.
•Confirmed Drive selection relays functioned
•Drives and motors tested at no load (DOL, Soft Start and Inverter)
•Portable diagnostic equipment used to check voltage and current waveforms to ensure they were correct (suitable for curriculum) prior to commissioning data acquisition system.
•Significant efforts to ensure speed feedback and torque control suitable for torque simulation required to deliver curriculum (current and future teaching).
3 4 (S1, S2,)
Hot Commissioning – Motor Steady State performance:
•Mapped Steady State performance of motor 1 & 2
•Current consumption of motor tested for magnetising and torque producing components as part of curriculum to prepare them for practice.
•Motor parameters (torque, speed and slip) tested at various frequencies as would be required by the revised curriculum.
2 3 (S1, S2, SD6)
Hot Commissioning Load simulation:
•Simple fixed torque vs. speed load types(constant, linear, squared) tested .
•Performance suitable for both revised and future curricula.
•Motor field weakening found to be visible as expected at frequencies over base.
3 4 (S1, S2, SD5, DD11)
Hot Commissioning – Motor Starting :
•Tested transient behaviour of fixed torque-speed loads and drives in various combinations to confirm function for revised curriculum and modular flexibility for future teaching.
3 4 (S1, S2, SD5, DD10)
Hot Commissioning – Sophisticated Load:
•Simulation of throttled pumping system tested as an exemplar for system capacity to simulate a variable torque-speed type load for future teaching needs.
•Non linear behaviour of simulated valve type and pump efficiency confirmed confirming fidelity of simulation and utility in preparing students for work with real world loads in practice.
2 3 4 (S1, S2, SD5, DD11, DD12)
V3: Verification testing started iteration
Hot Commissioning – SACDA Data Acquisition:
•Bench tested electrical Transducers to ensure confirm dynamic performance and suitability to make real world phenomena visible required for curriculum delivery (both current and future) and preparation of students for industrial practice.
•Tested Data Acquisition system in situ eliminating faults that would have caused issues with curriculum delivery.
•Indentified and iteratively addressed issues to suit curriculum and remove unnecessary cognitive leaps including:
•Star connected motor voltage reference issue identified
•Delta Connected motor reference issue identified
•Delta connected motor current measurement issue rectified by measuring motor winding current
•motor voltage measurement reference and current measurement, these were addressed.
•Extensive testing and remediation of signals form transducers in panels to ensure:
•Power flow through system visible
•All signals in system operating correctly to avoid unnecessary cognitive leaps in student learning due to acquisition system issues.
•Ensure correct signals available throughout system for future teaching
•Ensure fidelity of sensor operation
2 3 4 5,5i (S1, S2, S14, SD4, DD13)



Component Testing
Educational
Contextual
Technical
Project
CT1: Electromagnetic Noise on sensors
2 3 4 5,5i
Levels of electromagnetic noise on sensors reflectively adjusted to strike balance between ensuring signals qualitatively visible (avoiding unnecessary cognitive leaps) for curriculum but with sufficient noise to give students real world experience of signal processing (fidelity to industrial practice)
Noise levels not addressed
Noise levels addressed without reference to curriculum requirements
Hot Commissioning – Dynamic Testing of Torque Transducer:
•Tested torque transducer to ensure dynamic response suitable for current and future teaching requirements (capture of DOL start pulsations)
4 (S1, S2, SD4)
Hot Commissioning – NI DAQ:
•Tested performance of Data acquisition system in acquiring signals from transducers. Quality of acquisition was suitable for current and future reaching.
•Clarity of acquisition sufficient to avoid unnecessary cognitive leaps and provide for.
3 4 5
(S1, S2, SD4)
Hot Commissioning – PLC & HMI:
•Tested performance of PLC & HMI
•Code faults with HMI navigation remedied.
•Issues with sensor scaling remedied in HMI.
•Labelling of mimic screens improved for ease of student use.
3 5
(S1, S2, DD10)
CT2:Operation of equipment for motor curve generation
3 4 5
Automatic sequence implemented to avoid unnecessary cognitive leaps and equipment stress.
Equipment operated manually
CT3: Summative Testing of system – generation of motor torque speed curve
1 2,2i 3 5
(S8)
Issue with symmetrical motor sizing identified
V4:Verification testing started iteration
Maximum nameplate rating of motors used as testing criteria
CT4: Prototype Proof of Concept
Prototype Proof of Concept:
Performance of prototype hardware sufficient to gain stakeholder acceptance and support for full production model EMDET development.
EMDET Development Terminated
Hot Commissioning – General issues resolved
•Minor issues with data acquisitions that may have caused confusion to students (unnecessary cognitive leaps) and interfered with delivery of the curriculum
•Incorrect scaling resistors used, students.
•Unspecified wiring turns on current transducers giving the wrong current range
•Overly small cross section wire to panel meters causing VA loss and incorrect display
•Incorrectly supplied relays preventing metering point reference switching working
•Loose coupling bolts on a torque transducer
3 5 (S1, S2,S14)
Educational components Testing Completed:
•Editorial issues found and addressed
•Sections of procedure broken up or resequenced for clarity
•Review question added where an educational objective was not properly assessed (aligned assessment).
3 4 5
(S11, SD2 DD15)
Component Testing Complete


Integration Testing
Educational
Contextual
Technical
Project
WiSE Augmentation impacting Decision
1 Measure of student competency
2 Deliverable is student competency
3 Scope includes equipment and curriculum
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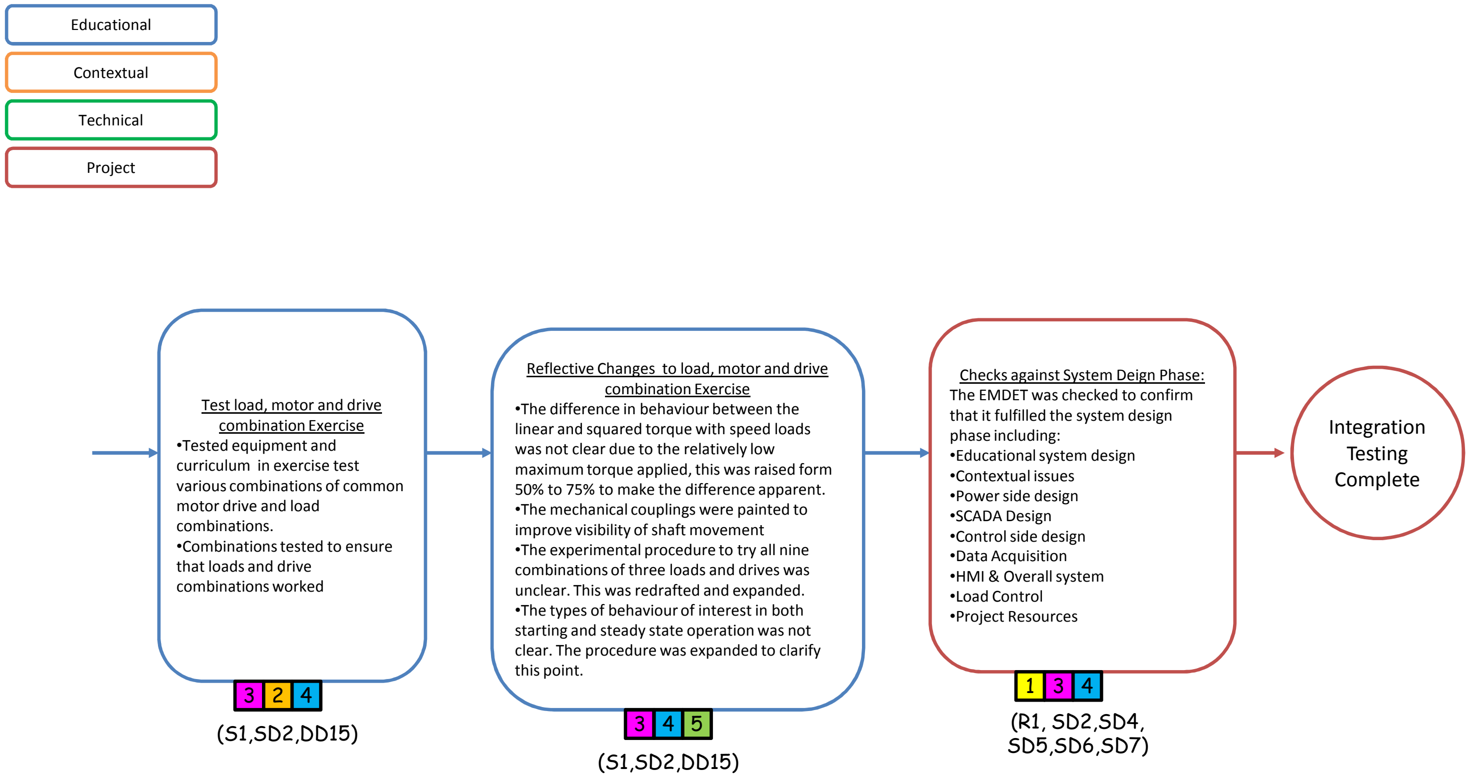
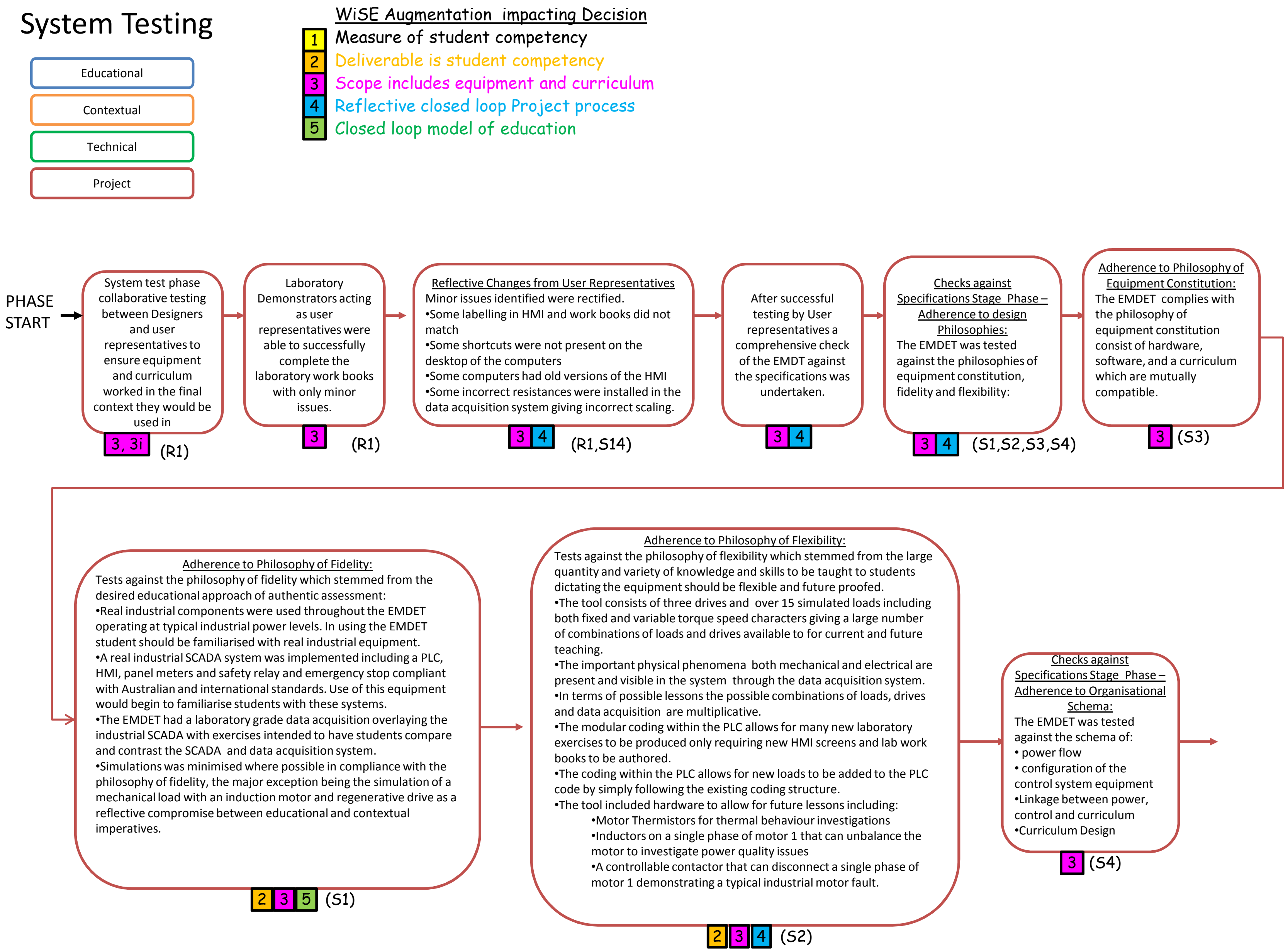
PHASE START
Integration test phase testing of curriculum using equipment to produce instructors solution manual
3, 3i
(R1, R7, S4)
Test of Industrial Safety Exercise
•Tested equipment and curriculum in exercise to introduce students to industrial safety practice.
•Preparation of solutions identified that an additional oral briefing and introduction to the equipment was required.
3 2 4
(S1,SD2,DD15)
Test of Introduction to Laboratory Equipment and Industrial EMD systems Exercise
•Tested equipment and curriculum in exercise to introduce students to the EMDET. This was both an introduction to the laboratory equipment and an introduction to a typical industrial EMD system controlled with an industrial SCADA.
•Tested exercise to trained students in the use of use system emergency stop to shut equipment down.
•Tested exercise to demonstrate diagnostic function of data acquisition system beyond standard industrial equipment.
3 2 4 (S1,SD2,DD15)
Reflective Changes to Laboratory Equipment and Industrial EMD systems Exercise
•Added a step in instructions to check motor name plate details as an authentic industrial exercise and to provide data for later exercises.
•Introducing check boxes to help prevent student inadvertently skipping instructions
•Breaking down of unnecessarily long or complex steps
•Updating labelling on HMI and lab work books to match
•Placing key files to run the HMI on the desktop of the computers.
2 3 4 5 (R1, S4,DD15)
Test of torque-speed behaviour of squirrel cage induction motor Exercise
•Tested equipment and curriculum in exercise to map the torque speed characteristic of the most common industrial electric motor.
•Automatic sequences tested to ensure that operation was simple enough for students, the full range of the motor was tested and that sufficient data at all points of the characteristic where gathered.
3 2 4
(S1,SD2,DD15)
Reflective Changes to torque-speed behaviour of squirrel cage induction motor Exercise
•Added a step in instructions to check students could operate the data acquisition system as instructional scaffolding
•Added steps to assist students in locating the file location of their data
•Altered the naming of the data in the logged file from generic to specific titles to avoid confusion
•Altered the name of the VI to clearly identify it to students.
•Real world non-idealities in test were described in instructors solutions.
2 3 4 5
Test of characteristics of squirrel cage induction motor Exercise
•Tested equipment and curriculum in exercise to examine the characteristics of the most common industrial electric motor under various combinations of electrical supply and mechanical loading.
•Tested motor torque, speed, current and voltage under various supply frequencies and mechanical loads.
3 2 4
(S1,SD2,DD15)
Reflective Changes to characteristics of of squirrel cage induction motor Exercise
•Altered supply frequency test points to ensure field weakening effects clearly visible.
•Addressed some differences in torque control found between the five EMDET's produced.
•Introduced a step to cross check panel meters and VI's to ensure both systems were working
•Added instructions for students to use torque value from DAQ due to its higher accuracy rather than HMI.
•Rearranged table for recording data values so that source data and derived values would be adjacent
•A loading case above base speed originally in the notes was outside of the motor frame rating. To prompt higher student learning the case was left ion the table with instructions for students to explain why the measurement could not be taken.
•The first draft of review questions overlooked the relationship between motor slip and torque, a question was introduced to examine this.
•Mismatches between labelling on the HMI and lab work books were corrected.
2 3 4 5 (S1,SD2,DD15)

Integration Testing

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PHASE START
System test phase collaborative testing between Designers and user representatives to ensure equipment and curriculum worked in the final context they would be used in
3, 3i (R1)
Laboratory Demonstrators acting as user representatives were able to successfully complete the laboratory work books with only minor issues.
3 (R1)
Reflective Changes from User Representatives
Minor issues identified were rectified.
•Some labelling in HMI and work books did not match
•Some shortcuts were not present on the desktop of the computers
•Some computers had old versions of the HMI
•Some incorrect resistances were installed in the data acquisition system giving incorrect scaling.
3 4 (R1,S14)
After successful testing by User representatives a comprehensive check of the EMDT against the specifications was undertaken.
3 4
Checks against Specifications Stage Phase – Adherence to design Philosophies:
The EMDET was tested against the philosophies of equipment constitution, fidelity and flexibility:
3 4 (S1,S2,S3,S4)
Adherence to Philosophy of Equipment Constitution:
The EMDET complies with the philosophy of equipment constitution consist of hardware, software, and a curriculum which are mutually compatible.
3 (S3)
Adherence to Philosophy of Fidelity:
Tests against the philosophy of fidelity which stemmed from the desired educational approach of authentic assessment:
•Real industrial components were used throughout the EMDET operating at typical industrial power levels. In using the EMDET student should be familiarised with real industrial equipment.
•A real industrial SCADA system was implemented including a PLC, HMI, panel meters and safety relay and emergency stop compliant with Australian and international standards. Use of this equipment would begin to familiarise students with these systems.
•The EMDET had a laboratory grade data acquisition overlaying the industrial SCADA with exercises intended to have students compare and contrast the SCADA and data acquisition system.
•Simulations was minimised where possible in compliance with the philosophy of fidelity, the major exception being the simulation of a mechanical load with an induction motor and regenerative drive as a reflective compromise between educational and contextual imperatives.
2 3 5 (S1)
Adherence to Philosophy of Flexibility:
Tests against the philosophy of flexibility which stemmed from the large quantity and variety of knowledge and skills to be taught to students dictating the equipment should be flexible and future proofed.
•The tool consists of three drives and over 15 simulated loads including both fixed and variable torque speed characters giving a large number of combinations of loads and drives available to for current and future teaching.
•The important physical phenomena both mechanical and electrical are present and visible in the system through the data acquisition system.
•In terms of possible lessons the possible combinations of loads, drives and data acquisition are multiplicative.
•The modular coding within the PLC allows for many new laboratory exercises to be produced only requiring new HMI screens and lab work books to be authored.
•The coding within the PLC allows for new loads to be added to the PLC code by simply following the existing coding structure.
•The tool included hardware to allow for future lessons including:
•Motor Thermistors for thermal behaviour investigations
•Inductors on a single phase of motor 1 that can unbalance the motor to investigate power quality issues
•A controllable contactor that can disconnect a single phase of motor 1 demonstrating a typical industrial motor fault.
2 3 4 (S2)
Checks against Specifications Stage Phase – Adherence to Organisational Schema:
The EMDET was tested against the schema of:
• power flow
• configuration of the control system equipment
•Linkage between power, control and curriculum
•Curriculum Design
3 (S4)

System Testing

Acceptance Testing

Educational

Contextual

Technical

Project

WiSE Augmentation impacting Decision

1 Measure of student competency

2 Deliverable is student competency

3 Scope includes equipment and curriculum

4 Reflective closed loop Project process

5 Closed loop model of education

PHASE START

User Testing - General Assessment

EMDET assessed from a general 'macro' perspective and judged to be acceptable by fulfilling the criteria that:

-There was a satisfactory overall completion of the student laboratory workbooks for the revised curriculum delivered to ECTE412/912 judged by student grades

- The capability of the EMDET to teach in areas of the preliminary curriculum beyond the scope of delivery to ECTE412/912 in accordance with the philosophy of flexibility.

-- Addressed IEAast accreditation audit

2 3 4 (S9,S2)

V5: Verification testing started iteration

User Testing - Specific Assessment

Production of Motor Characteristic Curves

The EMDET was assessed on the specific criteria production of motor characteristic curves. A number of issues indentified and addressed using reflective closed loop approach:

-Student difficulty with achieving cognitive leaps with planning analysis, converting peak to RMS values, filtering electronic noise and producing curves addressed with process description for analysis

- Additional time allowed for students to complete analysis outside of class.

2 3 4 5 (A6, A7, CT1,CT2, CT3)

V6: Verification testing started iteration

User Testing - Specific Assessment

War Story: Magnetising Current

The EMDET was assessed on specific criteria of student negation of war stories and associated theory. In this case recognising and understanding the significance of magnetising current in a real world context, A number of issues indentified and addressed using reflective closed loop approach:

-Student difficulty with applying laboratory learning in applied situation.

- Demonstrator coaching supplying additional scaffolding found to be effective was built into the curriculum including relating laboratory experimentation to motor physical construction and single phase equivalent circuit.

1,1i 2,2i 3 4 5 (DD18, A8, CT1,DD15,CT2, CT3)

V7: Verification testing started iteration

User Testing - Specific Assessment

War Story: Induction Motor Slip

The EMDET was assessed on specific criteria of student negation of war stories and associated theory. In this case applying the concept of induction motor slip in a real world context. A number of issues indentified and addressed using reflective closed loop approach: :

- Student difficulty with applying laboratory learning in applied situation, introductory vignettes added to laboratory work book.

-Student difficulty in relating individual laboratory exercises into a sophisticated relational understanding (according to SOLO taxonomy)

-Students not applying laboratory experimental work in review questions, added explicit instructions to provide linkage for students.

1,1i 2,2i 3 4 5 (DD16, DD17, A1,A2,A9)

User Testing - Specific Assessment

War Story: Capability of VSD

The EMDET was assessed on specific criteria of student negation of war stories and associated theory. In this case recognising the capability of a Variable Speed rive to save energy in a real world context. A number of issues indentified and addressed using reflective closed loop approach:

- Identified a lack of exercises providing students the opportunity to link VSD performance, variable shaft speed, reduced system power consumption and economic cost.

1 2 3 4 5 (DD16, DD17)

V8: Verification testing started iteration

User Testing - Specific Assessment

War Story: Drive and load types

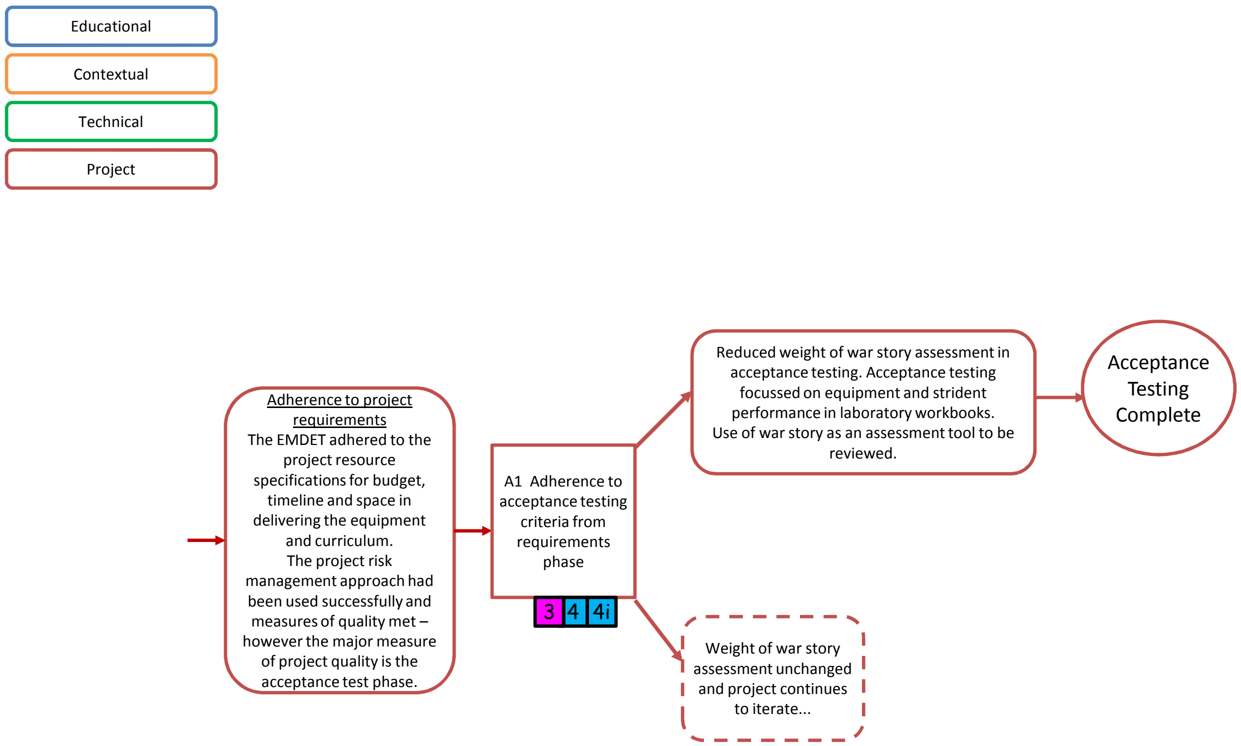
The EMDET was assessed on specific criteria of student negation of war stories and associated theory. In this case recognising appropriate load and motor drive combinations n a real world context. A number of issues indentified and addressed using reflective closed loop approach::

-Student observations of experimentation

-Experimental ordering and juxtaposition of drive and load combinations affording students the opportunity to observe desired contrasts.

1,1i 2,2i 3 4 5 (DD11, DD16, DD17,A10)

Acceptance Testing



Appendix C

War Story Scenarios

War story Assessment both before and after laboratory teaching

ECTE412/912 Induction Motor & Drives Laboratory
Pre-Lab Questionnaire

The following questions will be used to assess the material delivered to you as a student carrying out the Laboratory exercises and hopefully assess whether it has achieved its aim of giving you some of the skills you will likely need as a practicing electrical engineer.

These questions are not counted towards your assessment in any way. However it is in your best interest to answer them to the best of your current ability, as areas you may need development in with can be identified and appropriate assistance given as part of the lab program.

Answer the questions using your current level of experience and materials delivered to you during your undergraduate course. You do not need to carry out any in depth research to answer them.

The following questions are based on the real world experiences of practising Electrical Engineers. Read the brief scenarios and give your response.

Scenario Name: *No Flow in a Pumping System*

Knowledge Tested: *Motor magnetising current*

You are an supervising engineer on an industrial site. A fault is reported to you – a fluid pumping system is not delivering flow as it should. You despatch an electrician and a mechanical technician to investigate. They report back that all valves in the system are open and the pump motor is turning and drawing about 25% of its full load current. They conclude that the pump & motor are working OK and that there must be a blockage elsewhere in the system. They suggest that arrangements be made to shut down the system, disconnect the pipe work and look for blockages.

Do you agree?

Desired Answer: The motor is drawing its "no load" current. The motor is doing no mechanical work. There must be something wrong with the pump and motor. Typically expect that the motor is disconnected with the fluid moving component of the pump.

Scenario: *Motor & Drive Selection 1*

Knowledge Tested: *significance of thee induction motor curve*

You are an Electrical Engineer in a design office. One of your mechanical colleagues approaches you for assistance with the project you are working on together. There is a rotating load that the project needs a motor and drive system for. The requirements are fairly tight. The system needs to stay at near constant speed while it provides various amounts of torque. The system speed needs to stay within 5% of design speed from zero torque up to full power.

What sort of motor, drive and control system would you suggest?

Desired Answer: An induction motor will do this as part of its normal Direct On Line operation, nothing special is required. Induction motor no load speed is usually around 98% synchronous. Full load is usually around 95% synchronous.

Of course systems with closed loop control will do this but they would be overkill.

Scenario Name: *Variable Speed Drive Capabilities*

Knowledge Tested: *Affect of shaft speed control on a system*

You are an electrical engineer as part of a facilities management group. Your supervisor approaches you about some suggestions they have been given regarding some of your pumping systems.

A supplier has suggested that installing variable speed drives on some of your variable flow water handling systems could save a lot of power – enough to repay the installation costs in a few years.

Your supervisor wants to know is there some substance behind the sales pitch? How exactly do the benefits come about?

Desired Answer: Yes these claims are quite realistic. The fundamental way the system works is that a variable speed drive allows control over the amount of power put into a system. So only the power required to do the work is put into the system. Whereas conventional throttled pumping systems put a relatively inflexible amount of power into the system. If this is too much the excess power must be dissipated i.e. across the throttle.

There are many ways of expressing this concept, so a number of different answers may be given meaning the same thing ultimately.

Also less obviously variable speed drives add an additional control parameter to the system (shaft speed) to a system and often it is easier to accurately achieve a setpoint using this than other control methods (it improves system "controllability".

Scenario Name: *Drive System Recommendations*

Knowledge Tested: *Motor and Drive system behaviour*

You are an electrical engineer in a large project team. Your team leader (a civil engineer) approaches you for some guidance. Part of your project is to transport mineral ore through a number of processes via conveyor belts. The team is looking at how the system should be started and run. They are particularly concerned about sudden starts snapping loaded belts, damaging structure and jerking mineral ore off loaded conveyors and into other machinery causing problems. Your team leader asks for your advice on what sort of Soft Starters should be used.

Desired Answer: No soft starters should be used. The conveyors sound like they need high torque at low speeds combined with gradual and controllable acceleration. Traditional soft starters cannot provide this. Variable speed drives are really required in this instance.

ECTE412/912 Induction Motor & Drives Laboratory
Post-Lab Questionnaire

The following questions will be used to assess the material delivered to you as a student carrying out the Laboratory exercises and hopefully assess whether it has achieved its aim of giving you some of the skills you will likely need as a practicing electrical engineer.

These questions are not counted towards your assessment in any way. However it is in your best interest to answer them to the best of your current ability, as areas you may need development in with can be identified and appropriate assistance given as part of the lab program.

Answer the questions using your current level of experience and materials delivered to you during your undergraduate course. You do not need to carry out any in depth research to answer them.

The following questions are based on the real world experiences of practising Electrical Engineers. Read the brief scenarios and give your response.

Scenario Name: *Cooling System Fault*

Knowledge Tested: *Motor magnetising current*

You are a support engineer on a production line. The Chief Line Operator calls you to the control centre. When you get there they tell you there is a problem with the cooling system control. The cooling fans have been running for the last half an hour but nothing is cooling down. The Operator thinks that the temperature sensor in the control loop is likely to be faulty and suggest that you check it first. Looking at the operator's HMI screen you can see that: the process temperature is high and climbing; all cooling fans are reporting that they are healthy, running and drawing 33% of their full load current.

What do you do?

Desired Answer: The motors are drawing its "no load" current. The motors are doing no mechanical work. There must be something wrong with the fans. Typically expect that the motors are disconnected from the fans or that if there are dampers in the system these could be closed.

Scenario: *Motor & Drive Selection 2*

Knowledge Tested: *significance of thee induction motor curve – specifically torque and slip*

As part of a design team you are asked to select a drive system for a large positive displacement lubricant pump. It is critical that the pump is able to deliver the right amount of fluid under a wide variety of loading conditions. Both having too much or too little fluid delivered is problematic. Too much fluid will cause problems with system pressure control; too little fluid will mean that the system will not provide enough lubrication.

You are given the following information from the mechanical engineers for preliminary motor and drive selection:

- System flow requirements: Anything between 1050 and 1150 litres per minute is acceptable.
- Positive Displacement Pump flow delivery = 1.5 litres per revolution.

- Estimated Loading conditions:
    - Low Load (system pressure 345 kPA), 11 kW of mechanical power required
    - High Load (system pressure 1350kPa) 30 kW of power required.

What sort of motor, drive and control system would you suggest?

Desired Answer: An induction motor will do this as part of its normal Direct On Line operation, nothing special is required.

Min speed required = 700RPM

Max Speed required = 766.7 RPM

An 8 pole motor will have a synchronous speed of 750 RPM.

750 RPM x 4.5 litres/rev = 1125 litres per minute is the most the pump & motor will deliver (fits within upper band)

Min speed of RPM corresponds to around 7% slip – you would normally expect and induction motor to develop Full Load torque before this (say at 5% slip)

So an 8 pole motor sufficiently large to deliver the maximum power would do the job. So say 30kW or the next frame size up.

Of course systems with closed loop control will do this but they would be overkill.

NB As power figures are given the system pressures are largely irrelevant to the electrical engineer in this case and just cloud the issue. To convert fluid power to shaft power we need to know the pump mechanical efficiency.

Scenario Name: *Variable Speed Drive Capabilities*

Knowledge Tested: *Affect of shaft speed control on a system*

You are an electrical engineer as part of a facilities management group. Your group has received an air conditioning consultants report on an air conditioning system on one of your buildings. Your supervisor has asked you to review it.

The report indicates that a significant amount of power is being wasted on one of your air handling systems. There are a number of fans that are being significantly throttled by control Dampers.

The report has stated that by reducing fan speed by using PWM inverters a significant power saving could be achieved as follows:

- Throttled Conditions (Damper Partially opened):
    - Air Flow = 2500 litres per minute
    - Fan pressure = 500 Pa
    - Fan Power Consumption 2.1 kW
    - Fan Speed = 980 RPM
    - Fan Torque = 20 Nm
- Reduced Speed (Damper Opened)
    - Air Flow = 2500 litres per minute
    - Fan pressure = 370 Pa
    - Fan Power Consumption 0.9 kW
    - Fan Speed = 760 RPM
    - Fan Torque = 11.5 Nm

Your supervisor has heard of other buildings that have had trouble with inverter installations and asks you if inverters are suitable to carry out this duty? Can they provide the required torque accurately at the reduced speed?

Desired Answer: Yes! An inverter is perfect for this. The power savings would be significant.

There are some possible concerns with using shielded cables and motor cooling– however we have not introduced the students to this.

Scenario Name: *Drive System Recommendations*

Knowledge Tested: *Motor and Drive system behaviour*

You are an electrical engineer recently assigned to a construction project building a new multi-story office. You and your supervisor (a structural engineer) are commissioning an elevator for the first time.

Your are running the elevator up and down the shaft to different floors. Half way through you begin to hear an awful sound coming from the shaft.

Your supervisor turns to you and says ""Quickly get down to the switch room and check the lift motor current – if it's overloading shut it down! If it's something else leave it running, record how much current it is using and come back to me – get moving!"

Your hurry to the switch room. When you get to the switch room you find that the construction crew has not yet labelled all of the drive equipment – the lift motor drive is not labelled. There are three things running:

- A direct on line starter drawing 120% full load current
- A soft starter drawing 50 % full load current
- An inverter drawing 60% full load current

What do you do?

Desired Answer: The lift requires controllable speed and torque. It will obviously be operated by the inverter. Direct on line starters and soft starters would not be suitable.

The lift is not overloading so it can be left running.

You need to note down the currents and go back to your supervisor and tell them the labels are not in place but a DOL starter is running at 120%.

Appendix D

Linkage Matrix

An organisational schema was required to create a linkage between operational and educational concerns outlined in the requirements stage of the project to the design for the power and control system addressed in the system and detail design stages. This would map the needs of basic operation of the motors and drives and the educational requirements of the curriculum to specific functionality necessary in the power and control equipment. A linkage matrix was created to accomplish this mapping. An extract of the matrix is shown in table D.1.

Table D.1: Linkage Matrix.

Experiment	Item Aim	Load drive assembly Requirement		Input Drive Assembly Requirement		HMI Requirement		SCADA Requirements	
	Lessons to be taught or functinality required	Description	Specification	Description	Specification	Description	Specification	Description	update speed Specification
	run	run when directed	Run when activated from SCADA activated (digital or comms)	run when directed	Run when activated from SCADA (digital or comms)				
	direction	run in direction selected	Run in direction indicated by SCADA	run in direction selected	Run in direction selected by operator	allow operator to choose direction		Run in direction selected by operator - impossible or unsafe requests will be reused	Could be panel pushbutton, inverter front plate or selection from PC based software, similar
	speed			run at speed selected	run at speed selected by operator	allow operator to choose speed		Run at speed selected by operator - impossible or unsafe requests will be reused	Could be panel pushbutton, inverter front plate or selection from PC based software, similar
	torque	run with speed/torque relation selected by operator	Be able to run with a torque set off a signal from the SCADA (comms or Analogue IO)			allow operator to select speed torque relation		based of operator mode selection and or load speed calculate torque requirement and send to load drive	

Experiment	Item Aim	Load drive assembly Requirement		Input Drive Assembly Requirement		HMI Requirement		SCADA Requirements	
	Lessons to be taught or functinality required	Description	Specification	Description	Specification	Description	Specification	Description	update speed Specification
	What sort of Drives are there	be able to assume some sort of torque speed relation - selected by the operator		Be able to Execute start/ running either DOL or using drive		Allow selection of DOL or drive starting	Mode selection (may be panel buttons, via screen on PC)	execute drive selection request - refuse unsafe or impossible request	
	Demonstrate Different Motor Controls					Display drive motor current consumption	Display high starting current & transients on a historical trend. Say sampling freq of 1000Hz to see 50Hz wave, Higher still to see anything superimposed on this	historically record drive motor currents	Record high starting current & transients on a historical trend. Say sampling freq of 1000Hz to see 50Hz wave, Higher still to see anything superimposed on this
	-DOL start -Soft Starting? -simple drive - sophisticated drive (4 quadrant etc)	Be able to demonstrate power regeneration back into the mains	View current flow into drive			Demonstrate load motor & drive regeneration back into the mains	? Current flow from drive to mains?	Demonstrate load motor & drive regeneration back into the mains	View current and voltage on load drive

D.1 Equipment Groupings and Functionality addressed on the EMDET Linkage matrix

For the purposes of the EMDET linkage matrix four major groups of components were defined:

- Motor 1 and Drive 1
- Motor 2 and Drive 2
- The Human Machine Interface (HMI)
- The SCADA system

The following basic functions that the equipment would have to perform were identified:

- monitoring and reporting of equipment health. If any equipment began to operate dangerously or was damaged the tool should stop, report the faults to the operator and assist in diagnosing the fault. The tool should not restart until faults have been rectified.
- protection. The equipment should act to protect both the users from dangerous conditions and the equipment from becoming damaged. This includes:
  - clear indication of power being present or isolated from the equipment;
  - allow equipment to be easily and positively isolated if the lesson requires it.
  - include provision to quickly disconnect power in an emergency.
  - protection of wiring and equipment from electrical faults to AS/NZS 3000 [Ref AS/NZS 3000] including phase to phase, phase to ground faults and overheating of wiring.
  - protection of motors against overheating during operation
- operating motors, including starting, stopping setting direction, speed and reference torque required for simulating a load.
- feedback and capture of key parameters around the equipment including, currents, voltages, voltage frequency, electrical power, mechanical shaft torque, speed and power.

The equipment would have to perform the following functions to allow the refined curriculum to be delivered:

- loads:
  - simulate various simple loads including constant torque and loads, and

loads that increase with speed both linearly and to the square of shaft speed.

- electrical motors
  - be able to operate Motor 1 at a variety of speeds and supply frequencies at its maximum torque output.
- electric Drive systems
  - run motor and Drive 1 at various frequencies and supply voltages.
- the holistic EMD system
  - exemplify how equipment should be properly protected both mechanically and electrically.
  - allow students to safely approach and work with the motor and drive equipment; this would likely require appropriate electrical enclosures and mechanical guarding.
  - allow equipment to be easily and positively isolated if the lesson requires it as per the generic requirements.
  - allow students to try the various permutations and combinations of load and drive system to examine the behaviour of each.

The equipment would also have to be capable of carrying out functions to accommodate the areas of that the equipment should be capable of teaching in not addressed in the ECTE412/912 course. The equipment should be capable of:

- loads:
  - simulating a variety of torque speed behaviours inducing unusual load behaviours and inertia Electrical motors
  - demonstrating the key parameters that are required to properly size a motor and potentially try out a calculated motor size against a load. Potentially have a variety of motor types to test
  - demonstrate the behaviour of an induction motor with supply power issues including voltage unbalance and two phasing.
  - demonstrate the operation of key motor types
- electric Drive systems
  - displaying the temperature of the motors in the system and the temperature change with loading
  - the effect of drive switching speed on the supply voltage and the effects of this on sensitive equipment
- the Power supply system
  - the voltage waveform of the system supply when the drives are in operation

  - operating a motor on an imbalanced voltage or on two phases
- the holistic EMD system
  - simulating the operation of a motor in a sophisticated system, with the archetypical example being a pump using a throttle for flow control purposes. This would require Motor and Drive 1 to operate at variable speed and Motor and Drive 2 to simulate the torque of the throttles system
  - simulate systems where the capability of a variable speed drives makes system design and selection of components easier
  - carry out various closed loop control strategies on shaft speed, position and torque absorbed, display the relevant system parameters and allow for the steady state, and transient response of a system to be measured

Appendix E

Content-Behaviour statement of educational objectives

E.1 Content Behaviour description of educational objectives with EMD systems

In order to aid the development of the educational objectives in content-behaviour form, a picture was created of what a graduate engineer possessing the desired wisdom would be able to describe about the major components of a real EMD system to another engineer. This picture was drawn using a macro view of the EMD system and was synthesised from the preliminary curriculum and consideration of how an engineer with wisdom would interact with an EMD system at the macro level. This picture was a useful intermediate step that readily facilitated the development of educational objectives in the content behaviour format and is shown in figure E.1.

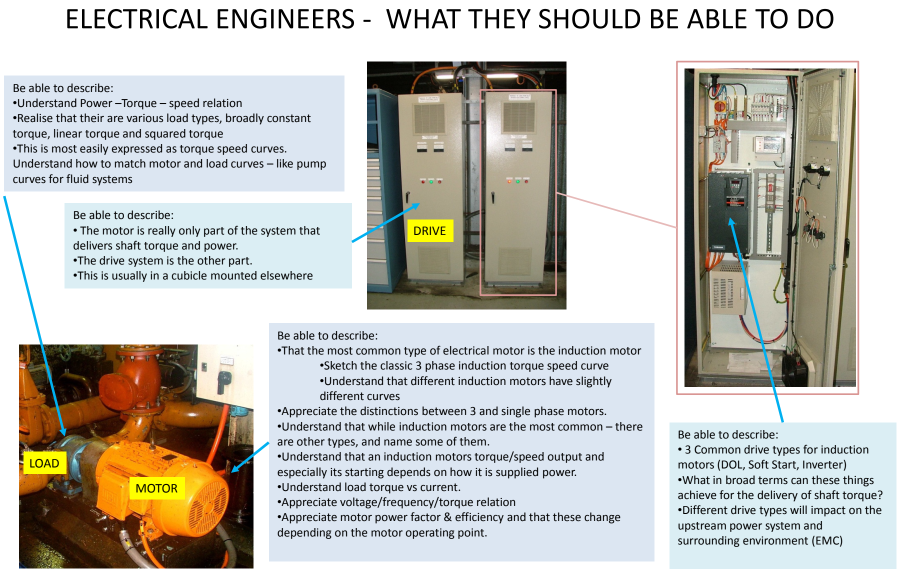


Figure E.1: Pictorial representation of what a engineer with desired wisdom could describe about EMD systems.

The five key components of an EMD system were easily identified from this picture which formed the content aspect of the objectives. These were:

- Mechanical loads including:
  - Rotating system dynamics
  - Key load types and the torque absorbed by them at various speeds
  - Load power consumption
- Electrical motors
  - Fundamental electrical knowledge including power-current-voltage relationships, phasors, 3 phase systems, single phase equivalents and harmonics.
  - Different types of electric motor with a focus on the squirrel cage induction motor.
  - Within induction motor the concepts of synchronous speed, current consumption, torque production, power output, motor limitations, power factor and efficiency.
- Electric Drive systems
  - The common types of drives available including Direct On Line (DOL), Thyristor soft starters, simple Pulse Width Modulated (PWM) inverters and sophisticated vector drives.
      - The utility and applicability of various types of drives
  - The limitations of various types of drives

  - The affect of the various drive types on motor performance
- The Power supply system
  - The affect of the motor and drives on the supply system
  - The affect of the quality of the supply on the motor
- The holistic EMD system
  - The safety concerns involved with EMD systems and methods or working safely with EMD systems.
  - The typical hardware and software involved with the EMD system including the motors, drives, and SCADA.
  - The combined behaviour of load, motor, drive and power system
  - The power savings offered by different drive types
  - The advantages and disadvantages of particular load and drive combinations.

E.2 Typical behaviour types associated with development of educational objectives

- relevant principles, theories, formulae and parameters:
  - is able to qualitatively identify the important parameters with a system and describe the relevant concepts
  - is able to qualitatively describe which parameters interact and in broad terms how they do so
  - has a quantitative knowledge of important parameters in a system including the engineering units used and the typical size of the parameter
  - can quantitatively describe the interaction of parameters in a system by use of the relevant mathematical relationship describing the physical behaviour
- information
  - is familiar with reliable sources of information on the subject
  - can synthesize relevant parameters from a real world scenario
  - knows reliable sources of data to find missing information
  - understands the implications and risks about using approximations when real information is missing
- application of principles:
  - able to recognise where relevant principles apply to real world problems
  - can explain real world equipment behaviour using relevant theories

- can use theoretical knowledge as a grounding to hypothesise possible causes of problems in given scenarios.

Table E.1: Content behaviour description of educational objectives for EMD systems.

	Behavioral Apsects of the Objectives									
	Relevant principles, theories, formua & parameters				Information					
	Qualitative knowledge of key parameters	Qualitative knwoledge of key parameter interaction	Quantitiative knowledge of key parameters (usual size, theoreis relating etc	Quantitative knwoledge of key parameter interaction	Familiar with reliable sources of infromation	Can synthesise relevant parameters from a real world sceanrio	Missiing infromation: Knows reliable sources of infromation to fill in	Missing Infromation:able to make approximations & estimates	Missing Infromation:able to make descisions about risk involved in using approximations & estimates	Able to recognise where relevant principles apply to real world problems
Industrial Safety										
Common Hazards	Concepts of mechnical & Electrical Hazards				OH&S Laws, Work Cover, Australian Standards, Corporate Ploicies e.g. UoW, BSL		Stop job if knowledge incomplete			Can identify hazards in Drives Lab
Safe System of Work	Method to identify, assess and control hazards.									Can create a JSEA for drives Lab work. What can be done? What Cannot? What controls are in place?
Safety & Risk	Concepts of a risk as a likliehood and consequence, risk controls and acceptable risk	Risk is reduced to acceptable by controls	Understand that this is always very subjective! Important things is consitancy relative to other risks - and the acceptable level							
	Hieracrchy of cotnrols (eliminate,etc)									
Safety Systems	Authority to Work, Job Safety Analysis									
Safety Equipment	PPE, Emergency Stops, safety relay									
Mechnical Loads										
Rotating System Dynamics										
θ,ω,α relation (θ, θ', θ'')	Yes				Yes (dynamics texts)	Able to work descriptions of various forms into familiiar equations for solution	Yes			Able to forumulate requirements of a mechanical load for communication with electrical engineers. Foumulate a Customer Requirement. Analyise unclear mechanical situation and provide clear & coherent specifcations to an electrical engioneer
$P = T\omega$										
Newton's 2nd Law as it applies to Roating systems ($\Sigma T = J\alpha$)										
Inertia										
Gearboxes & Referred Inertia	Yes									
Calculating Inertia for common bodies										
Power Diagram (T-ω)										

Appendix F

Material outside of ECTE412/912 Course that EMDET should be capable of teaching

The following is the course material that the equipment should be capable of teaching that would not be dealt with in ECTE 412/912. The following material was identified from the Requirements phase (section 5.1.3) and section 3.1.

- Loads:
  - Sophisticated load behaviour beyond what was presented in the ECTE412/912 course. This may include loads with time varying torque-speed characteristics, effects such as friction, inertia and backlash.
- Electrical motors
  - Thermal behaviour of electric motors
  - The behaviour of motors other than induction motors
  - How is a motor correctly sized for an application
- Electric Drive systems
  - Concerns with implementing PWM inverter systems including:
    - EMC and harmonics
    - Suitability of motor winding insulation
    - Suitably cooling motors driving high torque loads and the possible need for independent cooling fans.
  - The common types of drives available including Direct On Line (DOL), Thyristor soft starters, simple Pulse Width Modulated (PWM)
- inverters and sophisticated vector drives.

- The Power supply system
  - The affect of the motor and drives on the supply system
  - The affect of the quality of the supply on the motor, including phase imbalance and two phasing.
- The holistic EMD system
  - The energy efficiency benefits of using variable speed drive systems e.g to remove throttling loss and energy wastage.
  - The value of flexibility offered by variable speed drive systems in design, e.g. the advantages of controlling behaviour by motor speed rather than mechanical alternatives.
  - Various types of control executed with EMD systems:
    * Control of shaft speed; via open loop control, closed loop sensorless control, and closed loop sensor based control.
    * Control of shaft position
    * Investigation of closed loop control performance including steady state and transient response.

Appendix G

Ethics

The work involving interviews of laboratory demonstrators and examination of student workbooks and assessment items was covered under the University of Wollongong Human Research Ethics committee approval no HE15/411.

The approval from the University of Wollongong Human Ethics Research Committee and participant information sheet for laboratory demonstrators is included here.

APPROVAL after review
In reply please quote: HE15/411
Further Enquiries Phone: 4221 3386

2 November 2015

Dr Philip Ciufo
Faculty of Engineering Enquiry Centre
Bld 4
University of Wollongong

Dear Dr Ciufo

Thank you for your letter responding to the HREC review letter. I am pleased to advise that the Human Research Ethics application referred to below has been **approved.**

Ethics Number:	HE15/411
Project Title:	Evaluation of engineering teaching laboratory equipment and curriculum in delivering desired educational outcomes in electric motor and drive systems
Researchers:	Dr Philip Ciufo, Dr Thomas Goldfinch, Mr Craig McLaughlan
Documents Approved:	Application for privacy exemption Revised Ethics Application Request to use extracts of lab work V4 - 28/10/2015 Consent Form V4 - 28/10/2015 Participant Information Sheet for Laboratory Demonstrators V4 - 20/10/2015 Student Participation Email
Approval Date:	30 October 2015
Study Expiry Date:	29 October 2016

The University of Wollongong/Illawarra Shoalhaven Local Health District Social Sciences HREC is constituted and functions in accordance with the NHMRC National Statement on Ethical Conduct in Human Research. The HREC has reviewed the research proposal for compliance with the National Statement and approval of this project is conditional upon your continuing compliance with this document.

A condition of approval by the HREC is the submission of a progress report annually and a final report on completion of your project. The progress report template is available at http://www.uow.edu.au/research/rso/ethics/UOW009385.html. This report must be completed, signed by the appropriate Head of School, and returned to the Research Services Office prior to the expiry date.

As evidence of continuing compliance, the Human Research Ethics Committee also requires that researchers immediately report:

- proposed changes to the protocol including changes to investigators involved
- serious or unexpected adverse effects on participants
- unforseen events that might affect continued ethical acceptability of the project.

Please note that approvals are granted for a twelve month period. Further extension will be considered on receipt of a progress report prior to expiry date.

If you have any queries regarding the HREC review process, please contact the Ethics Unit on phone 4221 3386 or email rso-ethics@uow.edu.au.

Yours sincerely

Associate Professor Melanie Randle
Chair, Social Sciences
Human Research Ethics Committee

cc: Dr Philip Ciufo, Dr Thomas Goldfinch

PARTICIPATION INFORMATION SHEET FOR LABORATORY DEMONSTRATORS

TITLE: *Evaluation of engineering teaching laboratory equipment and curriculum in delivering desired educational outcomes in electric motor and drive systems.*

PURPOSE OF THE RESEARCH

The project aims to assess the effect of systems engineering project approach that was used to develop equipment and curriculum for an engineering teaching laboratory at UOW to prepare students for industrial practice with electric motor systems. The modifications to the standard project were to include educational goals and reflective practices throughout the design and construction of equipment and to include assessment of educational outcomes in students as a success measure for the project.

METHODS AND DEMANDS ON PARTICIPANTS

If you chose to participate you will asked to be involved in an interview of approximately 1 hour in length about your experiences of student interaction with the equipment and laboratory curriculum in the ECTE 412/812/912 laboratories you have supervised. Typical questions would include:

- Where there any issues with the student interaction with equipment (hardware/ software) that may have impacted on performance?
- Where there any logistical or curriculum delivery issues (insufficient time, curriculum materials not available) that may have impacted on student performance?
- Where there any student issues within the class that would not be evident from a student's workbook (e.g student punctuality, linguistic ability, apparent motivation, etc.)
- Did you have to provide additional coaching or teaching to students beyond what is in the curriculum materials to allow them to complete the laboratory?
- Is there anything else you think the researchers should be aware of about student interaction with ECTE412/912 equipment and lab workbooks?

The answers to these questions would be taken in a logbook by the researcher under a pseudonym in these notes to keep your identity anonymous. For convenience and later review to capture all of your data the researcher may like to make an audio recording of the interview. This is voluntary and you may participate in an interview but opt out of an audio recording being made. Only the PhD researcher will have access to the un-coded interview data (notes and audio recording).

POSSIBLE RISKS, INCONVENIENCES

You should be aware that the ECTE412/812/912 subject coordinator may see your comments in writing and may be able to identify you as a source of a quote due to the small number of laboratory demonstrators used in ECTE412/812/912. This should be considered before participation in the research and when answering interview questions. The audio recording would not be shared with the subject coordinator.

Apart from the time taken for the interview we forsee no risks for you. Your involvement in the study is voluntary and you may withdraw at any time and withdraw any data you have provided to that point. Any of the data that you provide used for publication would be done so anonymously. Non-participation in the research or withdrawal at any time will not affect your relationship with any of the parties involved in this research.

FUNDING AND BENEFITS OF THE RESEARCH

The project is part of a PhD project and is funded by the Faculty of Engineering and Information Sciences.

The project is aims to provide laboratory equipment and curriculum to improve preparation students for industrial practice with electric motor and drive systems.

ETHICS REVIEW AND COMPLAINTS

This study has been reviewed by the Human Research Ethics Committee (Social Science, Humanities and Behavioural Science) of the University of Wollongong. If you have any concerns or complaints regarding the way this research has been conducted, you can contact the UoW Ethics Officer on (02) 4221 3386 or email rso-ethics@uow.edu.au.

Appendix H

Tyler Tables

Tyler tables created for laboratory exercises as described in Section 8.4.

Equip students with the correct mindset to allow them to work safely in a hazardous industrial environment Do this by giving them a method to carry out a task safely in the hazardous environment. The focus here is on the safety of the individual or small work team doing a finite defined task.

Educational Purposes	*Learning Experience*	*Organisation*	*How do we tell if we have achieved purposes*
Introduce the concepts and methods commonly used to carry out a hazardous task safely in heavy industries (methods are common, but not universal) **Introduce the concepts of:** Hazards Risks Risk assessment Risk control Credible risks Acceptable risks **Introduce concept of a safe system of work**	Explicitly explain in pre-reading. Exercise to fill out JSA will necessarily include this	(1) Pre-reading & exercise NEED TO GIVE FULL VERSION OF UoW SAFE WORK PROCEDURE	Supervisor/assessor to use this terminology in discussion. Is it widely understood?
Have students associate industrial equipment with safety hazards requiring a safe system of work Fundamental process: Identify all credible risks and control them so that they are acceptable Identify risks Job steps Identify hazards at each step Identify controls for each hazard to make the risk acceptable	Fill out a JSA on a task in a small group as an exercise. Report back to the larger group on the results.	(2) small presentation to group. Try to impress upon them that this is about their safety. (4) give brief intro to equipment - enough to JSA. More detailed explanation to follow. (5) Students to carry out JSEA on various tasks on the equipment. (6) Groups to present their JSEA briefly. (7) Hand out my versions. Discuss differences.	Look for hazards identified by students in their JSEA. Have students identified credible risks? Do their controls seem reasonable? Did they break task down into steps? Did they identify hazards? Have adequate controls been identified?
Many slightly different variations on this same theme Not all are equal Difficulties posed by confusing job safety with organisational risk management Two processes can be confused. Organisational risk management tasks often creep into task safety procedures – often the Methods of risk control Some methods preferable to Hierarchy of control	Give different JSA formats to groups for comparison. Ask students to give their assessment on how well they achieve their goals Give in pre-reading. Possibly verbally reinforce in a brief presentation Give in pre-reading. Possibly verbally reinforce in a brief presentation	(3) Get them to compare & contrast Formats given in pre-reading. Report back later with their JSA.	How do students rate the different JSA forms. Do they look at how the different forms help to identify & control hazards. What are students opinions on the different JSEA?S Is the issue raised that the UoW Safe Work Procedure confuses corporate risk management & job safety Did students identify this when comparing different JSA forms

Figure H.1: Tyler Table for student introduction to Safety in Laboratory Exercise 1

Introduce students to Industrial EMD systems and the architecture and operation of the drives Teaching Facility

Educational Purposes	***Learning Experience***	***Organisation***	***How do we tell if we have achieved purposes***
Introduce the students to the Teaching system components at a high level so they can indentidy them (multistructural) and understand their interaction during equipment operations to prepare them to operate the system.	Brief introduction on system configuration in the system and the power flow	(1) Brief presentation on system from demonstrator focusing on energy flow.	Able to properly label direction of energy flow and energy type in review questions (6)
	Have the identify the components on a photo of the system	(2) Have students match name of components to a photo in their lab books	Able to properly label components in picture in (2)
Introduce students to a common configuration of an automated industrial system, allolw them to identify key componets and the likely interactions.	The teaching facility is set up like a typical industrial SCADA. Teaching them this will teach them a common industrial system	included in (1), (3) and (4)	If able to complete exercises (3) & (4) we have done this
Teach students how SCADA system hangs together HMI - PLC Comms PLC - Hardware Hardware-PLC PLC-HMI	Brief students on system and have students use various components of the system and in their instruction identify which part of the system they are interacting with	included in (1), (3) and (4)	Able to complete Exercises (3) & (4)
Introduce students to more advanced data acquisition that they may be able to use	Use DAQ system in exercises	Included in (4)	Be able to distinguish between what is commonly available instrumentation and lab instrumentation in review (5)
Introduce students to system components at a low enough level to allow them to operate them and understand their results	Have students perform functions that are either physically or conceptually obvious as a first introduction to the equipment.	included in (3) and (4)	Able to complete Exercises (3) & (4)
Teach students how to operate the system	Have students do an exercise that uses the main system components	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with a Human Machine Interface	Use HMI in exercises	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with panel Mounted Controls	Use panel controls in exercises	included in (3) and (4)	Able to complete Exercises (3) & (4)
Familiarise students with the Data Acquisition system	Use DAQ system in exercises	(4) Use contactor diagnostic mode to activate Siemens drive. Use DAQ system to observe voltage waveform and FFT peaks in supply voltage and Siemens supply current waveform	record voltage and current obserbed including the frequenies of the significant hamronics in the current.
Where the system can be operated from Various controls & their locations	Have the students use the controls in the different locations	included in (3) and (4)	Able to complete Exercises (3) & (4)
strengths & weaknesses of controls	Ask them to consider the strengths & weaknesses of the different controls	(5) ask students some review questions	
various indications & their locations	Have students use the different indications	included in (3) and (4)	Able to complete Exercises (3) & (4)
strengths & weaknesses of indications	Ask them to consider the strengths & weaknesses of the different controls	(5) ask students some review questions on relative merits of the controls	able to complete (5)
embed emergency response procedure to students (use panel E- Stop)	Use E-Stop as part of the exercises	(3) Use contactor diagnostic mode to start a cooling fan. Shut it off using the emergency stop. Reset system and get running again.	Able to complete Exercises (3) as witnessed by demonstrator during reset operation
Teach them where the system diagnostic page is and how to use it.	Use the system diagnostic as an exercise	included in (3)	Able to complete (3)
Teach them where the contactor diagnostic is	Use the contactor diagnostic as an exercise	included in (3)	Able to complete (3)
Introduce concept of energy flow though the system		(6) as part of a review question have them draw direction of power flow and label power types.	Able to complete (6)

Figure H.2: Tyler Table for student introduction to the EMDET in Laboratory Exercise 1

(1) to operate the drives teaching facility to its full capacity (2) to map the characteristic curve of an induction motor (3) understand how motor characteristic curve will result in motor behaving

Educational Purposes	***Learning Experience***	***Organisation***	***How do we tell if we have achieved purposes***
Basic Principles Newton's 2nd Law for rotating systems	Read Briefing Notes & Plot Motor Curve	(0) Read briefing Notes	Do they Know what a torque speed curve is.
Gain familiarity with industrial SCADA and EMD	Run facility		
Operate drives teaching facility at full capabilities operate applying torque	Run motor characteristic curve routine & simultaneously log the data	(1) run motor character routine	Successfully achieve (3)
use HMI, panel front & NI DAQ	Observe panel meters & DAQ meters while characteristic curve sequence underway.	(2) observe panel meters while underway. Log data on NI DAQ	Successfully achieve (3)
	(3) Plot logged data against time to see if it matches what was observed	(3) Quickly plot data - ensure it matches what was seen. Ensure it makes sense. Record what data is on what channel	Successfully achieve (3)
Deal with some real data			
understand signal noise & the need for filtering	(4) Process data - Smooth data by filtering (optional)	(4) after lab - analyse & process data	As part of review questions - match student data to sample data
Convert instantaneous data to RMS	(5) Process data - Convert instantaneous data to RMS data	(5) after lab - analyse & process data	As part of review questions
Map the full characteristic curve of an induction motor			
map this curve to see what it looks like Does the actual match the theory - compare actual curve to text book curves	6) Map out across the full motor performance & compare to theory & manufacturer's data	(6) after lab - analyse & process data	Check student curve matches sample curves.
compare actual curve to manufacturer's curve	plot torque Vs speed		
Get a hold of some real data on an induction motor	plot current vs. speed		
Understand motor behaviour across its full operating area	plot power vs. speed		
Understand how a motor will accelerate to operating speed	Plot Power Factor		
Understand motor behaviour in normal (near rated speed) conditions	Map out around rated speed (within 10%)		
How a motor will usually behave Understand how Motor curve results in key motor dynamic behaviours	(7) plot out motor character near rated speed an torque	(7) after lab plot motor character near rated speed	Check student curve matches sample curves.
How does the Motor start? How does the motor accelerate What speed will the motor run at?	(8) Get students to describe what will happen when motor is starting a load that needs a constant 75% of rated torque (0 speed to final speed). They will need to tie together basic dynamics, the motor torque speed curve they have logged and a load	(8) as part of review questions	Students can accurately and coherently describe this
How will a motor behave when it is inside its rated values	(9)Get students to describe what will happen if load is at equilibrium speed requiring 75% torque - then torque required increases to 100%	(9) as part of review questions	Students can accurately and coherently describe this

Figure H.3: Tyler Table for mapping the induction motor torque-speed curve Laboratory Exercise 1

Introduce Students to the characteristics of the induction motor.

Educational Purposes	Learning Experience	Organisation	How do we tell if we have achieved purposes
(1) Investigate the induction motor torque speed curve within the rated torque limit at various frequencies.	Run the motor at various supply frequencies and loadings. Measure & record, torque, speed, voltage and current	(1) run motor at various frequencies & loadings	Table filled out
(2) Understand supply frequency will change motor synchronous speed	Run the motor at different frequencies and measure speed. Calculate expected synchronous speed and compare to measured	(2) Calculate expected speed & compare to actual	Match and correctly comment on match between expected and actual
(3) Understand torque-speed-current relationships at different supply frequencies.	Analyse and plot torque speed relations at different frequencies	[14] Plot real data T-s	Plot filled out
	Analyse and plot current speed relations at different frequencies	[15] Draw anticipated curves through data	Anticipated curves drawn sensibly
		[16] Draw anticipated curves	Anticipated curves drawn sensibly
(4) Fit observations together with the concept of the torque speed curve. It moves at different frequencies.	Plot data from different frequencies on 1 plot. Draw expected curves through data	3,4,5 & 6 above	Describe that classic T-S curve is moved with frequency. Need to be careful that this actually involved v/f ratio matching
		(16) Maybe ask specifically what does changing freq do to classic T-S curve?	
	Calculate electrical & mechanical power at different torques & frequencies	[4] calculate mechanical & elect powers	Correctly calculated
Understand v/f ratio & Power Limit if machine.	Explain why high torque not achievable over 50Hz	[5] have students calculate v/f relation. Should be linear under 50Hz. What happens above. should be clear that motor has hit Rated Power. MUST TELL STUDENTS OF MOTOR NAMPLATE	Students explain that this is why motor is torque limited over rated speed - or that we have only asked them to use 40%
	In introduction give basic induction motor relations - enough to explain synch speed at v/f ratio	[9]Plot V/F ratio [10] Identify Machine frame power limit and filed weakening	
(6) Understand system behaviour being driven by motor at varying frequencies	Use measured data to theorise how a physical system would behave	(15) Load at 40 Hz with certain torque. Torque changes - what is resulting speed?	Correctly anticipated this.
(6) a Understand sync speed		(17) with a simple load torque-speed (linear) what is load speed at various frequencies?	Correctly say that load will be within a couple of % of synchronous speed so long as motor nameplate power is not significantly exceeded.
(6b) Understand that slip will occur at all supply fr			
(7) Gain confidence in motor performance prediction from commonly available info on a real plat (I & RPM) specifically illustrate importance of magnetising current	Compare mechanical & electrical power consumption.	[11] plot relation of mechanical Vs electrical power	Plot filled in
	Can a reliable relationship be found? If so what is it?	[12] Ask students if they feel it is reliable. What is it?	Motor efficiecny identified as slop of the curve
	Assess motor efficiency	[13] Compare calculated efficiency with name plate	compare calculated with nameplate
	Answer question - can measured current be used to estimate mechanical power.	[8] Do they think current is a reliable indicator of mechanical power?	Y/s no. Sensible justified
	Assess motor power factor	[13] is assumed value of motor power factor reasonable	justified assumption based on efficiency results
	Draw plot of Power Vs Current.	[6] Plot current Vs power CHECK IF CAN BE AT ALL SPEED OR JUST 50 Hz	Draw sensible current - power curve
	Point out significance of current at no load?	[7] Ask how much current drawn with no mechanical load? What is this current doing?	Identify magnetising current

Figure H.4: Tyler Table for investigating the characteristics of the induction motor in Laboratory Exercise 2