Dedicated to my kind and devoted parents

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DISCIPLINE BREAKDOWN STRUCTURE

BRIDGING PROJECT MANAGEMENT AND SYSTEMS ENGINEERING TO FORM AN INTEGRATED MANAGEMENT SYSTEM IN MULTIDISCIPLINARY RAIL PROJECTS

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Professor Alan Smith

Declaration

I, Hadi Sanei, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

The complexity of multidisciplinary projects requires that many specialities and disciplines work together. In rail infrastructure projects, the term ‘systems engineering (SE)’ is being widely used, yet it is still loosely defined. This PhD thesis proposes the use of a Disciplinary Breakdown Structure (DBS), an approach that better integrates SE as it is currently understood with traditional project management (PM) to make PM more efficient.

A review of PM, SE and their relationship, particularly in the rail sector, identified gaps in performance, the most significant of which is a lack of integration between the SE and PM activities. Case study material was examined and a survey was conducted. The results highlighted the lack of consensus and consistency of the definition of SE and its application by project practitioners at various levels. Interface management (IM) was identified as a key factor contributing in project failure or success. IM was reviewed in the context of SE and PM, and existing methods and solutions were examined.

The DBS as a new solution, was developed and introduced to improve the IM life cycle from definition to closure. This solution is based on industry discipline sectors (in this case, the rail sector) and therefore it is independent from project specific requirement. Exploring more detail of the DBS revealed its capability in integrating SE and PM more generally.

The DBS is a modular solution (with a potential to become an industry standard) that provides a basis for the rapid development of project-bespoke management systems, improving PM efficiency by saving time and resources.

The approach has been tested in two major rail project case studies in the UK and one in Canada and the results, benefits, constraints and the areas of improvements are discussed in more detail.

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Finally, my last word is for the love of my life, my wife, Neda. Your love, patience, support and encouragement made this journey possible. This would not have happened without you. I love you and thank you for all you have done!

Abbreviations

APM	Association for Project Management
APM BoK	APM Body of Knowledge
BM	Business Manager
CBS	Cost Breakdown Structure
CM	Change Management
CMS	Cable Management System
CoM	Configuration Management
CS	Case Study
D&B	Design and Build
DBS	Discipline Breakdown Structure
DoD	Department of Defense
DSM	Design Structure Matrix
DWF	Decision Weight Factor
ECF	Engineering Consulting Firm
ECI	Early Contractor Involvement
EPC	Engineering, Procurement and Construction
ICD	Interface Control Document
ICM	Interface Control Matrix
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	Interface Management
IMS	Interface Management System
INCOSE	International Council on Systems Engineering
IOS	International Organization for Standardization
JV	Joint Venture
LBS	Location Breakdown Structure
LRT	Light Rail Transit
MEP	Mechanical, Electrical and Plant
MIT	Massachusetts Institute of Technology
MOE	Margin Of Error
MR	Main Reason
MRQ	Main Research Question
MRS	Main Research Scope
NASA	National Aeronautics and Space Administration
NEC	New Engineering Contract
OBS	Organisation Breakdown Structure
OR	Opinion Ratio
PBS	Product Breakdown Structure
PC	Project Control (support) professional
PDL	Project Deliverable List
PERT	Program Evaluation and Review Technique
PFI	Private Finance Initiative
PLC	Project Life Cycle
PM	Project Management
PMBOK	Project Management Book Of Knowledge
PMI	Project Management Institute

PPP	Public Private Partnership
QM	Quality Management
RACI	Responsible, Accountable, Consulted, Informed
RIBA	Royal Institute of British Architects
RM	Requirements Management
RMS	Requirements Management System
SAGE	Semi-Automatic Ground Environment
SE	Systems Engineering
SEMP	Systems Engineering Management Plan
ST	Systems Thinking
TQ	Technical Query
TS	Technical Solution
UCL	University College London
V&V	Verification and Validation
VB	Visual Basic
WBS	Work Breakdown Structure
WI	Work Information
WP	Work Package

Foreword

I started this research in 2009, the second year of my career as a junior systems engineer in the UK Rail sector of Halcrow Group Ltd. Prior to this, I spent nearly 10 years working as project manager and business manager in the information technology sector, holding an engineering degree in computer hardware. In 2004, I moved to the UK and completed a master degree in computer networks in 2006. In my master programme, I worked on a research programme in the modelling of queuing systems with Markov processes to evaluate systems performance for which I developed a mathematical solution, to model multi-processor systems with breakdown and repair, overcoming the 'state space explosion' problem. The result of this research was documented in my MSc thesis, 'Approximate solution for 2-dimensional Markov processes modelling multi-server systems prone to breakdowns' (Sanei, 2006) for which I received a Master with Distinction degree. I also worked as a co-author with my supervisors, Dr Orhan Gemikonakli and Dr Enver Ever and presented my research papers in international conferences in this field (Sanei, 2006, Gemikonakli et al., 2007, Ever et al., 2008).

In 2009, when this research programme started, systems engineering (SE) was relatively new in the rail industry and many people had no or very limited understanding of its role, scope and benefit to projects. Although many of the key clients in the rail sector, including Transport for London and Network Rail, were beginning to mandate the discipline for their projects, there was still not enough understanding across the business. On the project sites, some were mistaking the systems engineers with rail systems engineers and so were engaging them in very technical railway system discussions, while others were seeing them as experts in information system and technology.

The SE identity crisis in industry became even more interesting for me after reading 'Confronting an identity crisis—how to "brand" systems engineering' (Emes et al., 2005). I therefore tasked myself to increase awareness within the rail sector, starting from the Halcrow office.

To begin, I gathered various quotes about systems engineering definition from people in industry into a short document entitled 'What is systems engineering?' While I was educating myself, I was also trying to collect and share information with others in different forms. Later, I published an internal company paper on systems engineering entitled ‘Requirements management’, in which I outlined a practical definition for SE and, more specifically, requirements management (RM). In this document, I also demonstrated the benefits of adopting SE and RM to save time and resources in project delivery (Sanei, 2007).

But the lessons learnt from these activities showed that while more effort is necessary to more define SE as a key role in PM, more constructive work was required to develop more a systematic approach for managing the interfaces in such multidisciplinary projects. For this reason in 2009, I started this research in the form of a part-time PhD programme at UCL while I was working for Halcrow as an interface manager for the railway system design of the AMG line project in Kuala Lumpur, Malaysia – a major national light rail train system with 19 km of elevated route and 12 new stations.

During this journey, I worked on various other large national and international infrastructure rail projects in the UK, Malaysia, Indonesia, India, Qatar, Brazil and Canada. I held many different roles and responsibilities, including systems engineer, requirements manager, interface manager, project manager, systems integration specialist, quality assurance manager and risk manager. Such a diverse work experience gave me a chance to gain practical experience and unique perspective of the systematic thinking in managing projects of this kind. The observations and the data gathered over the past 7 years have been crucial to support this research.

Hadi Sanei – Summer 2016

Chapter 1 INTRODUCTION

1.1. Research Background

1.1.1. Systems Engineering in Construction (Rail) Projects

Construction projects are becoming larger and more complex (Shokri et al., 2012, Shokri et al., 2015), involving multiple suppliers and sub-suppliers from project design to implementation, testing and completion. These suppliers and sub-suppliers have different responsibilities in a given project to deliver different parts; they also have different work cultures, backgrounds and, in many cases, work locations.

In recent railway projects, multinational contractors often work together to deliver a piece of a design package. Difficulties with integration among these suppliers is becoming a major risk to the project, and project managers require integrated approaches to overcome this risk. The systems engineering (SE) approach has been introduced to support project management (PM) to overcome part of these difficulties (Locatelli et al., 2014, Emes et al., 2012, Sharon et al., 2011, Calvano and John, 2004, INCOSE, 2004, Elliott, 2014, Elliott et al., 2011).

In the UK Rail sector, the requirement to adopt an SE approach and to provide evidence of compliance in the delivery of design and build projects began to appear in the literature in the late 1990s and early 2000s. The first general SE standard – IOS/IEC 15288, which covers processes and life cycle stages – was first shaped in 1994 and was formally issued in 2002 (IEEE, 2002). Also among the first systems engineering standards in the rail sector was the London Underground Ltd LUL-1-209 standard, which was issued in 2007 and revised in 2009. This standard was issued to mandate the use of the SE in the UK railway projects (London Underground Ltd., 2009).

When the author started working in the rail sector as a systems engineer in 2007, the role was mainly limited to develop Systems Engineering Management Plans (SEMPs) which detailed processes, procedures and data/information flow. Only some technical parts of such plans were put into practice. The SEMP in a given project, depending on its size and complexity, covered various sections that sometimes overlapped with the Project Management Plan. The SEMP produced for the detailed design phase of a major station upgrade project in London, for example, covers the life cycle model; requirements management (RM); interface management (IM); project information model; project change control; human factor; issue/risk and assumption management;

electromagnetic compatibility/electromagnetic interference; reliability, availability and maintainability; operability and maintenance assurance; and verification & validation (V&V) (Parsons and Wareham, 2010). In the SEMP developed for a Canadian Crosstown Light Rail Transit Station Design project in Toronto, however, only life cycle model, RM, IM, project information model and V&V were planned due to different project characteristic and scopes (Sanei, 2011). Review of various other SEMPs in different projects of different types indicates that the following three SE activities are the mostly common topics in the SEMP documents:

1. Interface and Integration Management Plan
2. RM Plan
3. V&V Plan

1.1.2. Systems Engineering and Project Management Integration

It was observed by the author when this research started that in many of the major projects, there was no practical connection between procedures developed in a SEMP and the functions of project management; 'systems engineering in silo' was a common theme in rail sector projects. As an example, in two major capital projects, it was observed that the design supplier issued the SEMP when the design was almost completed merely to demonstrate compliances with the project deliverables. This demonstrates a bigger issue, as not only was the supplier not practicing the SEMP, but the client never asked for it in progress audits.

It also was observed by the author that on rail infrastructure projects, senior managers with many years of experience tend to manage the projects on their own classic way. In some cases they completely dismiss SE because they see no value other than a complete duplication of overhead and effort to their PM role. Recently, however, the good work of many researchers and practitioners, as well as events organised mainly by the International Council on Systems Engineering (INCOSE), have resulted in better understanding among project managers, many of whom show a greater interest in understanding and applying an SE approach on their PM functions. This also could be driven by the shift in clients' attitudes toward the use of SE in the project delivery as they begin to understand its benefits to their projects – not only in relation to time and budget, but also in additional confidence in the quality of deliverables. Some researchers even focus on adopting an SE approach in the middle of the process to further support these benefits.

1.1.3. Project Management Efficiency

Cost, time and quality known as the famous Iron Triangle are the main three project constraints that should be satisfied by any project (Atkinson, 1999, Elliott, 2014).

In this research, therefore, making the project more efficient means improving the project management to save time and cost where and how it is possible, while complying with high quality standards.

1.1.4. Interface Management

The initial thoughts for this research emerged when the author worked as a systems engineer to develop and adopt a systematic IM process for the design life cycle of a major rail station modernisation and expansion project in central London. In this project, IM was the area of interest for both PM and SE and, therefore, some believed that IM was an SE function, while others were convinced that IM was a natural PM activity. In the design phase of this station modernisation project, the core responsibility of the interface manager was identified as:

1) Capture and manage the design interfaces
2) Provide ownership for the interfaces to collect compliance evidence
3) Provide a tool to facilitate the IM processes
4) Provide a systematic approach to collect the evidence, saving time and resources

As the work continued, and the procedures developed, the work also covered:

5) Capturing the project requirements from various documents into an RM repository
6) Categorising and assigning the requirements to the relevant parties/owners
7) Providing verification evidences against the requirements by linking the design deliverables to the requirements

The intention was to develop a procedure viable for all parties using the existing information, including:

- Various documents (Project Scope Document, Requirements Specification, Conceptual Design Statements, etc.), from which the requirements repository could be developed
- A Work Breakdown Structure (WBS) and organisational chart in the form of Organisation Breakdown Structure, from which the interfaces between various parties and teams could be captured
- A list of deliverables registered in the document control management system generated and delivered by various contractors at the completion of their works
- An approved SEMP developed by the team at the early stage of the project commission

The main challenges that needed to be addressed in order to develop the required interface management procedure were identified as follows:

1. <u>Identifying the interface points and relating them to the existing documents as compliance/closeout evidence:</u>

   It was observed that the project team was identifying the interfaces and presenting and discussing them in long, repetitive meetings and workshops. This was time consuming and inefficient and carried a high level of risk for both the project and the project team. The work was around different levels of information, and the parties required access to different parts of the project/system in order to coordinate the interfaces among parts of the system.

   Therefore, the Interface Management Systems (IMSs) need to be based on an information breakdown concept, as this is the only way that the parts involved in the project could be identified and their interactions and interfaces points could be captured, monitored and managed.

2. <u>Creating ownership for the interfaces across the project:</u>

   It was observed that through various workshops, the project manager and project engineering team agreed on the interfaces as they identified them and recorded the interfaces in action registers. This could be more efficient if the interface points were identified in advanced and could be communicated before the design took place.

3. <u>Creating a programme-wide V&V solution to verify and validate the compliance of the project interfaces by relating the evidence/deliverables to the project interfaces captured from various project documents or to the requirements identified within data repository systems:</u>

   Engineering design projects have several types of deliverables in the form of drawings, reports and other type of documents. These deliverables should provide assurance on the compliance of the project interfaces and requirements. In this station modernisation project, all the documents and deliverables were stored in a document repository database. Therefore, a system was required to develop links between the related deliverables and the project interfaces and requirements with minimal input from suppliers. Thousands of interfaces and hundreds of requirements were to be managed in this project. It was realised that the existing solutions in PM were struggling to manage this volume with a low margin of error. It is important to note that linking the deliverables to the interfaces is not the main issue; the complexity is in forming a solution that can establish a basis to identify the interfaces and expected evidences in advance of the design work.

4. <u>Integrating an SE approach with PM:</u>

   Managing the requirements, managing the interfaces and providing assurance through linking evidence to the requirements and interfaces are the common functions between PM and SE. Therefore, integrating the SE approach with PM through linking their tools and procedures is critical (Emes et al., 2012).

5. <u>Facilitating reusability of the procedure in similar projects:</u>

   In developing any form of a procedure or system, it is critical to think about the reusability of the procedure for similar projects in future. Therefore, the intention was to develop a modular system based on series of templates so that it can be customised and reused in similar projects.

1.2. Research Problem Definition

The main goal of this study is to make PM more efficient by formulating a solution to:

- Improve IM as one of the key PM activities in multidisciplinary projects
- Integrate SE and PM activities in managing projects

Considering the research background explained above, and the author's observation and experience in addressing the issue explained in a major project, the main research question (MRQ) is summarised as follows:

How can SE and PM activities be better integrated to support project managers to manage their multidisciplinary (rail) projects more efficiently?

(MRQ)

The work explained in the research background directed the attention of this research to focus mainly toward managing the IM among various engineering disciplines. There are many examples proving that projects of different scales fail due to the lack of proper and systematic IM (see Chapter 3, Chapter 5, and Chapter 6). Therefore, PM could be more efficient if an improved IMS can avoid reworks, thereby saving time and resources by reducing unnecessary works/changes (Staats, 2014).

Figure 1 summarises the thought structure initiating this research to further divide the MRQ to more verifiable sub-questions as follows:

<u>Work to be performed:</u>

1. **Propose a solution** based on a breakdown structure concept as it needs to communicate with different layers/levels of project information
2. Apply the proposed solution to improve **IM** and developing an IMS
3. Apply the proposed solution to bridge the SE and PM activities to **develop an Integrated Management System**

<u>Results that will be achieved:</u>

4. Improving IM and developing an IMS **improves PM**
5. Improving PM makes the project and its PM **more efficient**

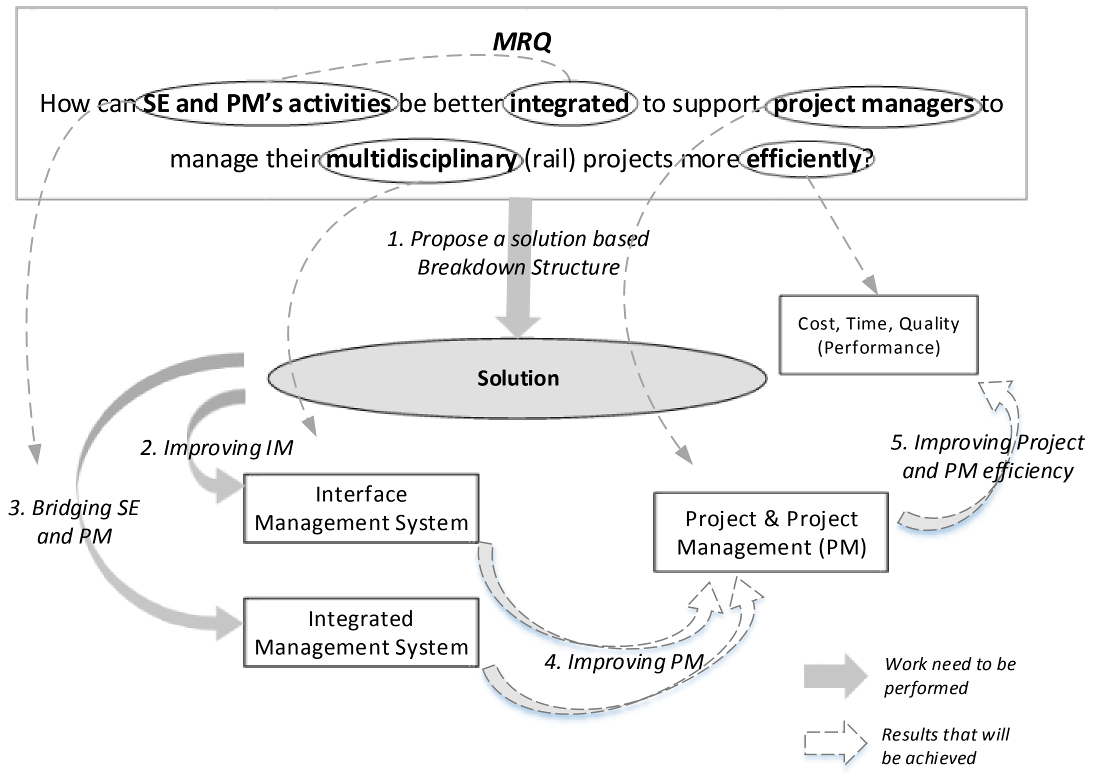


Figure 1: Research Thoughts Structure

The UK rail sector has been constantly working to adopt an SE approach to its projects. As a result, almost any project within the UK rail sector requires the involvement of some level of SE in the project. Therefore, more research is required to find more solutions that support systems thinking (ST) and SE capabilities in various branches of the rail sector, whether in management or in engineering. This will not only be a great contribution to the SE world, but will also provide more scientific evidence as justification for rail sector projects to invest in adopting systems thinking and SE.

The result of this research aims to contribute to the world of SE by providing some level of efficiency to PM.

1.3. Solution Development

Figure 2 presents a simple V-model used for the life cycle of the solution development in this research project.

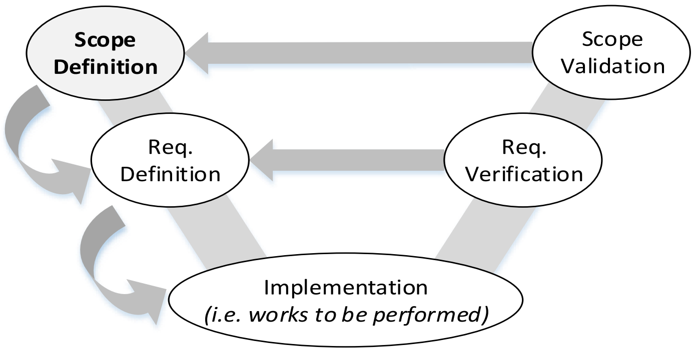


Figure 2: Solution Development – V Life Cycle

1.3.1. Solution Requirements Definition

As the first step, the requirements specification for the solution should be explored based on the MRQ. Considering the 'work to be performed' identified in the MRQ (see Figure 1), the following scope analysis is conducted to develop more specific requirements for the solution.

- **Propose a solution** based on a **breakdown structure** concept as it needs to communicate with different layers/levels of project information

Requirement 1. *The solution must be based on the breakdown structure concept, a 'divide and conquer' approach.*

Requirement 2. *The solution must be useful for both SE and PM to form an integrated management system – 'bridging PM and SE activities including functions, tools and procedures'.*

- Managing interfaces in a ***multidisciplinary*** rail project is essential. As noted, such projects involve interfaces between many different groups and suppliers. As presented in Figure 1, the focus is working to improve **IM** as one of the factors contributing in improvement of the project ***efficiency.***

Requirement 3. *The solution must provide a systematic way to identify and visualise the interface points and locations.*

Requirement 4. *The solution must provide a systematic way to allocate and assign the interfaces to the relevant parties/owners.*

Requirement 5. *The solution must be usable in creating a systematic data repository to link the project deliverables (as evidence) to the interfaces to demonstrate that the project has addressed the interface issues.*

- Further requirements must also be met in the solution:

Requirement 6. *The solution must be usable to create a structure to develop tractability among all other PM documents.*

Requirement 7. *The solution must be modular and reusable for the projects of the same kind in a bespoke form.*

Requirement 8. *The solution must provide time and resource savings.*

1.3.2. Solution Requirements Analysis

The scope of the research as well as the requirements for the solution are analysed in Table 1 to develop the work packages (WPs) necessary for this research life cycle.

Table 1: Solution Requirements Analysis and Work Required in This Research

Req.	Work Required
Req. 1	The WBS is a common tool based on the 'breakdown structure' concept used in PM in recent decades. Therefore, a review of literature is required to understand its origin, definition and existing use in IM and PM. Also, any other breakdown structure based concepts need to be reviewed. Further research and data are also required in projects where WBS is used to further justify the usability of the concept to achieve the objective of this research.
Req. 2	The Project and PM need to be reviewed and understood in order to design a solution that will benefit the efficiency of projects. Also, case study projects should be reviewed and analysed to assess project efficiency and explore the key failure factors. The SE concept needs to be reviewed because the goal is to develop a solution to integrated SE and PM activities.

Req.	Work Required
Req. 3, 4 and 5	The main focus of this research is to develop a solution that will improve IM. Therefore, research in the area of IM is required. It is important to understand why IM is necessary and how it impacts projects (with examples). It is also necessary to analyse projects to understand how IM is practiced and how IM impacts project efficiency. It is also required to conduct research on other similar existing work in this area, for example, the Design Structure Matrix (DSM) concept and WBS Matrix.
Req. 6, 7 and 8	These are the requirements needing to be met in the solution, including a tool that is modular, reusable and can be used across the project.

1.4. Research Question Analysis

From the research background, problem and thoughts structure, along with the requirements developed for the solution, the MRQ is analysed further to develop sub-questions this research needs to answer. The MRQ and the sub questions are as follows:

How can SE and PM activities be better integrated to support project managers to manage their multidisciplinary (rail) projects more efficiently?

MRQ

SQ1. What is the definition of SE and how does this relate to PM?

- *Literature review in project, PM and SE – Chapter 3*
- *Research and data collection on SE's impact on projects and the quality of its adoption in different sectors to justify the importance of an SE approach in project and PM – Chapter 5*

SQ 2. Why is IM important in multidisciplinary construction projects? How can this improve PM efficiency?

- *Literature review in IM definition and impact on projects – Chapter 3*
- *Literature review on new procurement strategies to explore further the importance of IM – Chapter 3*

- *Research and data collection on the application of IM on different projects, including the quality and the scope – Chapter 5*
- *Research and data collection on the impact of IM on the efficiency of projects in rail sector using real project case study – Chapter 6*

SQ 3. How is IM proposed in the PM and SE literature?

- *Literature review on IM definition from both PM and SE points of view – Chapter 3*
- *Research and data collection on IM in both PM and SE contexts – Chapter 5*

SQ 4. What is the WBS, including its definition and origin? How is WBS used in the context of PM and SE?

- *Literature review on WBS origin, definition and applications – Chapter 4*
- *Research and data collection on WBS application in current projects as well as the quality of WBS in different sectors – Chapter 5*

SQ 5. What will the proposed solution for IM look like and how will it work?

- *Introducing the new solution and the concept with detail and case study examples – Chapter 7 and Chapter 8*

SQ 6. How will this solution support developing an integrated management system?

- *Introducing the hypothesis on how the solution can support developing an integrated management system through integrating an SE and PM activities, with case study – Chapter 7 and Chapter 8*

1.5. Literature Review Structure

Based on the scope of the research as well as the requirements analysis conducted and the questions developed above, the structure of the literature review in this research is outlined below:

- Project and PM Foundation – The main **object** this research aims to enhance. This is to understand the foundation of project and PM as well as the PM's activities including tools and procedures.

- IM Function – An **area** within PM that needs improvement. This is to understand the PM and SE views of IM in projects, including tools and procedures as well as existing methods and solutions including DSM or WBS Matrix.
- ST and SE – The main **engine** to provide a solution for the research. This is to understand the foundation of SE in complex projects, specifically the tools and procedures of IM.
- WBS – An existing breakdown structure based **solution** within PM that needs to be understood to support forming a solution for this research question. This is to understand the foundation of WBS and its relation to PM, IM, ST and SE.

Figure 3 is a schematic view of the literature review as conducted in this research and summarised in the following chapters.

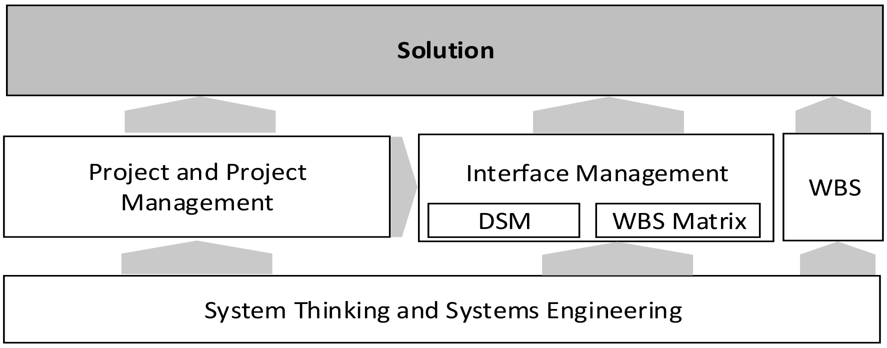


Figure 3: Literature Review Structure

1.6. Research Summary

1.6.1. Research Scope

Considering the requirements identified for the solution, the main research scope (MRS) is summarised and re-established in a research question as follows:

*The **research scope** of this study is to formulate a **fully integrated** approach to develop a **modular and reusable** solution that creates a traceable **relationship** between a **systems engineering** approach and **project management**, including project delivery tools and documents, in which all changes can be managed **better,** resulting in more **efficient** project management.*

(MRS)

Therefore, this thesis outlines the solution proposed to manage the interfaces within a complex design package of work. It further demonstrates how the solution, which is a breakdown structure concept, can be structured so as to bridge PM and SE in a form linking their respective activities, applications, tools and documents (see Figure 4). This research aims to develop a solution in a modular form that can be considered as a standard and can be reused in other rail projects in a bespoke form.

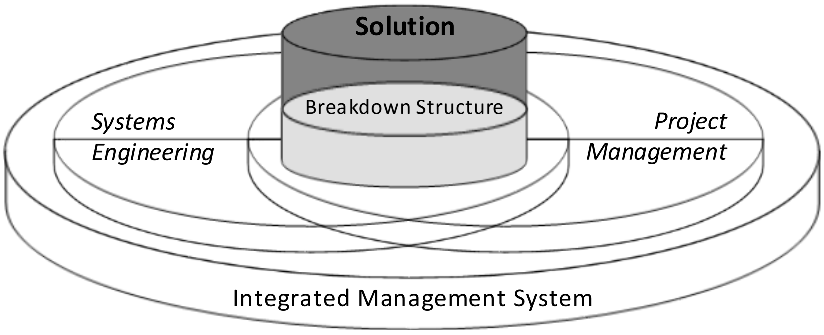


Figure 4: An Integrated Management System

1.6.2. Work Packages

Considering the MRS, MRQ and requirements captured for the solution, this research programme will conduct the WPs listed in Table 2, which also maps the identified WPs to the chapters of this thesis as the deliverables of this research programme.

Table 2: Research Structure and Deliverables

Scope	Work Packages	Deliverables
"The research scope of this study is to formulate a fully integrated approach to develop a modular and reusable solution to create a traceable relationship between a systems engineering approach and project management, including project delivery tools and documents, in which all changes can be managed better, resulting in more efficient project management." ***(Main Research Scope)***	WP 1) Developing background, logic and rational for this research, as well as presenting the research structure	Chapter 1, Chapter 2, Chapter 5, Chapter 6 Appendix 1, Appendix 2, Appendix 3
	WP 2) Developing a research methodology to suit the project scope and objectives based on the existing methods of research	Chapter 2
	WP 3) Conducting literature review to understand the foundation of the research based on Figure 3	Chapter 3, Chapter 4
	WP 4) Gathering and analysing data to justify the importance and impact of systems engineering, interface management and the breakdown structure concept on project and project management	Chapter 5, Chapter 6 Appendix 1, Appendix 3, Appendix 4
	WP 5) Developing and proposing a solution to address the main problem, demonstrate the logic and develop the concept in relation to interlinking of the project management and systems engineering functions	Chapter 7
	WP 6) Validating the solution by adopting the solution in a rail project as a case study and analysing the behaviour and results	Chapter 8 Appendix 5, Appendix 6, Appendix 7, Appendix 8, Appendix 9, Appendix 10, Appendix 11, Appendix 12

1.7. PhD Thesis Structure

Chapter 1 provides a background to the research and an overview of the thoughts structure behind this research, along with a more detailed structure on the problem that this research aims to resolve. The questions and objectives are put into context of the research, and the main problem of the project is broken down into smaller WPs. This chapter also structures the literature review requirements.

Chapter 2 provides the result of a survey conducted in research methodologies and methods in the scientific world. An investigation was carried out into many different research projects and various literature to better understand research methods, which further justify the method used in this research. The main purpose of the chapter however is to provide detail on the methods and procedures followed in this research project. The chapter presents a high-level description on the step-by-step activities conducted in this research project.

Chapter 3 describes the detailed literature review conducted in the areas of project, PM and PM efficiency parameters. It also describes the results of the literature review regarding IM as a major function in project and PM. Further literature review is conducted in the area of ST and SE. The concept of interfacing and IM from the SE view is further explored, and the applicability of ST and SE in PM is studied.

Chapter 4 reviews the wide range of literature regarding the WBS. The history of the WBS is studied along with the applications of WBS in projects of different types. The aim of this study is to explore the applicability of WBS and the general breakdown structure concept in managing interfaces in multidisciplinary projects.

Chapter 5 provides a report on the research survey conducted in this work. The survey methodology and the nature of sample are further detailed, and the gathered data are discussed in detail. This survey was conducted to test the hypothesis on the IM and RM applications within projects of different types from both the SE and PM views, as well as the WBS development concept and its relationship to an SE approach.

Chapter 6 provides a report on a central London rail project used as a case study to review the data to explore the key failure parameters as well as the relation to IM. The study methodology and the gathered data are explained and a detailed discussion and conclusion on the data is provided.

Chapter 7 develops and introduces the new proposed solution that addresses the main problem this research aims to resolve.

Chapter 8 provides a report on the case study projects in which the proposed solution adopted in three different projects (two in the UK and one in Canada). The case studies presented in this chapter provide validation for the proposed solution.

Chapter 9 provides a detailed conclusion of this study in general and recommends future work based on this study.

Chapter 2 RESEARCH APPROACH AND METHODOLOGY

2.1. Introduction

A detailed survey of the existing research methods and perspectives was carried out for this thesis. This chapter presents a summary of the existing research methodologies and approaches in order to provide rationale for the specific methods and procedures adopted in this research project. The main purpose of this chapter is to explain the step-by-step works carried out in this research project. This chapter also outlines the procedure and methods adopted for data acquisition, data analysis and discussions, solution development, and solution validation and verification.

2.2. Research Philosophy

Research is a careful enquiry and thorough search for new information on different topics (Kothari, 2006). Research also is defined as a systematic and organised effort to find a solution for a specific question or problem (Gray, 2014). Research is summarised as a continuing process of systematic investigation in an area of knowledge using the best applicable and appropriate scientific methods to collect and gather factual materials to solve identified real problems (Naoum 2006).

Similar to executing any other piece of work, to conduct research and produce results, a method of execution including the paths to follow and the tools to be used has to be developed (Project Execution Plan in the case of project and research methodology in the case of research project). Therefore, different procedures and processes that are applicable to the research are defined by the research methodology (Clarke, 2000). The methodology should be identified based on the measurable and known research methodologies and must be structured in a workable, reliable, unbiased and objective way. It is important to highlight that the methodology will be governed by a series of assumptions and the interpretation of its outcomes (Crotty, 1998, Easterby-Smith et al., 2002).

2.2.1. Ontology

Ontology is about the nature of reality and the environment in which the problem is identified (Easterby-Smith et al., 2002). This is a view on the nature of reality that can be measured from either ‘realist’, ‘critical realist’, or ‘relativist’ views (Coghlan and Brannick, 2014). The realist view sees the reality as something out there that needs to be found. It is based on the fact that the phenomenon is tangible, fixed and external and occurs independently (Coghlan and Brannick, 2014). The critical realist believes that there is a reality which exists independently of our experience, but acknowledges that reality is shaped by actions and dialogue (Coghlan and Brannick, 2014, Easterby-Smith et al., 2002). Relativist view, on the other side, is based on the fact that a plethora of realities may exist as subjective constructions of the mind (Easterby-Smith et al., 2002).

The ontology in this research is based on the critical realism view, as this approach believes that the reality exists but is influenced by the presence of the research itself.

2.2.2. Epistemology

Epistemology (theory of knowledge) is the relationship with the knowledge and justified belief (Steup and Matthias, 2014) that questions what constitutes valid knowledge and how it can be obtained (Easterby-Smith et al., 2002). The researcher's view will frame the interaction which is being researched depending on the ontological view. For example, the researcher's approach will be objective if knowledge is governed by the laws of nature or subjective if it is interpreted by individuals. Four different epistemologies are introduced as follows (Creswell, 2014):

- <u>Positivism</u>: Including determination, reductionism, empirical observation and measurement and theory verification
- <u>Constructivism and Interpretivism:</u> Including understanding, multiple participant meanings, social and historical construction and theory generation
- <u>Advocacy/Participatory:</u> Including political, empowerment issue-oriented, collaborative and change-oriented
- <u>Pragmatism:</u> Including consequences of actions, problem-centred, pluralistic and real-word practice oriented

The epistemology of this research is based on a positivist approach. The research predicts an issue and tests it by empirical observations and data gathering and analysis through project case studies. Then the research develops and introduces a solution/hypothesis to address the issue. More case studies and empirical data based on real world practices are used in this research to test the hypothesis and justify the solution. As the predicted issue in this research as well as the solution and the case studies deal directly with people (multiple participant), the constructivism and interpretivism approach also is adopted in this research project. Also adopted in this research is the pragmatism approach – a real-world practice-oriented approach that does not perceive the phenomenon as an absolute unity and looks into many approaches to gather and review data (Creswell, 2014). In this research, thoughts are used and considered as tools for prediction of problems and finding solutions and actions.

2.2.3. Paradigm

The research paradigm is a theoretical framework which describes the way that individuals view and approach problems within a research project (Fellows and Liu, 2008). The paradigm in research can take positivist, anti-positivist or interpretivist perspectives. Positivism (experimental testing) is based on the fact that there are certain laws of causation and therefore only clearly observable phenomena are considered for choosing research methods and analysing the data in hand (Woods and Trexler, 2001). According to the philosophical ideas of the French philosopher August Comte, true knowledge is based on experience and can only be obtained by experiment and observation. *"Positivistic thinkers adopt his scientific method as a means of knowledge generation"* (Dash, 2005). Anti-positivism also expresses that the individuals according to their own ideological positions see and understand the social reality and, therefore, base their knowledge on what they have experienced rather than what is acquired from or imposed from outside (Dash, 2005). Anti-positivism emphasises that reality is multi-layered and complex (Cohen et al., 2000). Interpretivism acknowledges that reality is context-dependant and thus it is expected that the data collected and analysed will be influenced by that fact (Fellows and Liu, 2008, Kumar, 2005).

The paradigm in this research, therefore, takes a positivist perspective because the researcher uses knowledge based on experimental work and real-world case studies to identify the problem and develop solution.

2.2.4. Objective

Every research project objective will either be exploratory, correlational, descriptive or explanatory (Kumar, 2005). The exploratory research is described as a type of research in which the researcher has an idea or has observed something and seeks to understand more about it. In most cases an exploratory research project lays the initial groundwork for future research. The explanatory is described as the attempt to connect ideas to understand cause and effect in which the researcher looks at how things come together and interact (Kumar, 2005).

The research objective type adopted by this research project is a combination of exploratory, descriptive and explanatory. This research investigates a specific problem as a phenomenon and the roots and foundation of this phenomenon. While the author has an idea to address this problem that needs to be described and investigated, the results and observations lead to exploration of more benefits of the proposed solution. This also will set a path for future research to be undertaken in this context.

2.2.5. Research Type

Research is either an applied research or a pure (basic) research, depending on its application (Kumar, 2005). Applied research is practical and directly relates to a pragmatic problem. It is a type of research in which the researcher(s) have a practical focus aiming to achieve a particular solution that addresses a specific problem and is suitable for a particular society or organisation. This means the outcomes of applied research could potentially be used in real-world applications to solve real problems. On the other hand, pure (basic) research is abstract and involves the development, analysis and validation of hypotheses that may not be applicable to a practical situation. This type of research is normally based on overall academic knowledge and interest in expanding knowledge in a specific area. The results could eventually be applied in a real-world application, but this is not the main objective of such research.

The research undertaken for this thesis is an applied research type as the author has a specific attention to a pragmatic problem in real industrial projects. The outcome of this research is in a form of a practical solution/product to address the problem. Case studies on the real projects were conducted to validate and verify the solution.

2.2.6. Mode of Enquiry

Qualitative research and quantitative research are the two main governing modes of enquiry (Naoum 2006, Creswell, 2014). The quantitative research approach focuses mainly on factual information that can be quantified and validated through testing and measuring. Information such as numerical data is collected through various methods that can be analysed (Blaxter et al., 2003). This method is generally used to quantify data and to develop a general result from the sample for the population of interest. It is also used to measure the incidence of different perspectives and opinions among the sample sources. The quantitative data enquiry is sometimes followed by qualitative research which is used to further explore some findings. The qualitative approach is a way to analyse and understand the world of human experience (Creswell, 2014). In qualitative research, data is collected in a natural setting and analysed in order to identify patterns or themes. This approach best suits a topic where the research problems need to be explored, where it is complex, and where a detailed understanding is required (Creswell, 2014). A more detailed presentation of the two approaches is shown in Table 3 (Kumar, 2005).

Table 3: The Differences between Quantitative and Qualitative Research (Kumar, 2005)

Difference with respect to	Quantitative Research	Qualitative Research
Underpinning philosophy	Rationalist	Empiricist
Approach to enquiry	Structures/predetermined methodology	Unstructured/semi-structures in a phenomenon of situation
Main purpose of investigation	Quantifies the extent of variation in a phenomenon or situation	Describes variations in a phenomenon or situation
Measurement of variables	Emphasis on some form of either measurement or classification of variables	Emphasis on description of variables
Sample size	Emphasis on greater sample size	Fewer cases
Focus of enquiry	Narrows focus in terms of extent of enquiry, but assembles required information from a greater number of respondents	Covers multiple issues but assembles required information from fewer respondents
Dominant research value	Reliability and objectivity	Authenticity but does not claim to be value-free
Dominant research topic	Explains prevalence, incidence, extent; discovers regularities and formulates theories	Explores experiences, meanings and perceptions
Analysis of data	Subjects variables to frequency distributions, cross tabulations or other statistical procedures	Subjects responses or observation data to identification of themes and describes these
Communication of findings	Organisation more analytical in nature, drawing inferences and conclusions and testing magnitude and strength of a relationship	Organisation more narrative in nature

In this research various data are collected through both quantitative and qualitative modes in a combined form.

2.2.7. Research Methods

The same research approach in the scientific world is transferable and, therefore, can be used across different philosophical perspectives (Fellows and Liu, 2008). For this reason, choosing a right research approach must be based on the type of data available in the research. Although most researchers attempt to identify and separate the approaches and present their research based on a specific research method, the reality is more complicated (Lewis, 1994). For the primary research, the decision on the approach to be taken for a research project should be based on the disciplinary expectations or the research question (Stern, 1994, Annells, 1996) as well as the research *"appeal, goal, cost, rigor, interpretation and usefulness"* (Glaser and Strauss, 1998). In addition, it is also argued that the choice of research approach should focus not only on the research but also on the people conducting the research and their style of work (Goulding et al., 2015). Secondary research focuses on studies that other researchers have conducted leading to books, articles, papers or even debates and discussions. In general, the doctorate literature review is an ongoing process throughout the duration of the project. The sections below outline some of the key research methods also adopted in this research project.

2.2.7.1. Case Study

This research is a practical research with a strong attachment to the real world and real projects. For this reason, a great deal of data for analysing the problem and identifying the research gap, as well as validation and verification of the solution, are collected through analysing and understanding of projects in which the author has been involved. Case studies have the advantage of focusing and exploring specific details of research that other methods often overlook (Denscombe, 2007). When a researcher is attempting to draw generalised conclusions, however, one has to state the assumptions considered in order to allow the case study conclusions to be transferable (Blaxter et al., 2003, Yin, 2009). These projects were assessed as case studies and the data recorded and analysed accordingly.

2.2.7.2. Grounded Theory

The creation of new knowledge involves a research approach that allows the researcher to assess the topic and collect and analysis any available data (Glaser and Holton, 2007), thus enabling the appearance of underlying patterns (Glaser and Strauss, 1998).

According to Glaser and Strauss, classic grounded theory offers a holistic approach for conceptualising such underlying patterns (Glaser and Strauss, 1967).

In this research a form of a grounded theory approach was used in unfolding the research problem and justifying the need for the solution to be developed. Review of literature as well as the project case study revealed a pattern on the same issue occurring in different situations, leading to appreciation of the need to address the issue.

2.2.7.3. Mixed-method

Due to the nature of research in recent years, works need to be conducted in a mixed-method approach as it offers different types of data for the same research problem, thus improving the quality of findings (Bryman, 2012). Through the mixed-method approach, limitations of some methods are mitigated by others. Each set of data being collected for a specific purpose and analysed accordingly provides the researcher with a data diversity that allows for a better perspective on the research problem (Bouma, 1996). A mixed-method approach is most suitable for applied research such as this one, as it is expected to produce tangible findings.

2.2.8. Data Collection Methods

The data collection method is very much related to the type of the data that is required in order to continue with the research. Generally, data can be categorised in two main types depending on their source. Primary data (or 'raw data') are the first-hand information gathered by the researcher directly through various methods such as interviews, observation, questionnaires, action research and workshops. Secondary data, on the other hand, are the information that have been analysed or collected by others, for example, the data gathered from previous research publications, official statistics and online information. Both primary and secondary data can be employed within a well-structured and rigorous research methodology. The data collection methods described below are the methods used in this research to collect the required data.

2.2.8.1. Survey/Questionnaire

A questionnaire is a structured series of questions with a pre-defined objective designed to capture data on a specific area of research. Depending on the type, size and the data in the questionnaire, as well as the targeted recipients, it can be developed and delivered using a variety of potential methods. As the questionnaires are completed in the absence of the researcher, they should be carefully designed and structured to avoid any possible ambiguity (Thomas, 1996). The delivery method of the questionnaire could be via face to face meeting, telephone, mail or email. There are also a number of online survey creators that not only help create the questionnaire based on the desired requirements, but also facilitate the distribution as well as follow up in great detail. In comparison to the data collection methods mentioned earlier, a questionnaire is less expensive and can also provide anonymity.

For this research, a survey questionnaire was developed which considered all the parameters explained above to cover the main blocks of knowledge for this research. The questionnaire was created in an online survey creator (Opinio) and was distributed to a large sample of recipients, as discussed in detail in Chapter 5 of this thesis.

2.2.8.2. Interviews

Various types of interviews – in structured, semi-structured or unstructured forms – can be conducted in a research programme (Kumar, 2005, Naoum 2006). Each interview method has its own merits and drawbacks. Structured interviews follow the same pattern. An identical set of questions is posed to all participants in the same way, with the same limitations of the participants' time and scope. In such interviews, researchers try to find a pattern in the answers to explore the targeted finding. Semi-structured interviews, on the other hand, include open-ended questions. The nature of the questions define the topic under investigation without limiting the interviewee. If the interviewee has issues with the questions, or finds them difficult to answer for any reason, the questions can always be rephrased. In an unstructured interview, the researcher is investigating a specific topic but has no specific questions for the interviewee (Hancock et al., 2009). This could be in a form of feedback on a specific trial or a general opinion about subject matter. Interviews can be conducted face-to-face, via the telephone or, in some cases, by email communication. Each method has its advantages and disadvantages. The face-to-face interview gives the researcher a possibility to observe reactions and to probe and clarify answers that may not be clear. However, this method may be more costly and time consuming and may contain interviewer bias and/or influence. The telephone interview is much faster and more cost effective and also allows for a greater geographic reach. The disadvantage is that the length is usually more limited and there may be a difficulty in discussing specific topics (Dawson, 2009). Written interview (like email) is the most cost-effective way. Another benefit of this type of interview is the time interviewees have to think about the questions before they answer; they also have a chance to read their own answers and rephrase or change if they feel it is required. This reduces to almost zero errors in capturing the answers, as the transcript of the responses is documented in writing.

In this study, different categories of people in the project case studied were face to face interviewed in the semi-structured or unstructured formats, to collect the required data. A number of email communications in the form of interview questions were also exchanged to capture feedback on the proposed solution and system in the case studies used in solution validation.

2.2.8.3. Observation

Direct observation research is a technique that has several applications, one of which is when data collected is of limited value or difficult to evaluate (Hancock et al., 2009). The principle of observation research (action research) is the direct involvement of the researcher in the process under investigation aiming to identify, collect, develop and evaluate data to assist him/her in answering the research question (Bryman, 2012).

Observation provided a transparent environment to collect data and information in cases where the author was actively involved in projects or tasks related to the company that sponsored this research.

2.2.8.4. Workshops

Forming focus groups or running workshops are the best techniques when the research requires brainstorming discussions about specific topics among a specific group of people (Bouma and Ling, 2004). Workshops could potentially be complex activities; therefore, proper workshop preparations are required for the facilitators so they can make the best use of such sessions. The conceptual framework of a workshop includes the group cohesion, the discussion process, group composition, research setting, the moderator and the group process factors (Fern, 2001). Ensuring the correct balance of all workshop variables minimises the potential bias of the data captured. The group cohesion refers to the sense of closeness and common purpose. The discussion process ensures that the group collaborates and that members contribute to the discussion uniformly without participants antagonising each other. The correct group composition is similar to the sampling method used in questionnaire research. It is critical that the focus group includes members that as a group can deliver a balanced option to the research topic raised (Fern, 2001). The research setting is also important, as the workshop should be conducted in an environment appropriate for the research topic with material and equipment suitable for the purpose of the workshop. One of the key sections of the workshop process is the discussion.

In this study, a number of workshops were conducted with different skilled groups in order to collect the required data for the newly developed solution. The workshops were finalised by a number of follow-up communications in various forms including email, meeting and teleconferences.

2.2.8.5. Data Triangulation

Triangulation can be used with both qualitative and quantitative data, irrespective of the way they were collected and analysed (Fellows and Liu, 2008). Triangulation is employed to add rigour to the research method employed by verifying the findings of the research. In addition, triangulation strengthens the research findings as is minimises deficiencies that other methods may have. This method allows any bias or weaknesses from the data collection or analysis to be identified and be included in the research conclusions (Silverman, 2004).

2.3. Adopted Methodology

This research project is based on a mixed-method approach. Regarding primary data collection methods, the data collected in this research were qualitative and quantitative data. Throughout this research a number of smaller research projects (work packages [WPs]) were identified and conducted. The research methods or tools used for each research block (chapter) are summarised in Table 4. Each chapter adopted a specific data collection method according to the requirements of the objective that was being addressed. This research comprised six WPs which have been mapped against methods and outputs in Table 4.

Table 4: Overview of Research Objectives, Methods and Outcomes

<table>
<tr><th>Scope</th><th>Work Packages</th><th>Research and Data Collection Methods</th><th>Deliverables</th></tr>
<tr><td rowspan="9">“The research scope of this study is to formulate a fully integrated approach to develop a modular and reusable solution to create a traceable relationship between a systems engineering approach and project management, including project delivery tools and documents, in which all changes can be managed better, resulting in more efficient project management.”

(Main Research Scope)</td><td rowspan="2">WP 1) Developing background and a logic and rational for this research, as well as presenting the research structure</td><td rowspan="2">- Mixed-method (grounded theory and case study)
- Questionnaire/ survey
- Interview</td><td>Chapter 1, Chapter 2, Chapter 5, Chapter 6</td></tr>
<tr><td>Appendix 12, Appendix 2, Appendix 3</td></tr>
<tr><td>WP 2) Developing a research methodology to suit the project scope and objectives based on the existing methods of research</td><td>- Literature review
- Secondary data collection</td><td>Chapter 2</td></tr>
<tr><td>WP 3) Conducting literature review to understand the foundation of the research based on Figure 3</td><td>- Literature review
- Secondary data collection</td><td>Chapter 3, Chapter 4</td></tr>
<tr><td rowspan="2">WP 4) Gathering and analysing data to justify the importance and impact of systems engineering, interface management and the breakdown structure concept on project and project management</td><td rowspan="2">- Case study
- Questionnaire/ Survey
- Interview</td><td>Chapter 5, Chapter 6</td></tr>
<tr><td>Appendix 3, Appendix 2, Appendix 3</td></tr>
<tr><td>WP 5) Developing and proposing a solution to address the main problem, demonstrate the logic and develop the concept in relation to interlinking of the project management and systems engineering functions</td><td>- Observation
- Exploratory
- Descriptive</td><td>Chapter 7</td></tr>
<tr><td rowspan="2">WP 6) Validating the solution by adopting the solution in a real rail project as a case study and analysing the behaviour and results</td><td rowspan="2">- Case study
- Observation
- Interview
- Workshop</td><td>Chapter 8</td></tr>
<tr><td>Appendix 5, Appendix 6, Appendix 7, Appendix 8, Appendix 9, Appendix 10, Appendix 11, Appendix 12</td></tr>
</table>

2.3.1. Literature Review

This research is built on main blocks of knowledge of project management (PM), systems engineering (SE), Work Breakdown Structure (WBS) and interface management (IM). Literature review carried out in this research provided a better understanding of the knowledge required for this research and helped clarify the research problem. The literature review also provided more justification on the need for a solution to address the research problem, as well as similar works conducted to address the problem in the academic and industrial worlds.

2.3.2. Data Acquisition and Analysis

The main data for various parts of this thesis (mainly Chapter 5, Chapter 6 and Chapter 8) were gathered using survey and case study methods followed by number of interviews.

2.3.2.1. Survey

A survey of practitioners was carried out using an online questionnaire creator application, 'Opinio', licenced and provided by UCL. The questionnaire was designed in the form of 37 questions (including generic optional questions to collect demographic information on the participants) (see Appendix 12). The survey was targeted to reach the practitioners registered as members with the International Council on Systems Engineering (INCOSE) and/or the Association for Project Management (APM) as well as professionals working in industries. INCOSE and APM were approached and they facilitated the distribution of the survey to their members. The survey was also distributed among many other firms, including CH2M (formerly Halcrow), to those classified as project managers in different grades. Finally, members of groups related to PM and SE on professional social network LinkedIn were also invited to participate in this survey. A copy of the cover letters used to communicate with parties mentioned are enclosed in Appendix 2. More detail on the breakdown of the numbers is provided in Chapter 5. Based on the assessments provided, it is estimated that the survey reached nearly 100,000 inboxes.

In a period of 4 weeks, over 500 responses were received. Of these, 259 were identified and labelled as reliable and relevant, from which 57 responses were related to the rail sector. The rest related to other sectors including highway, bridges and tunnels, maritime, aerospace, automation, finance, healthcare, academic research and development, energy, oil and gas, nuclear, environmental, water, defence and information and communication. The participants mainly have related positions including business managers, project managers, engineers/consultants, project control professionals and systems engineers, with experience in working on projects of different scales (please refer to Chapter 5 for more detail on the survey participants). In the data analysis for the two main categories of the data of this survey – 259 'All' entries and 57 entries in the 'Rail' subset – a 99 per cent confidence level is considered in all results calculations and discussions.

2.3.2.2. Project Case Study

A major railway-related project in central London was studied to identify the key failure parameters and test the hypothesis in regards to the role of IM in project success/failure. The data for this study were provided by a major engineering consulting firm (ECF) commissioned as the lead designer for the main design and build contracting joint venture, with the main responsibility of producing the premises design to a 'design intent' level. Premises is essentially architecture, but the architectural discipline as particularly applied to the rail industry. The 'design intent' provides an architectural concept and aesthetic feel for a design and outlines details such as fixings. More detail on the ECF's main responsibility and the programme scope is provided in Chapter 6.

The ECF's project manager granted access to the data requested. He also participated in a number of follow-up interviews in order to clarify the scope of work and the data that his team provided for the purpose of this study.

The data provided are a series of comments in different comment logs by the engineering team on the client side. These comments present issues on the drawings produced by the ECF as part of the overall design build contract. Each comment needs work and resources to be addressed and therefore it potentially impacts the project performance in terms of time and budget. In this case study, the aim is to identify the main reason (MR) of the creation of these comments to identify management activities that could potentially prevent the comment, hence eliminating the resource waste.

The data sample provided includes 49 folders, each of which contains a logbook. Each logbook contains information including the related packages of work, the drawings and report reviewed, revision numbers, communication parties and dates of discussions. In total, there are 7,536 comment lines in all the logs within the 49 folders. The data within the logbooks are generated within the period between 30 April 2012 and 17 November 2015. A full detail of the log format and the information within the comment logs is provided in Chapter 6.

Analysing the 7,536 comments within the 49 folders revealed the number of duplications in comments due to communication of the comments between client and suppliers. Therefore, further assessment on the data was carried out and the data was filtered down to remove duplications while maintaining the MR. As a result, a smaller sample of 2,179 comment lines were analysed.

In order to conduct a consistent data analysis, the 2,179 comments were combined into a single register to be analysed under the same terms. Every single comment within the combined register was reviewed in detail and categorised based on the MR the comment was generated. Chapter 6 further analyses the results and discusses the conclusion in detail.

2.3.3. Solution Development

Chapter 7 is a detailed description of the proposed solution to address the research main problem based on the new proposed hypothetical idea. The fundamentals of the proposed idea, its development life cycle and its applicability are discussed in detail in Chapter 7, along with the additional benefits and added values of the proposed solution in managing projects.

2.3.4. Solution Verification and Validation

The new solution should be validated and verified against the research main scope and questions. Case study, workshop and interview are the main methods used in this part of the research in order to adopt the proposed solution; develop a system based on the proposed solution and in accordance to the concept described in Chapter 7; and assess the solution's applicability and added values to the projects.

Case studies provided facility and real project environments in which the idea could be implemented and tested. Workshops were to gather information on specific disciplines from the technical experts. Various interviews were carried out to collect feedback from the project people on the solution applicability, suitability and value added.

The first case study (CS1) is a design phase for a complex metro station upgrade project in central London, contracted to a major ECF, with an appointed SE team to adopt applications of the SE in the design delivery in accordance with the client's requirements. The proposed solution was developed for the first time for this project. In order to develop the solution, a number of workshops with the lead engineering teams for different disciplines were conducted to capture information, as detailed in Chapter 8. The proposed solution led to the design and development of an application system (see Chapter 8 for the detail of the application and Appendix 12 for the codes developed) to be used based on the proposed solution.

The second case study (CS2) is also a design phase for a similarly complex project for a major upgrade of a rail station in London. CS2 was used as a trial to adopt the solution that was developed in CS1 and to assess the applicability and reusability of the proposed solution and the system, as well as the value added to the project.

The third case study (CS3) is also a complex design project for a new railway station in the city of Toronto, Canada, contracted to a major ECF. CS3 was, therefore, used as another trial to adopt the solution developed in CS1 and refined in CS2 as a template. As CS3 is designing a new station, the scope for CS3 is wider than CS1 and CS2 and, therefore, additional systems and sub-systems will be designed in this project.

2.4. Ethical Considerations

Ensuring research is conducted in an ethical manner is vital (Ritchie et al., 2013). In all interactions with interviewees or during questionnaires, everyone was informed of the purpose of the research and were all given a brief description of the research project. They were informed that they would remain anonymous and that the findings of this research may be published or presented in an academic context.

2.5. Conclusion of the Chapter

The governing ontology in this research is critical realism, and the epistemological assumption was positivism and pragmatism. A variety of data collection and analysis research methods were adopted, involving a collaborative approach towards a process of problem solving, in order to identify the need for change that would improve the practice in organisations and contribute to scientific knowledge within the PM science. The following chapters further discuss the detail of the methods, procedures and tools used in each WP of this research project in order to gather data, analyse data, develop results and discussions, develop a solution based on the proposed idea and validate the developed solution in various project case studies.

Chapter 3 PROJECTS, PROJECT MANAGEMENT AND SYSTEMS ENGINEERING

3.1. Introduction

This chapter summarises the literature review conducted in the following areas:

- Fundamentals of project and project management (PM) exploring the definitions, applications, success, failures and key tools and procedures.
- Fundamentals of interface management (IM) exploring the definitions, impact on project execution and efficiency and key tools and procedures.
- Fundamentals of systems thinking (ST) and systems engineering (SE) approach and management exploring the definitions, activities, applications and applicability.

First the definitions of project and PM are explored in literature to establish the differences between the project and PM concepts and understand how some research draws a line to separate them while some sees them as one entity. This part also looks into the project and PM success criteria and examines various factors that play role in this area.

This chapter also presents a detailed study on IM in the context of project and PM. The impact of the poor IM in the project is further investigated, and the need to improve IM is further justified. Also the new procurement strategies for the construction projects in the rail sector are further explored to justify the importance of IM in the delivery of such projects.

The discussion is continued further by looking into the SE definition in today's projects. The history of SE is explored, and the overlap of the SE and PM is presented. The main reason for this study is to find where, how and in what capacity SE can support PM to make it more efficient.

This chapter later explores how a form of a breakdown structure document, primarily the Work Breakdown Structure (WBS), could potentially be used as a tool to develop an integrated management system.

3.2. Project and Project Management

The word 'project' means *"a piece of planned work or an activity that is finished over a period of time and intended to achieve a particular aim"* (Cambridge Dictionaries Online, 2015). In order to understand the definition of 'project management', it is essential to review the definition of project in the literature.

3.2.1. Project

A project is described as a temporary organisation with assigned resources (such as human, material or financial) to perform activities to manage changes and uncertainties (Turner, 2006, Turner and Müller, 2003). A project is also explained as the achievement of a specific objective which requires a group of resource-using activities that have to be completed in a certain period of time and that has a specific start and end time (Munns and Bjeirmi, 1996). There is, therefore, a common understanding of the definition of 'project' based on the different literature in different areas. The key common phrases in the project definition are the **combination of actions, achievement of an objective,** and **satisfaction of a need.**

There is a fundamental difference between project and operation. Operation is a repetitive set of tasks that will be done over and over until it is set to be finished. Projects, however, are unique with their own unique characteristics: *"A project is a unique, transient endeavour undertaken to achieve a desired outcome"* (Association for Project Management 2006). Operations could be defined in a binary format and could be programmed to be done by machine, while projects are linear and involve different levels and hierarchies of people.

Every project has its own characteristics and requires its own planning and management. It is almost impossible to have two identical projects, even if they have the same goals. Even repeating a project is different from the original project in one or more aspects (such as commercial or administrative) (Lock, 2007). For this reason, management approaches are naturally different, depending on many factors, including the project nature, complexity, scale, environment and stakeholders. For this reason there can be no guarantee that prescribing a specific management method will deliver a successful project outcome. The success of each project and PM can only be measured after the completion based on various factors. For the same reason, it is almost impossible to define a fixed framework for PM that can be applied on all sorts of projects. For the purpose of this research a following definition is assumed for *'project'*:

A project is a unique piece of planned work or activity that is finished over a period of time and is intended to achieve a particular aim to satisfy a form of a need.

3.2.2. Project Types

Project is all about changes, uncertainties and risk; according to Dennis Lock, *"The principle identifying characteristic of a project is its novelty*" (Lock, 2007). He also continues in his book with a complete section in defining different project types. Although this is arguably not a full list, it is sufficient to categorise four major types of projects so the focus of this research can be further refined.

3.2.2.1. Type 1: Construction Projects

These are typically large-scale projects that should be implemented and developed in the actual site where the end result will be used. The size and complexity of these projects require a well-planned management process. Health and safety is a critical matter and needs to be managed before anything else. The cost of this type of project is normally set to be very high and, due to the complexity and involvement of multiple disciplines, various contractors will be involved. Therefore IM and addressing integration issues are critical in this type of project. Major construction projects in different sectors – rail, tunnelling, mining, oil and transportation development – are typical examples of this type of project (Lock, 2007).

This research project focuses on this type of project. Project delivery and PM rely heavily on human input, so human behavioural impacts play a key role. As people are very different from machines, there is more constraint in developing systematic solutions that work perfectly in such an environment.

3.2.2.2. Type 2: Manufacturing Projects

The end delivery of this type of project is manufacturing a piece of electronic or mechanical kit or a major item (system) such as a ship, train or aircraft. These projects normally are developed in a laboratory, factory or workshop while the end product is used in the field. Often the project will create a product which becomes 'first of class' or a prototype for wider production and commercial (or other) distribution. Such projects can be very complicated (Lock, 2007).

The 'kit of parts' for an aircraft, for example, is very large and will involve the coordination of numerous parties and contractors. Such integration and coordination is essential and brings a high level of risk to the project which needs to be defined and mitigated. Lock (2007) includes projects such as, new product research and development, equipment manufacture, shipbuilding, automotive, aircraft and aerospace, heavy engineering, food and drink and pharmaceuticals projects, in this type of projects (Lock, 2007).

What should be noted here is that delivering such products relies more on machine and automation after the design is completed by humans. Therefore, developing systematic methods and solutions works better in the production line once it is set up for the first time, and the production line can turn to an operation afterward.

3.2.2.3. Type 3: Management Projects

This is a common type of projects which address the internal management or infrastructure of the organisation. Sometimes, this can be called internal project/development for the benefit of the company itself. Relocating an office, preparing for launch of a new product or introducing a new IT system are good examples of this type of project (Lock, 2007).

These projects usually are not expected to make profit for the company, although they will eventually bring benefit and profit to the organisation as a whole. For example, implementing a new IT system will eventually bring some of the overhead costs down or escalate the capability and therefore bring more projects to the organisation (Lock, 2007). The performance and success of this type of project is very important, so the management process of this type of project is also essential. This is particularly true in a rapidly changing world where a company must adapt to an evolving competitive landscape.

3.2.2.4. Type 4: Scientific Research Projects

This project type is different from the others in that the final objectives of such projects can be hard to define, making it difficult to determine cost and duration. A research project could achieve a significant finding in a very short time and therefore return huge profit in industry. Or it might observe a significant amount of cost over a long period of time and never achieve a considerable outcome. Therefore, the risk associated with this type of projects is different and could potentially be very high. Research projects need a dynamic PM process, and the life cycle should be flexible to cope with change and unexpected outcomes and events (Lock, 2007).

3.2.3. Project Management

There are different understandings and views on the definition and outlook of management. Early civilisations proved that they had sophisticated organisation for their own time, as well as the ability to organise themselves into massive groups of people, tools, planning and tasks to perform large-scale activities. The building of Egypt's pyramids or China's Great Wall are good examples of such performances (Easterby-Smith et al., 2002). Formal records of historical management techniques can be traced back to Chinese philosopher Mencius, who dealt with models and systems (Easterby-Smith et al., 2002). Indeed, managing a project is one of the most respected achievements of mankind (Morris, 1994).

Project management which has been called *"an efficient tool to handle novel or complex activities"* (Munns and Bjeirmi, 1996), is a collection of techniques, skills, processes and procedures used to plan, coordinate and manage a group of activities with a common goal of achieving the identified objectives – within the allocated time and budget – and the specified quality that satisfies the need specified by the project.

Project management is a planning oriented technique (Söderlund, 2004) which is further defined as "*the process of controlling the achievement of the project objectives"* (Munns and Bjeirmi, 1996).

A project is described as a temporary organisation to assign resources to manage a change; the role of a project manager is explained as a chief executive for that organisation with roles of planning and executing work while keeping the team motivated (Turner and Müller, 2003).

The British Standard for PM, BS6079, describes PM as the planning, monitoring and controlling of all of the project's aspects, as well as developing motivation for all the project parties to complete the project and achieve the objectives of the project – including the quality and performance – using the project allocated resources (that is, time and cost) (British Standards Institute, 1996).

The UK Association of Project Management (APM) Body of Knowledge (BoK) has a similar definition to the BS6079, but also refers to the project manager as the single point of responsibility for achieving the project objectives (Association for Project Management 2006).

Reiss (1995) describes the project as a human activity that over a defined time scale will achieve an objective and so describes PM as a combination of management, planning and the management of change (Reiss, 1995).

Lock (2007) describes PM as an evolved management skill to plan, control and coordinate the activities that need to be conducted in a complex and diverse form to manage modern industrial and commercial projects (Lock, 2007).

Project management also is considered by Burke as a set of skilled management techniques to plan and control projects under a strong single point of responsibility (that is, project manager) (Burke, 1993).

Based on any definition of PM, the key terms of managing change; planning; monitoring; managing a set of activities; achieving agreed objectives; within time and budget; compliance with specified quality and performance; team motivation; single point of responsibility; and people management are the common terms defining PM of any kind. For the purpose of this research, the following definition is assumed for PM:

Project management is establishing a set of objectives and targets and managing activities that need to be conducted, performed and completed in a planned sequence to achieve the project goals to an agreed time, budget and quality.

For decades, researchers worked on finding solutions to better manage different types of projects. Regardless of the definition of PM and the method adopted, the project manager should satisfy the main three project constraints as explained in the famous 'Iron Triangle' shown in Figure 5 (Atkinson, 1999). Martin Barnes used this concept over 40 years ago with cost, time and quality at its corners (Elliott, 2014).

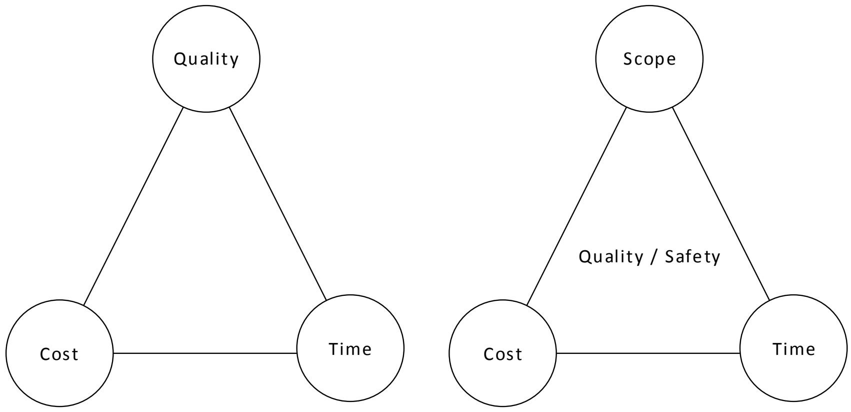


Figure 5: The Iron Triangle

In other literature, the quality corner has been changed to performance or scope, and quality and safety are included in the middle (Elliott, 2014, Baccarini, 2011, Emes et al., 2012).

3.2.4. Project Life Cycle

Projects have a phased life that much of the literature calls the project life cycle (PLC). This is a phased procedures to achieve the objective of a project from beginning to completion (Ismail et al., 2013). Some researchers suggest that there is a difference between the PLC and the PM life cycle. This has been further discussed in various literature where authors draw a line between project and PM success and failures. Munns and Bjeirmi (1996) express that the success of a project should be distinguished from the success of project management (Munns and Bjeirmi, 1996). The difference is further investigated by looking into the definition of PLC in different literature.

Novick (1990) lists the PLC phases as capital programming; concept study/alternatives analysis; design and contract document preparation; construction (including management and inception); operations, inspection, and maintenance; repair and rehabilitation; and reconstruction and replacement (or disinvestment) (Novick, 1990).

Kartam (1996) describes these phases as conceptual planning and feasibility studies; design and engineering; construction; and operation and maintenance (Kartam, 1996).

In a similar way, the PLC stages are elsewhere explained as the feasibility phase; design phase; construction phase; exploitation phase and dismantling phase (Alshubbak et al., 2009).

Saad (2011) also lists the PLC phases as the conceptual planning and economics (feasibility study) phase; engineering and functional design phase (including three sub-phases of preparing drawings and specifications, tender and award and procurement); construction and completion of the project (implementation) phase; and operation and utilisation phase (Saad, 2011).

Munns and Bjeirmi (1996); in a similar but a simple and generic form describe the phases of a PLC as the conception phase; planning phase; production phase; handover phase; utilisation; and closedown (Munns and Bjeirmi, 1996).

Although different forms of PLCs are introduced by different researchers, in principle they all follow the same concept. As shown in Figure 6, some consider the closedown of the project as part of a project cycle and others do not, but in reality this depends on the type of project. For the purpose of this research, which focuses on rail infrastructure projects, the closedown of a railway system or station will eventually be part of the system and will happen when the system is either obsolete or planned to be changed.

The main role of PLC, therefore, is to provide a 'birth to death' image of a project to provide a basis to develop and plan activities required for achieving the project objective(s) (Project Management Institute (PMI), 2006), including identifying a project management method. The key phases illustrated in a PLC are explained as follows:

> *Phase 1: Project Definition/Concept* – In this phase the project question or need will be identified to form the project scope. The initiation of a project happens in this phase. Most of the time, projects in construction environment begin with a recognition of a need for a facility (Saad, 2011). The public will be aware of the need for this important project (Novick, 1990). Knowledge of the scope and scale is limited or not available, and the estimated cost and time are very high level and based on many assumptions (Novick, 1990).

	Munns and Bjeirmi (1996)	Novick (1990)	Kartam (1996)	Alshubbak (2009)	Saad (2011)
Phase 1	Conception	Capital programming	Conceptual planning and feasibility studies	Feasibility Phase	Conceptual Planning and Economics (Feasibility Study) Phase
Phase 2	Planning	Concept study / alternatives analysis			- Preparing Drawings and Specifications - Tender and Award - Procurement
Phase 3	Production	Construction, including management and inception	Design and engineering Construction	Design phase Construction phase	Construction and Completion of the Project (Implementation) Phase
Phase 4	Handover				
Phase 5	Utilisation / Operation	Operations, inspection, and maintenance Repair and rehabilitation	Operation and maintenance.	Exploitation phase	Operation and Utilization Phase
Phase 6	Closedown	Reconstruction, replacement, or disinvestment		Dismantling phase	

Figure 6: Mapping the Different Project Life Cycle Phases

Phase 2: Planning Phase – Once the project and the scope are identified, project objectives will be derived and detailed. The outcome of this phase will shape the project structure, including the project requirements; project WBSs; project governance and organisational breakdown structure; plans on schedule and budget; procurement method; and PM and delivery team selection and appointment. Concept study and feasibility valuation also will be conducted, along with the planning for the next phase of the implementations (Novick, 1990, Kartam, 1996, Saad, 2011).

Phase 3: Development Phase – This phase includes design (which could be done in different phases on its own) and implementation of the design to develop the products/services required. In this phase, the project delivery team is on board and is taking over the execution of the project. Designs and the architecture of the project deliverables are implemented, products are developed/manufactured and integration is performed and completed (Munns and Bjeirmi, 1996). In a classic rail infrastructure project, this phase is delivered within sub-phases which include design stages and then construction stages. Different clients do have different paths such as Royal Institute of British Architects (RIBA) or Network Rail Guide to Rail Investment Process (GRIP) 1 to 8 stages. Further detail can be found in Figure 7. In this phase of the project identification and managing the interfaces is essential.

Phase 4: Commission and Handover – In this phase, the project execution team has completed its work. The final product is tested and the performance is checked and accepted by the client/users. Handover is completed and the product is ready to be commissioned (Munns and Bjeirmi, 1996). Some believe that the PLC will end when this phase does (Novick, 1990, Saad, 2011), while others consider the project finished when the post-project impacts are analysed and the product is disassembled or disposed of when the life of the product is over (Alshubbak et al., 2009, Ismail et al., 2013). Depending on the type of contract, the end of this phase in construction projects is more likely to be the end of the project delivery team commissions.

Phase 5: Operation – The end for delivery of a project which could be a product, service, etc., is when the final product is accepted by the sponsor and is in its operational environment. In rail projects, this is when the railway system is in operation and the project delivery team might still be in charge as part of the project for which they were commissioned.

Phase 6: Closedown – The life of the project is completed and the product is to be disassembled, and disposed of or removed (if required). As discussed, in the railway sector, this is the time the system is either obsoleted or is due to be modernised.

Churcher and Richards (2015) provide Figure 7, which is a comprehensive alignment of different PLCs based on a detailed examination of the different plans of work within various organisations (Churcher and Richards, 2015).

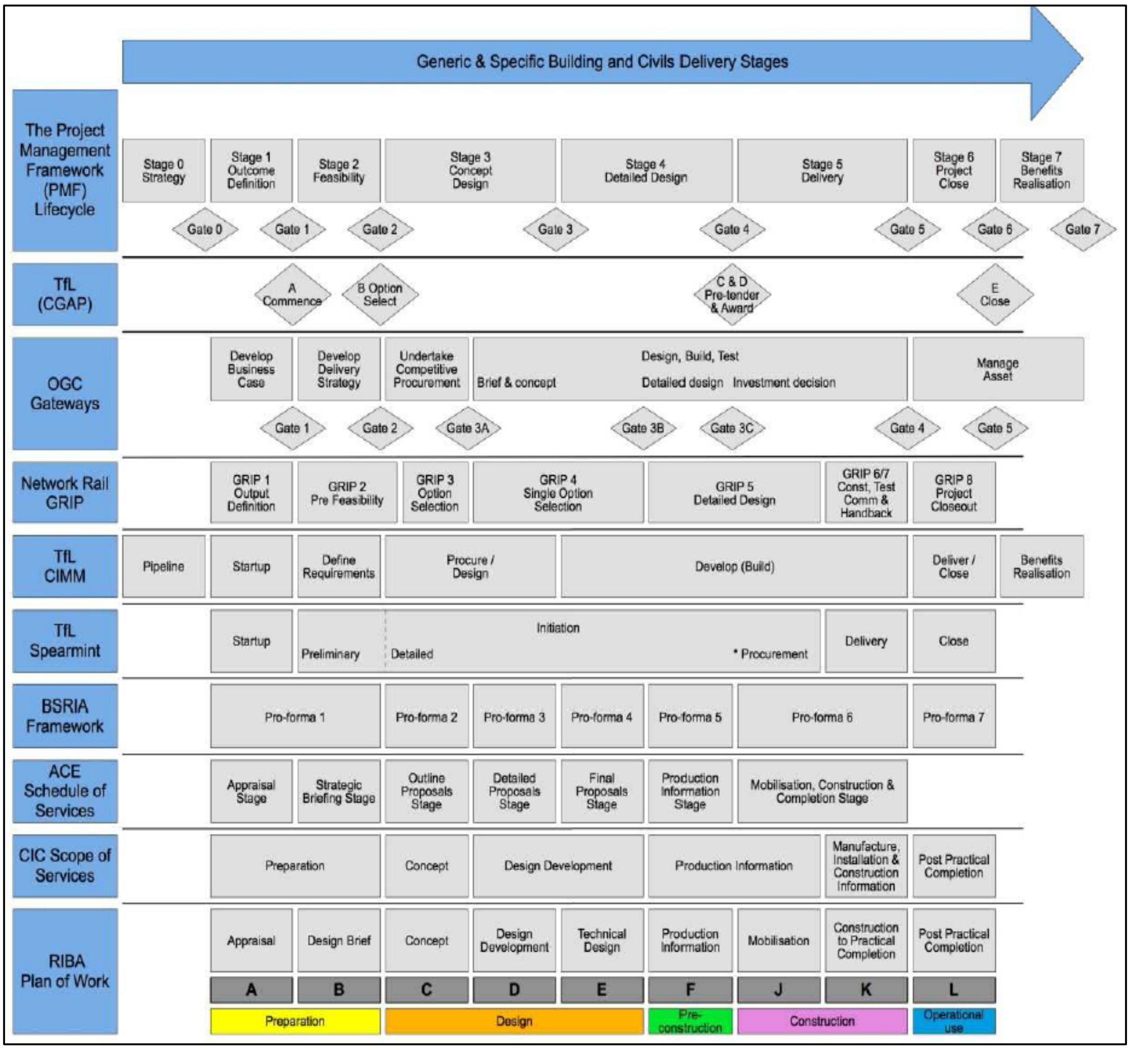


Figure 7: Alignment of Existing Plans of Work (Churcher and Richards, 2015)

Figure 8 is an integrated view which presents both the PLC and the product delivery PLC stages. The figure presents the following:

- The proportion of the time period for each stages of the PLC
- The possible parties involved in each phase of the project and the product delivery
- That the product delivery as a project has its own stages which typically align with project PLC phases 2 to 4 (Munns and Bjeirmi, 1996)
- That tasks such as planning, scheduling, controlling and monitoring to achieve the project requirements, objectives and eventually the scope PLC are iterative and recursive

- That in some cases, PLC could be extended, depending on the procurement strategy in which the product delivery team is also responsible to operate the system after completion
- The great amount of time (and resources) for the planning and scheduling at the beginning of a PLC that will be reduced when the project progresses

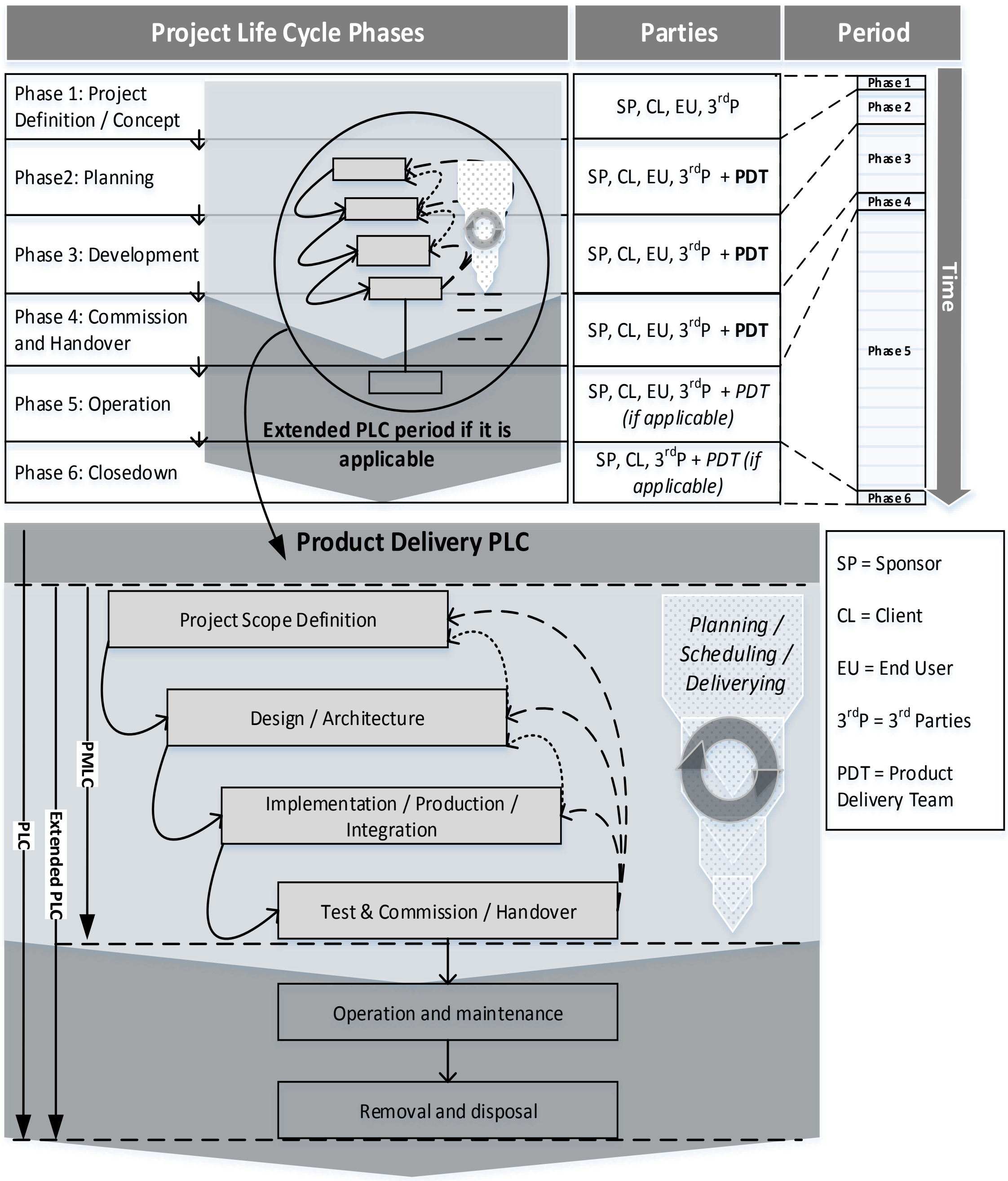


Figure 8: Integrated Project Life Cycle

Most of the time project requirements in construction projects are either not well defined or will be subject to change due to many different factors. As the result, the project cycle will continue to spin (that is, consume resources) until the result of the commissioning confirms that the project meets its requirements.

3.2.5. Project Success/Failure

Over the past 70 years, cost, time and quality (that is, the Iron Triangle) have been the main way to measure the success of project (Figure 9 illustrates PM success v. failure using the Iron Triangle approach). For this reason, in the past 20 years researchers published papers and documents to develop new frameworks for measuring the project management, using factors beyond the Iron Triangle. Atkinson (1999) suggests that the Iron Triangle criteria are no more than two best guesses (that is, time and cost) and a phenomenon (that is, quality) and not sufficient for this measurement. He then introduces the Square Route as an improvement upon the Iron Triangle (Atkinson, 1999).

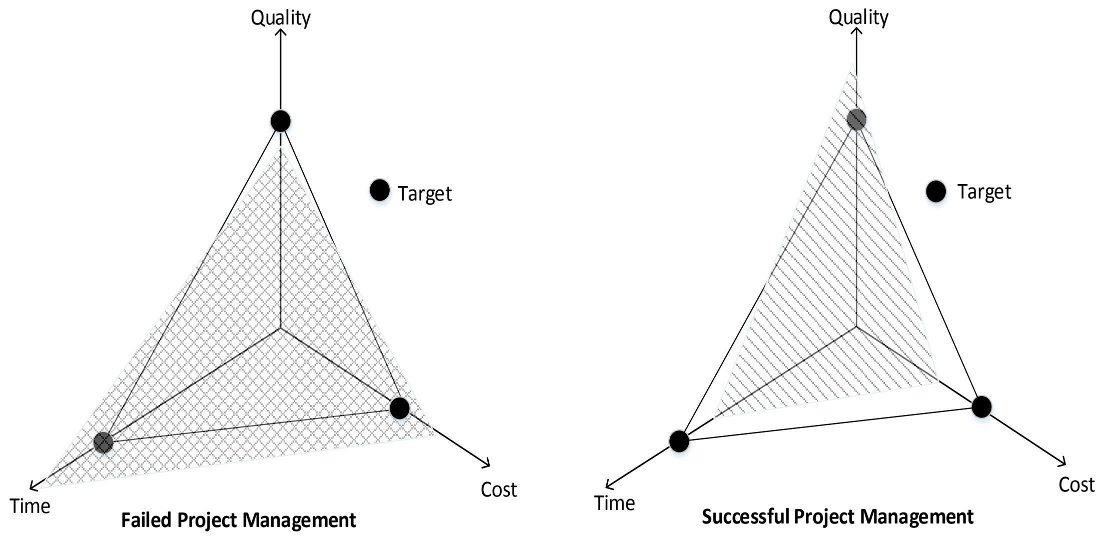


Figure 9: Project Management Success versus Failure Using the Iron Triangle

In parallel, some researchers suggest a clear difference between project and PM definition, scope and schedule (Munns and Bjeirmi, 1996). They mainly suggest that PM has objectives to deliver while a project has a long-term aim and benefit to realise, and therefore the success criteria of the two are different. This could be right if the project is only looked from the start to end from the project sponsor's view. In principle, it should be noted that the PM or 'product delivery phase' of a project for the project owner is potentially a complete project for the party commissioned to deliver the product. Therefore, a project is actually a combination of smaller projects with the same life cycle. For example, in a rail station design and build project within a central capital, from the sponsor's point of view the project continues from the feasibility study through the disposal. But the same project for a contractor commissioned for conducting a feasibility study, the project ends at the end of the feasibility study. It is understandable, then, that parties involved in a project debate over the realistic end line of the project so that they can measure their success on completion of their commission. Serrador and Turner (2014) on this topic state that:

> *"This focus on the end date of the project is understandable from a project and project manager's standpoint. The definitions of a project imply an end date; at that time the project manager is likely to be released or move on to another project."* (Serrador and Turner, 2014)

Reward schemes in many organisations also drive the project team and the manager to finish the project on cost and time and nothing else (Turner, 2009). Cooke-Davies (2002) highlights the difference between the critical factors for project and PM success by splitting the questions into *"what factors lead to project management success?", "what factors lead to a successful project?", and "what factors lead to consistently successful projects?"* (Cooke-Davies, 2002)

In the following sections two scenarios are explained to further clarify the difference between the project and PM success and failures.

3.2.5.1. **Successful Project Management for a Failed Project Scenario**

A project might be characterised as successful upon the completion of the product delivery cycle, if it is completed on time and budget and to the quality (that is, delivered in the shaded area as shown in Figure 10). However, if a deliverable in its intended operation environment shows a failure, the project has failed regardless of the successful management function. Many factors such as 'return of investment', 'profitability', 'competition' and 'marketability' are considered as important parameters within a project's goals in order to assess the project success (Munns and Bjeirmi, 1996). There are various examples when the project team successfully delivered the project to the time, cost and quality but the project failed for number of reasons.

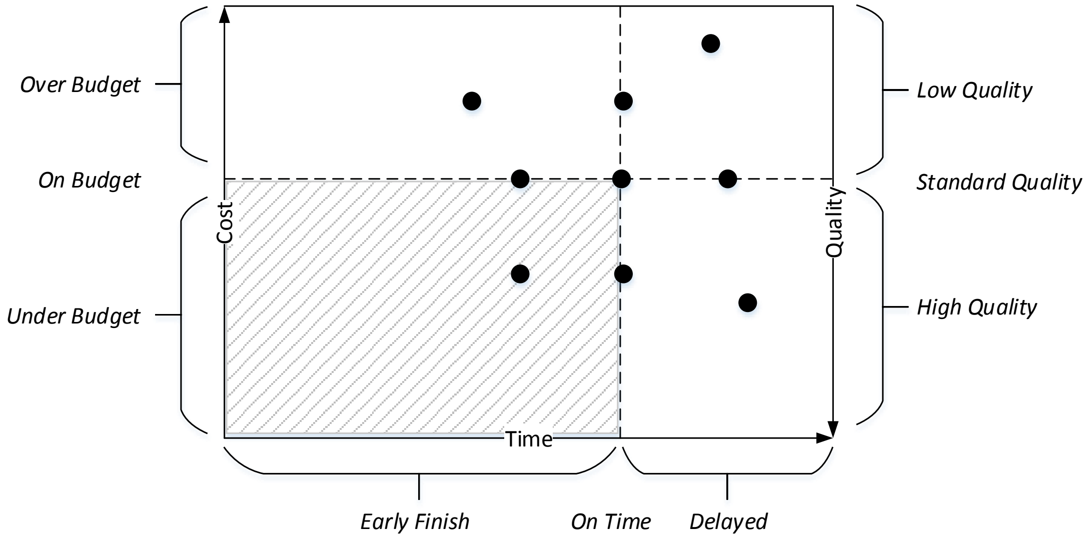


Figure 10: Project Management Success versus Failure

The Tacoma Narrows Bridge, for example, collapsed because of instability in crosswinds in the area. After the designers reviewed the requirements, they realised that though the bridge was built in accordance to the standards and quality, it was the wrong bridge for the environment (Bahill and Henderson, 2004).

The Edsel was a fancy car manufactured by Ford. A successful PM function delivered a car in full compliance with the requirements. The car, however, didn't sell because Ford did not conduct solid market research and instead of making something people wanted, they built a product that management wanted more (Bahill and Henderson, 2004).

The multibillion-dollar Iridium project of Motorola delivered on time and budget and was credited as a successful delivery, but failed massively commercially because it did not adjust to the changing in the business environment (Collyer and Warren, 2009, Highsmith, 2004) .

It can be concluded that many of these projects were delivered successfully and we can presume that the successes of the project delivery were celebrated and acknowledged upon completion of the project. But the massive failures in the post delivery and in their intended operation period and environment prove that a successful project delivery is not a sufficient criterion to judge the success of a project. Many of these projects were delivered in time and budget, however, so from the delivery teams' points of view, the very same projects were successful. The other key conclusion is in reference to IM.

Even is a poor IM is not impacting the PM success, it could potentially be a factor in project failure when it is delivered and is in its intended operational environment.

3.2.5.2. Failed Project Management for a Successful Project Scenario

In another scenario, a project might be seen as failed when it fails to meet the Iron Triangle criteria in the delivery stage. But if the same project proves to be a great success in its operation phase, with a satisfied end user, the management failure of the project (including project overspend or delay in delivery) will soon become irrelevant. Shenhar, Levy and Dvir (1997) note that:

> *"As time goes by, it matters less whether the project has met its resource constraints; in most cases, after about one year it is completely irrelevant. In contrast, after project completion the second dimension, impact on the customer and customer satisfaction, becomes more relevant."* (Shenhar et al., 1997)

In this context, Munnes and Bjeirmi (1996) similarly stress that when the PM is completed, the short-term objectives of the management function could have failed. But if the project's long-term and larger objectives are satisfied, the outcome of the PM is a success (Munns and Bjeirmi, 1996).

The film *Titanic*, for example, was produced extensively over budget and over time, but it was the first film in history to generate over US$1 billion revenue (Collyer and Warren, 2009). Similarly the Thames Barrier, the Fulmar North Sea oil project, Concorde, Channel Tunnel, Great Belt Link, Oresund Access Links and Oresund Coast-to-Coast Link are excellent examples of projects that failed in terms of the delivery but had relatively successful outcomes over time (Munns and Bjeirmi, 1996, Flyvbjerg et al., 2003).

As detailed in Table 5, a five-dimensional success model based on measuring on a timely manner is another attempt to measure project efficiency (Shenhar and Dvir, 2007). Shenhar and Dvir (2007) express that they adopted the term 'project efficiency' instead of PM success which means meeting cost, time and scope goals, and use 'project success' to mean meeting wider business and enterprise goals (Shenhar et al., 1997, Shenhar and Dvir, 2007).

Table 5: The Five-dimensional Success Model (Shenhar and Dvir, 2007)

Success dimension	Measures	Time
Project efficiency	Meets time and cost	End of project
Team satisfaction	Encourages team member satisfaction, growth, retention and skill development	End of project
Impact on the customer	Meets the functional performance and technical specification Fulfils the customer needs and solves the customer problem Product is in operation and used by a satisfied customer	Months following the project
Business success	Commercial success Creates a larger market share	Years following the project
Preparing for the future	Develops a new technology, creating a new market and a new product line	Years following the project

Turner and Zolin (2012) also present a phased success assessment of a project as follows:

- At the end of the project, assess the success based on the Iron Triangle criteria (that is, within time and cost and delivered to specification)
- In the months following the project, assess the success based on whether the product performs as required and gives the benefit predicted
- In the years following the project, assess the success based on whether the client achieves organisational improvement

Although this is a fact, it cannot eliminate the importance of successful project delivery based on the Iron Triangle.

3.2.6. Key Factors Impacting Project Success

Morris and Hugh (1986) list the key factors which impact on the success of a project as a realistic goal, competition, client satisfaction, a definite goal, probability, third parties, market availability, the implementation process and/or the perceived value of the project (Morris and Hugh, 1986). Other researchers include additional factors that affect the ability to achieve project goals: '(a) objectives; (b) project administration; (c) third parties; (d) relations with client; (e) human parties; (f) contracting; (g) legal agreements; (h) politics; (i) efficiency; (j) conflicts and (k) profit', (Munns and Bjeirmi, 1996, Cash and Fox, 1992, Baker et al., 1974a, Baker et al., 1974b, Kerzner, 2009, Kumar, 1989, de Wit, 1988).

Some of the famous failed projects with the main failure cause are gathered in Table 6 (Bahill and Henderson, 2004, BBC, 2014b).

Table 6: Famous Project Failures (Bahill and Henderson, 2004, BBC, 2014b)

Project Name	Year	Cause of failure	Failure Phase	Possible Failure Factor
Tacoma Narrows Bridge	1940	Scaling up an old design	Delivery	Poor Design
Edsel Automobile	1958	Failure to discover customer needs	Project	Poor Requirements Definition
Vasa Warship	1961	Workmen were using different systems of measurement	Delivery	Poor IM
Concorde SST	1976–2003	It was not profitable (1976–2003)	Project	Poor Market Analysis
IBM PCjr	1983	Failure to discover customer needs	Project	Poor Requirements Definition
The Gimli Glider	1983	Using different units	Delivery	Poor IM
Chernobyl Nuclear Power Plant	1986	Bad design, bad risk management	Delivery	Poor PM, including IM
New Coke	1988	Arrogance	Project	Poor Management
Lewis Spacecraft	1997	Design mistakes	Delivery	Poor PM, including IM
Motorola Iridium System	1999	Misjudged competition, mis-predicted technology	Project	Poor Market Analysis
Mars Climate Orbiter	1999	Use of different units	Delivery	Poor IM
Millennium Bridge	2000	The up-and-down synchronised footfall was considered but not the side-to-side effect	Delivery	Poor Design
Sep 11 Attack on World Trade Center	2001	Failure to anticipate terrorist threat	Delivery, Project	Poor Requirements Definition
Northeast power outage	2003	Lack of tree trimming	Delivery, Project	Poor Requirements Definition
Laufenburg Bridge	2003	Missed integration between two contractors	Delivery	Poor IM
French Railway	2015	Miscalculation of the size of the train and the platforms	Delivery	Poor IM
		Total number projects sampled	16 Projects	
		Failed in project delivery	11 of 16 Projects	
		Delivery failed because of IM	7 of 11 Projects	

The information in the table shows that in this small sample, 11 out of 16 projects (around 68 per cent) are failed in the delivery phase of the project. The other projects, however, are delivered as planned but are classified as failed projects because of various issues with the projects themselves, such as missed prediction for the profit. The data here also show that in 7 out of the 11 projects which failed in the delivery phase, interfacing and/or IM within the design and development stages play key roles in project failure. While the key role of a poor IM in project failures can be seen in many examples, there is not enough scientific research in this topic specifically with proposed solutions.

In addition to this, the new construction procurements strategies – specifically in the rail sector – have created more reason to justify the importance of interfacing and IM. The new project procurement strategies in rail infrastructure projects is explained in the next section to provide a full picture of the need for IM.

3.3. Project Procurement Strategies in the Rail Sector

Infrastructure projects and rail infrastructure projects in particular are becoming more complex (Shokri et al., 2012, Shokri et al., 2015) with managerial, technical and logistical problems with multiple activities from many parties delivering works with numerous strata of interfaces of hardware and software. The execution lives of rail projects are no longer limited to discrete and sequential phases like feasibility study, design and construction with project organisations of only client, designer and contractors (Staats, 2014, Anumba et al., 2007) and the full responsibility and accountability of the project sponsor.

Another issue that plays a part in this consideration is the notion of the level of risk transfer from public to private sector (Edkins and Smyth, 2006, Quiggin, 2005). In traditional rail projects, the real risk was arguably for the project sponsor. No matter what contract structure was in place, if a project failed completely, experienced massive delay, had major incidents, or the contractor went bankrupt, the risk was still with the promoter, owner and government – politically, financially and ultimately physically (Bing et al., 2005). It is therefore a shift in contract strategies with an aim to shift the risk more toward the private sector (contractors).

3.3.1. Rail Project Procurements Background

Initially, railway projects were funded by the private sector, by individual entrepreneurs who would raise their own funding (Gourvish, 1986). They would commission the design having conceived the project in the first place. They would then commission and contract their supply chain, procure the land (or not – which is why there are some interesting diversions to many of the early lines), build and operate. Many of these companies failed and were taken over by other organisations with the onset of war and the realisation of the importance of these critical pieces of logistical infrastructure, plus the effects of the deterioration of the networks as revenue constrained investment in maintenance. Thus most railways passed into public hands and became subject to government procurement structures (Gourvish, 1986), and the industry was completely nationalised by 1948 (Pollitt and Smith, 2002).

Innovation in the method of procurement did not advance greatly in most of the world until the 1960s when a wave of market recessions, the emergence from two world wars in 25 years and the public's more vocal and politically active requirement for value for money caused promoters to re-examine how this sort of infrastructure was procured.

> *"Pressure to change the standard model of public procurement arose initially from concerns about the level of public debt, which grew rapidly during the macroeconomic dislocation of the 1970s and 1980s."* (Quiggin, 2005)

This led to the emergence of a trend away from the traditional design, procure and construct approach and towards more market-based approaches with greater emphasis on output parameters and a move to a mix of finance sources that culminated in the rise of Public Private Partnership (PPP) structures which developed the Engineering, Procurement and Construction (EPC); Design and Build (D&B); Early Contractor Involvement (ECI); Design, Build, Operate and Maintain; and Design, Build, Finance, Operate and Maintain approaches. ECI, for example, requires that contractors get involved in the project during the design phase. Walker (2012), for example, states:

> *"It is widely accepted that contractors have much potential valuable advice to offer at the front-end of project development. This concept is sometimes called early contractor involvement (ECI) and encompasses various relationship-based project procurement (RBP) forms."* (Walker and Lloyd-Walker, 2012)

Reviewing literature in construction and engineering management provides detail on how the new procurement strategies are moving to the approaches that requires a much greater level of collaboration and cooperation between the project sponsor (client), the project design team and the contractor delivering the project (Walker and Lloyd-Walker, 2012, Mosey, 2009, Masterman, 2002, Walker and Rowlinson, 2008, Edkins and Smyth, 2006).

Although this new shift in procurement provides benefits to the project in many aspects, the more parties (participants) involved and the complexity of the relationship – specifically in the design phase – introduce new challenges in managing the interfaces (Edkins and Smyth, 2006, Smyth and Edkins, 2007).

> *"Co-operation, however, implies an increase in the number of participants. Also, in partnerships, the actors are usually dependent upon each other."* (Klijn and Teisman, 2003)

Rail projects are even more complex due to the fact that they involve large pieces of civil infrastructure – even in its most extreme, hardly cutting edge engineering development – which can be constructed in various pieces of individual work with complex interfaces. This has lent itself to ever more complex contractual structures which have in some places caused major challenges to cost, programme and functionality.

3.3.2. Traditional Design, Build and Construct

The traditional rail infrastructure projects follow the straightforward and simple stages of public procurement including design, build and construct. In this approach, the sponsor, usually government at some level, will do all front-end work from scheme Feasibility and Preliminary Operating Plan through to definition and detailed design, cost, programme, business case, procurement and delivery strategy. At this point, the sponsor will then go out to the market to find a contractor that can procure the delivery of their design. The procurement at this stage could be done in different forms, such as:

- Procuring packages of the civil works and the various component equipment for the systems from individual manufacturers while the sponsor project manages and integrates the systems and manages the interfaces

- Contracting a master contractor who manages the supply chain and delivery, including interface and integration, for the systems alone, with the civil infrastructure delivered as above
- Contracting a single contractor to deliver systems and infrastructure and manage the interfaces and integration

This was the norm for most projects up until at least the 1980s, when the public sector also retained the ownership of the assets and responsibility of the operation of the core service (Quiggin, 2005). This was also a standard model in the rail sector and is how, until relatively recently, many of the better known promoters like Hong Kong Mass Transit Railway (MTR), British Railway (BR), London Underground Ltd (LUL) and most of the major United States properties have managed the provision of this sort of project.

This method requires a great deal of management and only really works if the client is relatively well informed and either has a sufficiently large technical capability or buys in the technical and PM skills from the consulting industry, in addition to the project legal, financial, environmental services which may or may not be transferred as tasks to the contractor(s).

3.3.3. Design and Build or Engineering, Procurement and Construction

Once again, the sponsor will, up to a point, do the front-end work of scheme definition, feasibility project cost and business case. They will usually do prototypical designs and give the operating requirements and performance requirements. This will be further supported by systems specifications and these days by some basic interface and integration structures. This is often described as developed to '60 per cent or basic design', a description that is popular with promoters such as the international financial institutions like the Asian Development Bank, European Bank for Reconstruction and Development and the Japanese International Cooperation Agency.

The contractor will then take this over as a design and progress to complete and manage the procurement of the materials and workforce through compliance and construction to testing, commissioning and handover.

This can be done as a total project or as a combination of Design, Procure, and Construct for the civil infrastructure and the systems procured as D&B or EPC. Furthermore, the client may decide on larger projects to package the civil work and let these as D&B packages with a system-wide contract for rail systems.

The client will still need to employ or provide from its own resources the PM, supervision and other specialist expertise and will require a level of competence of the client organisation to ensure a successful project is delivered.

It is from these devolved finance and design models that the more recent approaches developed in the 1980s, 1990s and early 21st century.

3.3.4. Public Private Partnerships

Public private partnerships (PPPs) have been defined as *"any alliance between public bodies, local authorities or central government and private companies"* (Roe and Craig, 2004). This wide generic term covers all kinds of deal structures involving the public and private sectors. A private finance initiative (PFI) is defined as:

> *"a more formal [version] of PPP….generally [providing] the capital asset and services relating to that asset. The public sector specifies the level of service in return for a unitary charge."* (Roe and Craig, 2004)

> *"…a form of public private partnership (PPP) that marries a public procurement programme, where the public sector purchases capital items from the private sector, to an extension of contracting-out, where public services are contracted from the private sector."* (Allen, 2001)

Essentially, the PFI involves sub-contracting the design, building and operations of public services (particularly capital assets and related services) to private sector companies in a way that transfers construction and/or operational risk from the public sector to the private sector (Edkins and Smyth, 2006, Quiggin, 2005). PFI was introduced as a policy in the UK in 1992 as a means to increase investment, and in 1997 it became PPPs (Smyth and Edkins, 2007). Since then, it has been further developed through project experience.

Figure 11 shows the shift in the risk transfer by moving to the new procurements strategies as an example.

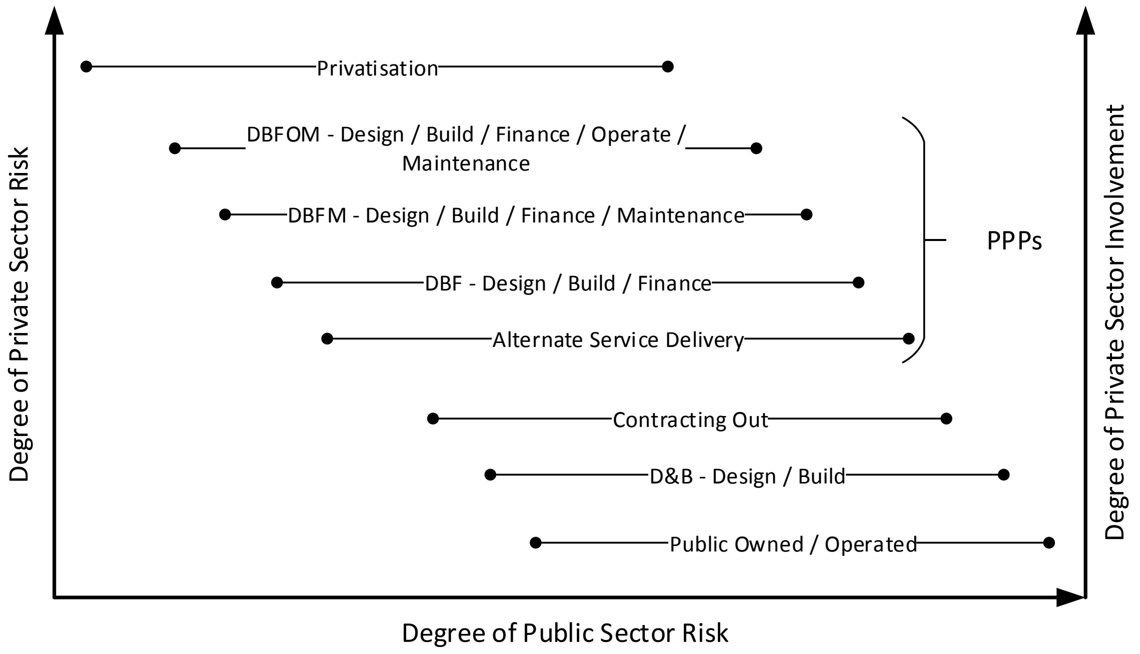


Figure 11: New Procurement Strategies and Risk Allocation

As shown, the more that private sector and contractors get involved, the more the risk is transferred to them. This means the projects will be done much more efficiently and the ultimate client (that is, tax payers in the case of rail projects) carry an overall lower level of risk. The projects should be more efficient because efficiency is a critical factor for the private sector. Therefore, any work leading to improved project efficiency by avoiding resources waste, reworks, delay, etc., is considered to be significant for private sector. This includes improving IM in procurement of multidisciplinary projects with complex technical, managerial, contractual and political interfaces.

3.4. Project Management View of Interface Management

Construction projects, particularly rail, are becoming more complex due to new advances in technology (Shokri et al., 2012) and greater depths of expertise and knowledge, as well as the new procurement strategies discussed above. Therefore, the projects are broken down into many more packages of works/projects, to be executed by many more numbers of parties/contractors. Interface exists when one party needs information from another party to complete a task of the project. It is described as a point of contact between independent organisations (for example, groups, parties, teams) that are interacting to achieve a larger system (Wren, 1967). Interfaces arise during the decomposition of a project into smaller packages of works and contracts and further down to the sub-systems and components (Staats, 2014). Equally the management of interfaces across the whole project is becoming important for each of those contractors. They are under pressure as they need to deliver to time, budget and quality, which could be impacted in the absence of a robust IMS (Tomiyama and Meijer, 2005).

> *"In building construction, interface issues exist between project or building components not only during the design, manufacturing, and construction stages, but also during the operation and maintenance phases of a building and its systems. Due to the lack of IM (interface management), a wide variety of inferior interfaces have repeatedly contributed to design errors, construction conflicts, and inter-party coordination problem on the jobsite. While the awareness of interface issues and IM increases, there is a lack of development of IM strategies and applicable tools, which is considered increasingly more important."* (Chen et al., 2006)

Interface management is also described as:

> *"an effective tool in proactive avoidance or mitigation of any project issues, including design conflicts, installation clashes, new technology application, regulatory challenges, and contract claims, and would enhance the successful delivery of megaprojects."* (Nooteboom, 2004)

Shokri et al. (2012) list the following as some examples of IM applications in construction (Shokri et al., 2012):

- Developing an effective and timely communication between a Main Automation Contractor and a Main Electrical Contractor (Calgar and Connolly, 2007).
- Project safety improvement and reducing the effect of hazardous processes (Kelly and Berger, 2006).
- Defining the human dynamics and communication strategies in agile PM (Chen et al., 2007)

Interfaces are either internal (within a single team and single scope) or external (between teams with a single scope) (Chen et al., 2007, Lin, 2009). And they are either functional (derived from functional requirements) or physical (objects are physical related) (Staats, 2014).

Some researchers believe that the early identification of the interfaces and plan to closing them down, in the design stage of a project, reduces the risk of reworks, resulting in preventing the project running over time, cost and budget (Chen et al., 2007, Calgar and Connolly, 2007, Nooteboom, 2004). It is therefore key for a project manager to identify early the area of interfaces and the parties involved, in order to facilitate interactions, information exchanges and early agreements among them. The actions taken for this purpose, and documents registered as the result, are invaluable for the quality and assurance purpose. Interface management should be an ongoing and iterative process throughout the life of a project with the ultimate goal of managing the balance between scope, time, cost, quality and resources, because as a project progresses, the interfaces change along with new relationships that should be managed continuously (Crumrine et al., 2005, Wren, 1967).

In almost all of the projects in which the author has been involved in the past 10 years, the project team has tried to develop an IM Plan at the early stage of the project to formulate some sort of an IMS that can address the issue. In a generic format, an IMS should cover the interface identification, interface assignment (ownership), interface communication, interface management (control and monitor), and interface close out as the key tasks (Lin, 2009, Calgar and Connolly, 2007, Pavitt and Gibb, 2003). Still, in any new rail infrastructure project, IM is a challenge and a risk to the project delivery.

In reviewing various PM textbooks, it is difficult to find a specific topic on IM. In the *APM Body of Knowledge*, for example, there is no heading on IM and only a few references to managing the interfaces under sections like stakeholder management, change control or conflict management (Association for Project Management 2006). Similarly, the *Handbook of Project Management Procedures* has no section for IM and only some references under the communication management plan, change report and change order sections (Hamilton, 2004).

Unfortunately, in construction projects (including rail sector), IM is mostly seen as a natural, even hidden aspect, of PM and the impact of it on project delivery is underestimated (Nooteboom, 2004).

> "*Currently, it is not widely known what IM means in construction and what scope is covered by IM.*" (Staats, 2014)

Interface management is important because it will help prevent the project from unnecessary reworks, therefore ensuring that the project will be delivered earlier, safer and to the performance specified by the client. This means that better IM results in more efficient PM. As a result of recent changes to the construction projects, researchers in the PM field are focusing on IM in construction projects, establishing different definitions (Chen et al., 2007).

Many of projects have been delivered late and over budget because of unnecessary extensions due to integration issues. In many such 'failed projects', the most expensive mistakes and delays are traced back to integration issues between the different design teams (Staats, 2014).

Many publications describe inefficiency in managing the communications over the interfaces (that is, IM) as a major cause for project cost and schedule overruns in mega-projects (Nikander and Eloranta, 2001, Nitithamyong and Skibniewski, 2004, Han et al., 2007, Jergeas and Ruwanpura, 2010, Wong and Zhang, 2013, Shokri et al., 2015).

Regarding London's Thameslink project, the National Audit Office (2014) reports that:

> *"Despite the programme's size and complexity, the Department did not devote enough attention to managing interdependencies between the infrastructure, train and franchise early on. The 3-year delay in procuring trains has made delivering other parts of the programme more complex. When we reported in 2013, the Department was expanding the programme management role of the Thameslink systems integration team, and establishing an 'interface steering group' to address interfaces between the infrastructure and other department-led programmes."* (National Audit Office, 2014)

In the same report, they show the shift in the management approach to focusing more on the interfacing and integration by reporting on the ongoing Crossrail project as follows:

> *"In contrast, Crossrail Limited's plans for integrating the programme were well advanced relative to other rail projects we reviewed. A director of operations reporting to the chief executive was in place from 2006 to 2008 during the development of Crossrail plans. In addition, operations staff have been in place throughout the programme. Crossrail Limited recruited the current operations director in early 2013, in advance of the appointment of the operator. The Joint Sponsor Team also worked closely with the Department's Crossrail and franchising teams to align Crossrail with other rail services."* (National Audit Office, 2014)

'French red faces over trains that are "too wide"' was the BBC's headline regarding a massive debacle which dominated global headlines. SNCF, the French train operator, realised that the 2,000 brand new trains it had ordered at the cost of €15 billion were too wide for many of France's station platforms (BBC, 2014b, BBC, 2014a). Although more detailed investigation is taking place, the nature of an error is rooted in a lack of proper IM.

3.5. Systems Engineering

Systems engineering in complex projects is the emerging solution to transfer the project governance from 'project base' to 'system base' to increase the chance of success that can be applied at different levels and different stages of a project (Locatelli et al., 2014, INCOSE, 2006, Calvano and John, 2004, Smartt and Ferreira, 2011b, Bahill and Clark, 2001). Applying SE in today's rail sector projects is also getting more attention (Elliott et al., 2011). Systems engineering is a collection of tools, techniques and methods, and cradle-to-grave technical points of contact for the project, that are bound together by some shared ideas (Elliott, 2014, Smartt and Ferreira, 2011a, Chen and Clothier, 2003). Ideas and objectives to make PM more efficient by providing a systematic approach and interdisciplinary supervision of the design help ensure that the project will successfully deliver the main objective and so the user 'need' (Loureiro et al., 2004). As a systems engineer working in the rail sector and facing complexities in PM, the author is trying to use any opportunity to adopt the SE approach to the benefit of PM.

As explained in Chapter 1, although the SE adoption on PM is not the main focus of this research, to achieve the objective of this study, it is important to understand ST and SE fundamentals. For this reason, the following part of this chapter gives a very detailed review on ST and SE, including their origin, definition, applications in construction projects and relationship to PM activities.

3.5.1. Systems Engineering Background

Using the term 'systems engineering' as a technical discipline is traced back to the 1930s where Bell Communication Co., used this approach in its Telephone Laboratories. A table in the International Council on Systems Engineering (INCOSE) handbook (see Table 7) shows a summary of the development of SE as a discipline over last 200 years (INCOSE, 2006).

Table 7: Key Dates in the Origins of Systems Engineering as a Discipline (INCOSE, 2006)

Date	Event
1829	Rocket locomotive: progenitor of main-line railway motive power
1937	British multidisciplinary team to analyse the air defence system
1939–1945	Bell Labs supported NIKE development
1951–1980	SAGE Air Defence System defined and managed by MIT
1956	Invention of systems analysis by RAND Corporation
1962	Publication of A Methodology for Systems Engineering
1969	Jay Forrester (Modelling Urban Systems at MIT)
1994	Perry Memorandum urges military contractors to adopt commercial practices such as IEEE P1220
2002	Release of ISO/IEC 15288

In 1992, the National Aeronautics and Space Administration (NASA) issued SE handbook as a formal document for the first time. The initial work to develop this document, however, was started in 1989 (NASA, 1995). Since then, various documents in the form of handbooks, user manuals, tool manuals, reports and standards have been developed and issued by various organisations and companies to explain SE and SE management in different domains.

3.5.2. Systems Engineering Definition

Systems engineering is described in different books, publications, handbooks and reports in different forms and characters. However, they all share the same concept of engineering of a system based on ST (Davidz and Nightingale, 2008). In fact, in many of the publications the term ‘systems engineering’ comes together with ‘strategy’ (Smartt and Ferreira, 2011b) which is based on ST.

The goal of ST is to understand how different components of a complex system work and interact (Twisk et al., 2015, Leveson, 2002, Skyttner, 2005). This means realisation of a system as a whole and understanding how the small parts work together to form the project/system as a whole. This is how the impact of the parts in the whole system can be realised and problems can be resolved before they become issues (Leveson, 2002).

> *“Complex systems cannot be understood by studying parts in isolation. The very essence of the system lies in the interaction between parts and the overall behaviour that emerges from the interaction. The system must be analysed as a whole.”* (Ottino, 2003)

Systems engineering in management of an engineering design is a systematic approach and inter-disciplinary supervision of the design to ensure that the project need and objective are well understood and realised and that the project requirements are well captured and modelled. It is also a solution to ensure that the project design and implementation’s different elements and sub-systems mesh coherently to provide a system which works together correctly as a whole.

The NASA SE handbook defines SE as a *“methodical, disciplined approach for the design, realization, technical management, operations, and retirement of a system.”* (NASA, 2007)

The INCOSE engineering handbook uses three representative definitions to illustrate SE as a discipline, a process and a perspective (INCOSE, 2006):

- *”Systems engineering is a discipline that concentrates on the design and application of the whole (system) as distinct from the parts. It involves looking at a problem in its entirety, taking into account all the facets and all the variables and relating the social to the technical aspect”* (Ramo, 2002).
- *“Systems engineering is an iterative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near*

optimal manner, the full range of requirements for the system" (INCOSE, 2004, INCOSE, 2006).

- *"Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems"* (INCOSE, 2004, INCOSE, 2006).

Systems engineering introduces a systematic approach to the PM of complex multidisciplinary projects in project realisation, requirements capturing, project scoping, planning, scheduling and managing. In such projects, the complexity of the project and number of parts that should be designed and implemented individually and assembled as a whole can be very challenging for the project managers. Each of these parts could potentially be a big project on their own in a large scale and size and therefore should be well managed individually.

> *"With increasingly complex systems, relying on systems engineering as an interdisciplinary method to manage engineering processes is essential for companies."* (XUE et al., 2014)

Systems engineering and PM are described as the two essential aspects in success or failure of a project (Boarder, 1995) and, therefore, the two should work together in an integrated management system (Emes et al., 2012).

3.5.3. Systems Engineering Essential Procedures and Tools

The author has been involved in rail infrastructure projects in the past 10 years. Based on his experience, the core responsibility of SE is the realisation of the project as a system and modelling the project requirements, as well as understanding and managing the interfaces between various small parts of the system. In theory, managing the scope and requirements, as well as managing the interfaces and integration within PM, are the main functions improved by an SE approach. In contrast to the lack of discussion on IM in PM literature, as described earlier, SE has more references to IM but still not in a great detail. Therefore IM in SE literature is also scarce (Staats, 2014). The *INCOSE Systems Engineering Handbook* does contain a section on systems integration and some materials related to IM (INCOSE, 2006).

In recent rail infrastructure projects, different processes, procedures, tools and documents are developed to adopt SE in the life cycle of a project. These vary depending on the nature and complexity of the project. The following section provides a brief description of the SE life cycle and the key processes and tools used in construction projects.

3.5.4. Systems Engineering Life Cycle

The SE life cycle is an iterative work cycle adopted to manage a project on a 'cradle to grave' basis. The focus is based on ST to see the project as a system and to break it down into smaller parts/sub-systems.

By adopting a SE approach to the PLC, periodic and iterative verification stages will be established in which the progress of the project and compliance with project actual requirements will be verified. The system life cycle is a process which defines the order that information should be developed and produced. The system development can follow a sequential linear process called waterfall or a V-Model with verification and validation stages.

In the waterfall system life cycle, users, developers and designers have responsibility for separate parts of the information individually (Stevens et al., 1998). In this life cycle, each step of the life cycle acts as a milestone in which the progress of the project can be monitored. The feedback and the consequent changes at each stage will be taken into account before moving to the next stage. Figure 12 presents a simple view of such a life cycle (Stevens et al., 1998).

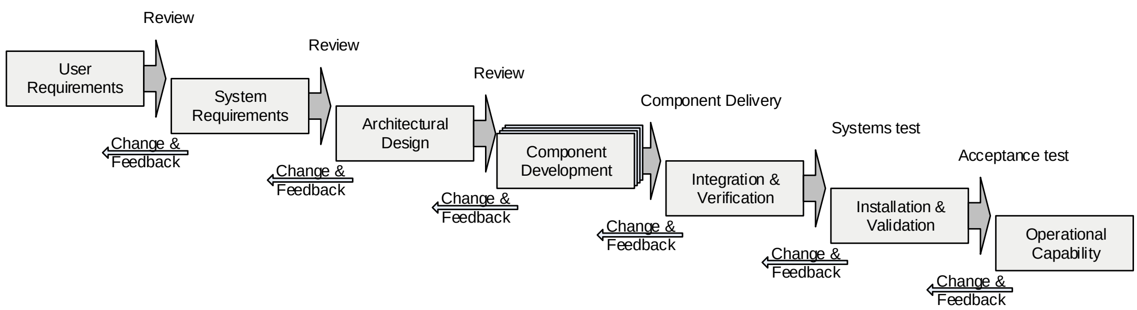


Figure 12: System Development Waterfall Life Cycle (Stevens et al., 1998)

The V-Model, however, is a system development life cycle in which the verification happens across the horizontal links as well as between the definition phases (Stevens et al., 1998). As Figure 13 shows, the project first goes through realisation. This means, as per the left side of the V model, 'what should be built' by the project should be identified and verified through ST by breaking down the system into smaller parts (sub-systems) and defining the system architecture. Once the system is defined, components will be implemented and developed.

Components will be tested and procured as per the right side of the V-model, and the integration and system test will be verified. The process continues all the way to the system operation where the developed system can be validated against the user requirement (user satisfaction).

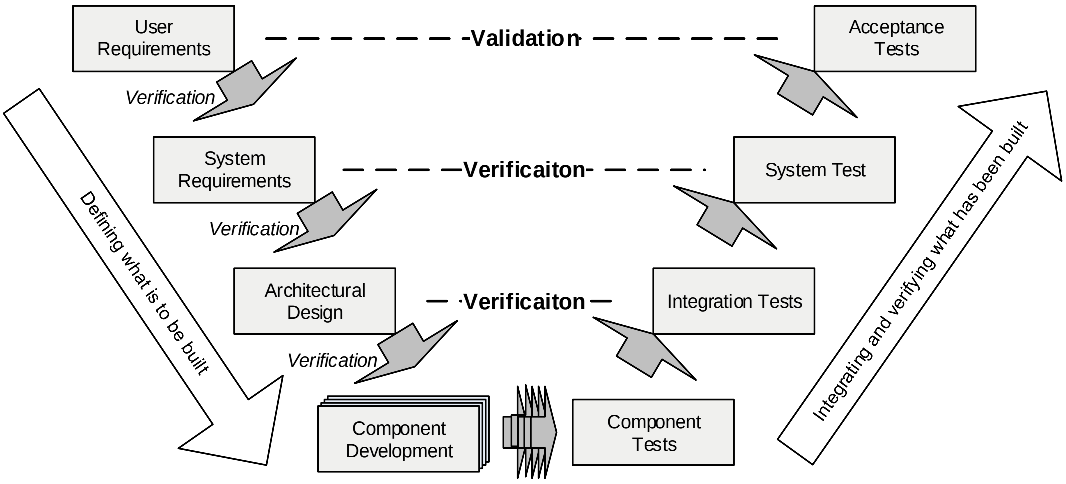


Figure 13: System Development V-Model Life Cycle (Stevens et al., 1998)

3.6. Systems Engineering View of Interface Management

3.6.1. System (Project) Interfaces

A ST view suggests that a system is completed (that is, the project has achieved its objectives) only when all the smaller parts of the system (sub-systems) are assembled and integrated and they can work together well with minimum error. Depending on how the project works are broken down, sub-systems potentially are either work packages (WPs), discipline tasks and responsibilities, teams and organisations or another form of work breakdown.

In manufacturing a complex product, sub-parts are designed and developed based on a separate, concurrent engineering approach. In train car manufacturing projects for example, the parts of the train are designed and manufactured separately and sometimes in different countries. Therefore, design and implementation of most of the modules of the product are highly dependent on information from other modules and parts.

Projects in the rail infrastructure sector are complex, and many disciplines and specialities are involved to deliver the project. Often, the scope of a small WP (sub-system) of a project is a complex project itself in which the level of integration is much greater. Therefore, it is necessary to have all sub-systems work and objectives well-coordinated. It is also important to understand how sub-systems are created. The design engineering of a typical new railway project needs many different engineering disciplines to work together and design different systems and sub-systems.

In a simple world, a project interface exists where there is either a physical link between two components of a project or where information from one component is required in order to complete the design and implementation of the other component, as described above.

> *"Interface is defined as the contact point between relatively autonomous organizations which are interdependent and interacting as they seek to cooperate to achieve some larger system objective."* (Wren, 1967)

Systems interfaces also are either hard or soft and either internal or external. The interface is internal when the work should be performed and coordinated in a single organisation (or discipline), and the interface is external when the work should be performed in more than one organisation (or discipline) (Healy, 1997).

3.6.2. Systems Interface Management

The flow of design parameters, work instructions, space scheduling information and resource use, must be coordinated across the abstract boundaries between all the project sub-systems (Chua and Godinot, 2006). Where the attributes and the information of one sub-system cause any constraint for the other subsystems, inadequate control of this constraint could potentially lead to work disruptions and reworks due to interfacial mismatch (Chua and Godinot, 2006). Interface management has been defined in various other literature in different contexts. Wren's paper (Wren, 1967) contains an excellent list of references in which various definitions and applications on IM in different environments are discussed.

As discussed earlier, systematic IM normally covers the following items (Lin, 2009, Calgar and Connolly, 2007, Pavitt and Gibb, 2003):

- Interface identification – requires a system decomposition and interaction analysis
- Interface ownership – requires assignment the interfaces to the owners
- Interface communication – facilitates the communication between parties over the interfaces captures and identified
- Interface control and monitoring – manages and monitors the close out of the interfaces
- Interface closing out – documents the close out and assuring the compliances

For the purpose of this research, the definition below is assumed for IM from the SE point of view:

> *The SE definition of IM is understanding of the parts of a system, realisation of the relationships between these parts and facilitating inter-links in order to complete a fully integrated system made of all the sub-systems.*

Over the past 10 years, the author has developed IM procedures and tools for many international rail projects, documented in different reports and plans (Sanei, 2011). In all of these projects, the author tried to cover the steps required in systematic IM. The author introduced the framework below on many of the rail projects as a backbone for the IMS:

1. <u>*Project/System Decomposition:*</u> Break down the project/system into small parts/sub-systems (as presented in Figure 14) in order to access to the lower level of the system and to understand and manage the system as a whole.

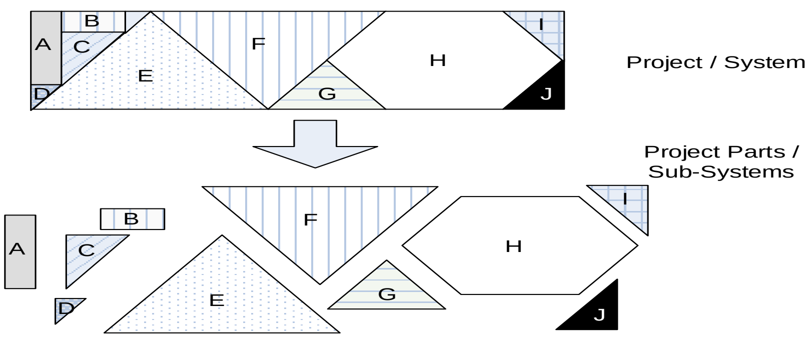


Figure 14: Project Decomposition

2. *Interface Identification:* Understand the inter-relationship between small parts of the project/system and identify the areas of interfaces by developing a N^2 interface matrix, as shown in Figure 15.

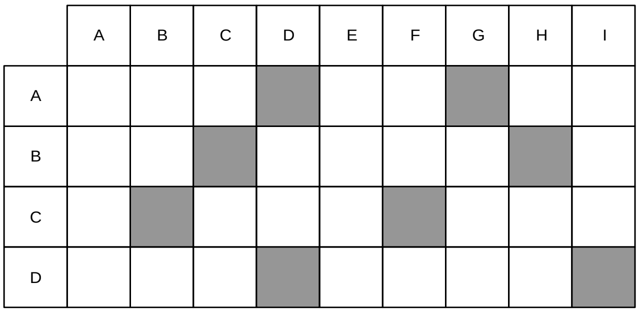


Figure 15: Interface Identification – Interface Matrix

Matrix to visualise the areas of interfaces between parts of a project

3. *Interface Allocation:* Assign interface responsibility to various parties and suppliers of the sub-systems to provide interface resolution. Each of the parties in the interface points have owners that should take the responsibility of the interfaces, as shown in Figure 16.

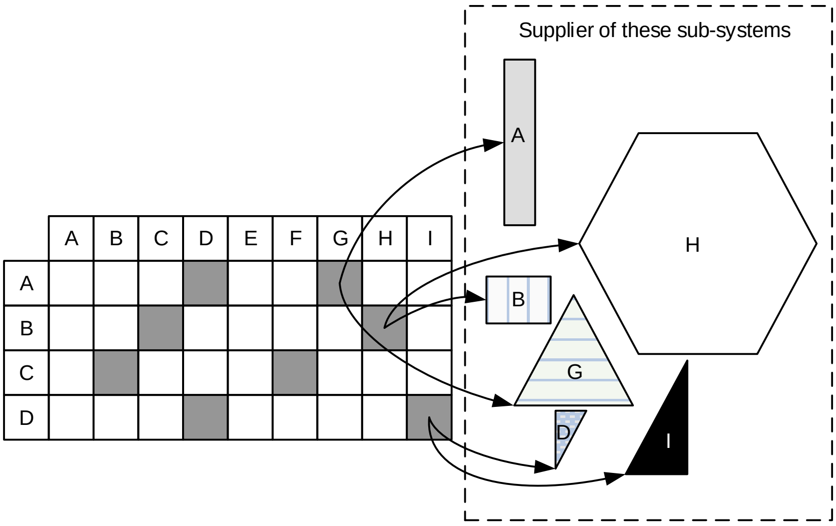


Figure 16: Interface Allocation to the Sub-system Suppliers

Allocating the responsibility of the interfaces to the relevant parties / suppliers involved

4. *Coordination and Communication:* Develop communication and coordination paths to facilitate the management of the interfaces between assignees.
5. *Interface Resolution:* Assign works to assignees to develop interface resolution.

6. *Interface Closeout and Verification:* Provide assurance evidence to verify the interface close out by developing identified interfaces to the project deliverables which can certify the resolution of the interface (see Figure 17).

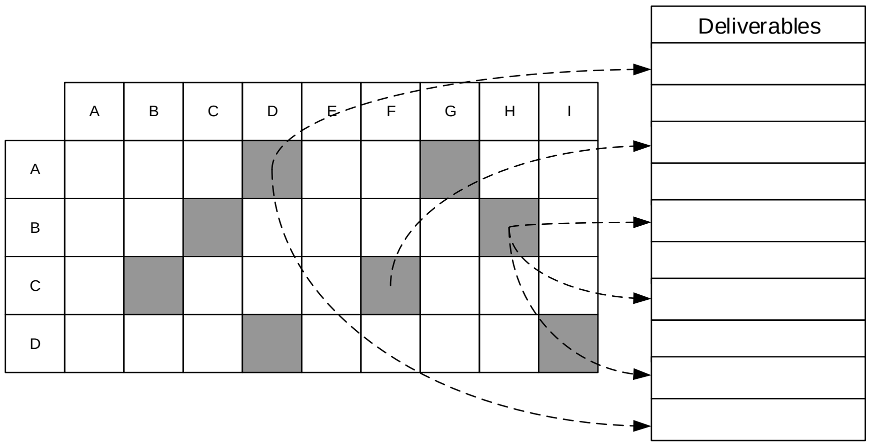


Figure 17: Interface Closeout – Evidence and Certificate

Interface management plays a key role in SE in complex multidisciplinary rail projects. Various methods and applications are developed and customised to adopt a systematic interface and integration management.

3.7. Project Management and Systems Engineering Activities

3.7.1. Requirements Management

The project requirement is the statement of what the customer needs (Macaulay, 1996). The project requirement states what a specific product should do or what a particular service should be. Systems engineering suggests that the requirements of a project should be captured and analysed in a structured format. They must be registered in a form of a document which clarifies the necessary attribute, capability, characteristic or quality of the system. Requirements engineering is the engineering process of developing and populating the requirement document (Macaulay, 1996).

In a multidisciplinary rail PLC, there are many types of requirements that need to be managed from design to completion. The formal requirement phase in a project includes the process of requirements elicitation, analysis, definition and specification. In a process of project development, requirements can be categorised as five major groups as follows:

1. *User requirements:* What the end user needs from the product or service. User requirements are either an affordance or a constraint imposed by a user (Alexander and Stevens, 2002, Henderson and Venkatraman, 1993, Kaplan and Norton, 2004).
2. *Business requirements:* Business requirements drive the goals of the business to increase profit, decrease costs, improve data management, increase knowledge transfer and improve efficiency. Business requirements are about defining goals pertaining to the external business market that are defined and elaborated by the organisation's top management (Babar and Wong, 2012).

> *"A business strategy is about defining a precise and meaningful set of financial and differentiating customer value targets agreed upon by all the top management. This indicates that the top management is involved in defining the strategy"*(Babar and Wong, 2012).

3. *Technical requirements:* The project should be designed, planned, developed and delivered to the technical specifications and standards specified as technical requirements for the system. The final delivery of a project should fulfil the technical requirements.
4. *Functional/Non-functional requirements:* Functional requirements are the behaviour of the system which may be expressed as services, tasks or functions that the system is required to perform (Malan and Bredemeyer, 2007). Non-functional requirements, however, include answers to the question of how well the system must perform the functional requirements (how fast, how accurate, how reliable, how user-friendly, how precise, etc.).
5. *Process requirements:* Procedural requirements include processes, limitations, methods, techniques that are required to be used in project development processes.

Studies show that in more than 60 per cent of failed software projects in the United States, 'poor requirements' is one of the top five reasons (Visitacion, 2002). Based on analysts' reports, 71 per cent of software projects globally fail because of poor requirements management (RM) (Lindquist, 2005). Lindquist (2005) further states that poor RM is the single biggest reason for project failure, even bigger than bad technology, missed deadlines or change management fiascos. Other studies also show a high percentage of project schedules overruns, with 80 per cent due to creeping requirements (Jones, 1994). As shown in Table 8, five of the eight major reasons for software project failures are requirements based (Alexander and Stevens, 2002). The table also suggests that the other three reasons relate to management while, interestingly, none are technical related (Alexander and Stevens, 2002).

Table 8: Reasons for Project Failure (Alexander and Stevens, 2002)

Reasons for project failure	**%**
Incomplete requirements	13.1
Didn't involve users	12.4
Insufficient resources/schedule	10.6
Unrealistic expectations	9.9
Lack of managerial support	9.3
Changing requirements	8.7
Poor planning	8.1
Didn't need it any longer	7.4

Figure 18 projects the expected cost and duration reduction of an application development project when the RM is applied on a project.

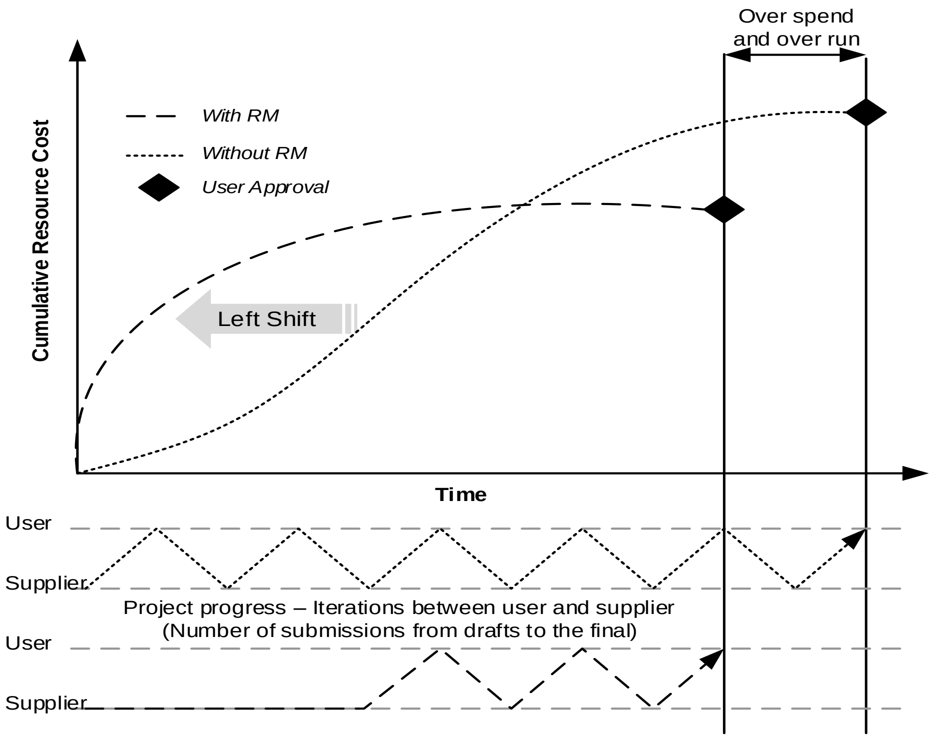


Figure 18: Reduction of Cost and Duration during Design Development

As the figure shows, in a project without RM, more iterations (that is, submissions of draft works) between project supplier and user will happen when compared to a project with RM. Therefore, more project resources will be spent over a longer time to achieve the user approval of the final submission (that is, project completion).This figure also presents the benefit of RM on project management performance. Where RM is not adopted, a project goes to execution straight away. Fewer resources are required at the beginning of the project, but more will be used over a longer time to achieve the user approval. However, in a project with RM, more resources are required at the beginning of the project to capture and manage the project requirements. Therefore, where a clear set of requirements is available, an efficient number of resources are used over a shorter time to achieve the project completion and user approval. This represents the left shifting concept presented in literature (Emes et al., 2012, Emes et al., 2007):

> "*The idea of left shifting to invest effort in the early stages of projects will seem like common sense to most systems engineers.*" (Emes et al., 2012)

3.7.1.1. Project Management View of Requirements Management

For PM, it is important to capture the requirements and establish a common understanding among all project parties and stakeholders at the beginning of the project. Different stakeholders have different understandings of the project requirements from their own point of view (Maylor, 2003, Alexander and Stevens, 2002). These understandings need to be managed, and agreement should be achieved in order to have a same expectation from the project objective and to protect the project from going to the wrong direction.

In classic PM, project requirements often are defined when the project objective is identified from the scope of the work (Association for Project Management 2006). For this reason, PM literature describes scope management and managing the requirements as hand-to-hand processes (Association for Project Management 2006, INCOSE, 2006).

3.7.1.2. Systems Engineering View of Requirements Management

As discussed, SE introduced in recent construction projects mainly focuses on IM and RM. Management of the requirements in a multidisciplinary project is essential to successful delivery of the end results. Systems engineering introduces an RM system that can enable the project team to track and demonstrate the close out of the entire project requirements (INCOSE, 2006). RM is a dynamic process with systematic activities throughout the PLC to provide assurance that the project's requirements are identified and understood at the early stage of the project. In short, RM is the science and art of gathering and managing requirements in a project. But what is important in the RM from the SE point of view is the fact that in SE, the project is broken down into the systems and sub-systems, and the requirements should be managed within different levels of the system (INCOSE, 2006).

The key to successful requirements management is a harmony and balance. Therefore, it is essential to develop a communications path among members of the development team. It should identify who owns each of the requirements and who will be responsible to deliver which requirement.

3.7.1.3. Requirements Allocation

When project requirements are captured, they need to be assigned and allocated to the right supplier to be delivered (Parsons and Wareham, 2010). In traditional PM, a WBS is the best mechanism to categorise, level and assign the requirements to each WP and therefore to the relevant supplier/discipline.

This study intends to explore the constraints and issues with this technique and propose a new solution to overcome the problem.

3.7.2. Scope Management

Scope management is described in in the APM BoK as:

> *"the process by which the deliverables and work to produce them are identified and defined."* (Association for Project Management 2006)

To define and manage the scope of the projects, various documents – typically a WBS, Product Breakdown Structure (PBS), Cost Breakdown Structure (CBS) and Organisation Breakdown Structure (OBS) – need to be generated.

Where the end result of the project is a physical product, a WBS will typically be developed from the project PBS. The PBS is a tree model of the project end products which should be delivered by the project.

In traditional PM, WBS and PBS drive the development of the project OBS which sets the project organisation and resources required in order to execute the project (see Figure 19).

Allocating duration, start and end time and priority to each WP in WBS is project scheduling. Project scheduling leads resource and cost planning and presents the performance of the project. This is the phase in which documents such as the CBS will be created. Project scheduling also sets the milestones which will be used to measure the progress and the success rate of the project. When the scope of the work is clear, the requirements can be developed.

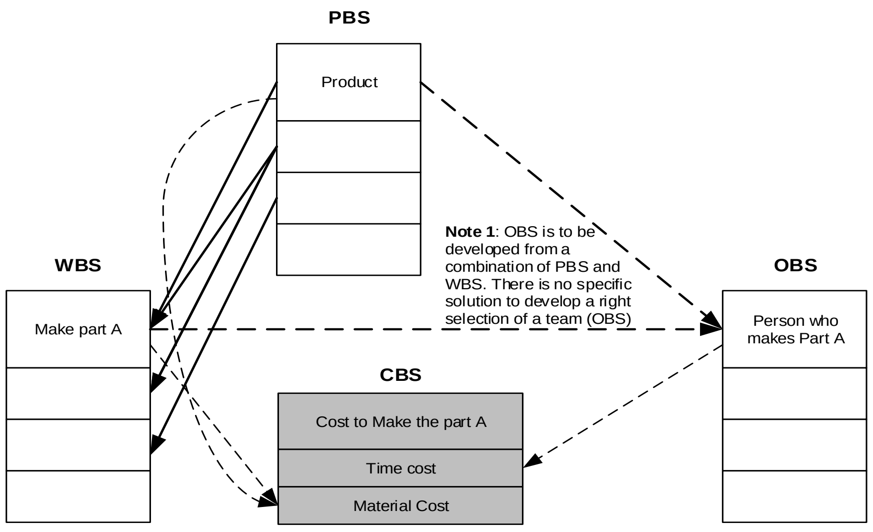


Figure 19: Project Management Breakdown Structures

3.7.3. Assumption Management

Assumptions need to be made in order to continue with the part of the work when there is uncertainty. The work continues based on the assumptions, but changes to the assumption status can impact the overall project, posing a risk to the completion of the project.

Managing the assumption in PM goes hand-in-hand with managing the requirements. In most cases an assumption will become a requirement or will change other requirements. For this reason, the PM view is to manage assumptions by registering them along with the requirements and link them to the requirements with dependencies so the impact of the changes to the status can be captured and managed. Relevant parties should be aware of these assumptions and should act once there is change in any of these assumptions.

Similar to the requirements, the project team will use various solutions and documents to link the assumptions to the parties involved and often a breakdown structure is required to enable the PM team to assign this assumptions to the right owners.

3.7.4. Quality Management

As discussed, the project scope, requirements and interfaces are captured and managed through project execution in different ways. There is, however, a need for a high-level of quality control ensuring that the end result of the project will satisfy. In fact, a process is required to provide assurance that the various systems and sub-systems operate correctly in the first place so that the overall project fit for the purpose.

> *"Quality management is the discipline that is applied to ensure that both the outputs of the project and the processes by which the outputs are delivered met the required needs of stakeholders. Quality is broadly defined as fitness for purpose or more narrowly as the degree of conformance of the outputs and process."* (Association for Project Management 2006)

In order to deploy a quality management (QM) process, the PM team should develop a QM Plan that addresses quality planning, quality assurance, quality control and continuous improvement (Association for Project Management 2006). The process should be deployed from the lowest level of the components and sub-systems to provide assurance that every element is designed correctly and will work as specified.

In order to access the various layers of the project activities and responsible parties, there is also a need in this process for a form of breakdown structure that enables the quality team to discover the project in different layers.

3.7.5. Resource Management

Execution of a project requires various types of resources, including people, materials, knowledge and funding. Resource management is the identification and assignment of the appropriate level of resources to different tasks within a project. Resource management ensures that appropriate resources are made available at the right time and location to be used with a project in a certain period of time. Various techniques such as resource allocation, smoothing, levelling and scheduling are used in PM to manage the resources (Project Management Institute (PMI), 2006).

As a basic document, an OBS may be developed at the early stage of the project, based on the knowledge and professions required in order to achieve the objective of a project. OBS is a tree model structure, which can be used to model the level of resources needed for the project and when. As presented in Figure 19, the PBS and WBS are major drivers in traditional PM to develop the OBS.

3.7.6. Commercial Management – Budget and Cost

Project budget and cost management is defining the project budget based on the project cost estimate and managing the project actual cost against the budget while taking into account the project progress and delivery (Healy, 1997, Lichtenberg, 1983).

The project cost estimate will normally be developed in the project definition phase. The approved estimated budget will become the project budget. Cost is a main factor to measure the level of project success, and this is essential to achieve the project objective within the project budget and timeline (Project Management Institute (PMI), 2006). In order to establish effective cost management, a solution is required to monitor the actual cost against the project budget in lower level of the project tasks. Therefore, a model is required to have a direct link between the project costs to the project budget for the WPs within the project. Without cost management, it will be very easy to overrun the cost before achieving the project objectives. The CBS is a tree model breakdown structure of the project budget which presents the project overall financial status in total.

In traditional PM, a CBS is developed against the WPs within the WBS or against the time and cost required by the project resources (the OBS) (Association for Project Management 2006). In more complex projects, a combination of both may be used.

3.7.7. Risk Management

Risk management is a systematic process to identify the project risks and plan to mitigate them to maximise project success. In order to perform a risk management process, there is a need to develop a Risk Plan and Risk Register at the early stage of the project (Aleshin, 2001). Once they are established, project risks should be registered in a central project risk management tool along with mitigation plan, impact factor and any other items related to the individual identified risk.

Risks should also be allocated to the relevant owners who are responsible to mitigate the risk. Therefore, a kind of a breakdown structure should be used by the project risk process to facilitate assigning the risk to the relevant owner(s) (Holzmann and Spiegler, 2011, Iranmanesh et al., 2007, Hillson, 2003).

3.7.8. Issue Management

Various events may happen during the life cycle of a project which will threaten the achievement of the project objective. Resolving the ‘project issue’ is often beyond the capability of the project manager. An issue may be identified at an early stage of a project as a risk which then becomes an ‘issue’ when they actually happen. A project issue, however, should not be confused with a project risk. Risk is uncertain and it might not happen, while an issue is certain and has already happened. A project issue is also different from a ‘problem’. Problems happen in a project and they can be resolved by the project manager, while project issue is a problem which cannot be handled by the project manager and is normally outside of the project manager control (Project Management Institute (PMI), 2006). For a complex project it is very important to develop a logbook to keep all the project issues.

Similar to project risks, issues need to be registered and linked back to the parties who will be impacted and to those who are responsible. The Issue Register is another document which needs to be developed in the PM process and assigned to various project suppliers. Therefore, a form of a breakdown structure of the project is deemed to be necessary for this assignment and management.

3.7.9. Project Environment and Stakeholder Management

When the project is defined, the project environment should be well understood. Different parties who have an interest or role in a project or who will be impacted by the project are the project stakeholders (Project Management Institute (PMI), 2006). Project stakeholders should be well identified in advance and their role, influence and level of impact should be defined and registered. Stakeholders do have a key role in defining the level of success in a project (Project Management Institute (PMI), 2006), and it is essential to have a plan to establish and manage the communication and integration routes with them. Requirements and interests of each of the stakeholders also should be understood and captured in various registers, such as a project stakeholder requirements register. It is important that a stakeholder management system be implemented in a complex project; this is essential to design and develop various tools and documents to enhance the management process of the stakeholders and their requirements, interest, impacts and interfaces.

Developing linkage between such registers to other PM documents and procedures is an important challenge for the PM of any type.

3.8. Integrated Management Tool

Many other tools and documents may be developed in a management of a project depending on the project size and complexity. These include a change register, technical query register, action register and communication register.

The challenge to the management of the major multidisciplinary complex projects is how all these tools and documents can be interlinked – how they can talk in the same language and how best to capture, assess and manage their impact on each other to mitigate the project risk and, therefore, assure the project success. In traditional PM, this is quite a challenging topic and there is no specific formulation to find a solution to link all the project documents and tools. As discussed, project managers use different documents, tools and procedures in different environments, making it very difficult to track changes to any item, causing heavy reliance on human intellectual activities and increasing the risk of human errors.

What is common from the discussions and brief descriptions of the PM processes above is the fact that one form of a breakdown structure of the project is always developed and used for all the PM and SE processes. Some are developed around the WBS, some PBS or OBS and some based on other different parameters.

An integrated management system, therefore, will be the solution to make PM much more efficient (Loureiro et al., 2004). In fact, the SE and PM activities, tools and documents need to be interlinked in an integrated management process (Emes et al., 2012).

3.9. Conclusion of the Chapter

This chapter explained PM and its essential tools and processes in the context of multidisciplinary construction projects with a brief reference to the rail sector.

It also explored the need for a better IM system in rail infrastructure projects by looking at the new procurement strategies as well as the complexity of the projects. It then detailed the importance of an IM system in PM efficiency, supported by many examples of projects that failed due to the lack of a proper IM system.

The SE approach as a discipline was described in more detail, and its relationship to PM in different sectors over the history was further investigated. The SE life cycle, activities, tools and procedures were briefly analysed, and the relation to today's projects was discussed. A literature review explored and detailed the role of SE in the execution of infrastructure projects.

In exploring the PM processes and tools, this chapter explained that the PM procedures and tools all require a form of a breakdown structure to be able to function correctly and communicate more efficiently. All parties should be informed periodically of changes to the status of this information to enable the PM and project team to perform impact assessments as required. For this reason, it was discussed that in traditional PM, a WBS is the core that links the various aspects of project planning and project design.

It was further concluded that there is a need for an integrated management system to make PM more efficient. Although no specific solution could be found in the literature and real projects to suggest that a WBS can interlink all the tools and procedures within SE and PM functions and activities, it was discovered that the project managers and systems engineers tend to use WBS as a form of a breakdown structure to categorise the project into smaller parts and manage the processes. For this reason, Chapter 4 presents detailed research on the definition, origin and applications of a WBS.

This chapter made two important points that need to be further explored to lead the research to achieve the objectives:

1. Interface Management is very important in multidisciplinary infrastructure projects. The focus of this research is to improve the IMS by developing a new solution and framework. For this reason, Chapter 4 presents more detailed research on existing IMSs.
2. An integrated management system is required to link the SE and PM activities, processes and tools. The solution must be a breakdown structure format in order to access to the different layers of a project/system information and components. WBS is identified as one of the most used documents by the project managers in industry.

Chapter 4 WORK BREAKDOWN STRUCTURES

4.1. Introduction

Chapter 3 concluded that project managers tend to use a Work Breakdown Structure (WBS) to categorise their projects into smaller parts and manage the project management (PM) processes around WBS elements. It also expressed the need for a novel structure which can be used as a core to develop an integrated management system by linking systems engineering (SE) and PM activities and tools (Emes et al., 2012). It was further expressed that this structure must be based on a breakdown structure (Chua and Godinot, 2006) in order to access the different layers of a project information. Chapter 3 therefore concluded that a modified version of the WBS or a new breakdown structure could potentially be the solution that is required to link PM and SE functions and activities to form an integrated management system.

The WBS is an approach for project planning which breaks down the project tasks in a hierarchical format into measurable and manageable packages. In addition to the key role of the WBS in project planning, the WBS is a vital part of management that could potentially be able to link all PM processes, including cost management and scheduling, risk and issue management, configuration management and their associated tools and documents, including various project schedules and registers (for example, requirements schedule, interface schedule, assumption register, issue register and action register). Project management tends to use different forms of information breakdown structure (like WBS) to categorise and manage the other part of the management processes; however, there is no well-defined rule or technique to formulate the use of a WBS for these tasks. The main reason for this is the WBS's constraints, limitations and development processes as well as differing views of the WBS.

This chapter revisits the WBS concept, as well as the concept of breakdown structure, along with its origins, varieties and relationship with organisational structure. The applications of the WBS will be further explored within various literature. The relationship between the WBS, interface management (IM) and systems engineering within multidisciplinary complex projects and PM will be further explored. A modified version of the WBS that adopts a systems thinking (ST) and SE approach to the WBS concept will be introduced, and its limitations and constraints will be further discussed.

4.2. Work Breakdown Structure

The WBS is a hierarchical division of work elements, the totality of which forms the scope of a project. It is fundamental to the planning process and is the natural manifestation of a ‘divide and conquer’ approach. The WBS has become a main tool to drive project planning, monitoring and hence efficient managing by slicing the works into small packages based on, for example, the project subsystems, phases, stages, location, organisation or a combination thereof. The WBS has been used in different types of projects in different domains for over half a century.

While there are various definitions for WBS, they all define the concept in a same way. To some, the WBS is a vehicle for allocating WPs to subcontractors. To others, it is a detailed itinerary of all that needs to be done (and specified) to achieve the project goals. For many, the value of the WBS is realised throughout the project. For others, its main benefit is to ensure that through its creation, the scope of the project is fully explored. In one guise or another, a WBS is present in the large majority of projects.

The nature of the WBS will depend upon the nature and the PM approach of the organisation that is to undertake the project, as well as any applicable regulations or obligations. Supply chain organisations for example, are structured around discrete identifiable elements of the project deliverables, while other organisations like, engineering consultancies are partitioned around specific knowledge and capabilities that are integrated within the project as a whole.

The format of a WBS, therefore, is not likely to be unique, and many forms which describe the same scope can exist. Choosing (or finding) the right format is key to the creation of an effective WBS and, while central to PM, there are few specific rules or techniques for their formulation which take into consideration both the differing uses and the differing nature of organisations.

4.2.1. Origins of the WBS

The WBS concept was born in the US Department of Defense (DoD) within its Program Evaluation and Review Technique (PERT). PERT itself, developed by Bill Pocock of Booz Allen Hamilton and Gordon Perhson, was introduced in 1958 by the Department of the Navy as a tool for scheduling the development of a complete weapons system

(Fleming and Koppelman, 1998, Malcolm et al., 1959, Cottrell, 1999). PERT was developed to support planning and scheduling by considering a project as an acyclic network of sequential events and activities with their own expected durations for task completion (Cottrell, 1999). PERT is able to incorporate uncertainty by making it possible to schedule a project while not knowing precisely the details and durations of all the activities. PERT is an event-oriented technique rather than start/finish-oriented one and is used more in projects where time, rather than cost, is the major driver/constraint. PERT is typically applied to very large-scale, one-time, complex, non-routine infrastructure and research and development projects (Malcolm et al., 1959).

PERT and WBS concepts rapidly formed between 1958 and 1965. By 1961, the term ‘Work Breakdown Structure’ was well established (Haugan, 2002). The chart presented in Figure 20 shows part of the WBS for the Fleet Ballistic Missile Maintenance Training Facility, as published in an article within the General Electronic Corporation (Haugan, 2002, Munson, 1961).

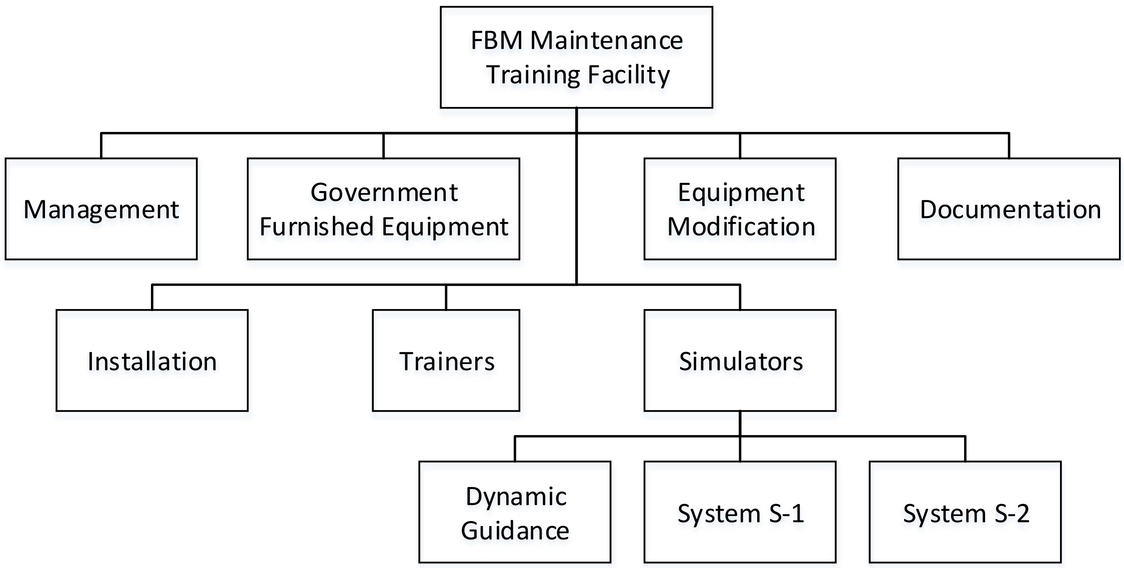


Figure 20: Work Breakdown Structure – 1961 (Haugan, 2002)

For the first time, the concept of a WBS was used in June 1962 by the DoD and the National Aeronautics and Space Administration (NASA) in collaborative research work for the purpose of controlling and planning large acquisition projects in order to develop and deliver weapons or a space system (Norman et al., 2008, Cleland, 1964). As part of this work, an extensive description of WBS in the form we know today was set in a document that was issued as a general guide for development of a uniform PERT/COST system (US Department of Defense, 1962).

In October 1962, NASA expanded its discussion of the WBS in the NASA PERT and Companion Cost System Handbook (NASA, 1962) in which a top-down development of the WBS was proposed with lower level tasks contributing directly to the final objectives of the project to ensure that the project is fully planned. It also noted that in any project in which cost and time are integrated, it is essential that both cost and time are derived and controlled from a common model (Haugan, 2002, US Department of Defense, 1962).

The *USAF PERT Implementation Manual*, published in August 1964 by the US Air Force to be used by the government agencies and private and public institutions, contains a section which emphasises the WBS's value as a basis for effective planning and scheduling (US Air Force, 1964).

In 1968, the Department of Defense issued MIL-STD-881, *Work Breakdown Structures for Defense Materiel Items* (US Department of Defense, 1968). This standard and the WBS requirements were made mandatory for application to all US defence projects developing or modifying the defence materiel items, which was being established as an integral programme element of the 5-year defence programme; or a research, development, test and engineering programme which was being established within an aggregated programme element where the project funds was estimated to exceed US$10 million (Haugan, 2002). This standard established uniform top-level templates (upper three levels) for common defence materiel items along with associated descriptions (WBS Dictionary) for their elements. The upper three levels of a summary WBS in this standard are organised and presented within the major defence materiel items including, aircraft systems, electronics systems, missile systems, ordnance systems, ship systems, space systems and surface vehicle systems. The primary objective of this handbook was to achieve a consistent application of the WBS. This could be considered as the first attempt to develop a predefined WBS that could be used as a template for different projects within the same industry.

This document was further revised and reissued as MIL-STD-881A in 1975 and was later updated to become MIL-STD-881B in 1993 (Defense, 1993, US Department of

Defense, 1975). The application of this later standard was made mandatory for most large US defence projects. In 1998, the MIL-STD-881B was formally cancelled and superseded by MIL-HDBK-881 (US Department of Defense, 1998) in a form of a handbook that was based on the existing MIL-STD-881B with no substantive changes in the WBS definition. However, because of a change in DoD philosophy, this handbook was issued as a guidance-only document. MIL-HDBK-881 also contains guidelines for preparing, understanding and presenting a WBS and provides instructions on how to develop a programme WBS. Also in this handbook, the role of the WBS in contract negotiation and award and in post-contract performance was examined and the definitions of WBSs for specific applications were stated. MIL-HDBK-881 remains targeted at defence materiel items. The WBS templates which were developed for the same seven DoD systems as in the original standard are still included in the handbook.

Figure 21 shows the WBS presented in MIL-HDBK-881 for surface vehicles along with definition and more detail of the components; this has remained the same in all revisions of this document since 1975 (US Department of Defense, 1975, Defense, 1993, US Department of Defense, 1998, US Department of Defense, 2005, US Department of Defense, 2011).

In 2005 the document was again reissued and renamed to MIL-HDBK-881A (US Department of Defense, 2005). The changes addressed advances in technology, modification of the acquisition process and incorporation of new developmental concepts and approaches. In January 2011, MIL-STD-881C was issued as a standard which superseded the previous handbook. This standard reflects new technologies and procedures (US Department of Defense, 2011).

Level 1	Level 2	Level 3
Surface Vehicle System		
	Primary Vehicle	Hull/Frame
		Suspension/Steering
		Power Package/Drive Train
		Auxiliary Automotive
		Turret Assembly
		Fire Control
		Armament
		Body/Cab
		Automatic Loading
		Automatic/Remote Piloting
		Nuclear, Biological, Chemical
		Special Equipment
		Navigation
		Communications
		Integration, Assembly, Test and Checkout
	Secondary Vehicle	(Same as Primary Vehicle)
	Systems Engineering/ Program Management	
	System Test and Evaluation	Development Test and Evaluation
		Operational Test and Evaluation
		Mock-ups
		Test and Evaluation Support
		Test Facilities
	Training	Equipment
		Services
		Facilities
	Data	Technical Publications
		Engineering Data
		Management Data
		Support Data
		Data Depository
	Peculiar Support Equipment	Test and Measurement Equipment
		Support and Handling Equipment
	Common Support Equipment	Test and Measurement Equipment
		Support and Handling Equipment
	Operational/Site Activation	System Assembly, Installation and Checkout on Site
		Contractor Technical Support
		Site Construction
		Site/Ship/Vehicle Conversion
	Industrial Facilities	Construction/Conversion/Expansion
		Equipment Acquisition or Modernization
		Maintenance (Industrial Facilities)
	Initial Spares and Repair Parts	

Figure 21: Surface Vehicle Systems Work Breakdown Structure and Definitions (US Department of Defense, 2011)

Meanwhile, in 1987, the Project Management Institute (PMI) documented the development of scope management techniques within a white paper entitled ‘A Guide to the Project Management Body of Knowledge (PMBOK Guide)’. This white paper was issued as part of work conducted to develop standards for general PM information and practices and covers a wide range of PM areas (Project Management Institute (PMI), 2000). Whereas an overview of the WBS concept is provided in the first formal issued edition of the similarly entitled document in 1996 (Project Management Institute (PMI), 1996), the 'Practice Standard for Work Breakdown Structures' is comparable to the DoD handbook, although intended for more general applications. Table 9 summarises the key development of the WBS over a period of time from 1957 to 2011.

Table 9: Development Key Stages of the WBS Concept over Time from 1957 to 2011

Date	WBS Development Key Events	Reference
1957	PERT developed by Bill Pocock of Booz Allen Hamilton and Gordon Perhson and introduced by the US Navy	(Fleming and Koppelman, 1998)
1959	Technical paper on PERT with a graph presenting WBS for the first time	(Malcolm et al., 1959)
June 1962	DoD and NASA describe the WBS concept	(US Department of Defense, 1962)
October1962	NASA publishes a document in which a top-down level approach for WBS implemented	(NASA, 1962)
1964	PERT implementation manual issues by the US Air Force	(US Air Force, 1964)
1968	DoD issues a WBS for defence material items – STANDARD	(US Department of Defense, 1968)
1987	PMI documents the expansion of WBS techniques across non-defence organisations	PMI (Project Management Institute (PMI), 1996)
1998	DoD major revision on the WBS for defence material items – HANDBOOK	(US Department of Defense, 1998)
2011	DoD major revision on the WBS for defence material items – STANDARD again	(US Department of Defense, 2011)

4.2.2. WBS Definition in Literature

Presently, Googling 'Work Breakdown Structure' will provide more than 6 million relevant websites. The WBS has been extensively discussed and recognised as a concept to organise and structure the project work hierarchically into smaller units for better performance control (Chua and Godinot, 2006, Globerson, 1994, Ayas, 1997, Tiner, 1985).

In some of the literature, the WBS is explained as a tool to define the project scope of the work by breaking down the project from its objectives into small parts (work packages [WPs]) (Bachy and Hameri, 1997). This definition tends to move WBS development toward project requirements capture and mapping into project resources to deliver the end objective of the project through delivering the small parts. In another view, however, the WBS is defined as the backbone of project planning and PM where the project scope is well defined beforehand. In this case, the WBS serves as a way of organising the work thematically, by discipline or any other criteria. In the following sections some of the key definitions in literature are provided and discussed.

Youker (1991) describes WBS as a breakdown structure which is an artistic blend of the sub-systems, life cycle phases and resources units (Youker, 1991, Globerson, 1994). This description highlights the role of the WBS as a planning and scheduling tool.

On the US Department of Energy website (*science.energy.gov*) in Project Management Tools and Resources, there is a module on Earned Value Management System by Booz Allen Hamilton. In the tutorial module 2 (Booz Allen Hamilton, 2012), WBS is explained as a project definition tool that groups the discrete work elements in a way that helps organise and define the total scope of the work. The WBS elements are defined as either product, data, service or any combination thereof. The module report characterises the WBS as a tool to provide a necessary framework for detailed cost estimation and cost control along with providing guidance for schedule development and schedule control. It is considered to be a dynamic tool that can be revised and updated as needed by the project manager. This definition, therefore, expresses both aspects of the WBS as a tool for planning as well as a document for defining the scope of the work.

In *NASA Procedural Requirement 9501.2D*, issued in 2001, the WBS is explained as a family tree subdivision of the effort required to achieve the objectives of the project that can be hardware, product, service or process oriented (NASA, 2001). In this document, WBS is explained as a tool which will provide a common framework for the natural development of the overall planning and control of a contract which also is a basis for dividing work into definable increments from which the statement of work can be developed and technical, schedule, cost and labour hour reporting can be established. The NASA 'Systems Engineering Handbook' also defines WBS as a hierarchical breakdown of the work necessary to complete a project (NASA, 2007) .

The Association for Project Management Body of Knowledge (APM BoK) describes the WBS as the backbone of the Project Management Plan which details the works to be done to deliver a project. This defines the WBS as a tool to specify the project scope of the work and which acts as a checklist to provide assurance that all areas of the project are covered in the project plan. The APM BoK also sees WBS as a way to identify responsibilities and resources required for the project and hence a basis for project budget and time estimation (Association for Project Management 2006). Similarly, the third edition of the PMBOK Guide describes the WBS as *"a deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables"* (Project Management Institute (PMI), 2004). This document also defines WBS as a tool to organise and define the total scope of the project in which each descending level represents an increasingly detailed definition of the project work. The WBS development in the PMBOK is also explained as the decomposition of the project into WPs.

Work packages are lower-level groupings of work elements that comprise a relatively self-contained contribution to the project and so lend themselves to sub-contracting, outsourcing or delegation en masse. Individual WPs may form the basis of a subproject's WBS. Work packages are then used as input to elaborate activities, resources and milestones that can be costed, monitored and controlled (Brotherton et al., 2008).

The deliverable orientation aspect of the WBS definition further evolved as the definition of the WBS further improved. Table 10 shows the changes to the definition of WBS through versions of the PMBOK Guide, as captured by Norman et al. (2008).

In summary, there are various definitions for WBS but they all share the same concept of hierarchical partitioning of the work necessary to meet the project objectives. The WBS is a bottom-up view of the project in which project tasks are broken down into a level which is manageable and measurable. Later sections will further discuss the role of the WBS and the development process.

Table 10: WBS Definition – Changes by Version (Norman et al., 2008)[1]

The Project Management Body of Knowledge (PMBPK) (1987)	**A Guide to the Project Management Body of Knowledge (PMBOK Guide) (1996)**	**A Guide to the Project Management Body of Knowledge (PMBOK Guide - Second Edition) (2000)**	**A Guide to the Project Management Body of Knowledge (PMBOK Guide - Third Edition) (2004)**
A task-oriented 'family tree' of activities	A deliverable-oriented grouping of project elements which organises and defines the total scope of the project. Each descending level represents an increasingly detailed definition of a project component. Project components may be products or services.	A deliverable-oriented grouping of project elements which organises and defines the total scope of the project. Each descending level represents an increasingly detailed definition of a project component. Project components may be products or services.	A deliverable-oriented hierarchical decomposition of the work to be executed by the project team to accomplish the project objectives and create the required deliverables. It organises and defines the total scope of the project. Each descending level represents an increasingly detailed definition of the project work. The WBS is decomposed into WPs. The deliverable orientation of the hierarchy includes both internal and external deliverables.

4.2.3. WBS Types

A WBS can be configured in a number of different ways depending on various factors such as project nature, deliverables and project tasks. This breakdown could be based on activities, products or organisations, as well as many combinations thereof (Chua and Godinot, 2006, Colenso, 2000, Christensen and Thayer, 2001, De Heredia and Santana, 1991, Lanford and McCann, 1983, Matthews, 1986, Reilly, 1993, Tiner, 1985, Smith and Mills, 1983, Saynisch, 1983, Ruskin and Estes, 1995, Warner, 1997, Albert, 1995).

The APM describes three types of WBS as, product-based WBS, work-based WBS and organisation-based WBS (Association for Project Management 2006). But no clear prescription on how a WBS is to be developed for a project is provided. Other forms of

[1] Sources: Project Management Institute, A guide to the project management body of knowledge (PMBOK guide), PMI, USA, 1996, 2000, and 2004.

WBS – like a time-phased WBS which is organised around the project life cycle phases or a resource-based WBS that is organised around the project resources – are also described in various literature in different domains (Haugan, 2002, Norman et al., 2008). Regardless of the type of the WBS, it is commonplace to see different types appearing at different levels within a particular WBS.

4.2.3.1. Product-based WBS

A product-based WBS uses the natural hierarchy within the deliverables as a basis for its underlying structure (Norman et al., 2008). The WBS is developed around the physical structure of the product to indicate works need to be done to deliver the products of the project goal (Haugan, 2002). Typically this type of WBS is fairly close to the Product Breakdown Structure (PBS). Often the elements in the PBS will be rephrased to form the product-based WBS.

4.2.3.2. Work-based WBS

A work-based WBS reflects the generic nature of the activities, the type of works or the services to be performed in the project (for example, engineering, management, construction, testing) (Norman et al., 2008). The APM introduces some common ways of breaking down the works within a project around discipline, project life cycle and sub-projects as follows (UCL, 2009, Association for Project Management 2006):

Discipline: Project tasks categorised based on the disciplines involved in the project, for example, civil engineering or electrical engineering in a construction project

Project Life Cycle Phases (Time-phased WBS): Project tasks categorised based on the phases in the project life cycle such as feasibility, definition, design or build

Sub-Project: Project tasks categorised based on the sub-projects where the project has various sub-projects at the lower level

4.2.3.3. Organisation-based WBS

Organisation-based WBS maps to the relationships within the project organisation, for example, departments, companies or contractors. Such organisational structure may pre-exist the project based on the existing organisation available to the project or may be created for a particular project depends on the project needs and requirements.

4.2.4. Suitable WBS Type

Where the project involves the development of a system, it is natural to use a product-based WBS since the work involves the creation of the various system elements and their integration into a more complex whole. This approach can also be applied to situations where the solution is less tangible, such as the creation of a service or the reconfiguration (or change) of an existing structure. In both cases it is usually possible to create something resembling a PBS as a starting point for the WBS.

Where the emphasis is assigning work to sub-contractors in a mature domain, then an organisation-based approach may be more appropriate. While an organisation-based WBS lends itself to the creation of distinct WPs that can be assigned to sub-contractors or other organisational elements, they will not necessarily form effective sub-projects. The interaction between WPs may be highly complex if the organisation is not mapped to the PBS. Where the PBS/Organisation Breakdown Structure (OBS) matrix is diagonal, then the allocation of high level WPs is likely to be more successful. Where the matrix is filled, then individual elements of the product are being developed through collaborations within the project organisation as a whole which may lead to difficulty and increased management effort. Organisational structures do evolve, however, and may become more aligned to the natural PBS as they mature.

The most likely optimal solution will arise when the PBS/OBS matrix has minimal complexity (assuming the capability exists for each part of the organisation to discharge its responsibility). For this reason, organisations often align around the typical PBS of their products, for example, in a supply chain. The OBS is likely to be more flexible than the PBS. Where there is mandated policy on the allocation of the workshare, additional complexity, ineffectiveness and increased risk are more likely. However, in the case that there is little PBS/OBS alignment, for example, in the civil engineering sector where contractors provide broad services rather than distinct product elements (for example, electrical installation), a demanding approach is required. Collaboration between WPs becomes essential and the PM approach must take this additional complexity into consideration. Table 11 suggests a typical characterisation for some common project domains.

Table 11: Typical Selection of the Type of WBS Development Based on Different Types of Projects

Project Domain	**WBS Type**
Large civil engineering projects	Work-based
Defence equipment, space infrastructure and aerospace	Product-based
Rail transport systems with staged service introduction	Time-based
New consumer product development	Product-based
Expeditions	Time-based
Organisational change[2]	Product-based
Capability improvement within an organisation	Organisation-based

4.2.5. WBS Development

A practical and effective way of developing a WBS could potentially be through the use of pre-existing templates. Where there are no suitable templates, a number of suggested approaches are available for the development of WBSs. For example, the PMI's first *Practise Standard for Work Breakdown Structure* suggests a staged process approach for the development of a WBS (Project Management Institute (PMI), 2001). Factors such as organisation culture, available resources, project time lines, locations and project stage/phase revenues influence the configuration of a WBS. For instance, in a railway line extension project, a WBS based on the project organisation and location would be developed (organisation based), while the same project within the same organisation and team would have a different WBS if the client asks for a staged service provision for the system (time based) so that it would be aligned with a wider phased project life cycle.

Haugan (2002) describes the development of a WBS in four phases (Haugan, 2002). The first phase is capturing and specifying the project objective, focusing on the products, services or results to be provided to the end user. This is where the requirements management (RM) process impacts the development of the WBS. The second phase focuses on the work necessary to create the deliverables of the project.

[2] Here the product is the organisation and its functional elements

The third phase identifies other enabling work elements necessary to assure the quality of deliverables and the effective management of the project. The last phase is the subdivision of each item in Phase 2 and Phase 3 to the level of components which can be measured and costed (Haugan, 2002).

NASA Procedural Requirement 9501.2D states that the development of a WBS begins with a consideration of the end objectives (NASA, 2001). These high-level objectives are then subdivided into a complete set of manageable components in terms of size, duration and responsibility (for example, systems, subsystems, components, tasks, subtasks and WPs). The highest level of the WBS reflects the objectives of the project and relates to the major deliverables (product based).

In the upper level of the WBS, major deliverables will be decomposed into logical groups. The lower level of the WBS will provide sufficient detail to support PM processes such as scheduling, cost estimation, resource allocation and risk assessment. A group of the activities at the lowest-level of WBS form the project WPs, which are measurable and manageable tasks that can be monitored and managed from the start to the end of a project. These WPs can also be used as input to the scheduling process to support the elaboration of tasks, activities, resources and milestones (Brotherton et al., 2008). Work packages can be contracted out as stand-alone projects to various contractors in some of the complex and large-scale projects/programmes.

Although there are many other ways suggested in different literature to develop WBS, it is quite impossible to formulate the WBS development into a single format. As discussed, development of a WBS very much depends on the project characteristics, and therefore many different WBS patterns can be developed for the same project. However, there has been very little work and discussion around developing standard-patterned WBS to be used in different projects of the same nature.

4.2.6. WBS Dictionary

To successfully use the WBS in management, the elements of the WBS need to be defined and clarified clearly at the earliest stage of the project. A WBS Dictionary is a form of a document in which the various elements of the WBS in a project are defined and clarified. A typical WBS Dictionary contains a high-level functional description (the general nature of the business), a description of the ideal situation post-implementation, general requirements or tasks and relationships or dependencies with other WBS elements from other streams (those not in a direct line) (Brotherton et al., 2008).

4.2.7. WBS Role

The WBS represents the project charter. The project charter is a statement of the scope and objectives of the project as well as the project participants. The high level of a WBS should match the statement of the scope. At the beginning, the WBS is a main core to manage the scope in PM because developing the WBS significantly aids capturing and managing the scope of the work before the project starts. Through the process of WBS development, the main scope of the work will be seen ahead of the project and grouped in manageable categories (Norman et al., 2008, Taylor, 2009).

The WBS also plays a main role in developing the project network diagram in order to develop and perform project scheduling. Work packages will be allocated in a block of the project network to perform project time scheduling. Dependencies to the other tasks, start and end time, duration, free float and total float in project planning can be achieved easily by using a WBS (Lockyer and Gordon, 1991, Association for Project Management 2006).

The WBS is also a main tool to perform project resource scheduling. Sufficient resource will be allocated to each WP within a WBS (Globerson, 1994). Therefore, the overall project resource schedule can be developed. Developing the resource schedule and time schedule will then be used to perform resource smoothing or levelling. The WBS plays a crucial role in the project Responsible, Accountable, Consulted, Informed (RACI) Matrix. The RACI Matrix, a two-dimensional matrix between the WBS and OBS, defines project tasks and allocates them to the relevant resources.

The WBS is also the main core to conduct an earned value management study on the performance of the project against the project tasks against time and cost. The WPs within the WBS will be used in this study (Brandon, 1998).

The WBS greatly assists the cost estimation, budget management and budget monitoring processes. Estimating the overall cost of the project will be much easier and more accurate by costing the WPs within WBS (Koonce et al., 2003).

The DoD handbook defines the WBS as the basis for the negotiation of an approved contract, contract budgeting and cost estimating (US Department of Defense, 2011).

The WBS should play a role in many other project and SE applications, tools and processes such as project RM, IM, risk management, assurance management, human factor management and procurement management. For the focus of this study, further research in the role of WBS in IM within projects is conducted.

4.3. WBS and Interface Management

The International Council on Systems Engineering (INCOSE) and APM views of interfacing and IM were reviewed in Chapter 3. As discussed, interfaces arise when different people execute different tasks to form a single part of a work (Stuckenbruck, 1983, Chua and Godinot, 2006). Managing the complexity of interfaces in project development is usually handled by mapping various kinds of project flowcharts and diagrams, such as PERT or Gantt charts, that are made of the project WBS (Yassine et al., 2001, Yassine, 2004). Poor IM hampers the collaboration of an interdisciplinary team and negatively impacts the project management performance (Töpfer, 1995). Therefore, managing the internal and external interfaces within a multidisciplinary project is essential to deliver successful PM and requires specific knowledge and skills (Healy, 1997, Stuckenbruck, 1983, Chua and Godinot, 2006). Managing time interfaces to move a project smoothly from conception to delivery (Caron and Marchet, 1998, Morris, 1988, Stuckenbruck, 1983), as well as technical interfaces to avoid reworks, time wasting and financial losses are also equally essential for a successful project delivery (Sundgren, 1999). Figure 22 presents five functional aspects proposed by Chua and Godinot (2006) to develop an interface management system (Chua and Godinot, 2006).

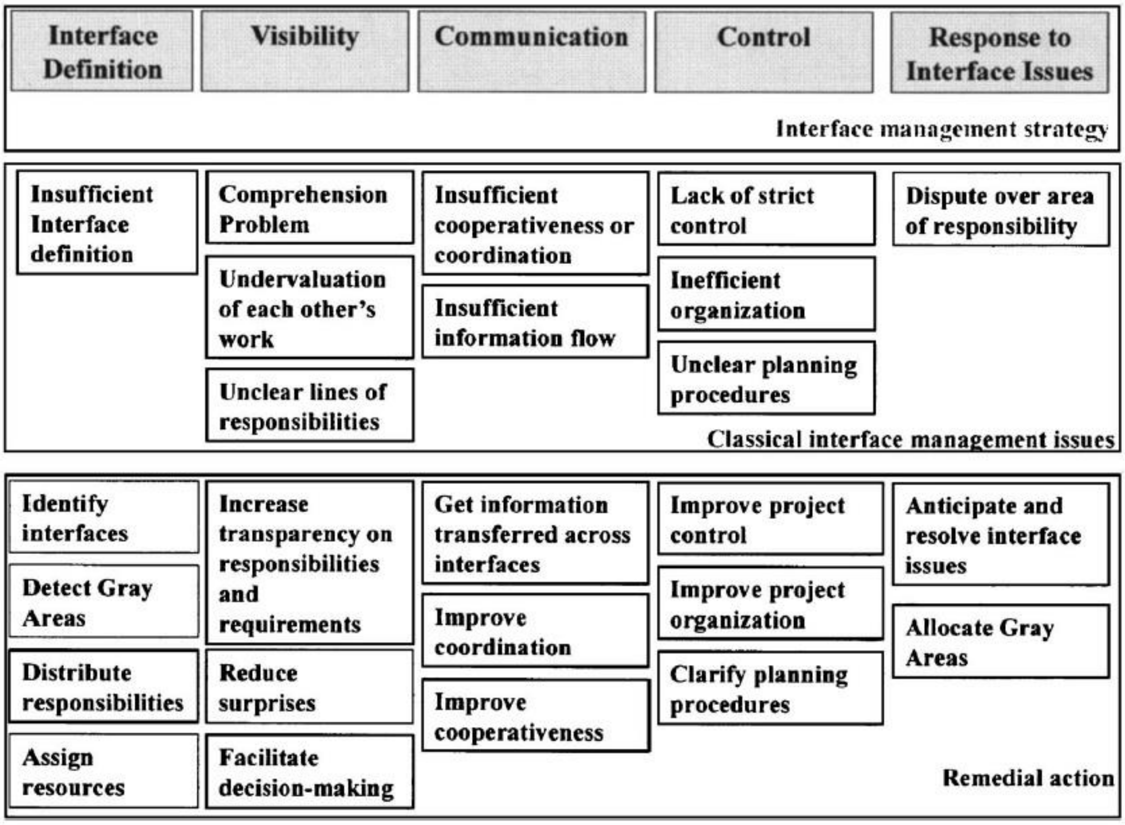


Figure 22: Five Functional Aspects for Interface Management (Chua and Godinot, 2006)

Interface definition, visibility, communication and control are the aspects in this model that deal with interface problems/issues and advanced mitigation and prevention. The response to interface issues, however, is the approach used to deal with the interface issue when it occurs. The section in the middle presents the interface issues as a result of deficiencies in the aspects in the section above, while the section at the bottom suggests the corresponding remedial actions (Chua and Godinot, 2006).

It is essential to identify the interfaces in advance when a project starts and to communicate and allocate responsibility to the interface owners (Stuckenbruck, 1983, Healy, 1997, Chua and Godinot, 2006). The systematic management of the projects considering interface and integration management requires tools and techniques for decomposition and integration (Browning, 2001). As also discussed in Chapter 3, visibility of the project requirements is essential and further supports the definition of the responsibilities, therefore smoothing management of the interfaces across the team (Morris, 1988).

"Ultimately, interface management is essentially a communication task wherein adequate communication flows and coordination among the diverse teams are necessary for full technical integration of a system. Interfaces are generally managed through meetings, which must gather technically knowledgeable, committed, and empowered people for each interface. In this regard, the interface management system must provide information and facilitate the process for communicating, controlling interface issues, and resolving interface conflicts when they arise." (Chua and Godinot, 2006)

4.3.1. WBS Matrix

As mentioned earlier, traditional PM tends to use a WBS in managing various aspects of a project including interfaces. However, there has been no specific framework or method to formulate the use of a WBS in managing the interfaces (Chua and Godinot, 2006).

Often people look at the project from both product and activities (Albert, 1995). The WBS matrix concept, therefore, is adopted to facilitate the relationship between project activities (that is, Activity Breakdown Structure) and products (that is, PBS) within a single matrix (Chua and Godinot, 2006). This concept was first introduced to combine the main components and the functions of the system to define the WPs for the WBS (Bachy and Hameri, 1997). The model further extended to incorporate all construction project phases including design, procurement, construction and testing, as presented in Figure 23 (Chua and Godinot, 2006). As the figure shows, the cross check between the PBS and the Activity Breakdown Structure provides various WPs. The WPs identify what should be done (from the Activity Breakdown Structure) in order to develop what (from PBS) (Chua and Godinot, 2006).

The WBS matrix concept is a solution to develop the WP definition include the scope of the work, the interface issues, the deliverables and the schedule and budget objectives within different phases of the project (Chua and Godinot, 2006). While the concept suggests a good approach to manage the interfaces within a multidisciplinary project, it presents two major issues.

The first issue relates to the capability of identifying the interfaces among the components of the project. For example, considering Figure 23, the WBS matrix identifies the WP required to design the stray current and earthing cables under the direct current traction power supply system. The interface between this component and other components that should be considered during the design stage, however, is not visible and should only be captured in WP sheets as explained in Chau and Godinot (2006). Therefore, this solution could be improved in such a way that the interfaces can also be visualised in a matrix format.

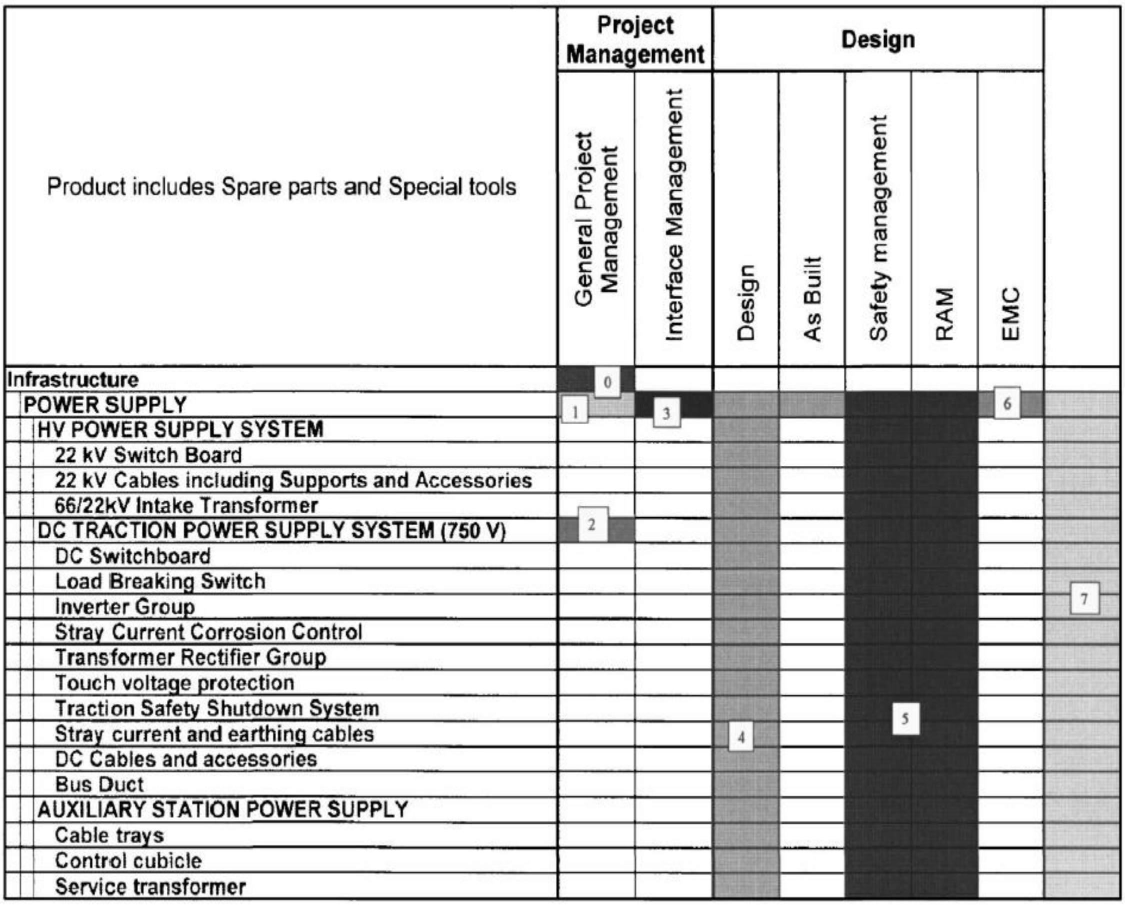


Figure 23: Part of a WBS Matrix Developed for the Case Study of a Transportation Project (Chua and Godinot, 2006)

The second issue relates to reusability of the approach for the projects of the same type. The WBS matrix approach needs to be built from scratch for each project because the matrix should reflect the project procurement and the organisation. These parameters normally vary from project to project, even within the same domain.

4.3.2. Design Structure Matrix

A matrix is a powerful tool to present interactions between different elements in any domain. A Design Structure Matrix (DSM), widely known as the methodology to handle dependencies and relationship between items (Danilovic and Browning, 2007, Steward, 1981), is a single and manageable matrix format document with identical rows and columns that models a system by representing the interactions between its elements, including products, tasks and resources (Eppinger and Browning, 2012, Browning, 2001, Danilovic and Browning, 2007, Yassine et al., 2001). Despite the traditional PM tools, the DSM methodology focuses on representation of the information flows rather than a work flow that represents the project network (Yassine, 2004).

The DSM concept was originally formed in 1960s and further developed and published in 1981 as a tool to identify the task dependencies in order to manage the design of complex systems by sequencing the development process (Steward, 1981, Carrascosa et al., 1998, Guenov and Barker, 2004). This concept was a natural successor to the N2 chart that was used for many years in SE (Becker et al., 2000, Guenov and Barker, 2004, Lano, 1977, Lano, 1979).

The use of the DSM concept increased in both academia and industry in the 1990s, and since then it has been used extensively in various domains for different modelling tools and techniques (Browning, 2001, Browning, 2002). The concept was used and adopted to the fields of building constructions (Huovila et al., 1995, Koskela et al., 1997, Austin et al., 1996, Austin et al., 1998) semiconductors (Eppinger, 2001, Osborne, 1993), automotive (Sequeira, 1991, Malmstrdm et al., 1999, Rushton and Zakarian, 2000, Smith and Eppinger, 1997a, Smith and Eppinger, 1997b), photographic (Ulrich and Eppinger, 2000), aerospace (Ahmadi et al., 2001, Ahmadi and Wang, 1994, Clarkson and Hamilton, 2000, Grose, 1994, Makins and Miller, 2000, Nour and Scanlan, 2000), telecommunications (Pinkett, 1971), small-scale manufacturing (Lewis and Cangshan, 1997), factory equipment (Hameri, 1999) and electronic industries (Carrascosa et al., 1998).

The DSM can be developed in different ways depending on the system being modelled. For example, an interactions matrix among the components of a product will be used to model the product architecture. The communication among resources can be modelled using a DSM where the elements are the team members (Eppinger and Browning, 2012). Therefore, by adopting a DSM, a network of interfaces among activities within a project can be developed. While DSM and WBS can develop the task interface diagram, they cannot present the timing and the duration of the tasks.

In summary, DSM is a method to engage different types of breakdown structure and visualise and manage the interactions among their elements. Therefore, the scope of DSM varies depending on the type of the breakdown structure that the DSM is managing.

4.4. Other Breakdown Structures

Various breakdown structures are used to manage projects in different formats, so a brief review of the various terms is useful for this study.

Activity Breakdown Structure: Activities required to be done during the life of the project and in order to develop the project deliverables (Chua and Godinot, 2006, Ahlemann and Backhaus, 2006)

Assembly Breakdown Structure: The sequences of the assembly of the final product in a project (Bachy and Hameri, 1997, Hameri and Nitter, 2002, McClatchey et al., 1998, Baker et al., 1998)

Functional Breakdown Structure: A form of a breakdown structure identifying the functions that must be addressed to perform a generic mission in a modular format (DeHoff et al., 2009)

Goal Breakdown Structure: A hierarchical structure of the project needs, goals and objectives (Stanicek and Winkler, 2010). This is a structured descriptions of concrete physical assets or core processes (Ulrik et al., 2009)

Organisation Breakdown Structure: A breakdown structure of the range of resources and skills available to the project (Turner and Cochrane, 1993)

Product Breakdown Structure: A breakdown structure of the products (bill of materials or part list) for the project (Bachy and Hameri, 1997, Turner and Cochrane, 1993)

Risk Breakdown Structure: A hierarchical structure of the project risks to assist in understanding the distribution of risk on a project or across a business (Aleshin, 2001, Hillson, 2003, Holzmann and Spiegler, 2011, Iranmanesh et al., 2007, Tah and Carr, 2000)

Stage Breakdown Structure: A breakdown structure of the project key milestones, information coordination and phases to correctly model the project execution and relationship to the other parties involved (Vaculin et al., 2012, Conroy and Soltan, 1997)

System Breakdown Structure: A hierarchical structure of the systems within a system (system and sub-systems) that as a whole describes the system and its behaviours (Clark, 2009, Loureiro et al., 2004)

4.5. WBS Limitations

As discussed, a WBS cannot be a fixed document but should instead be developed in various ways for the same project. Various factors such as project environment, project nature, organisational culture and personal interest play key roles in WBS development, and as a result WBSs vary in many aspects of their nature.

This is a not a major problem if a WBS were to be used only for a specific purpose such as project scheduling and programming. Different project managers or project planners can plan the project in different ways, but as long as the project can be monitored against the plan there is no issue.

The main issue of the WBS becomes obvious when the WBS is intended to be used for multiple purposes. For instance, a WBS which is developed for scheduling will not necessarily be a good document for interface identification and IM. Or the same document will not necessarily be useful for project requirements allocation and management.

4.6. Systems Thinking in WBS Development

In a complex multidisciplinary project life cycle, information flow between various WPs is an important part of PM. The level and complexity of interaction and dependency between WPs should be minimised to reduce project risks and optimise the overall PM efficiency. While communications within a project are useful and helpful, a PBS that is not closely mapped to the system architecture will mean that system elements will tend to be the result of collaborations between WPs with the consequential risk of misunderstanding and conflicting priorities.

For a product-based WBS, ST can be used to create a more coherent and simpler structure. An N-squared (N^2) diagram can be used to show the complexity of information flow in a particular project.

Figure 24 presents an example of a top level WBS-N^2 diagram where there is a relatively poor alignment between PBS and the underlying system architecture. Most WPs interact with most other WPs, increasing the project risk and slowing down the project progress.

PM	X	X	X	X	X
X	WP-A	X		X	
X	X	WP-B		X	X
X	X	X	WP-C		X
X			X	WP-D	
X	X	X			WP-E

Figure 24: Example of an N^2 Diagram for Typical WBS (PBS Level) around PBS with No Systems Thinking

The PBS can be explicitly mapped against the systems architecture. While this adds an additional element to the flow of activity, it ensures a simpler downstream project organisation. The proposed project planning process would now look like:

- Capture and validate requirements
- Develop high level systems architecture
- Define PBS
- Define WBS and OBS
- Define schedule, cost, etc.

This process has to be aligned with SE life cycle in accordance with Figure 25. Note the systems engineering effort can be considered as an investment towards an effective project implementation.

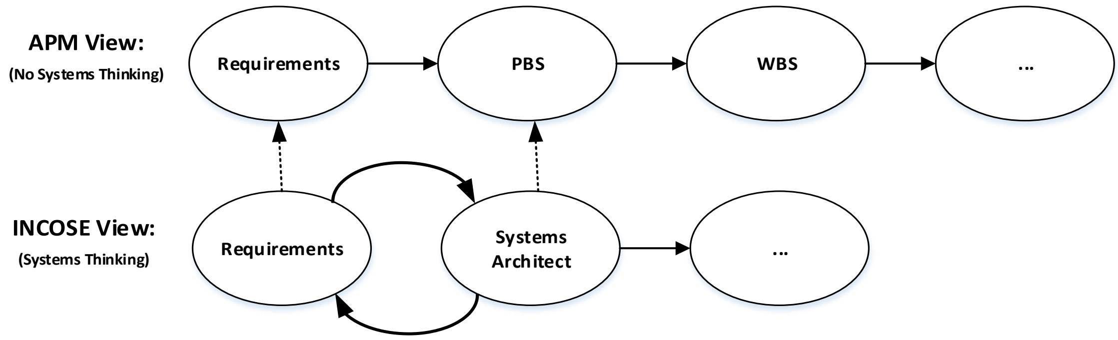


Figure 25: Systems Thinking Alignment with WBS Development Process

Of course the above is a simplification and does not include such important considerations as risk management; the process is also likely to be iterative.

Nevertheless, an important consideration is added here, that is some serious consideration to system architecture/systems design has to be done before the WBS definition is in place. This means that SE cannot be left to the implementation phase, as it provides an important input into project planning. Often at the onset of a project planning phase, the high-level systems architecture is known, based on previous systems developments within the domain, for example. In such cases the definition of systems architecture may be largely one of fine tuning.

Explicitly including an SE WP can introduce a further simplification, which is particularly useful where the architecture is not predefined. Through the SE WP, coordination between the elements of a PBS-based WBS is assured. As shown in Figure 26, individual system elements also have their own associated, recursive lower level WBSs.

Of course the introduction of an SE WP is commonplace in many sectors and has many other advantages to support the development of a successful solution. We note here the importance of this function in the management of the project and the need to minimise communications complexity.

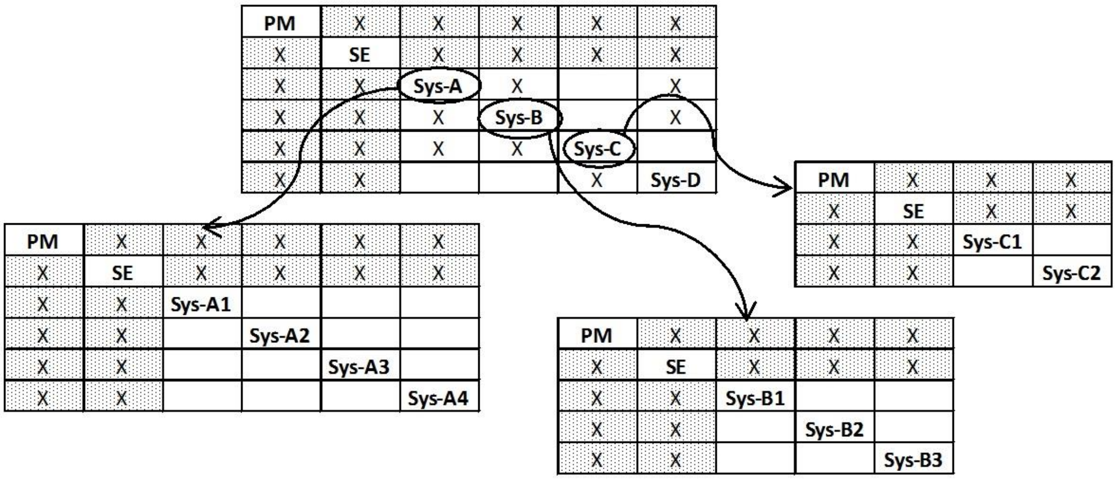


Figure 26: Example of an N^2 Diagram – WBS (PBS Level) with System Design Level and Relation to the Sub-systems

Managing interfaces at sub-systems level makes the interfaces less complex in the design system level

Where a system comprises largely independent, major sub-systems (sometimes referred to as a system of systems) which may be brought into service at different times (Garrett Jr. et al., 2010), it can be beneficial to introduce a level in the WBS that reflects this high-level system architecture. Table 12 presents an example of this in a hypothetical new rail network project.

Table 12: WBS Levelling Comparison with Two Alternate Approaches That Include Systems Thinking

WBS	Typical	With ST
Level 1	Project	Project
Level 2	PBS	***Systems Architecture***
Level 3	Discipline	PBS (Sub-systems)
Level 4	PBS within discipline	Discipline or PBS within discipline
Level 5		PBS within discipline or discipline

The sub-systems combine in accordance with the system architecture to deliver the required capability. Such sub-systems can be further broken down as necessary. The addition of the system-aligned Level 2 ensures greater coherence at the highest level with a minimum level of complexity between system-of-system sub-systems PM communications.

4.7. Conclusion of the Chapter

The WBS is an engine to drive the main works of PM activities. In traditional PM, the WBS is developed in an early stage of the project. The WBS breaks the tasks involved in a project into small categories as WPs in a measurable and manageable format. Completing these WPs will lead to completing the project in total.

The WBS is the main backbone of the Project Management Plan and plays an essential role in the following PM aspects:

- Project resource scheduling by assigning WPs to the different resources in multidisciplinary, team-based projects
- Project time scheduling by allocating time and priorities to the WPs
- Project cost estimation and budget management by associating cost and budget to the WPs
- Many other project activities, such as project risk management, RM and IM, by studying the WPs

A project is a unique function with its own unique characteristics and, therefore, WBSs tend to be developed in various ways depends on many different factors, including the type of the project, type of industry, project manager work principle, company regulation and legislation, project environment and parties involved. Therefore, it is not possible to formulate the WBS development in a standard format. Some industries, however, have developed generic WBS formats which still need to be customised and tailored to suit the project.

Where the WBS is best structured around the PBS, it is proposed that efficiency will be improved and risk reduced if the PBS is itself structured around the inherent system architecture. Through the introduction of a system architecture (or, more generally, an SE) WP, the complexity of interactions within the project can be reduced significantly. However, this requires a close cooperation between the PM and SE functions at an early and formative stage of the project and/or a phasing of the project such that a WBS can be created for the later stages only after progress with the system definition.

Regardless of the type of the WBS, or development process, such breakdown structure is a natural and imperative method to be used to manage interactions and interfaces among different element of a project or a system. Improving the quality of the breakdown structure of a project or a system will improve the quality of IM, leading to better, more efficient PM.

Chapter 5 SURVEY OF PRACTITIONERS

5.1. Introduction

In order to test the hypothesis discussed in this thesis, a survey was conducted. The parts of the survey used for this chapter were designed and developed in order to:

- Understand how individual professionals in different industries identify the scope for systems engineering (SE) and project management (PM) in relation to managing the interfaces and requirements in different projects.
- Collect data in relation to the quality of the execution of interface and requirements management (RM) activities in projects.
- Collect data on different types and forms of Work Breakdown Structure (WBS) and its development as well as the project tools and application incorporating WBS
- Understand the relationship between WBS and SE philosophies in PM

In this chapter, the methodology of the data gathering for the survey is explained, followed by the nature of the sample. The data in relation to this chapter are filtered and analysed in a phased approach and conclusions are given in detail. While this survey collected information for the purpose of this thesis, it also collected additional valuable data that could be used in future work beyond the scope of this research.

5.2. Survey Methodology

The main target sample pool for the survey were the professionals registered as members with the International Council on Systems Engineering (INCOSE) UK Ltd and the Association for Project Management (APM). Both INCOSE and APM were approached through formal communication with their registries. INCOSE UK Ltd placed the survey in its websites under the Academic Research section, and APM communicated the survey through mass email to its members and associates. Cover letters describing the purpose of the questionnaire were also attached to the survey and distributed through these channels. The questionnaire was further distributed among CH2M (formerly Halcrow) employees classified as project managers in different grades, as well as major contacts including partners, competitors and clients of CH2M through formal communication. Members of PM and SE groups on LinkedIn, the professional social network, were also invited to participate in the survey. Table 13 summarises the survey distribution list. An image of the survey is attached in Appendix 12, and images of all cover letters and communications are attached in Appendix 2.

The survey created in the Opinio which is an online survey creator licensed by the UCL. The Opinio also generated a machine report based on the results stored in its database that is enclosed in the Appendix 3 as further information.

Table 13: Survey Distribution

Organisation/ Group	About	No. of Members	Distribution method	Link to the survey
INCOSE UK Chapter	*"INCOSE UK Limited is registered in England under no. 3641046 Registered address: 56 Adams Meadow, Ilminster, Somerset, TA19 9DD All material © INCOSE UK Ltd 2009 - Present"*	900	Website under "Academic Research"	http://www.incoseonline.org.uk/Normal_Files/Research/Academic_Research.aspx?CatID=Research
APM UK	*"Association for Project Management is a company limited by guarantee. Registered in England & No. 1218334. Registered office as on this page. Association for Project Management is a registered charity No. 290927. VAT number 285 1708 43."*	21150	Mass email communication through the registry	N/A
CH2M PM Team	CH2M is an engineering company that provides consulting, design, construction and operations services for corporations and federal, state and local governments. The PM team are the employees graded as project managers with a specific grade in the organisation.	978	Mass email communication	N/A
LinkedIn - The APM (Official group)	*"The award-winning Association for Project Management is a professional body which exists to develop the art and science of project management. This group helps all APM members*	45656	LinkedIn group discussion	https://www.linkedin.com/groups/30804/30804-6004566619643277315

Organisation/ Group	About	No. of Members	Distribution method	Link to the survey
	and non-members to network with each other and share ideas."			
LinkedIn – Systems Engineering Group	*"This group is open to all engineers who feel herself/himself as a part of the complex whole and made all the designs and developments with a harmony with this complex whole."*	8213	LinkedIn group discussion	https://www.linkedin.com/groups/36892/36892-6004566957830004737
LinkedIn – IBM Rational DOORS (ex Telelogic DOORS) User Group	*"This IBM Rational DOORS (ex Telelogic DOORS) User Group encourages discussions, experience sharing, job searches…between professionals working with (or simply interested in) the tool 'IBM Rational DOORS' (ex Telelogic DOORS)."*	3802	LinkedIn group discussion	https://www.linkedin.com/groups/769057/769057-6004566384586088450
LinkedIn – International Systems Engineering Network	*"This is an international networking group for the members of ALL organizations that promote and support Systems Engineering and for all professionals who want to share their knowledge and experience related to Systems Engineering."*	15932	LinkedIn group discussion	https://www.linkedin.com/groups/1218517/1218517-6004566957830004738
LinkedIn – INCOSE New England Chapter	*"Welcome to the INCOSE New England Chapter group on LinkedIn."*	54	LinkedIn group discussion	https://www.linkedin.com/groups/904/904-6004565758410055681
	Grand Total	96685		

After a period of 4 weeks, the survey was frozen and the data of over 500 entries were captured for further analysis. The data were filtered through review stages to a smaller sample with completed and more reliable data.

The survey includes generic questions to collect demographic information on the participants, including the type of the services and the size of the firms for which they work, the scale of the projects in which they have experience, the industries in which they have worked and some project experiences.

5.3. Nature of Sample

As shown in Table 13, it is estimated that the survey reached out to around 100,000 inboxes, within a reasonable margin of error. But as many of the people have memberships in both APM and INCOSE, as well as other social web-based networks, it is not possible to confirm the number of unique individuals who received and/or reviewed the questionnaire.

At the first phase, over 500 responses received. The raw sample was reviewed and analysed to remove duplications and incomplete data. After two rounds of detailed reviews, 259 responses were identified as reliable and relevant, from which 57 responses were related to the rail sector. Demographically, participants were categorised based on the following four main factors:

1) The type of industry sectors they have been involved, including rail, highway, bridges and tunnels, maritime, aerospace, automation, finance, healthcare, academic research and development, energy, oil and gas, nuclear, environmental, water, defence and information and communication, as well as options to specify other industry where applicable.
2) Their role in the business including:
   a. Business Managers (BMs) – Directors in charge of approving project overall schedule and budget
   b. Project Managers – Project managers who manage the project operation and cost/time/budget; also generally in charge of making decisions on team appointment as well as tools and procedures selection and approval
   c. Engineers/consultants (Eng.) – Engineers or consultants who build the product
   d. Project control (support) professionals (PCs) – Project planners and any other control function
   e. Systems engineers – Systems engineers in charge of SE responsibilities as defined in the project
3) The scale of the projects they have been involved in, including major programmes (value more than US$100 million), major projects (value more than US$20 million), medium-sized projects (value more than US$1 million) and small-sized projects (value greater than US$10,000).

4) Whether they work on the client or supplier side (that is, contractors, consultants, manufacturers)

Anywhere in this thesis that there is reference to this survey, the sample and the analysis will be presented in two major forms:

i. **The 'All',** meaning all 259 entries
ii. **The 'Rail',** meaning the 57 entries with rail sector experience

5.3.1. Overall Sample – the 'All'

Table 14 provides a numerical view of the participants and Figure 27 is a graphical presentation of the participants' demographic attributes (see Figure 28 for the 'Rail' participants). As Figure 29 shows, the sample includes a mixture of people with different level of roles in business and, therefore, different level of influences in decision making (that is, the decision weight factor [DWF]). DWF is further described in Section 5.4.

It is important to have results from people with different levels of influences or DWF because the decision in the governance of the project could be different depending on how people think and what level of influence they have to turn their opinions into practice.

Table 14: Survey Participant Demographical Distribution for the 'All' Sample

Participants		**Project Scales**				**Service Type**	
Role	Sample Size	Major Programme >$100m	Major Project >$20m	Medium Project >$1m	Small Project >$10k	Client	Supplier
BMs	**38**	29	20	20	15	7	31
Systems Engineers	**59**	45	38	40	20	7	52
Engineers	**22**	14	10	12	5	6	16
PCs	**30**	19	16	14	8	3	27
Project Managers	**107**	51	49	53	33	20	87
TOTAL	**256**						

The sample includes 42 per cent project managers, 81 per cent of whom work for major supplier firms including consulting firms, contractors and builders and manufacturers, and the rest for client organisations such as government agencies and ministries. Around

50 per cent of the project managers have experience of working in major projects and programmes of over US$100 million.

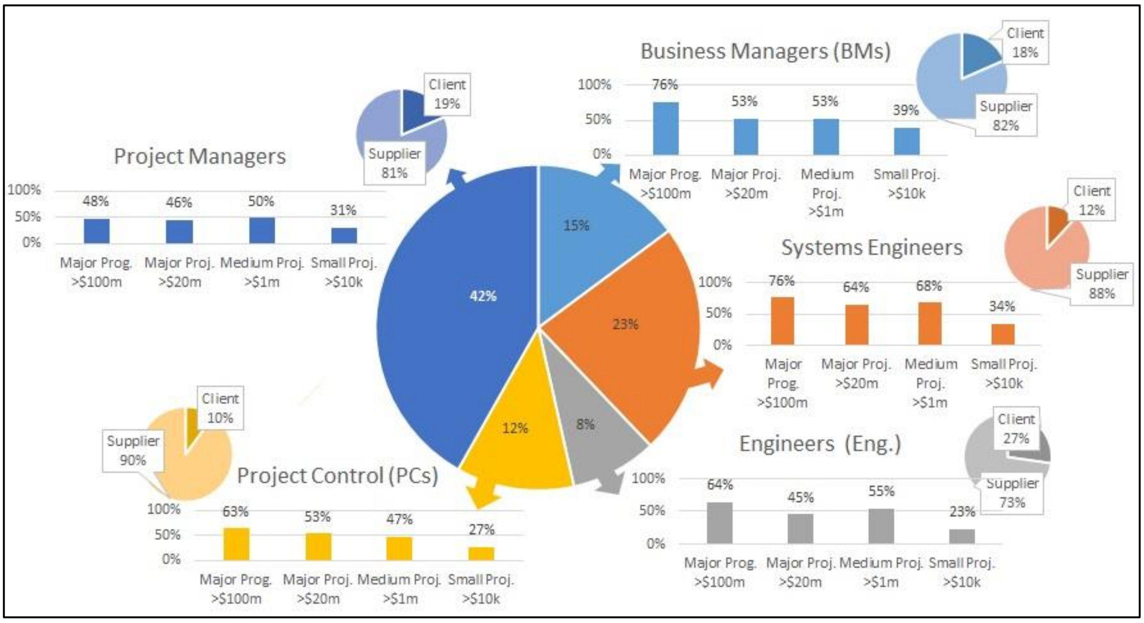


Figure 27: Survey Participant Demographical View for the 'All' Sample

Fifteen per cent of the sample are business managers, including project directors, practice leaders, sector directors and business development directors, 82 per cent of whom work for major suppliers and 18 per cent of whom work for the clients. Around 80 per cent of the business managers who participated in the survey have experience of working in major programmes of over US$100 million.

Twenty-three per cent of the overall sample are systems engineers, 88 per cent of whom work on the supplier side and 12 per cent of whom work on the client side. Around 80 per cent of the systems engineers also have experience of working for major programmes of over US$100 million.

The remaining 20 per cent of the sample are the other project team members, including engineers, consultants and project support and control.

In summary, the sample includes relatively more project managers and a good balance of systems engineers. The majority of the participants are from the supplier side, which could potentially increase their attention to saving time and budget in project delivery. On average, over 70 per cent of the sample do have experience of working in major projects and programmes of over US$100 million. This sample provides a wide view of the project professionals to further support the study.

5.3.2. Rail Targeted Sample – the 'Rail'

In a similar table and graph to the previous section, Table 15 and Figure 28 provide numerical results and graphical presentation of the participants, considering the demographic attributes but only focusing on people from rails sector.

Table 15: Survey Participant Demographical Distribution for the 'Rail' Sample

Participants		**Project Scales**				**Service Type**	
Role	Sample Size	Major Programme >$100m	Major Project >$20m	Medium Project >$1m	Small Project >$10k	Client	Supplier
BMs	**14**	11	10	8	7	4	10
Systems Engineers	**19**	17	12	11	4	2	17
Engineers	**7**	6	3	2	1	2	5
PCs	**4**	3	3	2	1	1	3
Project Managers	**13**	10	6	4	2	2	11
TOTAL	**57**						

The distribution of the rail-related results is also very similar to the overall results, only with a smaller portion of project managers. But in principle the results for the rail sector have a better balance between systems engineers and project managers with a smaller gap.

Forty-two percent of the participants with rail experience are project managers, 85 per cent of whom come from supplier side and the other 15 per cent from client side. In a very different figure from the 'All' sample, around 80 per cent of the rail project managers worked in major programmes of over US$100 million.

In the 'Rail' sample, a slightly larger margin of 25 per cent are business managers, 70 per cent of whom come from the supplier side and 30 per cent from the client side. Around 80 per cent of the business managers in the 'Rail' sample claim have experience of working in major programmes of over US$100 million.

The 'Rail' sample includes more systems engineers, 33 per cent of the total participants. Around 90 per cent of the systems engineers work for suppliers, and around 90 per cent of them have experience of working in major programmes of over US$100 million.

The remaining 19 per cent of the 'Rail' sample were from project support team and provided their view to give a different prospective to the results achieved.

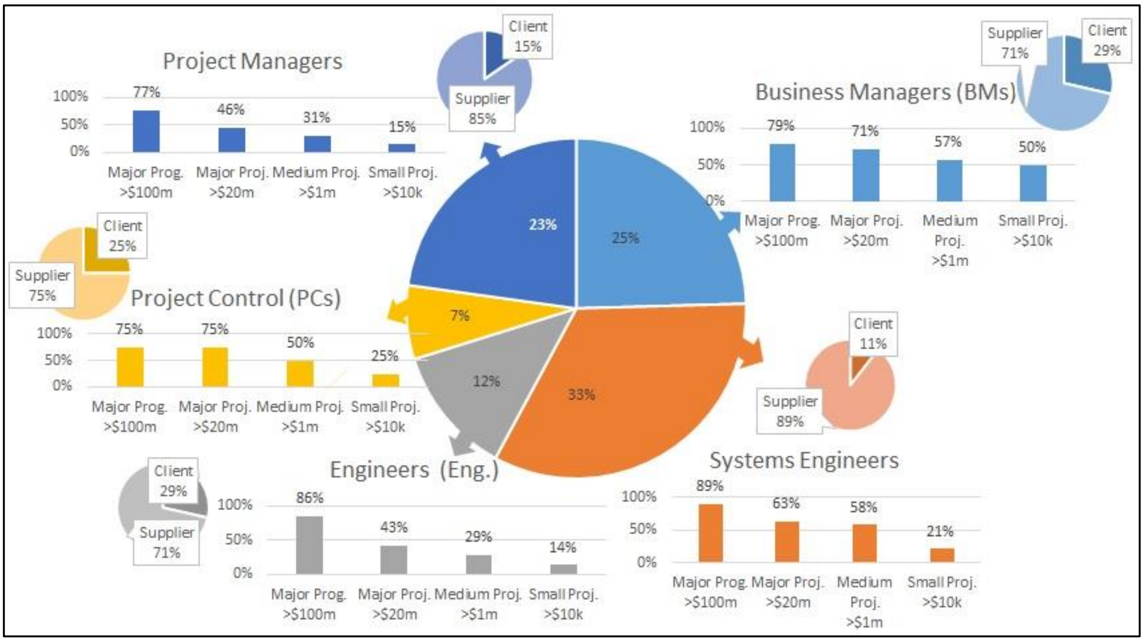


Figure 28: Survey Participant Demographical View for the 'Rail' Sample

In summary, the 'Rail' sample has a better balance of project managers, systems engineers and business managers, providing smoother and more balanced results. Similarly in the 'Rail' sample also most are from the supplier side, and most have experience of working in major multi-million dollar programmes.

5.4. Decision Weight Factor

In practice on any project or in any organisation, different roles have different level of influence (the decision weight factor or DWF, as previously discussed) over different types of decisions. Factors such as PM's behaviour and emotions influencing the project success, have been subject of much research. Müller and Turner (2007), along with various other research, leadership programmes and schools, have presented how in the general management context, the management and leadership style influences the performance of the projects (Müller and Turner, 2007, Dulewicz and Higgs, 2004, Goleman et al., 2002, Kets de Vries and Florent-Treacy, 2002, Whitmire and Nienstedt, 1991, Zaccaroa et al., 2001). However, Turner and Müller (2005) observe that the PM literature almost ignored the impact and influence of the project manager's competence and style on the success of their project (Turner and Müller, 2005). In a research study in 2007, Turner and Müller concluded that "*1) the project manager's leadership style influences project success; and 2) different leadership styles are appropriate for different types of project"* (Müller and Turner, 2007).

The style of the project managers and other management teams, therefore, drive their opinions, and has an important role in identifying the approaches to be adopted in managing a project.

In more than 10 years of working in rail infrastructure projects, the author has observed that in such projects, project managers normally have more influence over assembling the project team and allocating the responsibility ownership and will, in fact, end up choosing the approaches, tools and procedures for managing different parts of a project.

Top managers, including the business managers and project directors, have higher responsibility in defining the project for the business, approving the project budget and time, appointing the project management team, deciding partnering and competitions, etc. Top managers are involved in defining and assessing business strategy (Babar and Wong, 2012, Johnson and Lederer, 2010, Chan and Huff, 1992). Once the project is approved and started in its execution life, business managers' influence over the project-level decisions such as assigning the project team and choosing the management approach is limited to making recommendations to the project managers. Project managers are responsible to deliver and, therefore, are the best suited to make the ultimate decisions at the project level.

If systems engineers are appointed in a team by the project managers, they potentially can have a great level of impact in pushing decisions toward structuring the team around SE resources where applicable. The DWF of systems engineers to encourage the project managers to use an SE approach and tools in the execution of the project is potentially greater than business managers, as they have more capability to convince the project managers to use an SE approach by justifying the benefits to the project.

The other project team members, including engineers, consultants, project control and support, have minimum impact on structuring a team and using a specific approach for management. Their opinions, therefore, could help with decision making but have a much lower impact. The engineers and consultants or those who actually design and build the product, however, have a much greater DWF over technical decisions such as engineering calculations, choosing the suitable products and designing the systems and sub-systems.

While it is almost impossible to measure the DWF to an accurate number, it is reasonable to make some level of comparison between the different groups. Figure 29 visualises the relation of the project team's DWFs to the type of the decisions made in a project over different scenarios based on the author's observation on major projects in the rail sector.

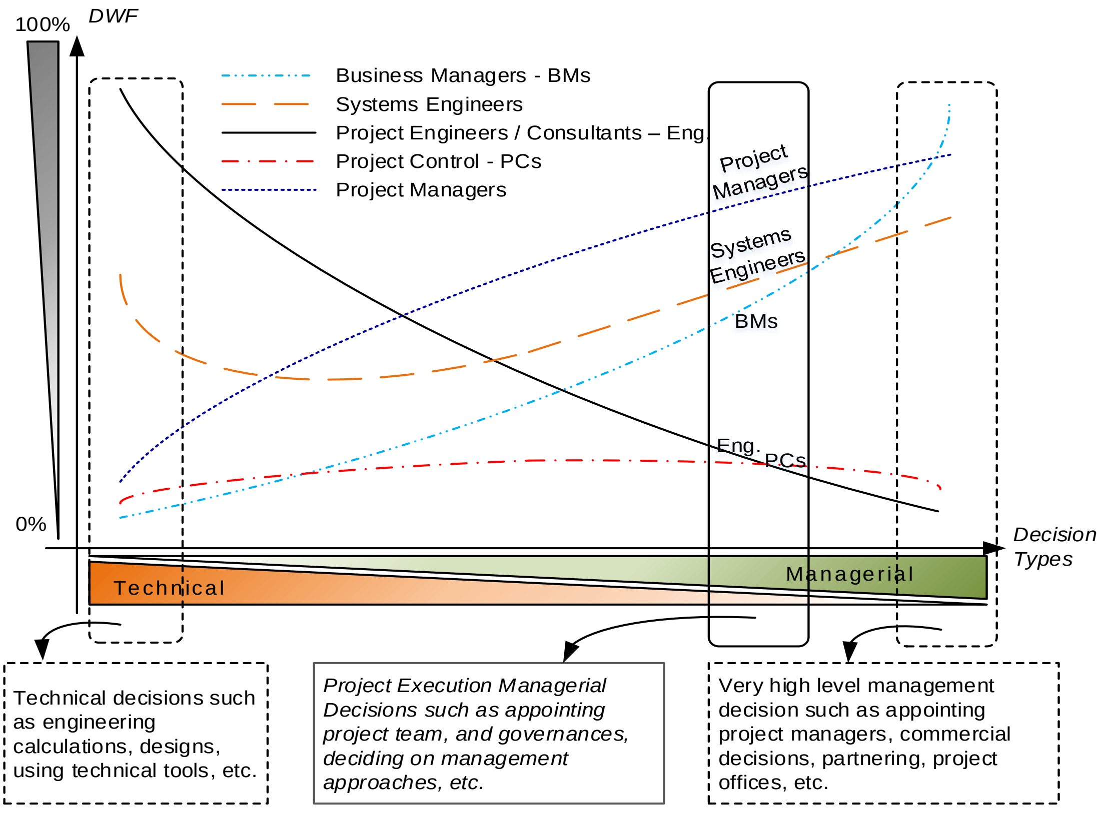


Figure 29: Decision Weight Factors' Relations to Decisions Made in Major Rail Projects

It is beyond the scope of this research, but if future research can measure DWF in a numerical form, then it could potentially be used to normalise the Opinion Ratio (OR) results from similar type of surveys to predict the likelihood of responsibility distribution for various activities among a project's different parties using the equation below:

$$Applied\ Ratio\ (AR) = OR \times DWF$$

5.5. Survey Results and Discussion

The questions within the survey were designed to discuss the interface management (IM), requirements management (RM), Work Breakdown Structure (WBS) and systems engineering (SE) in three major separate sections. Within each section, the survey directed the participants to provide data to support the areas of the discussion based on the following:

1) Their opinion on the roles and responsibilities of the project managers and systems engineers in relation to the IM and RM to calculate the OR
2) Their experience of the quality of IM and RM within their projects to find out the areas of improvement
3) Their experience in dealing with the WBS concept and relation to SE and systems thinking (ST) philosophy

5.5.1. Opinion Ratio

As part of the questionnaire, the participants were asked about their opinion, based on their own experience, of the ownership of responsibility of IM and RM and the relationship to the SE and PM. While the answers were expected to be informed by their experiences, the questions were designed in such a way for them to provide their opinion on the best practice to be applied in future projects. The data and the results were analysed around a parameter called the 'Opinion Ratio' in this research, described as follows:

$$OR_{(x)} = \frac{Number\ of\ \text{entries}\ agreed\ on\ (x)}{Total\ number\ of\ \text{entries}}$$

In the section of the survey that was specifically designed for this chapter, a multiple choice of responses including an additional box to provide more information was included. This section of the survey was designed to capture the opinion of the participant on the ownership of IM and RM in two separate questions which were designed to gather data required to visualise the OR for RM and IM, respectively. The questions were as follows:

- *Q12: "Do you think Requirements Management is a natural part of Project Management and/or Systems Engineering?"*
- *Q29: "Do you think Interface Management is a natural part of Project Management and/or Systems Engineering?"*

The options provided were as follows:

1) Responsibility of the project managers only

2) Responsibility of the systems engineers only
3) Shared responsibility between project managers and systems engineers
4) Interface management is not the responsibility of the project managers or systems engineers
5) No Response (or don't know)

Table 16 summarises the gathered responses and presents the numerical results for different scenarios and demonstrates the results for both the 'All' and the 'Rail' samples in the scenarios which focus on IM and RM.

Figure 30 presents a graphical representation of the results of the OR from the table. The graphs focus on the bigger sample and provide a like-to-like comparison presenting the general OR of professionals in different industries over the responsibility of IM and RM.

In order to provide a more accurate view of the results with more focus on the responses from the project managers and the systems engineers, a margin of error based on the sample size is considered in the data analysis. For a simple sample, the maximum margin of error (MOE) is a simple re-expression of the sample size $\boldsymbol{n}$. The numerators of these equations are rounded to two decimal places as $1.29/\sqrt{n}$ for MOE at 99 per cent confidence, $0.98/\sqrt{n}$ for MOE at 95 per cent confidence, and $0.82/\sqrt{n}$ for MOE at 90 per cent confidence (Aufmann et al., 2008). For the purpose of this graph, a MOE with a confidence level of 99 per cent is considered for the results given by the project managers and the systems engineers. Therefore, the MOE is calculated as follows:

$$MOE_{\ PMs} = \frac{1.29}{\sqrt{n_{PMs}}}, where\ n = sample\ size$$

$$n_{PMs} = 107 \quad » \quad MOE_{\ PMs} = \frac{1.29}{\sqrt{107}} = 9.67\%$$

$$MOE_{\ SEs} = \frac{1.29}{\sqrt{n_{SEs}}}, where\ n = sample\ size$$

$$n_{SEs} = 59 \quad » \quad MOE_{\ PMs} = \frac{1.29}{\sqrt{59}} = 13.73\%$$

Table 16: Survey Numerical Results for RM and IM Responsibility – Opinion Ratio

Questions	Sample	Positions	BMs	Systems Engineers	Eng.	PCs	Project Managers	SUM
Q12. "Do you think Requirements Management is a natural part of Project Management and/or Systems Engineering?"	All	Sample Size	38	59	22	30	107	256
		PM	8	0	6	12	50	76
		SE	5	27	1	1	3	37
		PM+SE	12	22	5	2	9	50
		Neither	1	0	2	0	2	5
		No Response (don't know)	12	10	8	15	43	88
	Rail	Sample Size	14	19	7	4	13	57
		PM	4	0	2	3	9	18
		SE	1	8	0	0	0	9
		PM+SE	6	7	2	0	2	17
		Neither	1	0	1	0	1	3
		No Response (or don't know)	2	4	2	1	1	10
Q29. "Do you think Interface Management is a natural part of Project Management and/or Systems Engineering?"	All	Sample Size	38	59	22	30	107	256
		PM	7	6	5	8	35	61
		SE	8	21	4	1	7	41
		PM+SE	7	14	2	3	12	38
		Neither	0	1	1	0	3	5
		No Response (or don't know)	16	17	10	18	50	111
	Rail	Sample Size	14	19	7	4	13	57
		PM	5	1	1	3	6	16
		SE	2	5	2	0	2	11
		PM+SE	2	5	1	0	3	11
		Neither	0	1	0	0	0	1
		No Response (or don't know)	5	7	3	1	2	18

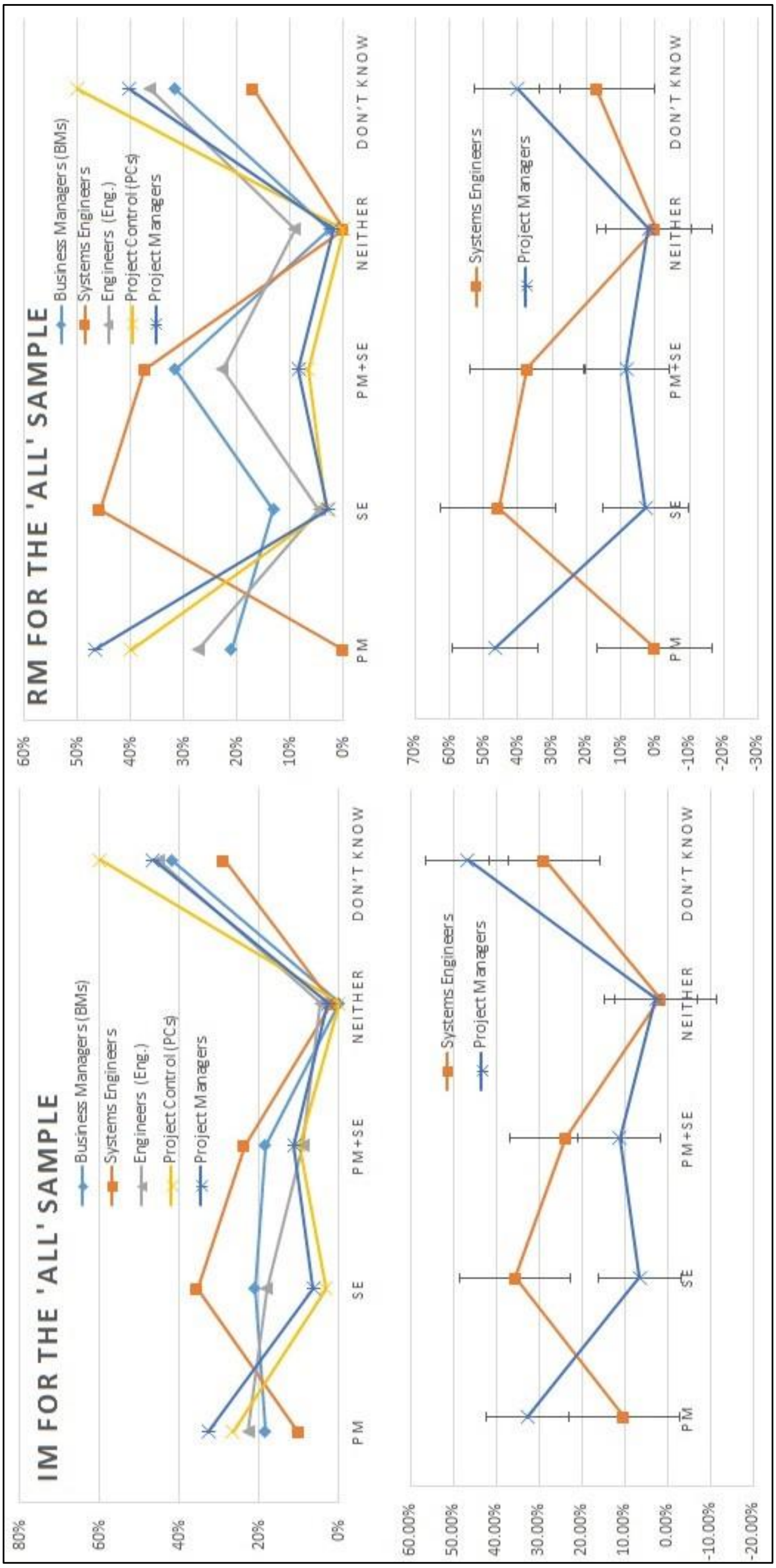


Figure 30: Opinion Ratio for IM and RM Responsibility for the 'All' Sample

The first interesting result is that for both functions, the graphs have very similar behaviour. The most important conclusion from the graphs is an indication of different views between the project managers and systems engineers. While the rest of the project team almost have a flat opinion, the majority of the project managers believe that the functions are best handled by PM while the systems engineers claim that both functions are natural parts of SE.

The almost flat OR of the other project team members, including the business managers, can further be considered as proof of the lack of consensus over the responsibility to execute the IM and RM functions in a wider spectrum, which is a risk to the project of any type. In addition, a high percentage of people skipped the question with no response. If this is to be interpreted as 'don't know', then this could also be seen as further evidence of the lack of consensus described above.

The error bars in the graph show overlap in a scenario where PM is to handle the interfaces as well as the scenario where a shared responsibility of PM and SE to manage the requirements within a project is considered.

Figure 31 projects a similar analysis but in a smaller group of rail sector professionals, the main focus of this study. The sample size of 57 for the rail sector is a relatively small scale and therefore carries a higher MOE (MacCallum et al., 1999). Similar to the previous case, the MOE at the 99 per cent confidence level for this sample is also calculated as follows:

$$MOE_{\ PMs} = \frac{1.29}{\sqrt{n_{PMs}}}, where\ n = sample\ size$$

$$n_{PMs} = 13 \quad » \quad MOE_{\ PMs} = \frac{1.29}{\sqrt{13}} = 27.74\%$$

$$MOE_{\ SEs} = \frac{1.29}{\sqrt{n_{SEs}}}, where\ n = sample\ size$$

$$n_{SEs} = 19 \quad » \quad MOE_{\ PMs} = \frac{1.29}{\sqrt{19}} = 22.94\%$$

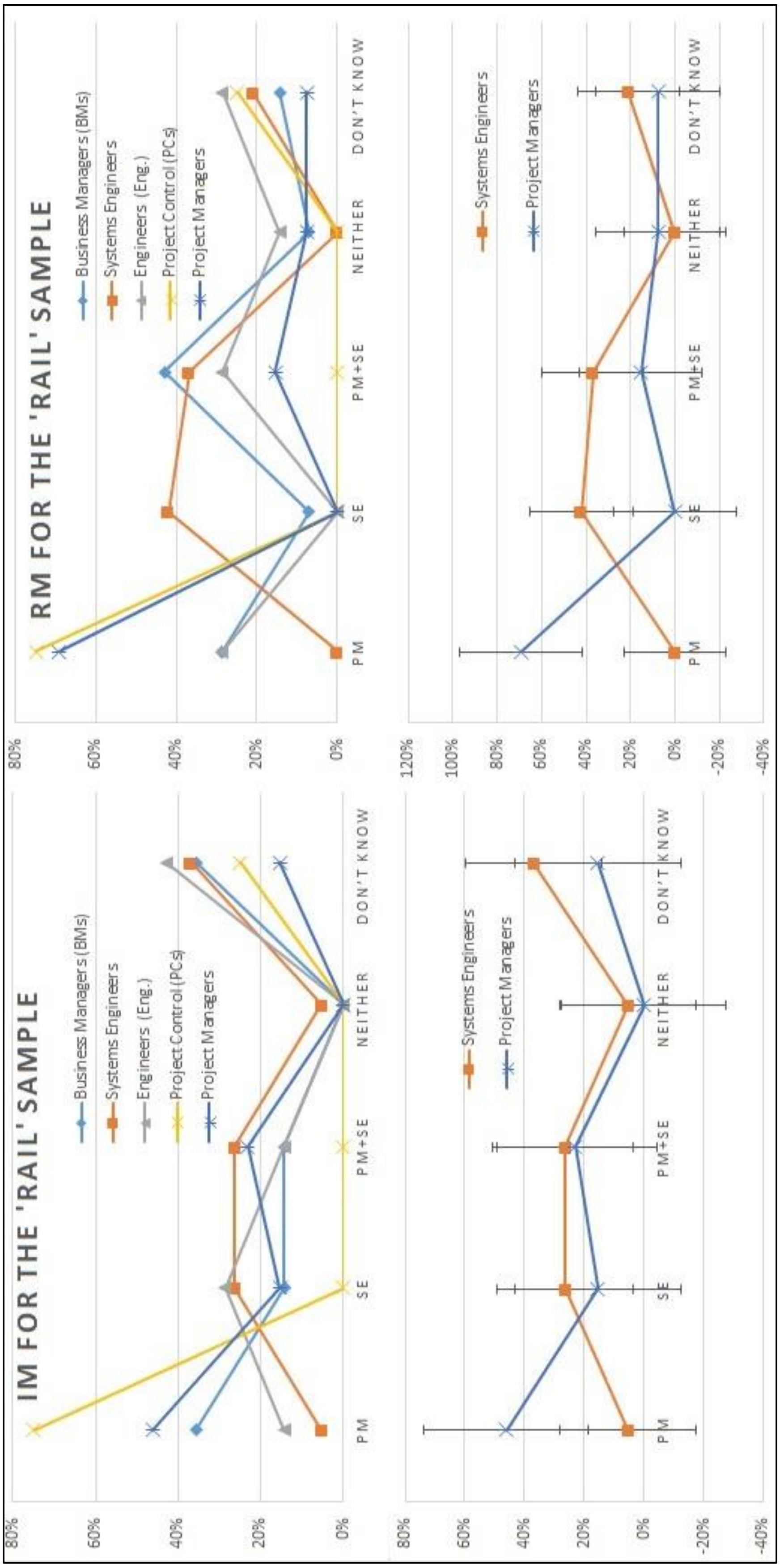


Figure 31: Opinion Ratio for IM and RM Responsibility for the 'Rail' Sample

In a very similar situation to the 'All' sample, rail project managers also claim that the IM and RM are the natural parts of PM.

Another interesting conclusion from the graph is that the engineers mostly believe that IM is an SE function while, similar to project managers, they still think that requirements in a project should be handled and managed as part of PM.

The graph also shows a smaller number of people skipping the question without response. Although this is a better news for the rail sector, the average rate of 20 per cent of project managers and systems engineers skipping the question could potentially indicate a high level of risk. This, therefore, further shows that the complexity of the projects is required for the project team to be made more aware of systematic thinking to make projects more efficient (Davidz and Nightingale, 2008).

The error bars are overlapped very closely and, therefore, the results can be considered as the same under some circumstances. Still, even within such MOEs, the graph presents the same lack of consensus described earlier among the systems engineers and project managers over responsibility of RM in a project.

5.5.2. Interface Management and Requirements Management Execution Quality

Question 24 is a standalone question designed to ask participants to grade the IM in their existing projects. Questions 17 and 18 in the context of RM and questions 34 and 35 in the context of IM, however, are designed to collect data required to understand how people observe, assess and rate the overall quality of IM and RM execution from the other parties they are involved with, according to their project experiences. The questions are as follows:

- *Q24: "How well are the interfaces managed in your projects?"*
- *Q17: "How do you rate the quality of Requirements Management at your client organisation?"*
- *Q18: "How do you rate the quality of Requirements Management at your supplier organisation?"*
- *Q34: "How do you rate the quality of Interface Management at your client organisation?"*

- *Q35: "How do you rate the quality of Interface Management at your supplier organisation?"*

All five questions are Likert-type scale questions, which is an approach to unidimensional scaling (Likert, 1932, Alphen et al., 1994, McIver and Carmines, 1981, Allen and Seaman, 2007) with rating scales from poor to excellent and additional options of 'Not Applicable', 'Absent' and 'Don't know'.

A wider range of scales is used in this question in accordance to the general rule Likert and others recommend, because no matter how wide the range of data is, they can be collapsed into condensed categories, if appropriate (Allen and Seaman, 2007, Likert, 1932).

Table 17 details the numerical results of responses to the above five questions. One-hundred-seventy-one people answered questions 17 and 18 in relation to RM, 148 responded to question 24 and 147 responded to questions 34 and 35 in relation to IM.

Table 17: Survey Numerical Results for IM and RM Execution Quality

Questions	Excellent	Very Good	Good	Average	Poor	Very Poor	Absent	Not Applicable	Do Not Know	Total
Q17. Quality of RM at your client organisation?	7	13	38	54	26	7	2	8	16	171
Q18. Quality of RM at your supplier organisation?	4	7	33	51	19	9	2	24	22	171
Q24. Quality of IM in your projects?	10	24	58	39	12	1	0	0	4	148
Q34. Quality of IM at your client organisation?	7	10	41	48	16	6	2	1	16	147
Q35. Quality of IM at your supplier organisation?	2	7	33	50	16	4	0	13	22	147

Figure 32 also is a graphical presentation of the results that shows a very small bar for the grades of Excellent and Very Good for all of the questions.

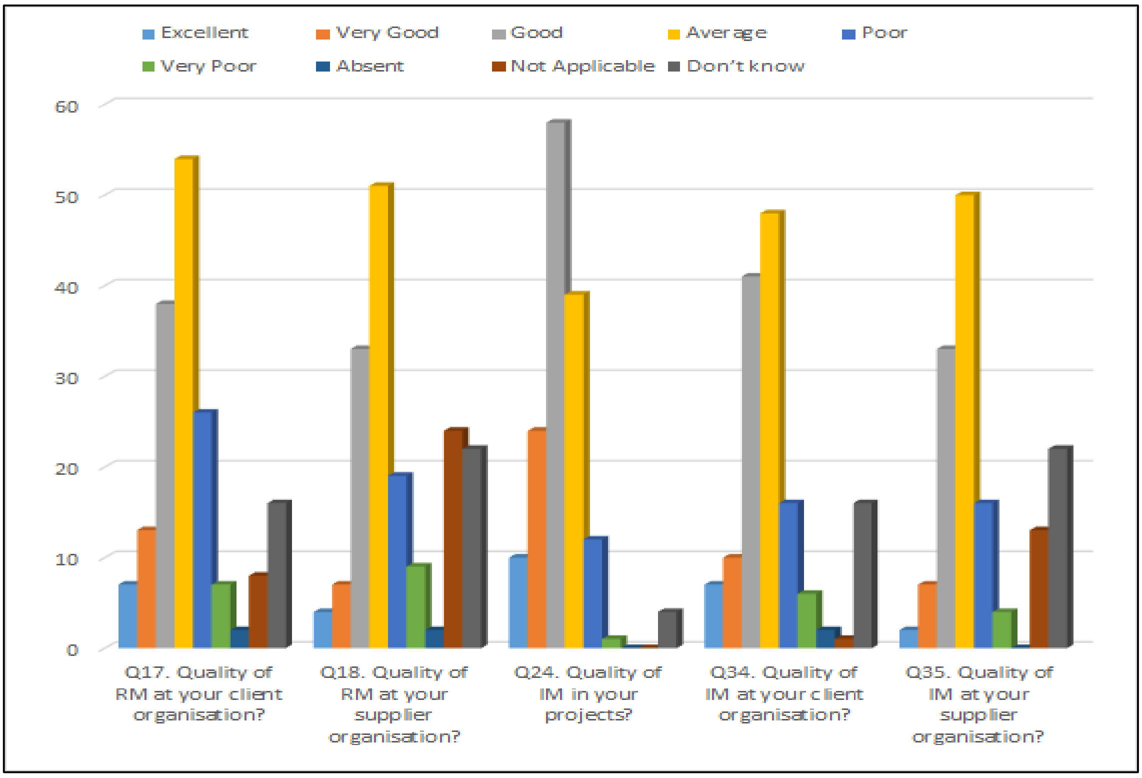


Figure 32: Q17, 18, 24, 34 and 35 Results Proportions

The data obtained from the Likert-type questionnaire can be assessed further to calculate a mean score for each of the questions. Therefore, a model is required to take into account the number of participants, as well as how they have graded the quality of the functions within each these question, in order to calculate an overall score for each question.

In order to calculate the mean score for each of the questions the following solution is used:

1) Assumption made: $\mathbf{G_i = Grade,}$ where, G_1 = Excellent, G_2 = Very Good, G_3 = Good, G_4 = Average, G_5 = Poor, G_6 = Very Poor, G_7 = Absent, G_8 = Not Applicable and G_9 = Don't know.
2) The Likert grades are scored as, and $\mathbf{SG_i = 0\ to\ 6}$, where 6 represents Excellent and 0 represents Absent, Not Applicable and Don't know, with 1 as the interval (that is, $SG_1 = 6$, $SG_2 = 5$, $SG_3 = 4$, $SG_4 = 3$, $SG_5 = 2$, $SG_6 = 1$, $SG_{i=7,8 \text{ and } 9} = 0$
3) $\boldsymbol{n_i}$ is considered as the number of entries of each grade against each question
4) Score band (Sb) as a score for each grade against each question is calculated as $\boldsymbol{Sb_i = n_i \times G_i}$

5) The total number of entries per question is considered as $\propto$, which is calculated as

$\propto = \sum_{i=1}^{9} \boldsymbol{n_i}$ per each question

6) The sum of score bands per question is considered as β, which is calculated as

$\boldsymbol{\beta} = \sum_{i=1}^{9} \boldsymbol{Sb_i}$ per each question

7) Mean Score for each question is considered as μ which is calculated as $\mu = \beta/\propto$

Table 18 shows the number of entries for each question with a calculation for scoring each grade against each question, and Table 19 presents the calculation for the mean score for each question based on the equations above.

Table 18: Q17, 18, 24, 34 and 35 Results Scoring

Questions	Grade	Excellent	Very Good	Good	Average	Poor	Very Poor	Absent	Not Applicable	Do Not Know
	G_i	1	2	3	4	5	6	7	8	9
	SG_i	6	5	4	3	2	1	0	0	0
Q17. RM / Client	n_i	7	13	38	54	26	7	2	8	16
	Sb_i	42	65	152	162	52	7	0	0	0
Q18. RM / Supplier	n_i	4	7	33	51	19	9	2	24	22
	Sb_i	24	35	132	153	38	9	0	0	0
Q34. IM / Client	n_i	7	10	41	48	16	6	2	1	16
	Sb_i	42	50	164	144	32	6	0	0	0
Q35. IM / Supplier	n_i	2	7	33	50	16	4	0	13	22
	Sb_i	12	35	132	150	32	4	0	0	0
Q24. IM / Existing Pro.	n_i	10	24	58	39	12	1	0	0	4
	Sb_i	60	120	232	117	24	1	0	0	0

The results within Table 19 show that the mean score for all the questions are between poor to average, with the exception of question 24 being between average to good. This further presents the relatively poor to average quality of IM and RM in the industry and, therefore, justifies the requirements to develop better solutions to improve these activities and make the projects more efficient.

Table 19: Q17, 18, 24, 34 and 35 Mean Score Calculations

Questions	Scoring Calculations		$\mu_q = \frac{\beta_q}{\propto_q}$	SCALE
Q17. RM / Client	$\propto_{17} = \sum_{i=1}^{9} n_i$	=171	$\mu_{17} = 2.81$	$poor < \mu_{17} < average$
	$\beta_{17} = \sum_{i=1}^{9} Sb_i$	=480		
Q18. RM / Supplier	$\propto_{18} = \sum_{i=1}^{9} n_i$	=171	$\mu_{18} = 2.29$	$poor < \mu_{18} < average$
	$\beta_{18} = \sum_{i=1}^{9} Sb_i$	=391		
Q34. IM / Client	$\propto_{34} = \sum_{i=1}^{9} n_i$	=147	$\mu_{34} = 2.98$	$poor < \mu_{34} < average$
	$\beta_{34} = \sum_{i=1}^{9} Sb_i$	=438		
Q35. IM / Supplier	$\propto_{35} = \sum_{i=1}^{9} n_i$	=147	$\mu_{35} = 2.48$	$poor < \mu_{17} < average$
	$\beta_{35} = \sum_{i=1}^{9} Sb_i$	=365		
Q24. IM	$\propto_{24} = \sum_{i=1}^{9} n_i$	=148	$\mu_{24} = 3.74$	$average < \mu_{17} < good$
	$\beta_{24} = \sum_{i=1}^{9} Sb_i$	=554		

5.5.3. Work Breakdown Structure

A section of the survey was designed to collect information on the WBS development and applications on the real projects as well as the relationship to SE philosophy.

5.5.3.1. WBS Development

In Section 4.2.5, the different ways of WBS development were reviewed in different literature. No data could be found in any literature suggesting a prescription to build WBS in a single format that can be used in different kinds of environment. Also, minimal work and discussion could be found regarding development of a standard patterned WBS to be used in different projects of the same nature.

Question 19 of the survey asked attendees how they have developed a WBS in their projects. The question and the choices are designed to categorise two fundamental ways of WBS development: using a template or building from scratch for each project. Table 20 presents the structure of the question and the choices. There also are options for those who never developed one or have different opinions that all are take into account when the results are discussed.

Table 20: Survey Q19 Structure

Question	Category	Choices
Question 19: How have you developed WBSs?	Template / Standard	1. Used template
		2. Used previous similar projects
	Develop from scratch depending on different project parameters	3. Structured around the project deliverables
		4. Structured around the team or disciplines
		5. Structured around the nature of the work

The same sample of the 'All' and the 'Rail' are used to see the overall results in industry and compared to the rail sector. Table 21 presents the detailed numerical results based on the absolute frequency as well as relative frequency by choices made by the participants. The table also categorises the results into the main two scenarios mentioned for the two data samples of the 'All' and the 'Rail'.

Table 21: Survey Question 19 – Detailed Results

Choices	Absolute frequency		Relative frequency by choice		Category	Absolute frequency		Relative frequency by choice	
	'All'	**'Rail'**	**'All'**	**'All'**		**'All'**	**'Rail'**	**'All'**	**'Rail'**
1. Used template	58	13	18%	14%	Template / Standard	109	27	33%	28%
2. Used previous similar projects	51	14	15%	15%					
3. Structured around the project deliverables	104	28	31%	29%	Develop from scratch depending on different project parameters	209	61	63%	64%
4. Structured around the team or disciplines	45	16	14%	17%					
5. Structured around the nature of the work	60	17	18%	18%					
6. Never developed one	13	7	4%	7%	N/A	13	7	4%	7%
SUM	**331**	**95**	**100%**	**100%**		**331**	**95**	**100%**	**100%**

Results detailed in Table 21 and visualised in Figure 33 shows that in both overall industry and the rail sector, over 60 per cent of those involved in developing a WBS in projects have to do this from the scratch considering the different project-specific characteristics such as project deliverables and works and tasks involved.

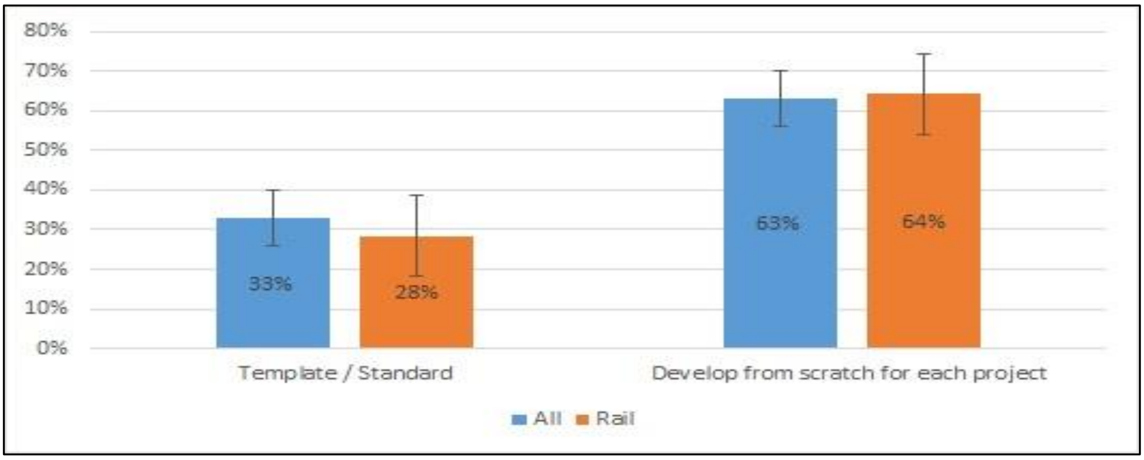


Figure 33: WBS Development Paths

Only 20 to 30 per cent either used a template WBS or used previous projects as templates to build a new WBS for the new project. This result provides further evidence that there is little work to develop a form of a standard breakdown structure that can be used in managing projects.

5.5.3.2. WBS Applications

Many forms of breakdown structure are defined in the literature and many are used in projects in different formats. Figure 34 presents the results from question 20 in the survey, which show that over half of the projects only use one form of WBS in a project while others use multiple types to serve different purposes within different project tools and applications.

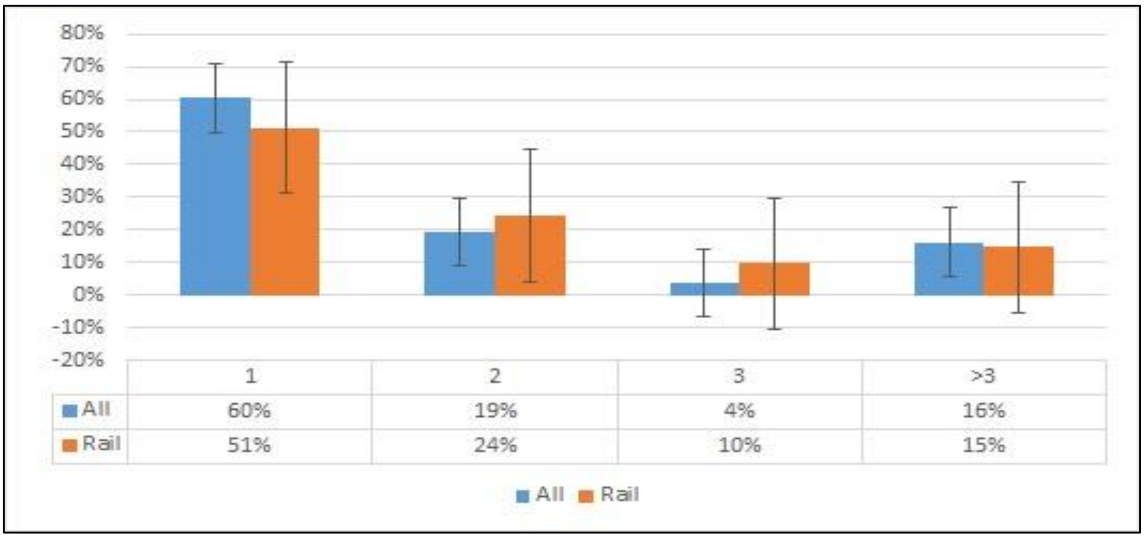


Figure 34: Number of WBS Forms Used in the Same Project

The purpose of question 21 in the survey is to identify the project functions and application that use one or more form of a WBS in a project. The results presented in Figure 35 show that, as expected, the primary use of WBS in projects is in project planning and scheduling. Over 35 per cent in all industries as well as rail sector use WBS in project planning tools. Results show that a relatively low percentage of respondents use WBS in different formats and in various other PM tools and application such as resource management tools or risk management tools.

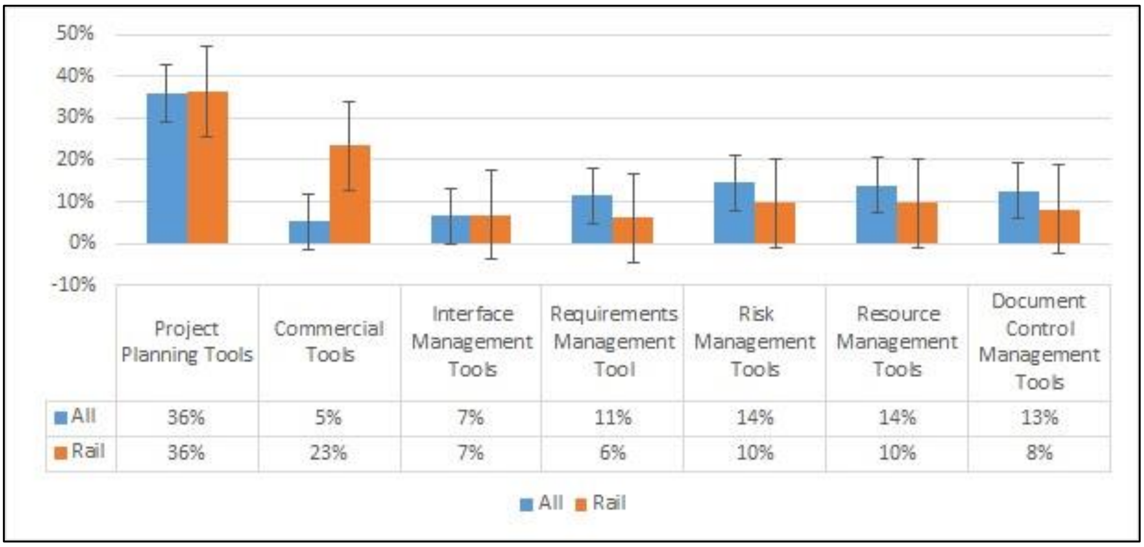


Figure 35: WBS Incorporated in Project Tools and Applications

The interesting result, however, is that over 20 per cent of people in the rail sector use a WBS approach in commercial management while a very low percentage, less than 5 per cent across all businesses, use a WBS in commercial tools and applications.

Another conclusion from this result is a very weak link to SE tools and application to any form of a WBS. If requirements and IM tools are to be considered as SE tools, the graph shows that a very low percentage of the people link a WBS to these tools. This further demonstrates that just around 0 to 10 per cent of the people use WBS or a form of breakdown structure in IM.

It is also interesting to understand, where there is only one form of a WBS, what the percentage of the people using the same WBS in different tools and application is. For this reason, the same analysis as above was conducted for the scenario with only one single form of WBS in the project.

Figure 36 presents the results from this study, which show that the single form WBS is mainly used in project planning tools and applications. But around 10 to 15 per cent of the people using a single form of WBS also use other PM tools such as resource and risk planning tools. A very low portion of people use a single form WBS for IM and RM.

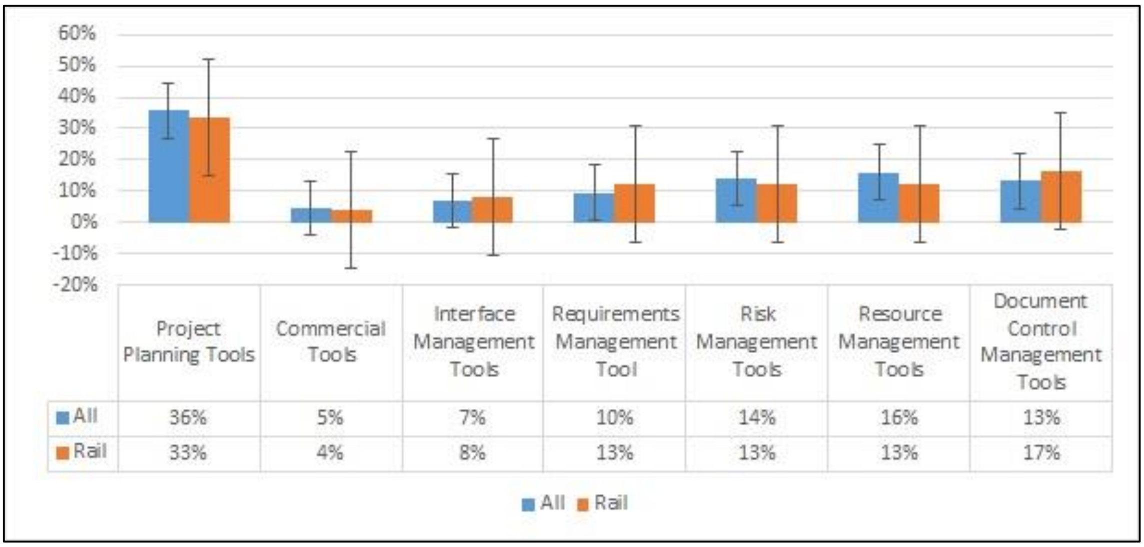


Figure 36: Single Form WBS Incorporation into the Project Tools and Applications

A very interesting result is in regard to the use of WBS within the project commercial tools. In this scenario, the result shows that a very low percentage, less than 5 per cent, of both the ‘All’ sample and the ‘Rail’ sample use the same planning WBS within their commercial tools to model the costs and expenses based on the resources and activities in the WBS. Considering the high percentage of the people in rail sector using a form of WBS for commercial use, this shows that the rail sector uses different types of breakdown structures for managing the commercial tools, which is not necessarily similar to the overall project WBS.

5.5.3.3. WBS Types

In Section 4.2.3, different types of WBSs were described and methods to choose the most suitable WBS form to serve special purpose within specific work sectors was reviewed within the literature. Within this survey, question 22 was designed to understand how people tend to build a WBS within their projects. The choices given included WBSs developed around product, service, resource and discipline. An ‘others’ option was also given for additional information for those who have other experiences.

The responses outside the choices were reviewed and consolidated into the responses. As a result, the additional information, task and functional oriented WBSs are also included in the results to be presented.

As shown in Figure 37, in general, a majority of the WBSs are developed around the product and final deliverables of the project. Around 40 per cent of the WBSs within the 'All' sample are created around the project products. The result also show a high percentage, around 30 per cent, of the WBSs within industry are developed around the project disciplines, tasks and functions within the project.

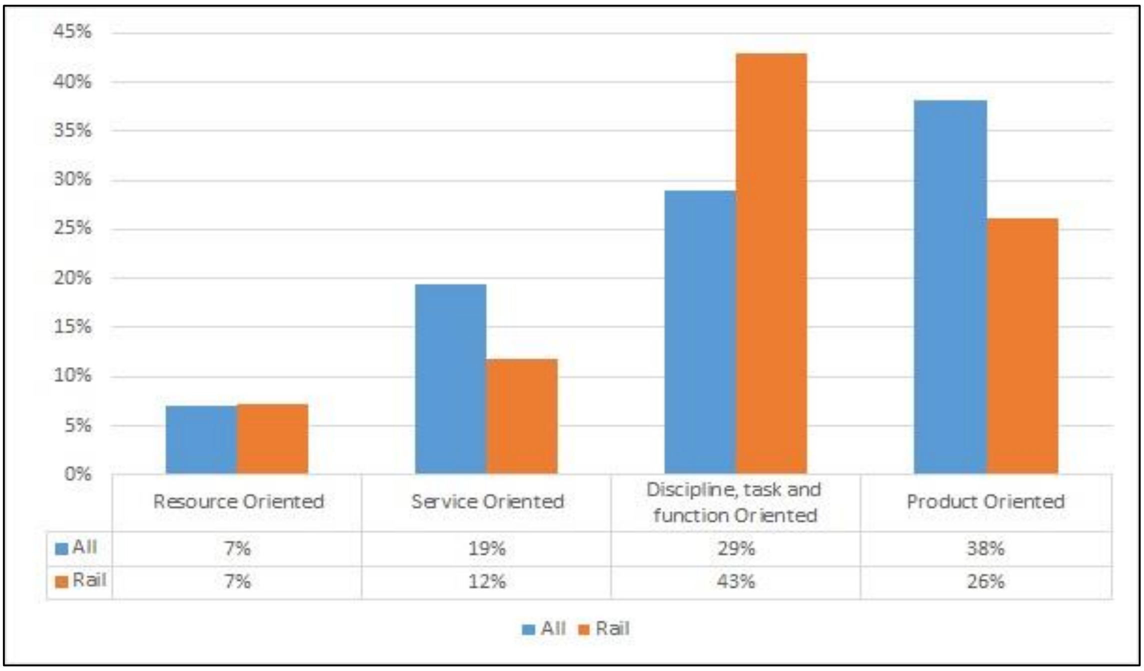


Figure 37: WBS Structure

In the rail sector, however, there is a higher interest in developing WBS around the project disciplines, tasks and functions. The same results were reviewed in Chapter 4, where it was concluded that the major civil construction projects tend to use work-based WBSs (see Figure 37, page 160).

5.5.3.4. WBS and Systems Engineering

Question 23 explored the link and relationship between the WBS concept and an SE approach[3] within the projects. The question is as follows:

[3] The intention in this question is to understand, if a WBS is used in any of the SE tools and procedures.

- *Q23: "How well connected is the WBS to systems engineering management in your opinion?"*

Question 23 also is Likert-type scale question with rating scales from poor to excellent with additional options of 'Not Applicable', 'Not at all' and 'Don't know'. Similar to the other questions discussed in Section 5.5.2, this question collapses a wider range of scales into a condensed category (Allen and Seaman, 2007, Likert, 1932).

Table 22 details the numerical results of the people who responded to the question within the data sample of the 'All' and the 'Rail'; 156 people answered the question, 42 of whom were from the rail sector.

Table 22: Survey Numerical Results for WBS – SE Relationship

Questions	Excellent	Very Good	Good	Average	Poor	Very Poor	Not at all	SUM
Q23 – the 'All'	9	26	36	43	17	1	1	156
Q23 – the 'Rail'	3	5	9	13	5	1	1	42

Figure 38 is a graphical presentation of the results that compare the rating from the 'All' sample with that from the 'Rail' sample. The same model used in Section 5.5.2 is used to calculate a mean score for the two scenarios.

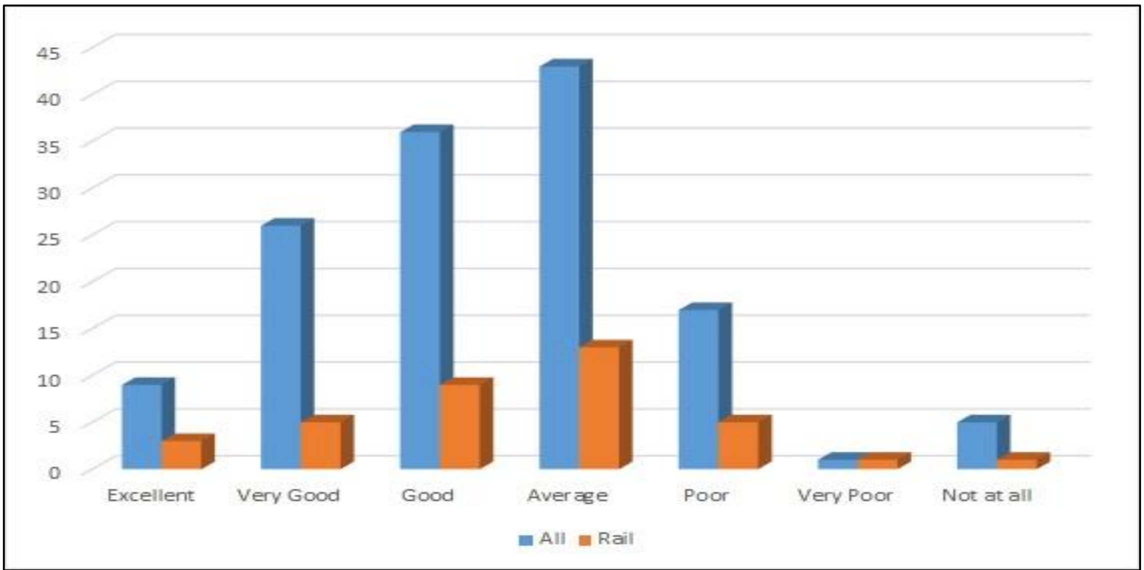


Figure 38: SE Application and Relationship with WBS

Table 23 shows the number of entries for the question per sample with a calculation for scoring for each grade against each question. Table 24 presents the calculation for the mean score for each scenario based on the model described in Section 5.5.2.

Table 23: Q23 Results Scoring

Questions	Grade	Excellent	Very Good	Good	Average	Poor	Very Poor	Not at all
	G_i	1	2	3	4	5	6	7
	SG_i	6	5	4	3	2	1	0
Q23 – the 'All'	n_i	9	26	36	43	17	1	5
	Sb_i	54	130	144	129	34	1	0
Q23 – the 'Rail'	n_i	3	5	9	13	5	1	1
	Sb_i	18	25	36	39	10	1	0

The results within Table 24 show that the mean scores for both samples are around average. This, therefore, further presents the relatively poor link/relationship between SE and the WBS concept.

Table 24: Q23 Mean Score Calculations

Questions	**Scoring Calculations**		$\boldsymbol{\mu_q = \frac{\beta_q}{\propto_q}}$	**SCALE**
Q23 – the 'All'	$\propto_{all} = \sum_{i=1}^{7} n_i$	=137	$\mu_{all} = 3.59$	$average < \mu_{all} < good$
	$\beta_{all} = \sum_{i=1}^{7} Sb_i$	=492		
Q23 – the 'Rail'	$\propto_{rail} = \sum_{i=1}^{7} n_i$	=42	$\mu_{rail} = 3.07$	$average < \mu_{rail} < good$
	$\beta_{rail} = \sum_{i=1}^{7} Sb_i$	=129		

5.6. Conclusion of the Chapter

This chapter detailed a survey that was conducted to test the main parts of this research hypothesis. The survey methodology, crowd targeting, engagement methodology, data filtering and data analysis was explained. After a phased approach on the data review and analysis, the results in this context were presented in various graphs and tables.

The data analysis within this chapter first indicates a lack of consensus among the project players, including management and delivery teams, about the importance of managing the interfaces and requirements within complex projects as standalone functions. In addition, the survey clarifies that a PM view is to manage the interfaces and requirements as natural part of managing a project, while an SE view is to have a standalone and systematic approach, along with procedures and tools to conduct such management functions.

The key conclusion from this data analysis is, therefore, a further clarification of the identity crisis of SE in today's projects and PM (Emes et al., 2005). The fact that there is still such debate over the ownership of two such important management functions justifies that more work is required to link the SE approach to PM in a more systematic way so that the project can function more efficiently. This conclusion also further explains why major projects of different types fail, simply due to very obvious interface and quality issues, as discussed in Chapter 3.

The analysis also shows that because the interfaces and requirements are not being managed well in industry, there is a major risk to the projects as they get larger and more complex. This is a further justification to develop better solutions to enhance and improve the IM and RM functions within managing the complex projects to make the projects more efficient.

The survey also asked questions related to the WBS concept and its types, development and applications, as well as its relationship with an SE approach. The key conclusion of this section provided further evidence regarding the little work and research conducted to create a standard breakdown structure concept that can be adopted in managing projects of the same nature. This provides a justification on the requirements to conduct such works and research.

It also concluded that the majority of the projects only use a single form WBS, and they mainly tend to use this WBS in project planning and scheduling tools and documents. The results clarified further the lack of projects using WBS or any other form of breakdown structure to link different PM and SE tools and functions. This is more significant, as it shows that the WBS concept has not been able to be used in IM within multidisciplinary projects and, therefore, this reveals a need for further work in this subject area.

The survey also presented a relatively poor connection between an SE approach and the WBS concept that will provide more justification on requirements to adopt such research work.

Chapter 6 KEY FAILURE FACTORS IN A RAILWAY PROJECT CASE STUDY

6.1. Introduction

In order to further explore key failure parameters in multidisciplinary rail projects, a major railway related project in central London was chosen as a case study to be examined.

The project team and the management of a major engineering consulting firm (ECF) that have had major roles in this project were approached and granted access to some data that will be explained in detail within this chapter. The project manager of the current project was also interviewed in various sessions and through various email communications, providing series of data and information.

In this chapter the project being studied is explained and its scale and timeline is detailed to provide a context to the research. Also the project governance is presented and the tools and procedures used in project management (PM) is explained.

Further detail on the data provided by the project is given and the methodology on the data assessment is explained. Based on the methodology designed, the data is analysed in detail and the results are presented and discussed. The results obtained are further studied and the conclusion is provided.

As the project is an ongoing and high-profile national project, no permission was granted to the author to use the actual name of the project and the name of the project parties. However, full permission is given to use the data for academic research only.

6.2. Case Study Project Description

The project used in this research as the case study is a single project that is contracted between a major design ECF and the main design and build contractor. Figure 39 is a schematic view of the programme in whole and the case study project within the programme.

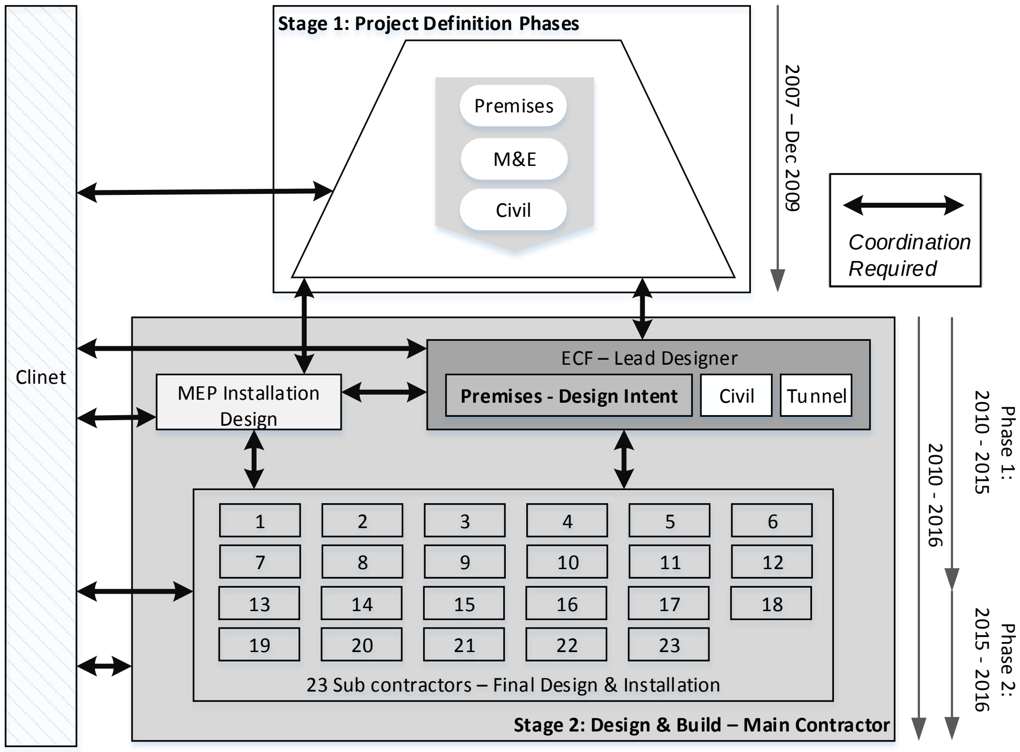


Figure 39: Case Study Project within the Programme

6.2.1. Programme Scope

The primary objectives of the programme are congestion relief and capacity enhancement of a central London rail underground station, as well as improving public access and interchange. Provision is to be made for passengers with reduced mobility and for improved emergency escape. The upgrade will include enlarging the existing ticket hall with new lifts, escalators, platform connections and step-free access from street level. Station modernisation is also a major part of the scope of this programme, from technology improvements to architectural modernisation. As the station is being expanded and major alterations applied, fire safety improvement is also another key major scope of this programme.

As Figure 39 shows, the programme consists of two major stages. Stage 1 was the period from 2007 to December 2009 in which an existing concept design was developed into a detailed tender design, Royal Institute of British Architects (RIBA) Stage G (refer to Figure 7: Alignment of Existing Plans of Work (Churcher and Richards, 2015)). Stage 2 is the construction period in which the designer provided design services to the design and build contractor.

The construction is contracted out to a main design and build joint venture (JV) contractor as a New Engineering Contract (NEC) Option C with the target cost of approximately £300 million, with construction to be conducted in two phases of 2010–2015 and 2015–2016, as shown in Figure 39. These two phases are only related to the sections of the station to be commissioned in different phases.

NEC Option C is a contract with a target cost and the schedule of the activities in which the outturn financial risks will be shared between the contractor and the client in a proportion that is agreed in advanced (Broome and Hayes, 1997, NEC, 2013, Institution of Civil Engineering (ICE), 2015). This is a type of contract that was adopted in major UK contracts such as London 2012 Olympic and Paralympic Games and Crossrail.

6.2.2. Case Study Project Scope

A JV of major international contractors formed and was awarded the construction contract for a major station upgrade project in London in December 2009. The major ECF in the UK that was approached and interviewed for the purpose of this study has been involved as the lead designer on the project since 2007. Initially working for the end user directly under a multidisciplinary design contract, it developed the design from RIBA Stage D to RIBA Stage G and developed the tender documents. Disciplines covered include civil/structural; tunnels; premises; mechanical, electrical, and plant (MEP); communications; fire; human factors; and public health. The outcome of this stage of the project was the set of project requirements specifications as well as work information (WI[4]) that should be used as the main requirements to be designed and delivered in Stage 2 (design and build) of the project.

Since 2010, the ECF, under a completely separate contract and separate project team, has been commissioned to work as the lead designer for the main design and build contracting JV, retaining responsibility for the civil/structural, tunnels and premises design. The implementation design for the MEP, fire, public health and communications disciplines however is now resides with an MEP contractor.

[4] Work information (WI) is equivalent to the project requirements specification. This is a contractual document specifying the work required to be delivered by the supplier

The ECF has produced the premises design to a 'design intent' level. The design should be in compliance with the project requirements specifications as well as the WI developed in Stage 1 of the project. This work is then developed by the relevant subcontractor for final installation design and physical installation.

The design intent provides an architectural concept and aesthetic feel for a design and outlines details such as fixings. For example, for ceilings, the design intent drawings provide sufficient information for the subcontractor designer to complete detailed design of the fixings and connections, but the overall aesthetic of the completed elements has already been set out in the design intent package.

Premises is essentially architecture, but is the architectural discipline as applied particularly to the rail industry. This major client especially has its own idea about what it wants to see. All products have to be on their approved register – a principle established after the 1987 King's Cross Station fire to ensure that all products were not combustible. The ECF project manager who was interviewed for this study stated:

> *"The role of the register has expanded now and it is as much a register of products the client is comfortable can be maintained economically as it is a fire safety initiative. It is very hard to get a product on the register as the client bureaucracy is very slow (this stifles innovation but that's the subject of another Ph.D.…)."* (ECF Project Manager, 2015)

The premises discipline has been selected for this exercise as it is the key discipline with major coordination interfaces with all the other disciplines. As discussed, the ECF as part of this contract has produced a design intent to then be detailed up by the subcontractor designer/installers. There are 23 of these subcontractors providing items from cladding to doors to tiling. Most but not all have a design and drawing production responsibility for their area. Through the Technical Design Review process, the ECF has responsibility to review and comment on their drawings.

The contract between the main contractor JV and the ECF that interviewed for this study is worth £10 million to the ECF and includes all contractor design alternatives and the production of final Issued For Construction drawing packages.

6.2.3. Project Governance, Tools and Procedures

The ECF project manager was interviewed to understand the project governance and team structure. The ECF overall project team and the interaction with the ECF client in this specific contract that is the main design and build JV is summarised in the organisation chart presented in Figure 40. The project team consists of a project manager who reports to a project director. The project manager leads three main blocks: quality management and assurance; project control, cost and legal; and the design team. According to the project manager, a *"systems engineering role was not required in the contract with design and build [and] didn't use any tools or procedures to manage the requirements and interfaces*" (ECF Project Manager, 2015). The coordination with other contractors and clients managed through the assurance regime is detailed in a Project Assurance Management Plan.

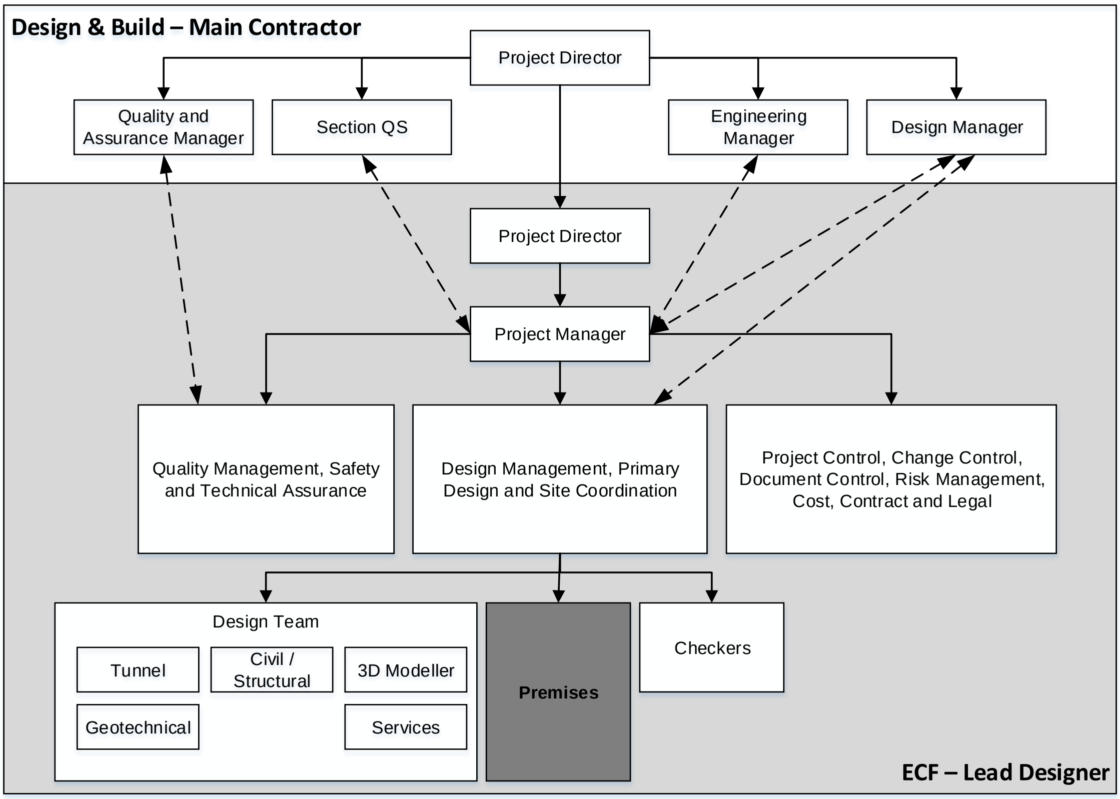


Figure 40: ECF Project Team Structure

The assurance regime makes the assumption that the lead designers understand the requirements within project requirements specification and WI, and therefore it is only concerned about the technically quality of the deliverables as well as overall constructability. When the quality is controlled, deliverables are issued to the client for acceptance or comment. The deliverables should be revisited based on the client and/or other parties' comments and request for changes. In this regime, no specific solution or procedure is designed to control the deliverables in terms of compliance with detailed project requirements specifications, WI and standards.

The project manager also stated that the architects changed the design completely from what was done as part of Stage 1 without any clear instruction:

> "*They don't appreciate the change they are making and the impact they have to the project….They do what they do because they think this is what the client wants"* (ECF Project Manager, 2015).

They made the changes and they designed based on the new changes in the absence of any sort of compliance review/audit with the project requirements specifications and WI.

According to the project manager, there are also no systematic requirements or interface management (IM) on the client side:

> *"To be honest the client keeps changing their mind." "Some of the comments show that we change the same thing three times because the client keeps changing their mind….[The] client won't tell you what they exactly want because it would be telling us our job, but they just keep asking for changes to what we provide….We have to try to interpret what the comment says and work based on that."* (ECF Project Manager, 2015)

Another key issue to generate changes to the work is the lack of managing the innovation and technology that impacts the project requirements specifications and WI:

> *"Quite often when the comment says, 'it is not in work information', it is because of the time from 2008 to now. [The] supplier changes the equipment and there is no system to capture the changes systematically*." (ECF Project Manager, 2015)

Therefore, it can be concluded that the absence of a system to manage and track requirements from customer to supplier has led to issues with requirement volatility and solution traceability (that is, requirements validation).

6.3. Nature of Sample

The project manager of the ECF was approached by the author to discuss the possible data that could be made available for the purpose of this research. As the project is an ongoing project and multiple parties are involved, there is a high level of sensitivity over the data sharing that limits the access to data. However, after various sessions with the project manager, some data were made available related to the construction support contract between the ECF and the main contractor JV who is responsible in building the station.

The data are in a form of series of comment logs related to the client's comments on the packages produced since the contract between the ECF and the JV contractor began in 2010 and specifically the period March 2014 to November 2015. The data only relate to the premises design package, which was the only remit in the contract between the ECF and the main contractor JV. Civil and tunnel packages were all pretty much complete before this specific period. The MEP comment logs were also produced, but they were issued to the MEP and services installation designers. The comment logs have been produced by the engineering team on the client side, presenting their issues and comments on the drawings produced by the design consulting company as part of the overall design build contract. According to the project manager, *"The comments mainly reflect what they see as inaccuracies, items not coordinated or items not in sufficient detail (in their opinion)"* (ECF Project Manager, 2015).

6.3.1. Documents/Logbook Format

Figure 41 is a snapshot of a typical logbook in which the comments and responses are stored. Some of the logbooks have additional columns to accommodate more discussions between the client and the supplier, but in principle the parameters required for this study are shown in Figure 41.

The logbooks are populated based on these terms:

- *Discipline:* In this column, the discipline lead who has generated the comment is identified by his/her technical discipline (for example, electrical, mechanical, premises or fire).

- *Section:* In this column, the section of the project that the reviewed drawings belong to is identified for the ease of reference for the suppliers.
- *Issue/Comment:* In this column, the issue/comment is detailed.
- *Required action:* In this column, the reviewers have described the actions expected to be taken to address the issue/comment by the supplier.
- *Supplier Responses:* In this column, the suppliers have responded to the comments from the client after review and taking required action.
- *Further Client/Supplier Responses:* In these columns, the dialogues between suppliers and client is archived.
- *Client Status:* In this column, the sensitivity of the comment is flagged by the reviewer as Red (this action shall be completed before submission is accepted), Yellow (accepted but comments must be addressed on next submission), Green (accepted but issue to be noted/closed), and White (observation).

	Client Comments Log	Date	XXX	
		Revision	XX	
Project:	XXX	This action shall be completed before submission is accepted		Red
Document Reviewed:	The list of document supplied by designer and reviewed as part of this review logbook	Accepted but comments must be addressed on next submission		Yellow
		Accepted but issue to be noted / closed		Green
Client Reference:	XXX	Observation		Observation

Srl	Discipline	Section	Issue / Comment	Required action	Supplier Response	Further Client Response	Further Supplier Response	Client Status
1	Electrical							R
2	Premises							Y
3	Fire							G
4	Comms							O

Figure 41: Comment Logbook Template

6.3.2. Data Set

The sample provided includes 49 folders, each of which contains a logbook in Excel format. Each logbook contains information including the related packages of work, the drawings and report reviewed, revision numbers, communication parties and dates of discussions (see Figure 41). Each of the folders also provide some supporting drawings with hand-sketched comments.

In total, there are 7,536 comments lines in all the logs within the 49 folders. Each entry has various attributes including the nature of problem, the sensitivity of the comment, the detail of the person who generated the comment (including the discipline name and detail) and actions the client is expecting the supplier to take to address the comment/issue. Table 25 presents a list of documents made available to the author. The table presents the date shown on each document as well as the dates related to the first and last revisions of the same document. It also shows the number of comments in each log as well as the total number of revisions of the document to date.

Table 25: Full Data Set

Document Review		Date On the Doc. Reviewed	1st Rev. Date	Last Rev. Date	Total Revs.	No. Comm.
Doc.	1	24/10/2014	10/09/2013	28/10/2014	5	35
Doc.	2	21/10/2014	21/06/2013	17/08/2015	35	222
Doc.	3	27/10/2014	21/04/2013	18/08/2015	23	126
Doc.	4	29/10/2014	06/03/2013	17/11/2015	35	155
Doc.	5	03/11/2014	14/10/2013	20/07/2015	22	182
Doc.	6	08/11/2013	08/11/2013	05/01/2015	4	15
Doc.	7	04/12/2014	06/03/2013	17/11/2015	35	175
Doc.	8	12/08/2014	04/04/2014	11/11/2014	4	75
Doc.	9	04/12/2014	21/06/2013	17/08/2015	35	213
Doc.	10	22/12/2014	14/11/2013	20/07/2015	22	194
Doc.	11	19/12/2014	06/03/2013	17/11/2015	35	181
Doc.	12	21/11/2014	08/11/2013	05/01/2015	4	15
Doc.	13	29/01/2015	21/06/2013	17/08/2015	35	229
Doc.	14	09/02/2015	14/08/2013	18/05/2015	12	46
Doc.	15	13/02/2015	03/06/2014	26/01/2015	5	24
Doc.	16	09/02/2015	14/08/2013	18/05/2015	12	45
Doc.	17	26/01/2015	03/06/2014	26/01/2015	5	23
Doc.	18	13/03/2015	14/11/2013	20/07/2015	22	223
Doc.	19	04/03/2015	04/07/2012	04/03/2015	88	596
Doc.	20	18/03/2015	11/08/2014	18/03/2015	3	5
Doc.	21	18/03/2015	18/03/2015	18/03/2015	1	22
Doc.	22	11/04/2015	02/08/2013	23/09/2015	49	382
Doc.	23	28/04/2015	06/03/2013	17/11/2015	35	180
Doc.	24	10/04/2015	12/04/2013	18/08/2015	23	126
Doc.	25	29/04/2015	21/06/2013	17/08/2015	35	213
Doc.	26	24/04/2015	19/12/2012	07/08/2015	13	23

Document Review		**Date On the Doc. Reviewed**	**1st Rev. Date**	**Last Rev. Date**	**Total Revs.**	**No. Comm.**
Doc.	27	18/05/2015	20/08/2014	07/09/2015	7	42
Doc.	28	13/05/2015	06/03/2013	17/11/2015	35	180
Doc.	29	18/06/2015	07/11/2012	04/09/2015	21	60
Doc.	30	22/06/2015	14/08/2013	18/05/2015	12	49
Doc.	31	11/07/2015	02/08/2013	23/09/2015	49	380
Doc.	32	20/07/2015	06/03/2013	17/11/2015	35	180
Doc.	33	20/07/2015	01/06/2013	30/09/2015	23	95
Doc.	34	20/07/2015	14/11/2013	20/07/2015	22	223
Doc.	35	31/07/2015	21/06/2013	17/08/2015	35	213
Doc.	36	04/08/2015	06/03/2013	17/11/2015	35	180
Doc.	37	19/12/2014	07/11/2012	04/09/2015	21	95
Doc.	38	10/08/2015	21/06/2013	17/08/2015	35	215
Doc.	39	07/08/2015	19/12/2012	07/08/2015	13	21
Doc.	40	24/08/2015	02/08/2013	23/09/2015	49	380
Doc.	41	18/08/2015	12/04/2013	18/08/2015	23	126
Doc.	42	07/09/2015	20/08/2014	07/09/2015	7	43
Doc.	43	17/08/2015	21/06/2013	17/08/2015	35	213
Doc.	44	02/09/2015	06/03/2013	17/11/2015	35	180
Doc.	45	04/09/2015	07/11/2012	04/09/2015	21	137
Doc.	46	23/09/2015	02/08/2013	23/09/2015	49	380
Doc.	47	24/09/2015	06/03/2013	17/11/2015	35	180
Doc.	48	30/09/2015	01/06/2013	30/09/2015	23	58
Doc.	49	17/11/2015	06/03/2013	17/11/2015	35	180
Total number of comments:						7536

As the table presents, the data within the logbooks are generated within the period of 30 April 2012 (that is, the date of the first revision of the first comment log – Doc. 35) to 17 November 2015 (that is, the date of the last revision of the latest comment log – Doc. 21).

6.4. Study Methodology

These comments are the client's issues regarding the design works produced by the premises designer as part of the main contractor design and build contract that is issued in during the period of the contract where the reviewers captured an issue in the design. Each comment potentially impacts the project performance in terms of time and budget. Comments have different impact weights to the project performance, but in principle if any action could prevent any of the comments, then the action could potentially save cost or time in the project and therefore make the project more efficient.

The aim of this study is to explore the main reason (MR) for creation of each of these comments and to identify the activities that could potentially prevent the comment in the first place. Therefore, the main interest of this study is the first revision of each comment. Although the first response from the supplier could potentially be useful to support a better understanding of the nature of issue, it is not necessary to have. The further discussions do not need to be reviewed for the purpose of this research although they carry valuable data for future research beyond the scope of this work.

The methodology design to conduct this study is based on the following steps:

Step 1: Data Selection: The data should be reviewed and combined into a single register so they can all be studied under the same terms to achieve the results. In this practice, the data are analysed and the duplications are removed to have a single set of data suitable for a detailed study.

Step 2: Data Analysis: Once the single register is created, the comments should be studied in detail. They will need to be categorised based on the MR that the comment is generated and that the activity could prevent the generation of the data. For example, a comment could be prevented if there were proper coordination and IM between two disciplines in the design stage. But also a set of 'reasons' needs to be identified to have a consistent review across the whole package of data.

Step 3: Result Analysis and Discussion: Once the results are completed, the discussion will be conducted to provide the final conclusion.

6.4.1. Data Selection

After brief review of the comment, and sorting the data based on date, it appeared that many of the documents are different revisions of the same document appearing in different folders. This means many of the comment logbooks include duplicated comments from other documents with only more discussions in the newer revisions.

Considering the scope of this research, the data were analysed and filtered down to smaller set of data including every single comment in all the 49 documents with no duplication. In order to filter the data two major rules applied:

<u>*Rule Number 1:*</u> As Table 25 shows, each document has different revisions. The earlier revisions are developed as the result of discussion between client and supplier. These revisions hold the most number of comments before they are addressed and closed, or removed in some cases. Therefore, Rule Number 1 is to choose the earlier revisions with the most number of comments.

<u>*Rule Number 2:*</u> The data gathered also show that as the documents are reviewed with different discipline leads within the client side, new revisions are created each time new comments are added. Therefore newer revisions have more comments. But also as the project moves to the end, and as the comments are addressed, many of the comments are removed and/or the sensitivity flag is changed. Therefore, Rule Number 2 is to pick a time slot from the overall project timeline and only select logs with the date within this period.

After a brief review of different revisions of the comments, and based on the suggestion from the project manager, a 12-month time slot was selected as a base, as presented in Figure 42. This figure also shows a schematic view of the increase and decrease of the number of comments in the logbooks across the period of the time.

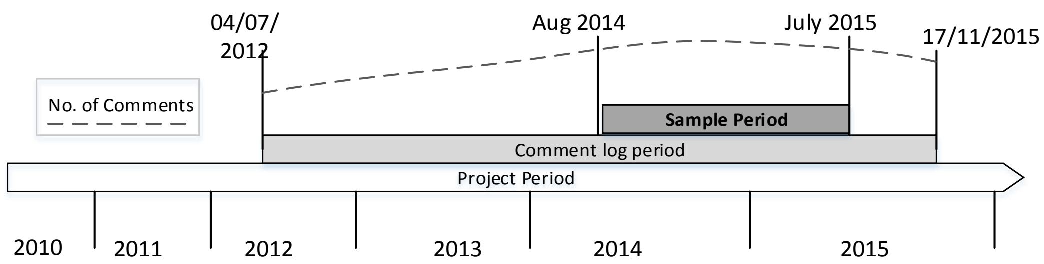


Figure 42: Sample Period for the Purpose of This Research

By sorting and grouping the data and applying the rules above as per Table 26, revisions of the logbooks are selected in which the maximum number of comments are included along with at least one line of response from the supplier to provide better understanding of the root of the issue. Within this table, the documents selected for data analysis are highlighted in bold.

Table 26: Categorising the Full Data Set into a Short List of Data to be analysed in This Research

Doc. Review		LOG	Date On the Doc. Reviewed	1st Rev. Date	Last Rev. Date	Total Revs.	No. Comm.	Rev. to be Reviewed	
Doc	19	A	**04/03/2015**	**04/07/2012**	**04/03/2015**	**88**	**569**	**88**	**Yes**
Doc	37	B	**19/12/2014**	**07/11/2012**	**04/09/2015**	**21**	**95**	**21**	**Yes**
Doc	29		18/06/2015	07/11/2012	04/09/2015	21	60	21	No
Doc	45		04/09/2015	07/11/2012	04/09/2015	21	137	21	No
Doc	26	C	**24/04/2015**	**19/12/2012**	**07/08/2015**	**13**	**23**	**13**	**Yes**
Doc	39		07/08/2015	19/12/2012	07/08/2015	13	21	13	No
Doc	4	D	29/10/2014	06/03/2013	17/11/2015	35	155	35	No
Doc	7		04/12/2014	06/03/2013	17/11/2015	35	175	35	No
Doc	11		**19/12/2014**	**06/03/2013**	**17/11/2015**	**35**	**181**	**35**	**Yes**
Doc	23		28/04/2015	06/03/2013	17/11/2015	35	155	35	No
Doc	28		13/05/2015	06/03/2013	17/11/2015	35	155	35	No
Doc	32		20/07/2015	06/03/2013	17/11/2015	35	155	35	No
Doc	36		04/08/2015	06/03/2013	17/11/2015	35	155	35	No
Doc	44		02/09/2015	06/03/2013	17/11/2015	35	180	35	No
Doc	47		24/09/2015	06/03/2013	17/11/2015	35	180	35	No
Doc	49		17/11/2015	06/03/2013	17/11/2015	35	180	35	No
Doc	24	E	10/04/2015	12/04/2013	18/08/2015	23	126	23	No
Doc	41		18/08/2015	12/04/2013	18/08/2015	23	126	23	No
Doc	3		**27/10/2014**	**21/04/2013**	**18/08/2015**	**23**	**126**	**23**	**Yes**
Doc	33	F	**20/07/2015**	**01/06/2013**	**30/09/2015**	**23**	**95**	**23**	**Yes**
Doc	48		30/09/2015	01/06/2013	30/09/2015	23	58	23	No
Doc	2	G	**21/10/2014**	**21/06/2013**	**17/08/2015**	**35**	**222**	**35**	**Yes**
Doc	9		04/12/2014	21/06/2013	17/08/2015	35	213	35	No
Doc	13		29/01/2015	21/06/2013	17/08/2015	35	213	35	No
Doc	25		29/04/2015	21/06/2013	17/08/2015	35	213	35	No
Doc	35		31/07/2015	21/06/2013	17/08/2015	35	213	35	No
Doc	38		10/08/2015	21/06/2013	17/08/2015	35	215	35	No
Doc	43		17/08/2015	21/06/2013	17/08/2015	35	213	35	No
Doc	22	H	**11/04/2015**	**02/08/2013**	**23/09/2015**	**49**	**379**	**49**	**Yes**
Doc	31		11/07/2015	02/08/2013	23/09/2015	49	379	49	No
Doc	40		24/08/2015	02/08/2013	23/09/2015	49	379	49	No
Doc	46		23/09/2015	02/08/2013	23/09/2015	49	379	49	No
Doc	14	I	**09/02/2015**	**14/08/2013**	**18/05/2015**	**12**	**46**	**12**	**Yes**
Doc	16		09/02/2015	14/08/2013	18/05/2015	12	45	12	No
Doc	30		22/06/2015	14/08/2013	18/05/2015	12	45	12	No
Doc	1	J	**24/10/2014**	**10/09/2013**	**28/10/2014**	**5**	**35**	**5**	**Yes**
Doc	6	K	08/11/2013	08/11/2013	05/01/2015	4	15	4	No
Doc	12		**21/11/2014**	**08/11/2013**	**05/01/2015**	**4**	**15**	**4**	**Yes**
Doc	5	L	03/11/2014	14/11/2013	20/07/2015	22	182	22	No
Doc	10		**22/12/2014**	**14/11/2013**	**20/07/2015**	**22**	**194**	**22**	**Yes**
Doc	18		13/03/2015	14/11/2013	20/07/2015	22	194	22	No
Doc	34		20/07/2015	14/11/2013	20/07/2015	22	194	22	No
Doc	17	M	26/01/2015	03/06/2014	26/01/2015	5	23	5	No
Doc	15		**13/02/2015**	**03/06/2014**	**26/01/2015**	**5**	**24**	**5**	**Yes**
Doc	20	N	**18/03/2015**	**11/08/2014**	**18/03/2015**	**3**	**5**	**3**	**Yes**
Doc	27	O	**18/05/2015**	**20/08/2014**	**07/09/2015**	**7**	**42**	**7**	**Yes**

Doc. Review		LOG	Date On the Doc. Reviewed	1st Rev. Date	Last Rev. Date	Total Revs.	No. Comm.	Rev. to be Reviewed	
Doc	42		07/09/2015	20/08/2014	07/09/2015	7	43	7	No
Doc	21	P	**18/03/2015**	**18/03/2015**	**18/03/2015**	**1**	**22**	**1**	**Yes**
Doc	8	Q	**12/08/2014**	**04/04/2014**	**11/11/2014**	**4**	**74**	**4**	**Yes**
Total Number of comments to be analysed:							2179		

In summary, 17 logbooks were picked and studied for the purpose of this chapter as Table 26 shows including 2,179 line comments that need to be analysed for the purpose of this research.

6.4.2. Data Analysis

The comments need to be grouped based on the MRs of their existence as well as the activities that could prevent them. But also a set of 'reasons' should be identified to have a consistent review across the whole package of data. In order to develop a set of consistent reasons and activities, a small sample of the data was reviewed and the MRs and activities were identified. The comments within the 49 identified documents were grouped and categorised based on a consistent set of reasons and activities, as presented in Table 27.

Table 27: Main Reasons and Activities for Data Analysis

Activity to prevent the issue	Main Reason – MR
1. Interface Management (IM)	Assumption – waiting for information from other parties
1. Interface Management (IM)	Missing interface requirements
1. Interface Management (IM)	Non-compliance with interface requirements/standard/specification
1. Interface Management (IM)	Poor interface requirements definition from client
2. Requirements Management (RM)	Missing requirement
2. Requirements Management (RM)	Non-compliance with client requirements/standard/specification
2. Requirements Management (RM)	Poor requirements definition from client
3. Verification & Validation (V&V)	Poor compliance evidence presentation
4. Change Management (CM)	Late change information from client
4. Change Management (CM)	Poor change management and communication
4. Change Management (CM)	Poor communication for the changes with parties
4. Change Management (CM)	Poor managing the changes through request for information (RFI)
5. Configuration Management (CoM)	Poor configuration management
5. Quality Management (QM)	Poor quality check
6. Technical Solution (TS)	Technical solution issue/recommendation
7. Technical Query (TQ)	Technical query/clarification

Once this review was completed, and the comments were categorised based on ‘main reasons’, ‘activities to prevent’ and ‘disciplines related’, the results were combined into a single register in order to conduct detail analysis and discussions. A snapshot of this single register is presented in Figure 43. Parts of the register are also presented in Appendix 4 as a reference.

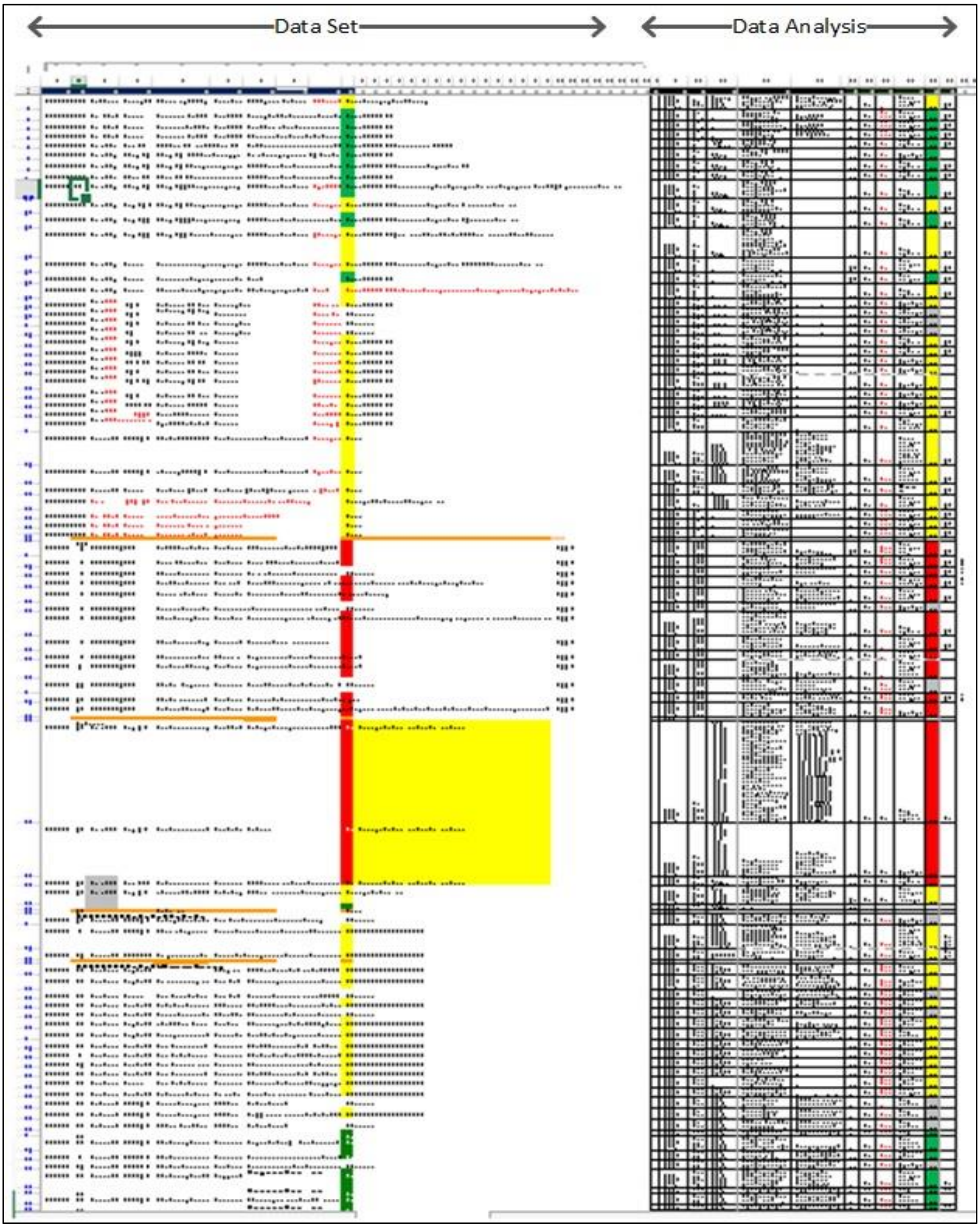


Figure 43: Snapshot of the Combined Results Register of 2,179 Reviewed and Analysed Comments

6.5. Results and Discussion

The 2,179 comments raised on this design package of work are generated from the discipline leads with the distribution shown in Figure 44.

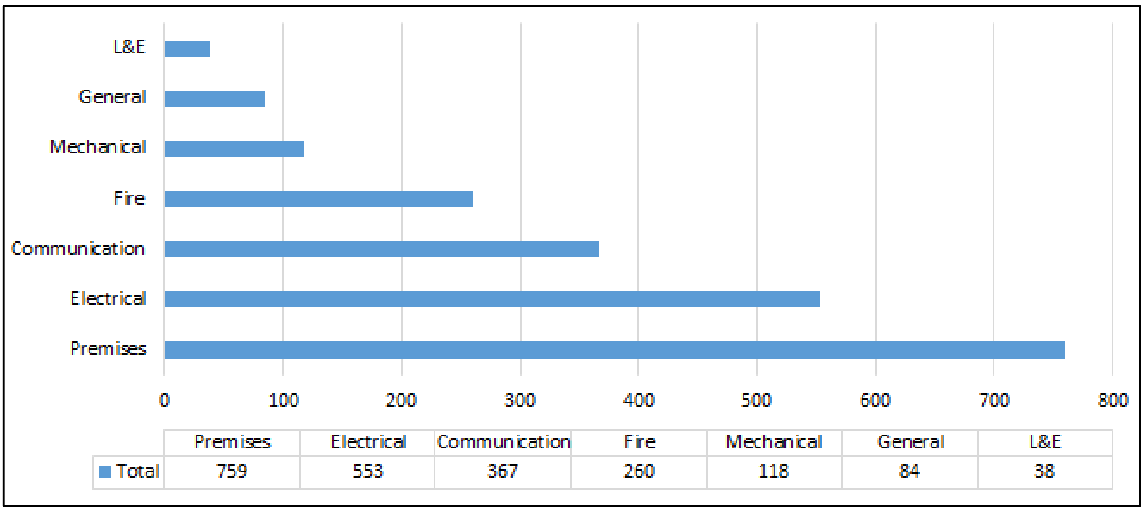


Figure 44: Discipline Leads' Number of Comments

In this grouping, the comments tagged as Civil and Architect are combined into the Premises comments. The Electrical comments also include those tagged as Power. All other generic comments or those related to disciplines such as Human Factor and Electromagnetic Compatibility (EMC) are shown as part of General comments. The results presented in Figure 44 provide a view of how comments are generated, but they potentially could also be used for more detailed analysis for work beyond the scope of this research.

The scope of this study is mainly concerned with the issues that led to the comments. Table 28 shows the breakdown of the 2,179 comments based on the MR and the activities to prevent the issue identified in Table 27.

A margin of error (MOE) based on the sample size of 2,179 is considered in the data analysis. The maximum MOE is a simple re-expression of the sample size **n,** as discussed previously. The numerators of these equations are rounded to two decimal places as $1.29/\sqrt{n}$ for MOE at 99 per cent confidence that is applied for this sample (Aufmann et al., 2008). Therefore, the MOE is calculated as follows:

$$MOE = \frac{1.29}{\sqrt{n}}, where\ n = sample\ size$$

$$n = 2179 \quad » \quad MOE = \frac{1.29}{\sqrt{2179}} = 3\%$$

Table 28: Breakdown of the Comments Based on the Nature of Issue

Comments are related to:	Number of comments
Interface Management (IM)	812
Requirements management (RM)	390
Technical Solution (TS)	234
Technical Query (TQ)	210
Qualify Check/Control (QM)	173
Verification & Validation (V&V)	112
General Notes/Comments (GN)	93
Change Management (CM)	85
Configuration Management (CoM)	70
Total	**2179**

The results, as shown in Figure 45, show that poor interface and requirements/scope management are the two top reasons – together responsible for around 55 per cent – that generate discussions and disagreement among the project parties, thus generating more work, cost and time.

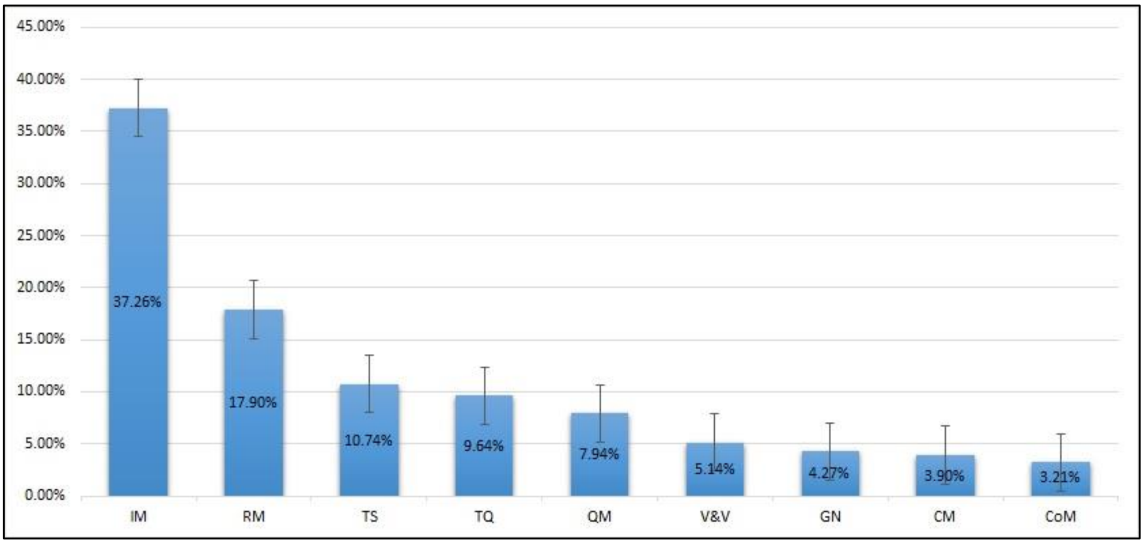
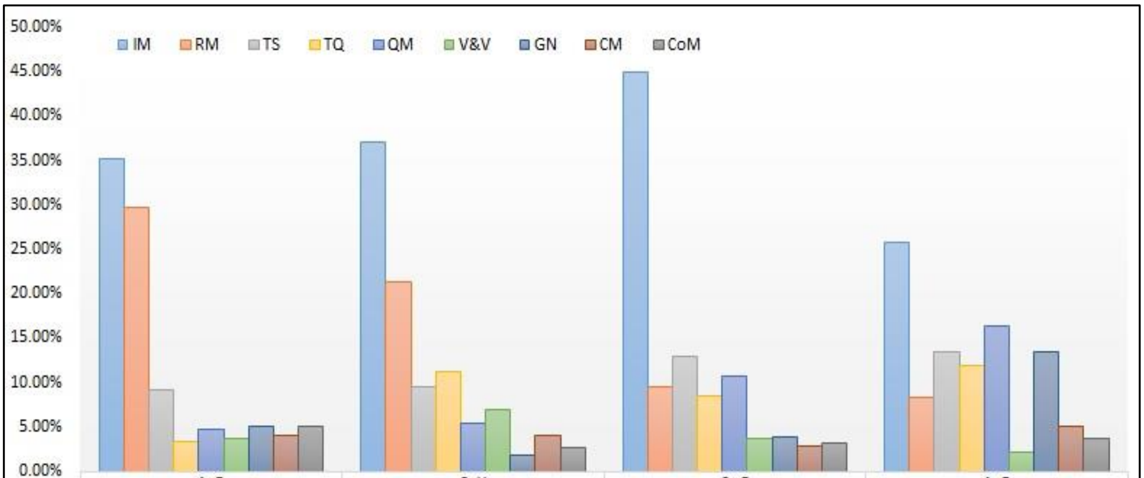


Figure 45: Comments Distribution Based on the Main Reasons/Activities

The data also provide the sensitivity and the importance of the comments based on how the reviewers rated the comments using the colour code of Red, Yellow, Green and

White as described earlier. Figure 46 summarises the breakdown of the comments base on their importance parameter.



	1. R	2. Y	3. G	4. O
IM	35.16%	37.12%	44.98%	25.72%
RM	29.67%	21.35%	9.46%	8.33%
TS	9.16%	9.46%	12.93%	13.41%
TQ	3.30%	11.17%	8.49%	11.96%
QM	4.76%	5.41%	10.62%	16.30%
V&V	3.66%	6.94%	3.67%	2.17%
GN	5.13%	1.80%	3.86%	13.41%
CM	4.03%	4.05%	2.90%	5.07%
CoM	5.13%	2.70%	3.09%	3.62%

Figure 46: Data Breakdown Based on Sensitivity Factor

Red and Yellow comments impact the project performance in a greater margin as they potentially stop the acceptance and generate new additional work to resolve the issue before the project can progress further.

As Figure 46 also shows under the Red and Yellow comments, poor IM as well as poor requirements management (RM) are the two top reasons comments are generated. The chart also shows that the poor IM is the single reason for most issues across all four categories. Under Green comments as well as the White observation comments, however, technical solutions and quality check are the two main reasons after poor IM.

Poor verification and validation (V&V) makes around 5 per cent of the comments, which is relatively low in comparison to IM and RM. This, however, could be explained based on the fact that the project is not completed yet. The results from the V&V processes in a project life cycle are normally more visible when the project is in its final stage and, therefore, this could be different if the comments are revisited when the project is closed.

The results are narrowed down in the chart presented in Figure 47. As shown, 12.5 per cent of the total 2,179 comments are Red flagged, with around 50 per cent Yellow and 24 per cent Green.

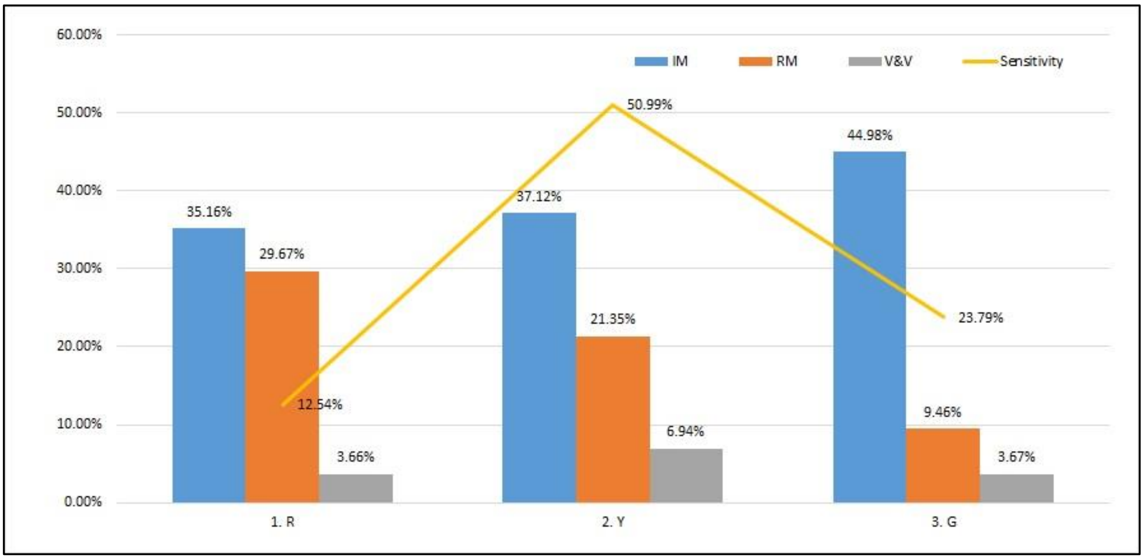


Figure 47: Comments Sensitivity in Relation to IM, RM and V&V

The results show that the poor IM, RM and V&V process together make up around 60 to 70 per cent of the comments under each of these categories.

In comparison to the Red and Yellow categories, Green-labelled comments result from a relatively low percentage for RM issues. This shows that the majority of the comments that are related to the poor requirements are the comments that stop project progress and need more attention.

6.6. Conclusion of the Chapter

This chapter discussed the study that was conducted on the performance of project management and delivery as part of an overall major programme of a railway station modernisation project in central London. Access was permitted to a set of folders including over 7,000 lines of comments communicated between the client and the supplier over the acceptance of the design work of the premises performed by the ECF that was interviewed for this study.

The results from the analysis of the data show that poor management of the interfaces and coordination between different disciplines and parties, as well as poor understanding and management of the project scope and requirements, are the top two reasons to generate a considerable volume of discussions and disagreement among the project parties, which results in generating more work, cost and time.

Poor IM and RM together with a poor V&V process make up around 60 to 70 per cent of the comments, which shows how they can impact the project efficiency. This therefore provides more justification on a need to work on this area.

As explained in Chapter 4, improving the quality of the breakdown structure within the system or projects has a direct impact in the quality of interfacing and IM that further justifies the solution required for a better breakdown structure.

Chapter 7 PROPOSED DISCIPLINE BREAKDOWN STRUCTURE CONCEPT

7.1. Introduction

Through the literature review and the research conducted, we can conclude that project management (PM) and systems engineering (SE), as the two essential aspects in success or failure of a project, should work together in an integrated management system (Boarder, 1995, Loureiro et al., 2004, Emes et al., 2012). Previous chapters also explained some of the PM and SE functions and activities. This chapter introduces and explains the concept of forming an integrated management system with a focus on rail sector projects.

Information is layered hierarchically in projects. Therefore, the integrating structure must be similarly layered. The concept that is proposed in this chapter is a breakdown, tree-form structure called the Discipline Breakdown Structure (DBS), which is able to communicate with various levels of the information in a project.

This chapter explains the proposed DBS concept and examines the applicability of the DBS within projects, as well as the relation between the proposed DBS and other existing breakdown structures.

7.2. Discipline Breakdown Structure

7.2.1. DBS Concept

Projects in rail sectors are typically multidisciplinary since various disciplines work together to design and implement different parts of the required infrastructure. The rail supply chain comprises organisations operating within relatively clearly defined disciplines. These disciplines are therefore related to a project Organisation Breakdown Structure (OBS) (which in part is a description of the supply chain), the Work Breakdown Structure (WBS) (the work involved in the form of activities and work packages naturally relates to disciplines, especially if the WBS is work-based) and the Product Breakdown Structure (PBS) (since each element of the product is related to one or more disciplines).

The DBS, therefore, is a hierarchical breakdown of disciplines that form the core of a project organisation. Since disciplines are more fundamental than work, products or organisations (for example, we have institutions and universities shaped around disciplines like civil, mechanical and electrical engineering), it is the application of a discipline that forms an activity, and products are the result of the application of a discipline to a problem. Therefore, the DBS presents the disciplines' responsibilities in order to develop various parts of a project and to deliver and integrate the project deliverables, along with defining the skills required.

Figure 48 shows an example DBS model proposed for a rail station design project. At the physical component level are the cameras that should be designed and installed in the station for security purposes; these can be traced back to the responsible discipline, which is the communication engineering discipline in this project. In the case of the camera, the DBS shows the disciplines responsible for determining the requirements, procuring and installing such a device within a rail context. It is relatively generic and could be applied to many situations; the fine detail would depend upon project-specific requirements, such as the specific technology of the camera.

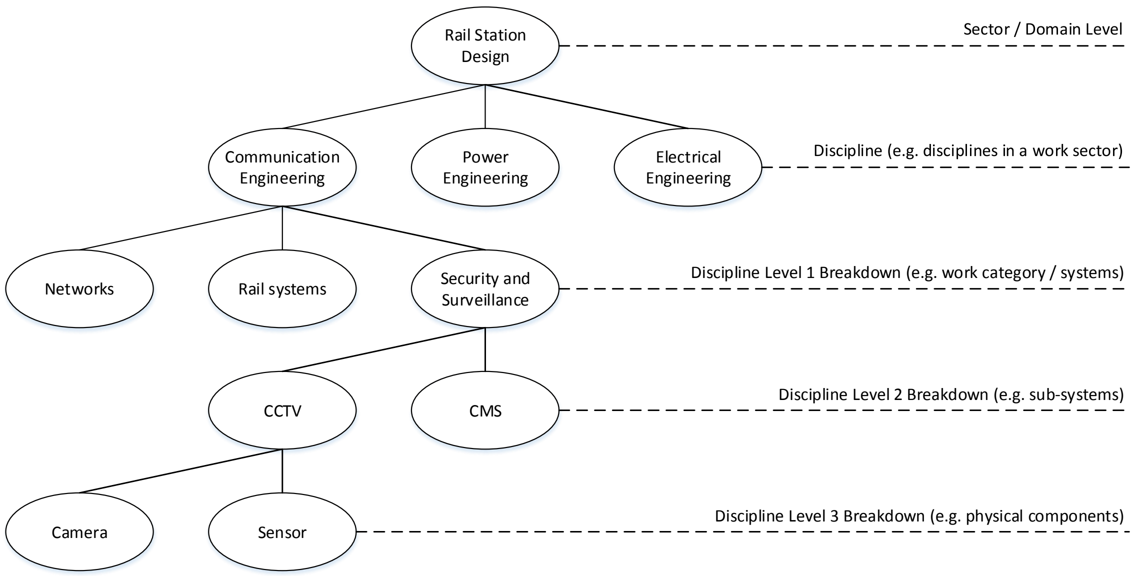


Figure 48: DBS Model Example for a Component in a Rail Project
Including a presentation of the DBS levelling.

The proposed DBS is based on the industry/domain in which the project is executed. The project-specific scope will identify the relevant parts of the DBS for use in the management system.

7.2.2. DBS Relation with WBS, PBS and OBS

The PBS is a breakdown of the products which should be assembled to form the final delivery of the project. Therefore, in a typical rail project, the PBS represents the products to be developed by the disciplines through the activities within the WBS. The PBS is a project-specific document that is developed based on the project-specific requirements and scope. In construction design projects, PBSs are often defined as the series of the documents in the form of drawings, reports, tables, schedules, etc.

The WBS is a hierarchical breakdown of a project into different packages of works. The WBS is a project-specific document that is formed based on the project-specific scope and the products to be developed by the project (that is, the PBS). The WBS can be shaped around different factors such as tasks, phases/timing and resources. Within different packages in WBS, several disciplines are involved. Chapter 5 concluded that over 50 per cent of projects in the rail sector only have a single WBS and no other form of breakdown structure. They mainly use the WBS for the purpose of the project planning and scheduling.

The OBS is a breakdown of the resources holding various responsibilities within a project structure. These people have different skills from different disciplines. They will be conducting the activities of the WBS in order to develop the products of the PBS. Therefore, the OBS in projects is also developed for the specific project.

Figure 49 summarises the relation of the proposed DBS with WBS, PBS and OBS with an example of a making a power control system as part of design and implementation of a train station project. It shows that to supply a design for a power control system, the DBS will help to understand what sort of technical skills are required, enabling the allocation of suitable resources to this activity.

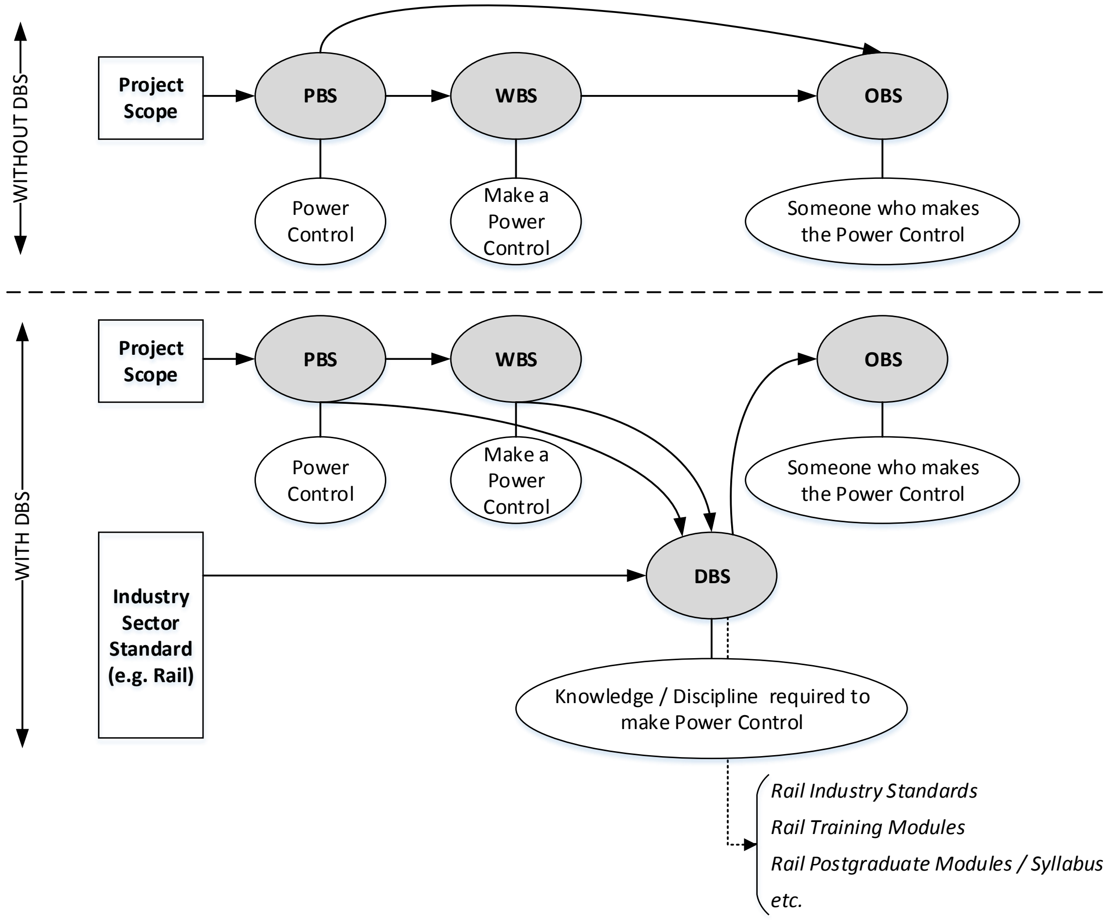


Figure 49: DBS Relation with WBS, PBS and OBS

Example shown: making a power control. The upper part of the diagram shows the current situation and the lower part shows the role of the proposed DBS.

7.2.3. DBS Development

The DBS development is based on the industry requirements. In practice, a template DBS for an industry sector is best produced through the examination of several or even many individual projects, together with a consideration of industry needs, supply chain structure and norms. Considering the number of disciplines involved in typical project, the projects and their existing WBS, PBS and OBS are valuable sources of information to develop such a DBS

The development of the proposed DBS in this study is based on a project in a rail station upgrade domain and its contractual requirements (that is, scope of the work). The latter is supported by using previous experiences on working in similar projects in a similar domain and with consultation with domain experts.

Once a DBS has been developed and tested for a particular project, then the DBS can become a template for others in the future in the same domain, as presented in Figure 50.

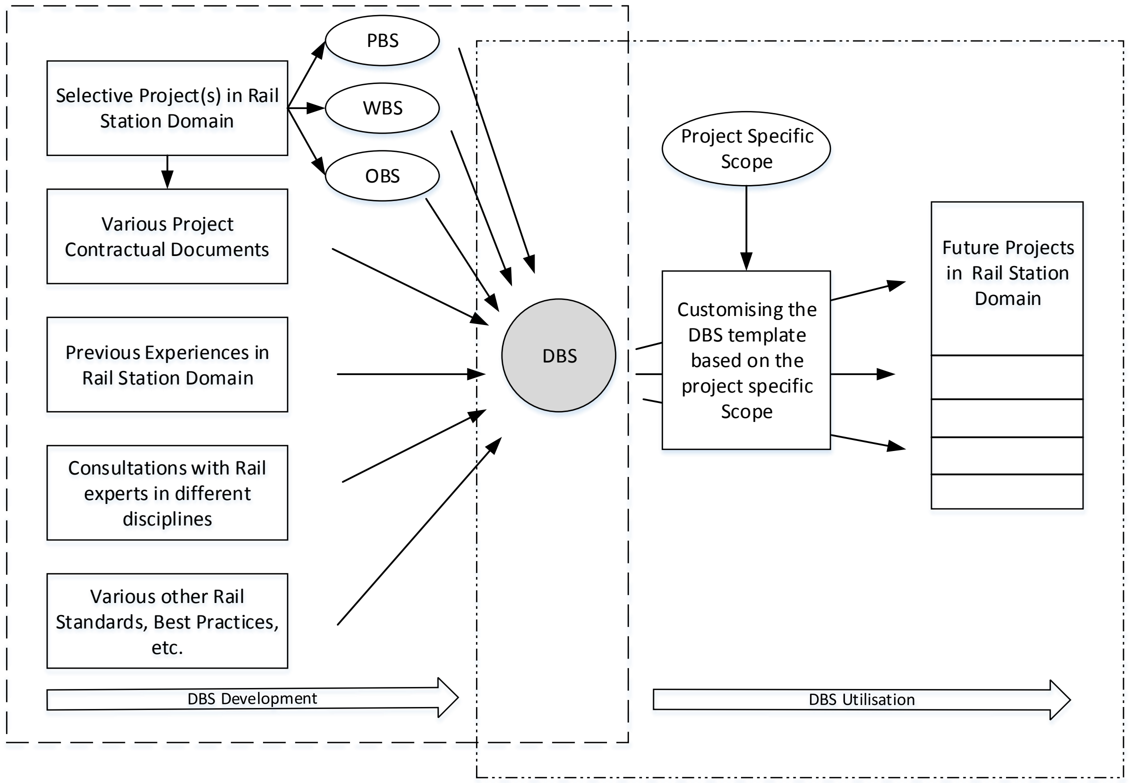


Figure 50: Life Cycle of the DBS Development and DBS Use Proposed in This Study

7.2.4. DBS Format

Similar to the WBS structure, as presented in Figure 51, the proposed DBS is also formatted in a tree model, as a logical breakdown of disciplines, skills and competences they need to have in order to complete the project. The proposed DBS could be presented in different levels depending on the nature of the disciplines involved. In this study, three levels of elaboration below the discipline level are considered.

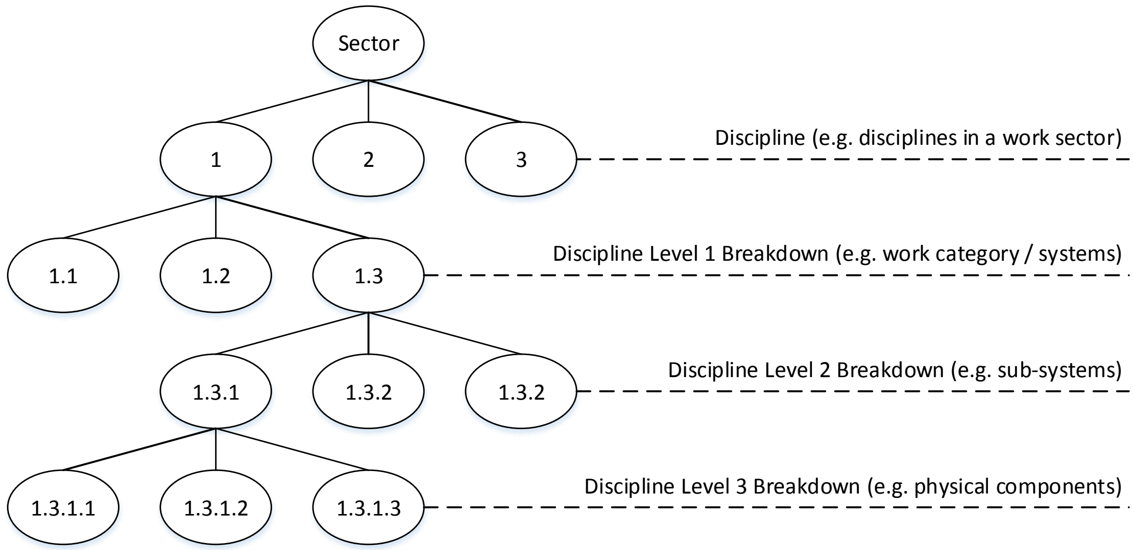


Figure 51: DBS Tree Model and Levels Proposed in This Study

When the DBS is created for a specific work domain, it is proposed to be formatted in a master modular database system. The database can be customised for specific projects by selecting the modules related to the scope of a project. This means some of the baseline documents, such as the interface matrix, or some of the key generic discipline-related risks within the risk register should be predefined when the project is started. The development of the database system in a form of an industrial application is beyond the scope of this study. However, the DBS concept creates an opportunity for future works to develop such industrial applications and software to enhance PM.

7.2.5. Other Benefits of DBS

When the proposed DBS within an industry sector is developed, it could also be used for other purposes, including industry standards, industrial training modules, educational courses or university degree syllabuses.

The proposed DBS also allows an assessment of the capability of the supply chain to deliver a particular project and the identification of any weaknesses. Therefore, the DBS acts as a measure of the supply chain's capability and competency to deliver particular skills and activities within a project.

7.3. Integration of the Management System

Figure 52 presents what this study assumes are the key activities of PM in a typical project in rail sector. This presents a high-level view of the procedures and tools and the relationship through the various breakdown structures. The assumptions are as follows:

- **Study Domain:** Rail sector – Rail station upgrade domain
- **PM Activities:** Scope Management, Planning/Scheduling, Activity Management (for example, Design Management), Risk Management, Resource Management, Commercial Management, Quality Management and Configuration Management
- **SE Activities:** Requirements Management, Interface Management, Verification & Validation and System Architecture
- **Breakdown Structure Documents:** PBS, WBS, OBS and Cost Breakdown Structure (CBS)

As Figure 52 shows, each of the activities require various tools and documents. To manage the interfaces, for example, the SE uses various interface matrices and interfaces data sheets. Various breakdown structures are also used in the management system. The PBS is created in accordance to the scope of the project. The WBS is developed based on the scope of the project as well the PBS. It then provides information required to establish the OBS. All the breakdown structures contribute to create the CBS that feeds information for the commercial team in order to model the project finances.

These breakdown structures provide information for other activities. For example, the WBS is the core for the project planning and scheduling and provides information for activity management such as design management. Also, the WBS and the PBS together contribute to project interface and requirements management. The OBS informs the resource and communication management activities and their related tools and documents. Therefore, all of the activities are related to the various breakdown structures in different capacities. While the WBS, for instance, feeds information directly to project planning, risk management as an activity uses the OBS information in order to communicate the project risks to the responsible risk owners.

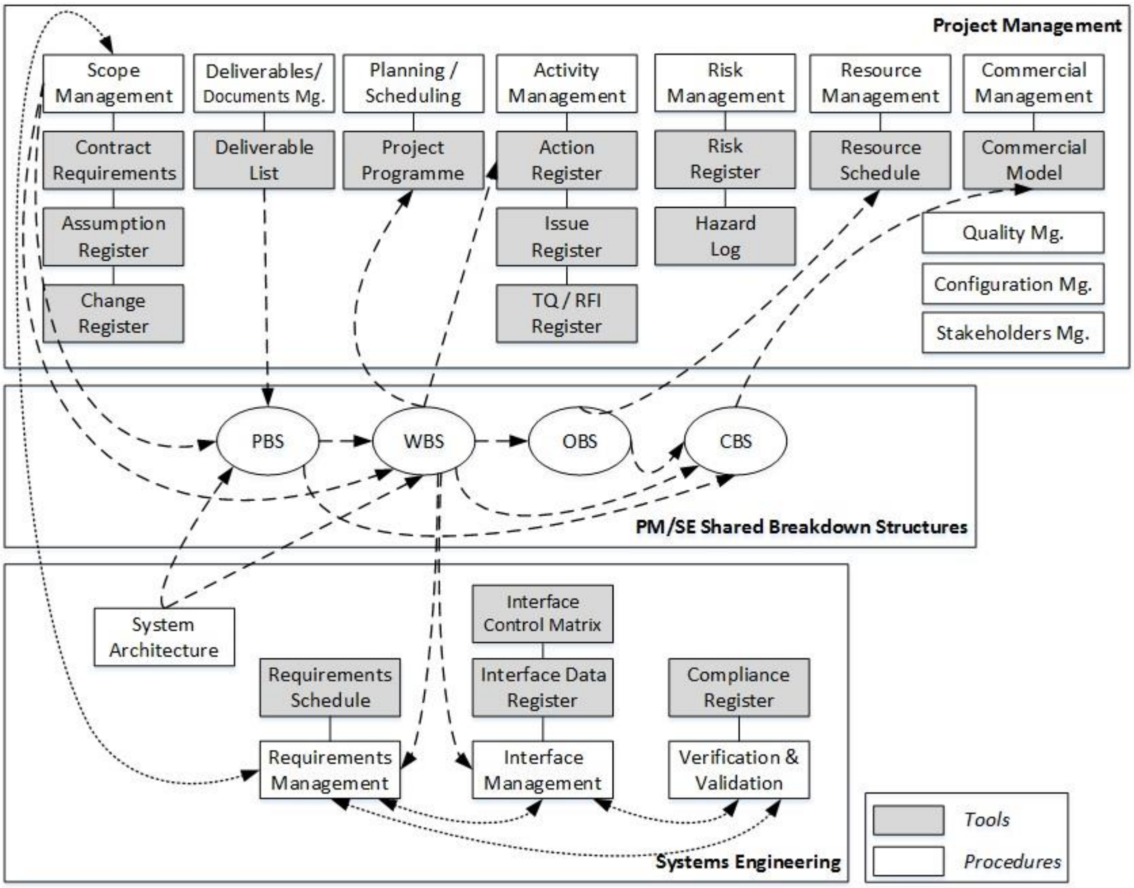


Figure 52: PM and SE Activities and Relationship through Breakdown Structures

Breakdown structures are the shared components of SE and PM.

Considering the given assumptions and the model, the DBS concept is proposed to be used as a single core to create interlinks among all the PM and SE activities to form an integrated management system, as presented in Figure 53. The proposed DBS, therefore, should be able to communicate with the PM and SE activities, tools and documents such as the WBS, Interface Management System (IMS), Requirements Management System (RMS), Deliverable and Document Management System and Validation and Verification.

In a traditional PM, as shown in Figure 52, many of the project documents and activities are connected through the link they have to other breakdown structures such as the WBS, PBS, and OBS. The WBS developed for project planning and scheduling in rail infrastructure projects is normally a single breakdown structure tool that also has links to various project documents. The proposed DBS is not introduced as a replacement for the WBS in this study; rather, the DBS concept is introduced as a core that also links the WBS to the rest of the PM and SE tools and documents in a more structured and fundamental way.

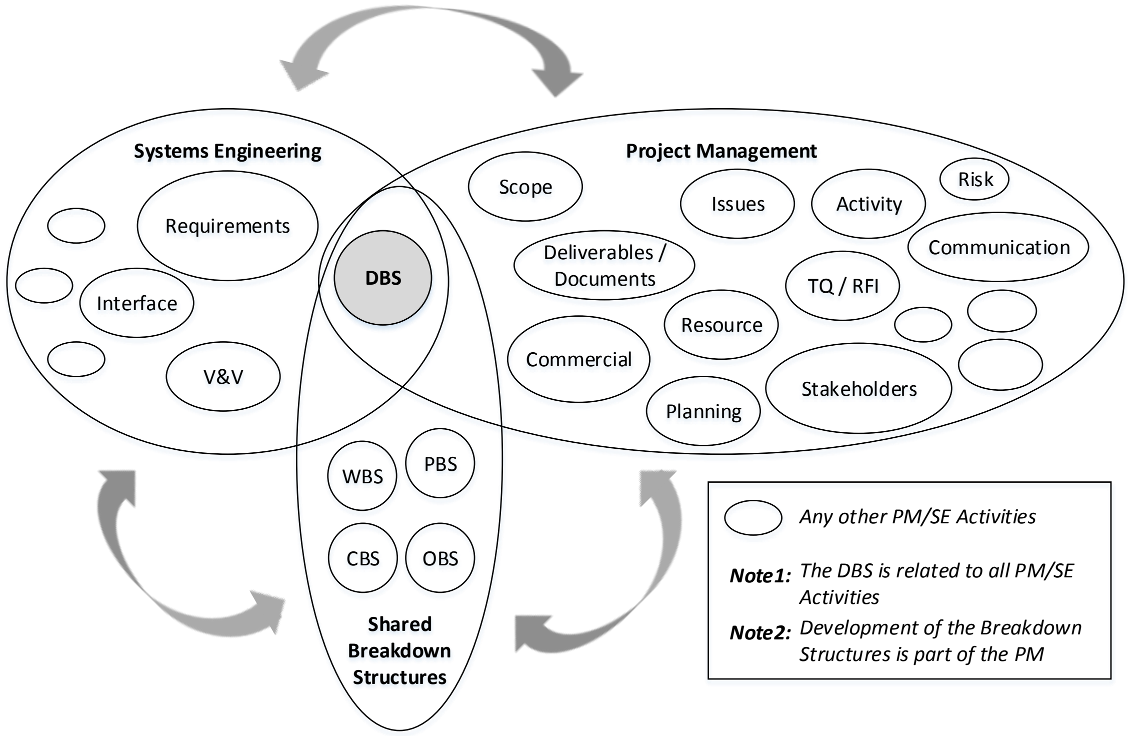


Figure 53: DBS Concept to Form an Integrated Management System
Breakdown structures are the shared components of SE and PM.

7.3.1. DBS and Project Interfaces

Chapter 4 reviewed in detail the Design Structure Matrix (DSM) method, a matrix-based tool that can handle capturing and managing the interactions between different elements of various breakdown structures in any domain. The DSM, as the methodology that handles dependencies and relationships between items (Danilovic and Browning, 2007, Steward, 1981), was described as a matrix-based document with identical rows and columns to represent the interactions between its elements including products, tasks and resources (Eppinger and Browning, 2012, Browning, 2001, Danilovic and Browning, 2007, Yassine et al., 2001).

Therefore, the typical databases of the interfaces within different disciplines within an industry sector can be captured and used as a pre-identified interface schedule by adopting the DSM method using the proposed DBS. This method visualises and manages the interactions among the elements of the DBS in the given industry sector/domain (see Figure 54).

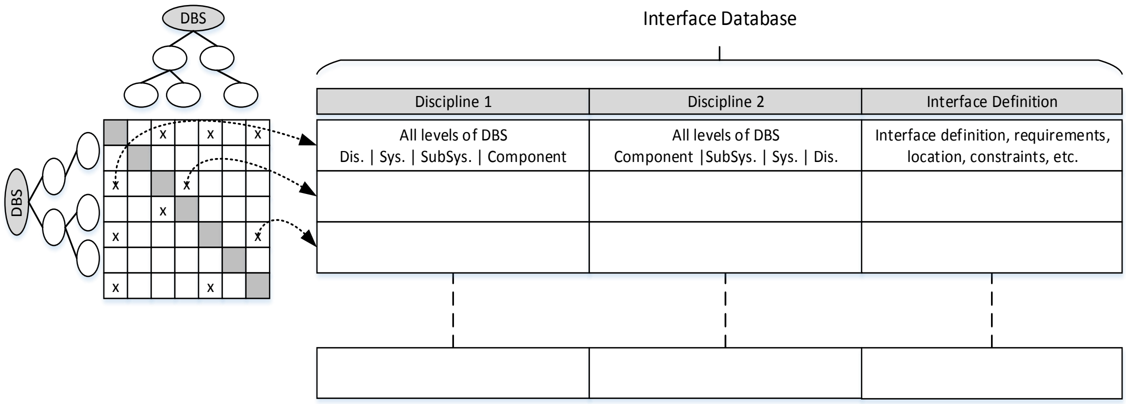


Figure 54: Interface Management System Adopting DBS on a DSM Structure

7.3.2. DBS and Project Scope/Requirements

Based on its nature and level of detail, each requirement in a project should eventually be delivered by one or more discipline(s) and, therefore, every requirement can be related to the DBS items. Some of the requirements that are written as more high level are related to the system or sub-systems levels of the DBS, and some that are more detailed could be related to the DBS component level. Regardless of the PM methods, in any project there will be some identification of the project requirements that need to be fulfilled. A typical requirements schedule should be codified based on the proposed DBS through the concept presented in Figure 55.

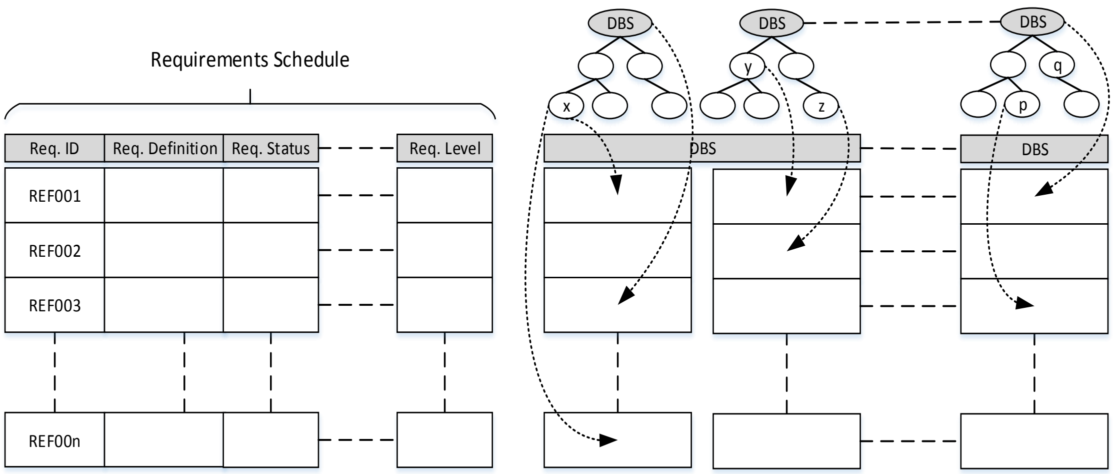


Figure 55: Requirements Management System Codification Concept Based on the DBS
Each requirement within the project requirements schedule will be linked to relevant item(s) from the DBS (based on the discipline and/or sub-disciplines involved in addressing the requirement).

7.3.3. DBS and Project Deliverables

The final deliverables of the design stage of a construction project consist of a series of deliverables in the form of reports, drawings, schedules, etc. The Project Deliverable List (PDL) often is provided by the client at the beginning of the project. The PDL, therefore, is a form of a PBS for a project of this type that identifies the design products needed to be developed by suppliers.

The proposed approach is to codify the products within the PDL based on the proposed DBS, similar to the approach that was taken for the requirements schedule. Each of the deliverables should be generated by one or more discipline(s) and, therefore, depending on the type of a product within the PDL, it can be related to one or more items in different levels of the DBS. The concept is presented in Figure 56.

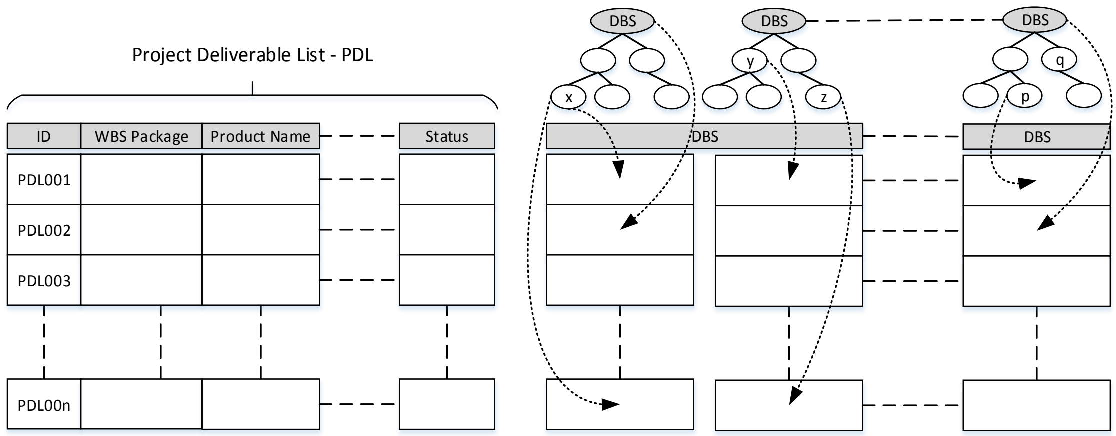


Figure 56: Project Deliverable List Codification Concept Based on the DBS
Each deliverable within the project deliverable LIST (i.e. PBS) will be linked to relevant item(s) from the DBS (based on the discipline and/or sub-disciplines involved in delivering the deliverable).

7.3.4. Management Activities Integration

As the requirements schedule and the PDL are codified based on the proposed DBS, and as the interface matrix is developed based on the proposed DBS, it can be concluded that there is a relationship established among the project requirements, interfaces and deliverables. Through this relationship, the relevant deliverables through the PDL can be shortlisted against each requirement, with a relationship to the relevant interface(s). Figure 57 shows the integrated approach concept that links these key project activities.

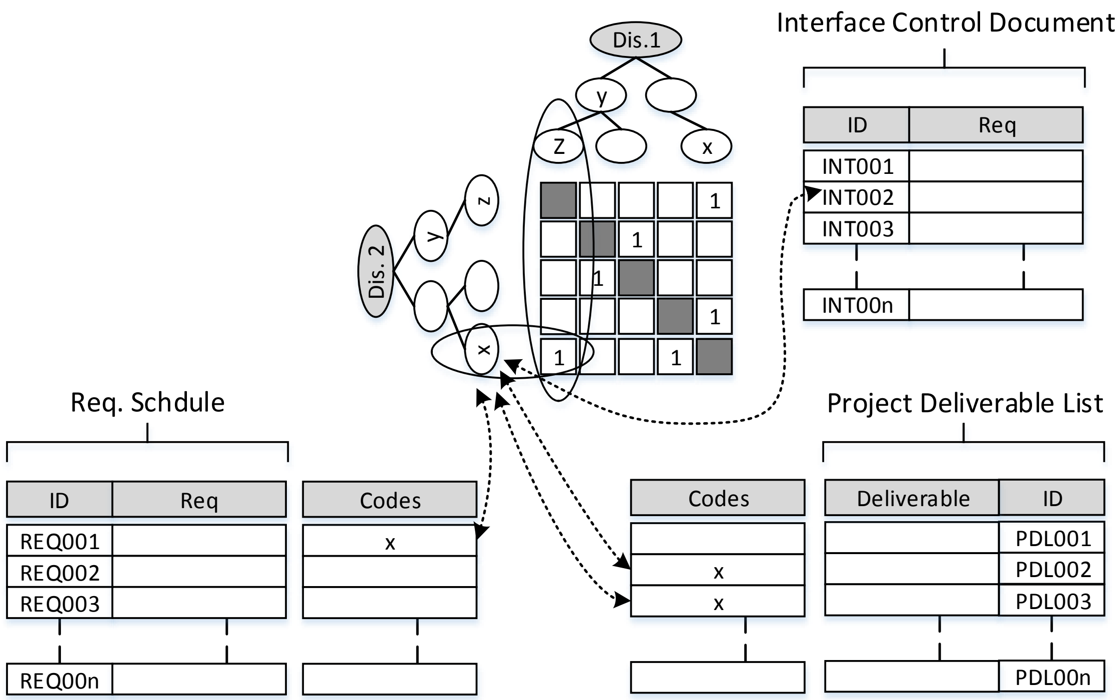


Figure 57: Integrated Approach for the Systems Engineering and Project Management Activities

As Figure 57 shows, the deliverables PDL002 and PDL003 are the potential evidence to show the project compliance with the project requirement, REQ001. The interface matrix shows that the item ‘x’ of Discipline 2 interfaces with item ‘z’ of Discipline 2. The interface information and the requirements are detailed in the Interface Control Document, item INT002. Therefore, the PDL002 and PDL003 are also potential evidences to show that the project interface, INT002 is addressed and the project is in compliance with the requirements set in the INT002. Therefore as an example, any changes to the requirement REQ001 will impact the interface INT002 and its requirements that means changes are required in deliverables PDL002 and PDL003.

The same concept is applicable across the other SE and PM activities explained earlier. This means that if all other PM and SE registers and tools are codified based on the proposed DBS, a relationship is developed among all these project tools and document.

7.4. DBS Project-specific Customisation

Even within the same industry sector, each project has its own unique scope and requirements. However, similar disciplines are involved to perform similar types of activities to achieve the projects’ objectives.

The proposed DBS is a modular database document that details all the possible disciplines within a specific sector with the type of the work they conduct from high level to the component level. One of the important aspects of the DBS concept is reusability. The DBS shows its main benefit when it can be reused in different projects of the same nature. Therefore, at the beginning of each project, the template DBS should be customised based on the project scope and requirements review and analysis, as shown in Figure 58. If this concept is well implemented, it means the baseline of the project interfaces as well as many of the basic project registers already exist when the project is implemented.

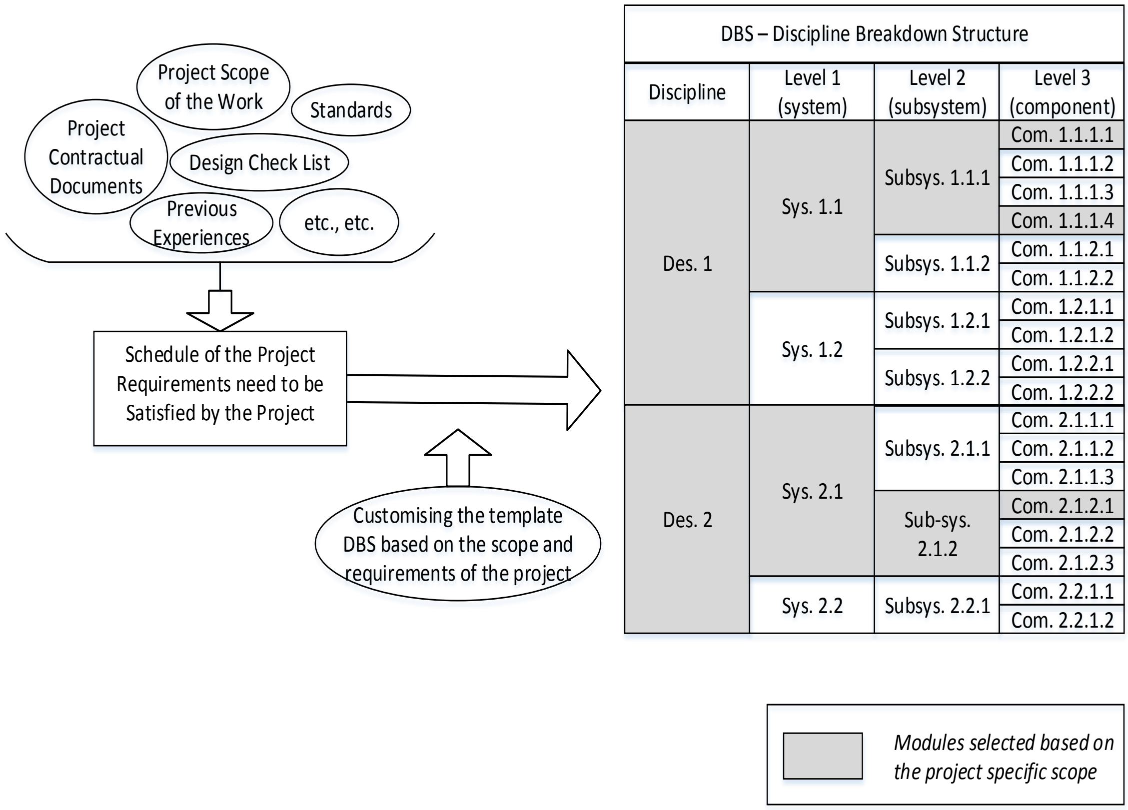


Figure 58: Customising the DBS Based on the Project-specific Requirements

A modular database, therefore, should be developed in which items of the DBS template can be chosen according to a combination of the project-specific contractual documents, requirements specifications, scope documents and any other available information. Developing such an application is beyond the scope of this work, but is work for the future development, as such application can help systems engineers and project managers to select the modules related to the project based on the scope of the work and can generate many of the management schedules and reports instantly.

7.5. Project Information System

As part of this study, a project information system is designed, modelled and developed in a form of an application in which the project requirements schedule, the project interface database and the project deliverable register are linked through the proposed DBS. The model provides an integrated navigation through the information that facilitates monitoring, controlling and reporting the project progress against the requirements and interfaces. The model also facilitates managing the impact of the changes to one element of the project to the others. Figure 59 summarises the project information model developed as part of this study. This application is developed with Visual Basic on a Microsoft Excel platform as a basic tool that was utilised in the project case studies described in Chapter 8.

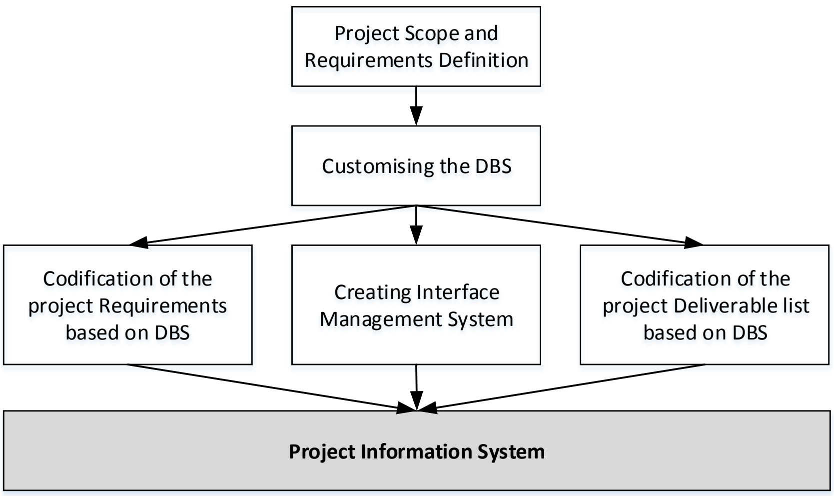


Figure 59: Project Information System Based on the DBS

7.6. Conclusion of the Chapter

This chapter discussed a new concept to integrate the management systems of multidisciplinary projects in the rail sector by interlinking various PM and SE activities, tools and documents. This chapter identified the proposed DBS and further discussed the development and applications within typical projects in the rail sector.

The key conclusions of this chapter are as follows:

1. The proposed DBS is a breakdown structure of various disciplines that are involved in projects within a specific domain. This breakdown is based on the skills and competencies required by disciplines within an industry sector.
2. The proposed DBS is aimed to become an industry standard DBS for a specific sector/domain (for example, the rail sector or rail station upgrade domain), depending on the level of information available.
3. The initial development of the DBS requires information collection in the selected domain, such as industry standards and best practices, as well as consultation with domain experts. Also practicing the solution in several projects is required.
4. The proposed DBS is in the form of a modular database that needs to be customised based on project-specific scope and requirements at the early stage of the project definition.
5. The proposed DBS creates links between all project activities by communicating with their tools and documents. For example, it provides a platform to develop an interface management system when the project starts. All other project documents can also be codified based on different levels of the DBS to create an integrated information management system in order to bridge the activities of the PM and the SE in rail sector projects.
6. The proposed DBS can improve the project efficiency through supporting the project information architecture by providing access to various predefined information when a project starts, such as possible risks, project requirements and project cost elements related to the selected modules of the DBS.
7. The proposed DBS can eventually become a reference for projects in a specific domain. This reference can drive the baseline of what is required for projects supporting both the client and supply chain to identify the project requirements. It can also become a reference for educational purposes in a specific domain.

In the next chapter, the proposed theory of DBS is applied in a rail station upgrade project to test the hypothesis. The purpose of this case study is to further develop a master DBS for the rail station project domain. Also, the case study tests the theory to explore strengths and weaknesses in a real rail sector project.

Chapter 8 THE DBS APPLICATION IN RAIL STATION PROJECTS – CASE STUDIES

8.1. Introduction

To provide context and to demonstrate the applicability of the Discipline Breakdown Structure (DBS), this chapter develops examples of specific DBS applications and presents case studies of different projects in the rail sector. The results of these studies have helped refine the concept and provide insight into its application in the form of processes, procedures, tools and document structure.

The chapter introduces three projects in which the DBS concept was deployed. The three projects are identified and the process for the DBS development and adoption is explained.

Case Study 1 (CS1) is a project in the UK in which the full DBS development process and its application in project management (PM) activities are explained in detail. In CS1, therefore, the proposed DBS is developed for the first time.

Case Study 2 (CS2) is also a project in the UK with a very similar scope to CS1. This case study used the DBS developed in CS1 as a template, and its benefit to the project process development and refinement is explored.

Case Study 3 (CS3) is a similar project in Canada with slightly different scope and objectives. In CS3, the DBS that was developed in CS1 and refined in CS2, is used as a base template in order to further refine the DBS and show the applicability of the same DBS in similar projects of the same sector.

The three works together enabled the development of a possible DBS template for rail station design projects as a specific domain.

8.2. CS1 – A Rail Station Upgrade Project in the UK, 2009

8.2.1. CS1 Introduction

CS1 is a design phase of a major and complex rail station upgrade project in central London, contracted to a major engineering consulting firm (ECF). The ECF appointed a systems engineering (SE) team to adopt applications of the SE in the delivery of the design in accordance with the client's requirements.

This project progress proved the importance of interface management (IM) in such construction project. According to the design engineering manager of the project who was interviewed for the purpose of this case study:

> *"On average, there was one major issue per day due to the lack of interface management."* (CS1 Design Engineering Manaager, 2010)

When the project delivery and the design production was half way through, the author joined the design team to develop a new systematic solution to manage the interfaces among various design works to provide assurance that the design deliverables, including drawings and reports, sufficiently addressed the interface requirements.

The proposed Interface Management System (IMS) was specified as a system to enable identifying the areas of interfaces, assigning the interfaces to the relevant owners and providing links to the relevant deliverables in order to provide evidences on the interface compliance. As the design production was already started and many of the deliverables were already delivered, the system was required to work with the existing documents with minimum input and engagement from the contractors who completed their tasks and left the project.

The proposed DBS concept was used to develop the IMS as it was specified. Also, the outcome of the work was built into an integrated tool to create links between interfaces and the relevant deliverables in the project master deliverables repository. As further work, the proposed DBS was also used to link the project Requirements Management System (RMS) to the IMS. The work conducted proved that the proposed DBS had potential to provide what was necessary to create a project-wide verification and validation (V&V) tool enabling the project team, including systems engineers and project managers of both the client and supplier sides, to navigate through the system to identify deliverables showing the compliance of the project interfaces and requirements.

The IMS and the V&V tool that was developed based the proposed DBS concept, was presented in different formats such as posters, user manuals, reports, etc., and distributed across the ECF offices globally to be developed and utilised in future projects in different sectors. Figure 60 provides images of the key documents developed based on the prosed DBS concept. Copies of the documents are also enclosed in Appendix 5, Appendix 9, Appendix 10, and Appendix 11.

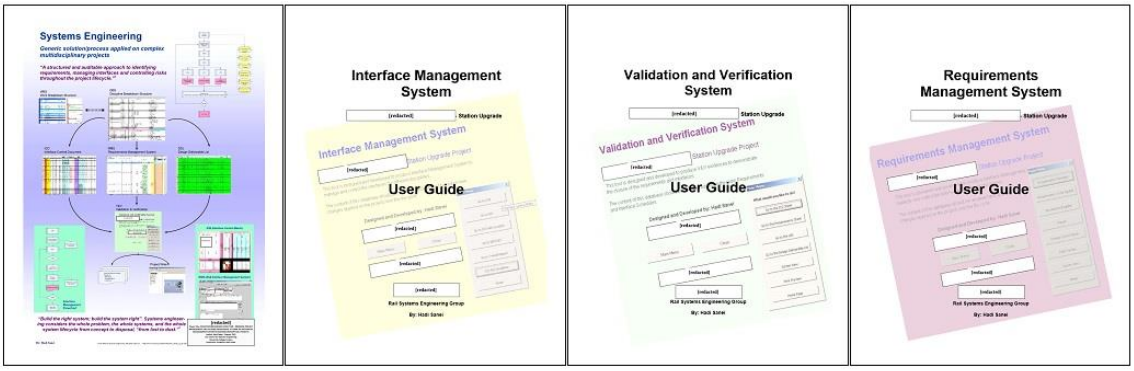


Figure 60: SE-related Documents Issued by Hadi Sanei[5]

Refer to Appendix 9, Appendix 10, and Appendix 11

The following parts present and explain a step-by-step detail on the development of the IMS based on the proposed DBS. In addition to the DBS description, capabilities and advantages, the constraints and limitations are also demonstrated.

8.2.2. CS1 Systems Engineering Approach

The project Systems Engineering Management Plan (SEMP) explained adopting the SE approach for this project as capturing and developing the project requirements into a fully integrated design submission. It also included a detailed review of the existing information to ensure that the project captured all the requirements to deliver a compliant design, taking into account any constraint arising from the technical interfaces. Once the requirements were identified and agreed, they would need to be allocated to the relevant owners in order for them to progress with the design deliverables relevant to their respective technical areas. This allocation would provide assurance that the designs were developed in accordance with the technical requirements, standards and applicable legislation. This assurance evidence would be collated at interdisciplinary checks at key points during the project and would support the approvals by the client-appointed acceptance body.

The ECF, therefore, assembled an SE team at the beginning of the project to provide a coordinated approach to the development of an integrated design. This team was also supposed to undertake the necessary V&V activities to ensure the delivered design would be robust and would fulfil the project requirements. The PM and SE teams also

[5] Copies of these documents are included in Appendix 5, Appendix 9, Appendix 10, and Appendix 11.

maintained various registers and repositories separately and independently to manage the interface requirements, design risks, technical assumptions and hazards data, etc., for demonstrating and managing.

8.2.3. Existing Project Systems Engineering and Project Management Activities, Tools and Documents

As discussed, this project appointed a systems engineer in charge of overall SE activities. Other PM activities including project commercial, scheduling and planning, etc., were also in place in accordance with traditional PM standards and best practices. The key activities and documents were as follows, without any physical link among the information within these documents.

- Work Breakdown Structure (WBS): The project planning team developed the master WBS for the single purpose of project planning and scheduling. The WBS was stored in a planning tool (P3) and was used for project scheduling as well as cost monitoring for the work packages defined in the WBS. The WBS was used as the main guide/structure to develop the proposed DBS.

- RMS: The appointed SE team developed an RMS system in order to capture and define the main objectives, scope and requirements of the project, as well as to provide compliance check and audits necessary to provide design assurance. This process was supported by the PM and SE teams at the early stages of the project through the review of the project source documentation.

  The requirements capture and definition was an iterative process during the life cycle of the project, and they were stored in an Excel spreadsheet as a schedule of requirements. The requirements were captured and generated through a series of analyses on the project's initial documents, including the results from a series of requirements workshops, the client's Request for Proposal or Invitation To Tender, the Conceptual Design Statements for various parts of the project, the project contractual agreement, the project scope documents and the Project Requirements Specification document for applicable systems and sub-systems, as well as the key standard documents.

- Change Register: Change control management and requirements variation control as part of the PM activities were also ongoing iterative processes during the project that were embedded into the RMS. A separate register was maintained by the PM team to keep the changes to the project scope and requirements. This register was the main document for the change management and change control in the design delivery phase of the project.

- Assumption Register: Any project progresses based on assumptions. The PM team developed an assumptions register as a standalone document in which any assumption made with a discipline or team were registered. Assumptions would have been challenged and changed to domain knowledge, redundant information or a requirement as appropriate.

- Design Deliverable List (DDL): A list of deliverables to be prepared and delivered by the supplier (that is, the ECF).

- Risk Register: The PM team developed a separate risk register to record the risk introduced to the project by various team members. The risks were monitored in the register until resolution was achieved. Any risk raised by any parties were to be kept and updated in this register without any specific structure or any link to any other project documents.

- Technical Query (TQ) Register: The PM team developed a register in which they logged the technical queries raised by the design team and responses received by the relevant parties (mainly suppliers). Responses and all further actions as the result of the responses were recorded and monitored in this register. Responses to TQs could potentially be another source of new requirements or assumptions of the project. The TQ Register was also a standalone register that was independently monitored.

- Issues Register: Another document developed by the PM team to store the project issues identified and raised by the project team. It was important to take control of the project issues as some could lead to major risk to the delivery of the project. This register also was a standalone register with no link to any other project document.

- Design Action Register: The action register developed by the project delivery manager is a form of a work/activity checklist for the project team. The design needed to be performed as activities were identified from either the project requirements schedule or the design reviews sessions with other parties. The design action register was held in the project folder. This register stored the actions related to the design activities, need to be conducted by the responsible designer. This spreadsheet tool was used to drive the completion of the outstanding design items on the project by the management team. This register was version controlled and held on project drive. There was no physical link between the items here and any other project documents.

The project assumption, risks, technical queries, issues, design actions and change items impact each other and potentially will be the source for new requirements and interfaces for the project. Also, any changes to the project requirements and interfaces has potential impact on all other items named above. Therefore, a solution to interlink all these document can provide a great deal of benefit to PM.

8.2.4. Proposed Interface Management System Based on the DBS

The proposed IMS was developed based on the approach explained in Figure 54 (see Section 7.3.1). Therefore, the first step in developing the IMS is to create the proposed DBS for the first time.

8.2.5. CS1 DBS Development

The proposed DBS for this project was developed based on the concept explained in Section 7.2.3. Figure 61 is a modified illustration of Figure 50 that shows the DBS development for the purpose of this work for CS1. As Figure 61 shows, the five main sources used for developing the DBS in CS1 are as follows:

1. Selective project(s) in Rail Station Upgrade domain – CS1
    - PBS – The DDL developed by the client
    - WBS – Developed by the project planning team
    - OBS – The proposed project organisation chart by the ECF

2. Various project contractual documents – Including the Invitation To Tender, Letter of Commission, Contract, Scope documents, Conceptual Design Statements, and Feasibility study report
3. Previous experiences in the rail station upgrade domain – Various references in the company based on similar projects
4. Consultation with rail experts in different disciplines – Running workshops and separate interview with discipline leads in the ECF to formalise the DBS
5. Various other rail standards, best practices, etc.

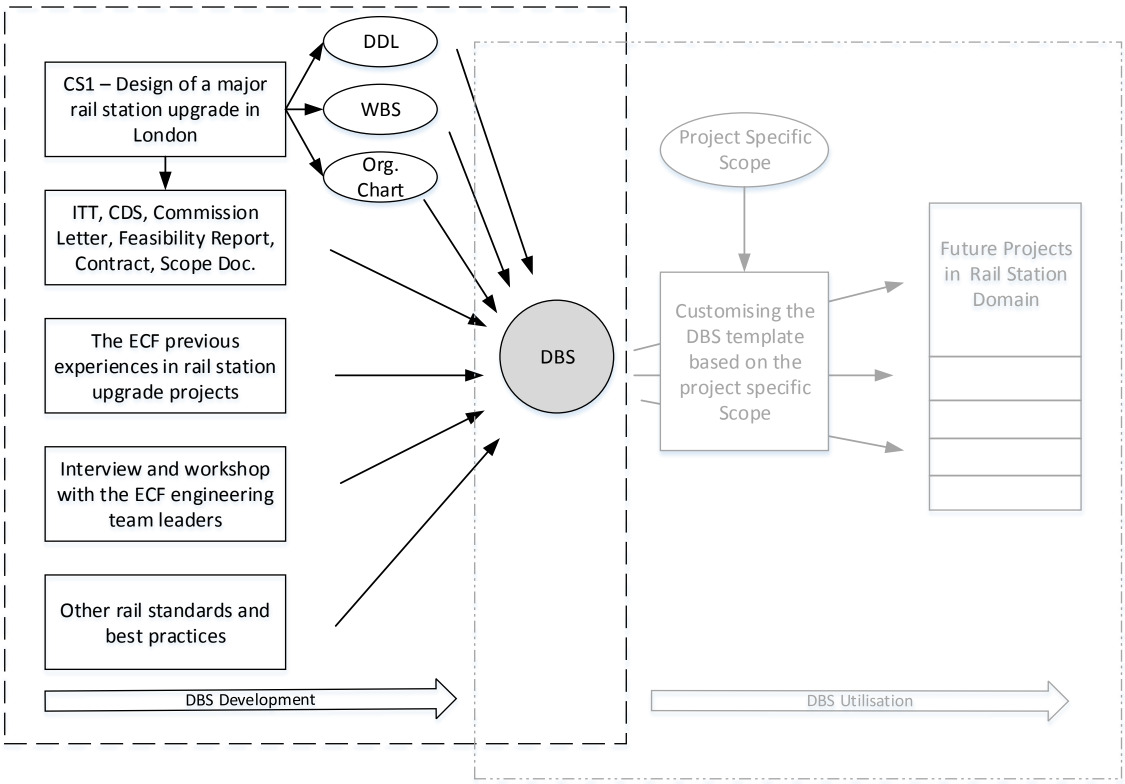


Figure 61: DBS Development for CS1

One workshop per each discipline was followed by a number of consultations meetings with the team leaders was carried out in order to develop the initial DBS for CS1, and refining and finalising it. Many of the team leaders selected for this consultation process were not part of the project team. They had no or very limited knowledge about the project and its detail scope. This selection was an intentional decision, as the DBS needed to be applicable to the industry at large, not only this single project. Therefore the less knowledge about the specific project requirements was actually helpful to capture more broad discipline information.

The DBS developed for CS1 was a three-level breakdown based on the format described in Section 7.2.4., including systems, sub-systems and physical components under each discipline defined in the engineering team of the ECF. In total, 116 items were identified as physical components distributed among 8 disciplines under 11 systems and 28 sub-systems. A copy of the DBS is enclosed in Appendix 6.

The DBS was developed and stored in a database system developed for the purpose of this work in Microsoft Excel. The DBS was codified based on the sample code structure shown in Figure 51 (see Chapter 7, page 192).

8.2.6. CS1 Interface Management System Development

There was a large number of interfaces between different disciplines that required satisfaction. Such a multidisciplinary project would struggle in design and execution if good communication between different disciplines was not established. Duplication in design, missing deadlines and noncompliance with the allocated budget were the key issues raised as a result of a weak IM that could be addressed by developing an effective IMS. The main scope of the IMS was therefore summarised as:

1. Identify the interface areas
2. Provide ownership for the interfaces – responsibility assignment
3. Verify interface compliance

Figure 62 shows the IMS process flow that was adopted in developing the IMS based on the proposed DBS. Figure 63 shows the IMS process including location information, as discussed below.

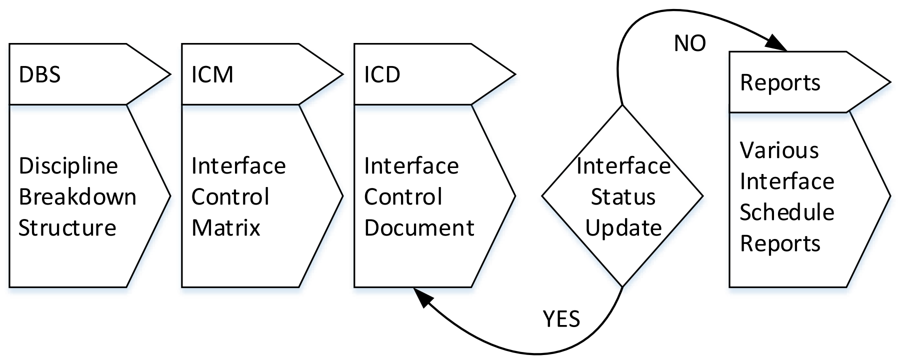


Figure 62: Interface Management System Process Flow

Interface Control Matrix (ICM): The ICM was the initial driver of the IMS process. The Design Structure Matrix (DSM), as explained in Section 7.3.1, was used in order to develop the ICM to establish the interfaces among the DBS components. Therefore, the ICM was formed as a two-dimensional matrix, accommodating the DBS on each dimension. This provided a visual way to define all possible interfaces among different physical components of different disciplines.

In order to identify the interfaces, the expert opinion of the various discipline leaders in the rail sector was required. Therefore, a series of independent workshops was conducted with discipline experts to identify the interfaces of the chosen discipline with the other disciplines. In this way, for each discipline, each area of interfaces was discussed and agreed from both sides of the interface in at least two separate workshops.

The result of this effort was summarised in the project ICM that is stored in Microsoft Excel in a matrix format. The matrix was further codified and colour coded to be used as project-wide interface presentation to the project team, as presented in Figure 64.

Interface Control Document (ICD): The ICM is a powerful tool to present the interfaces between different disciplines. However, every interface should be defined in more detail along with its other features and requirements. ICD is a form of an interface database that holds information about the interfaces identified in the ICM (see Figure 54).

Therefore, a system was required to transfer each of the interface points into a database. As the ICM was created in Microsoft Excel, for the purpose of this work, a Visual Basic (VB) code[6] was developed to build a separate datasheet in Microsoft Excel holding the interfaces with their parents, sub-systems, systems and disciplines against each other. The datasheet enabled entering new data in additional comments against each interface to further explain the interfaces. This work provided additional space for comments regarding ‘Component Definition’, ‘Interface Notes’ and ‘Interface Descriptions’. More items could be added in separate columns. Once the ICD was populated by the VB macro, all the data related to the interfaces were added into the ICD and sent to the lead

[6] A copy of the Visual Basic code script written to develop the tool is enclosed in Appendix 12.

engineers for review and comment. Figure 65 shows a snapshot of the ICD created in this work.

As the ICD was based on the DBS, it followed the same codification established for the DBS. Each interface in the ICD had two related sets of codes, each representing a member of the DBS. In CS1, a total number of 3,501 interfaces were captured as line items in the ICD. The detailed number of the interfaces per disciplines is given in Appendix 7.

Interface Location: The ICM and the ICD presented the interfaces between physical components used in the station upgrade project. Many of these interfaces occurred a number of times but in different locations. As the project progressed, further detail of interfaces was required. Any single interface could potentially occur in different locations; therefore, the location of each interface was defined and included in the system.

For the purpose of the work in CS1, a new Location Breakdown Structure (LBS) was created and included in the ICM, as shown in Figure 66. Although the LBS data cannot be presented due to the confidential information on the physical locations, in principle, the LBS was integrated in the ICM as a new dimension enabling cross-check between locations within the LBS and the DBS components and their interfaces. These crosses provided more information on the locations that the same interfaces applied within the project area.

Adding a new dimension of the LBS into the ICM provided information on the number of locations to which each individual interface applied. Therefore, the VB macro was enhanced to rebuild the ICD per location in a new master ICD. As the result of this practice the total number of line items (interfaces) within the newly refined ICD increased from 3,051 interfaces to 36,842 interfaces, including all the locations. The number of interfaces increased by this large margin because the same interfaces occur in a number of different locations and they all are captured in the new ICD. The breakdown of the interfaces based on location as well as the DBS is enclosed in Appendix 7.

Therefore, the IMS process shown earlier was refined based on the LBS included in the IMS, as presented in Figure 63.

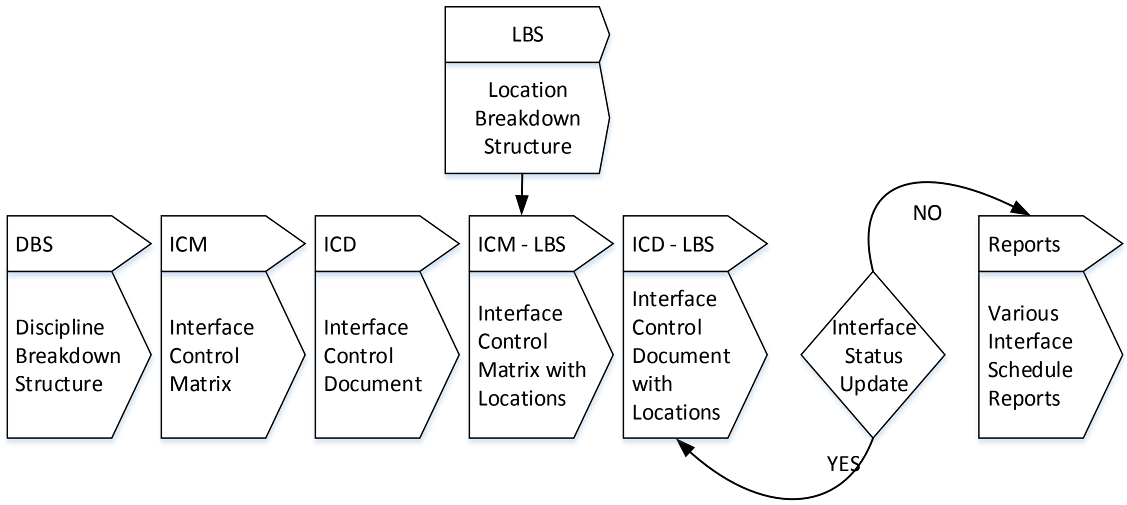


Figure 63: Interface Management System Process Including Location Information

This IMS system was formalised into a user-friendly application based on Microsoft Excel and VB codes. More detail on the developed application and the features it provides in IM are provided in the *Interface Management System – User Guide* included in Appendix 9.

8.2.7. Management System Integration Based on the Proposed DBS

8.2.7.1. Requirements Management System

The requirements of the project were already captured and stored in an in-house repository register in Microsoft Excel that was designed and developed for the requirements data storing, editing, analysing, searching and reporting by the ECF's Requirements Management team. Requirements management is an ongoing iterative process during the life cycle of the project. The schedule of requirements held in the project RMS was a live document that changed based on the new information received from various project parties. The changes or close-out of a requirement impacted the status and relevant deliverable(s) of one or more interfaces. The proposed DBS, therefore, was used to experiment linking the IMS to the existing RMS.

The existing requirements schedule within the RMS was analysed in conjunction with the DBS. Additional columns were added to the requirements register and each individual requirement was codified based on the DBS codes created earlier. Figure 67 shows the snapshot of the project RMS codified based on the DBS.

As requirements are related to the DBS and as the DBS items through the DSM concept identify the areas of interfaces, the combination of these systems creates an integrated system in which each requirement can be traced to the relevant interfaces. The impact that any changes to any of the requirements have on the other parts of the system/project can be traced and analysed through this integrated approach.

8.2.7.2. Design Deliverable List

The main delivery of a construction design project like CS1 is a series of documents in the form of reports, drawings, schedules, etc. The deliverable list often is provided by the client at the beginning of the project. The DDL is a form of a PBS for a project of this type. In CS1, the DDL was provided by the client in a separate document. This was a fixed list that was kept by the project document control team. Any changes to the DDL were considered as changes to the project scope and were analysed through change analysis.

In the proposed IMS, the products within the DDL were asked to be used as evidence to show the project compliances with the requirements and interfaces. Therefore, a relationship should be established between the project requirements and interfaces and the DDL items.

In CS1, the same concept used in RMS was adopted by converting the DDL document into a register in a form of a database in Microsoft Excel. Additional columns were created to accommodate the DBS codes. The created matrix enabled a codification process for the items in the DDL based on the DBS codes, as presented in Figure 68.

8.2.7.3. Compliance Process

In CS1, a compliance process was identified to provide assurance that the deliverables satisfied the project requirements. The generic term V&V is used to refer to all of the activities that are aimed at making sure the final project will function as required. The process is iterative, and encompasses a number of checks and reviews at key stages of the project in the V life cycle of the project. In principle, as part of the SE activity in CS1, the suppliers were required to provide a list of deliverables against each requirement in which they can show and prove the compliances. The deliverables they listed were part of the project main design deliverable list in most cases. There were some exceptions in which the DDL was updated based on new deliverables identified for the project.

8.2.8. CS1 Proposed Verification and Validation System Tool

In order to develop the concept and create the links and codifications as discussed, an integrated information system in a form of an application was developed with VB on the Microsoft Excel platform. The application held the ICD as well as the codified requirements schedule and the DDL in a same workbook. The application was equipped with a search engine in order to create a short list of deliverables from the DDL based on a chosen requirement or interface. The engine searched through all the codes against the DDL and filtered those matches with the codes related to the chosen interface or requirement item. The architecture of this tool is based on the concept summarised in Figure 57 (see Section 7.3.4).

The proposed DBS, therefore, was the core for this search engine. Once the final versions of the ICD, Requirements Schedule and DDL were issued and codified based on the proposed DBS, they were all imported into the V&V application. The application was then made available for use in generating short lists of deliverables based on any chosen interface from the ICD or any requirement from the Requirements Schedule. More detail on the application features and the structure was provided to the project team in the *Verification and Validation Tool User Manual* included in Appendix 10.

The V&V application also linked to the main project cloud-based document control system (ProjectWise[7]) to provide live access to the physical deliverables stored in the document repository.

Figure 69 illustrates the overall system architecture used to develop the CS1 project information system based on the proposed DBS and used to integrate the project RMS, IMS and DDL in a V&V application tool.

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[7] ProjectWise is a cloud based application that provides project information and document management and collaboration services, developed by Bentley

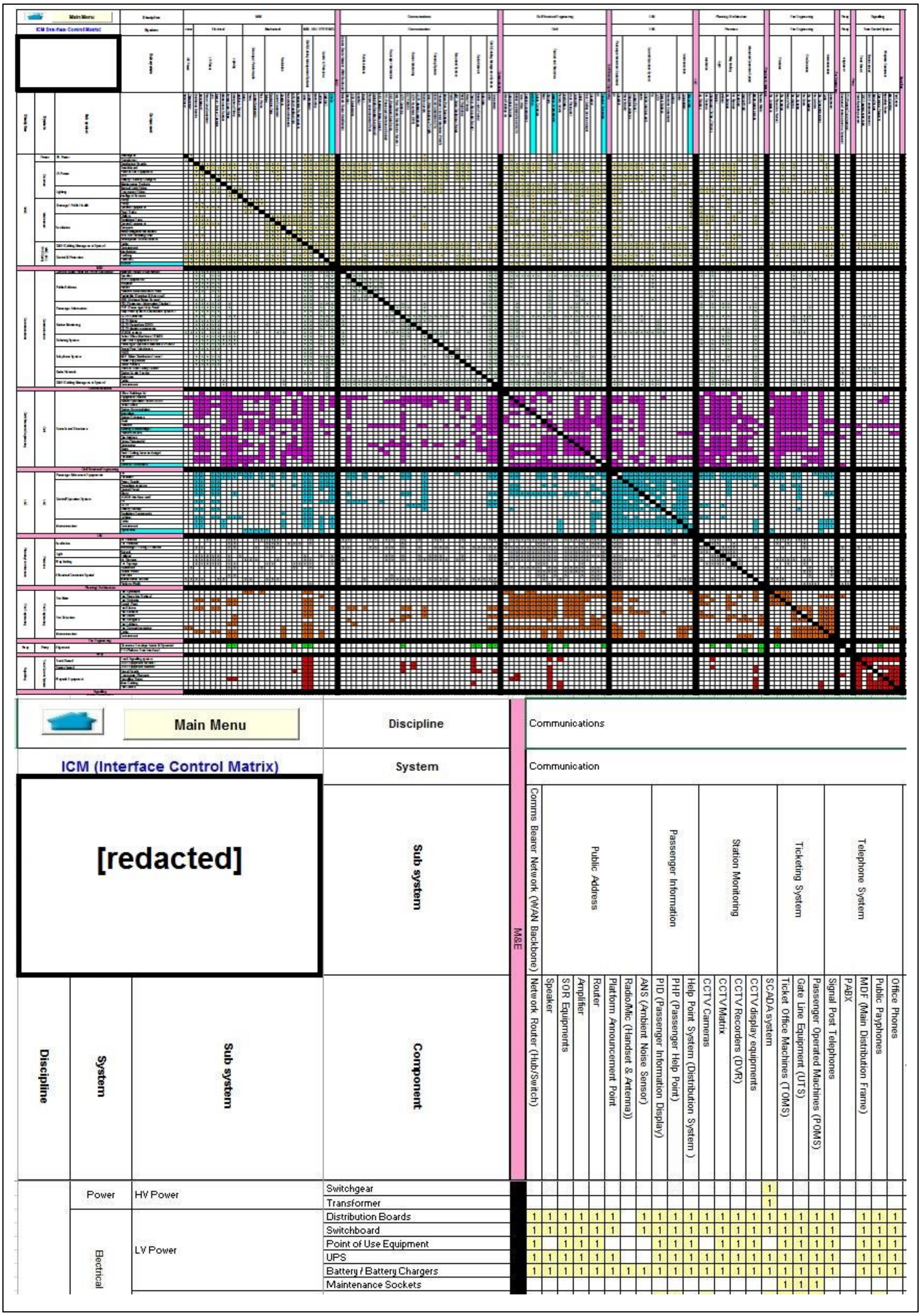


Figure 64: ICM Developed Based on the Proposed DBS for CS1[8]

[8] A large printed copy of this ICM is located in Appendix 7.

Pway						Main Menu		Number of Interfaces: 20				
ID	**Discipline**	**System**	**Sub System**	**Component**	**Component Definition**	**Interface Notes**	**Interface Description**	**Component Definition**	**Component**	**Sub System**	**System**	**Discipline**
5915	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To provide high visibility & Not to obstract the way by light fitting components	Physical / Design Interface	Different type of light fittings	Normal Light Fitting	Lighting	Electrical	M&E
5916	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To provide high visibility & NOT to obstruct the Pway by light fitting components	Physical / Design Interface	Where emergency lighting is applicable	Emergency Fitting	Lighting	Electrical	M&E
5917	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To not to obstruct the Pway	Physical / Design Interface	Air handling / Fans + louvers to distribute cooled air to specified areas. (e.g. Platform, ticket office, etc.)	AHU (Air Handling Unit)	Ventilation	Mechanical	M&E
5918	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	Provide interconnection & NOT to obstruct the Pway	Physical / Design Interface	Any cable used for power supply	Cable	CMS (Cabling Management System)	M&E, (ALL SYSTEMS)	M&E
5919	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	Provide cable management and protection and NOT to obstruct the Pway	Physical / Design Interface	Any type of Ducts, Trays, Conduits, Risers etc	Containment	CMS (Cabling Management System)	M&E, (ALL SYSTEMS)	M&E
5920	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To provide station monitoring	Physical / Design Interface	Cameras situated throughout the station which provide images to a central point for the purposes of safety and security for passenger/staff and equipment	CCTV Cameras	Station Monitoring	Communication	Communications
5921	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To not to obstruct the Pway	Physical / Design Interface	TETRA radio - cab radio	Track to Train Leaky Feeder	Radio Network	Communication	Communications
5922	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	? Not sure about this interface	To be Deleted	Station ops staff radio	Station Leaky Feeder	Radio Network	Communication	Communications
5923	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To not to obstruct the Pway	Physical / Design Interface	Any cables (Fibre Optic, Copper, etc.)	Cable	CMS (Cabling Management System)	Communication	Communications
5924	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	To not to obstruct the Pway	Physical / Design Interface	Any type of Ducts, Trays, Conduits etc	Containment	CMS (Cabling Management System)	Communication	Communications
5925	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	Clearance Envelope to be considered in Platform design and structure	Physical / Design Interface	As stated	Platform	Tunnels and Structures	Civil	Civil/Structural Engineering
5926	Pway	Pway	Alignment	Clearance Envelope (static & Dynamic)	Clearence within envelop to equipments / structure. (i.e. vertical / horizantal allignment, Cant and Curvature.	Clearance Envelope to be considered in overbridge design and structure to avoid any Pway obstruction	Physical / Design Interface	As stated	Overbridges	Tunnels and Structures	Civil	Civil/Structural Engineering

Figure 65: Interface Control Document developed for CS1

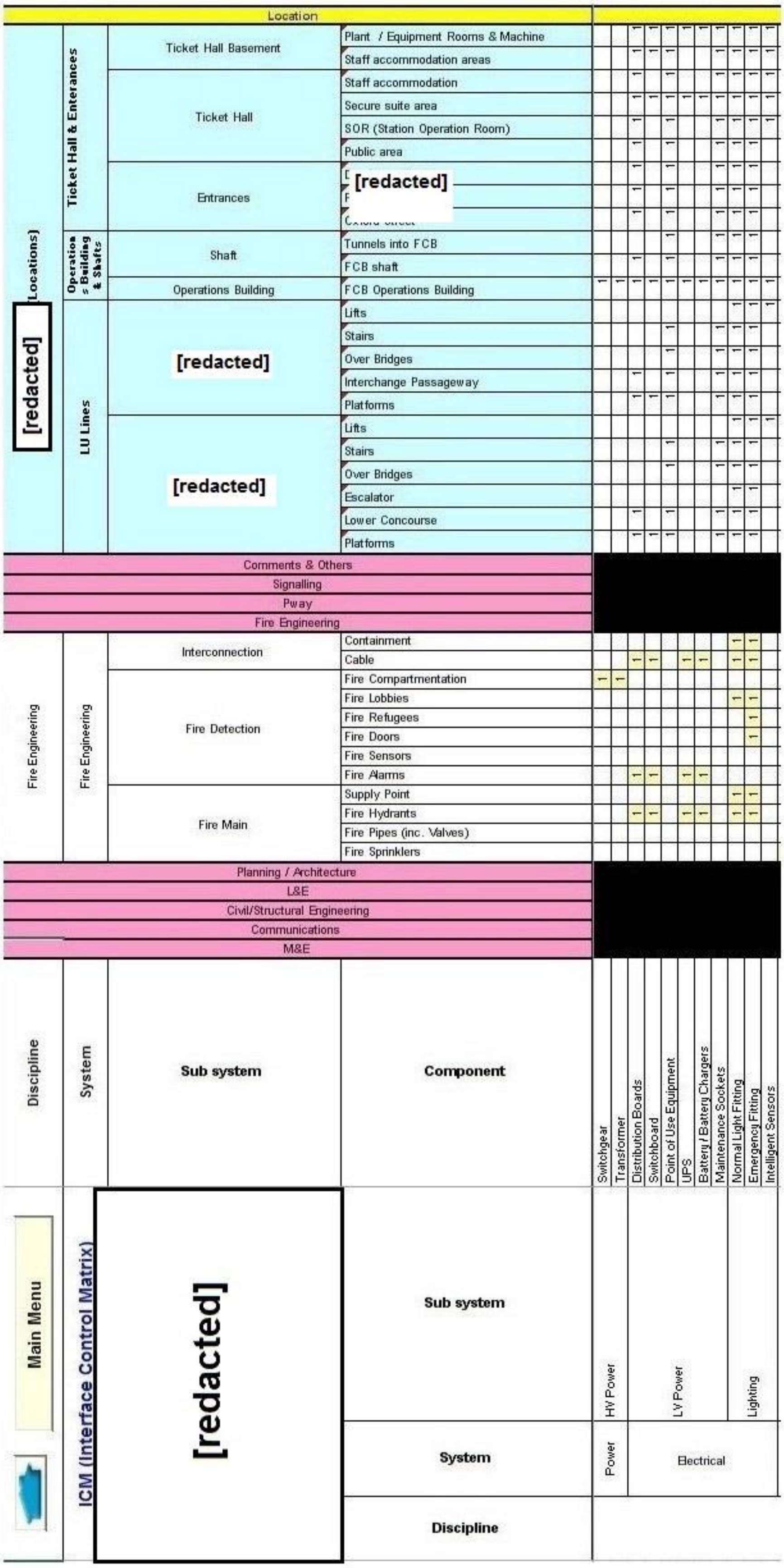
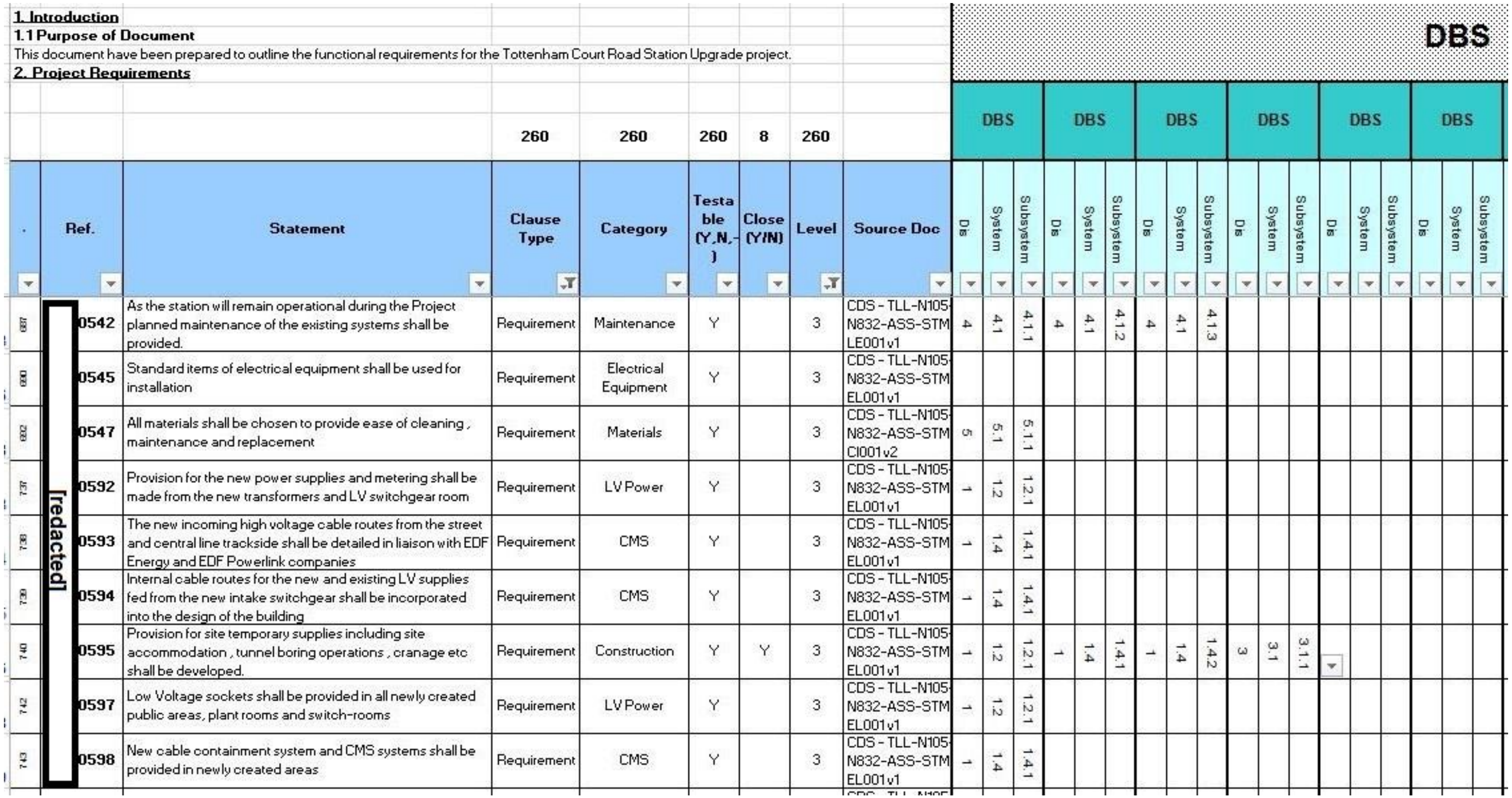


Figure 66: LBS Cross-check against ICM developed for CS1



1. Introduction

1.1 Purpose of Document

This document have been prepared to outline the functional requirements for the Tottenham Court Road Station Upgrade project.

2. Project Requirements

.	Ref.	Statement	Clause Type	Category	Testable (Y,N,-)	Close (Y/N)	Level	Source Doc
			260	260	260	8	260	
[redacted]	0542	As the station will remain operational during the Project planned maintenance of the existing systems shall be provided.	Requirement	Maintenance	Y		3	CDS - TLL-N105-N832-ASS-STM LE001v1
	0545	Standard items of electrical equipment shall be used for installation	Requirement	Electrical Equipment	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0547	All materials shall be chosen to provide ease of cleaning, maintenance and replacement	Requirement	Materials	Y		3	CDS - TLL-N105-N832-ASS-STM CI001v2
	0592	Provision for the new power supplies and metering shall be made from the new transformers and LV switchgear room	Requirement	LV Power	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0593	The new incoming high voltage cable routes from the street and central line trackside shall be detailed in liaison with EDF Energy and EDF Powerlink companies	Requirement	CMS	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0594	Internal cable routes for the new and existing LV supplies fed from the new intake switchgear shall be incorporated into the design of the building	Requirement	CMS	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0595	Provision for site temporary supplies including site accommodation, tunnel boring operations, cranage etc shall be developed.	Requirement	Construction	Y	Y	3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0597	Low Voltage sockets shall be provided in all newly created public areas, plant rooms and switch-rooms	Requirement	LV Power	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1
	0598	New cable containment system and CMS systems shall be provided in newly created areas	Requirement	CMS	Y		3	CDS - TLL-N105-N832-ASS-STM EL001v1

Ref.	DBS Dis	DBS System	DBS Subsystem	DBS Dis	DBS System	DBS Subsystem	DBS Dis	DBS System	DBS Subsystem	DBS Dis	DBS System	DBS Subsystem	DBS Dis	DBS System	DBS Subsystem	DBS Dis	DBS System	DBS Subsystem
0542	4	4.1	4.1.1	4	4.1	4.1.2	4	4.1	4.1.3									
0545																		
0547	5	5.1	5.1.1															
0592	1	1.2	1.2.1															
0593	1	1.4	1.4.1															
0594	1	1.4	1.4.1															
0595	1	1.2	1.2.1	1	1.4	1.4.1	1	1.4	1.4.2	3	3.1	3.1.1						
0597	1	1.2	1.2.1															
0598	1	1.4	1.4.1															

Figure 67: Codification of the Project RMS Based on the DBS developed for CS1

																	DBS		
ID	WBS Package Numb	Project	Discipline	Type1	Type2	Level	Seq	Rev	Title1	Title2	Title3	Scale	Due	Current Physical % Comple	Tranche	Type	Dis.	System	Sub Systems
	410	HAG-N105-8742	ARC	D	PLN	1	01220	01	Oxford Street Entrance	As Existing Street Level Plan, FFL 125.000 Varies		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	2	01221	01	Oxford Street Entrance	As Existing Plan Tunnel to Ticket Hall Level Plan, FFL 119.340		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	1	01224	01	Oxford Street Entrance	Street Level Plan, FFL 125.320		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	2	01225	01	Oxford Street Entrance	Concourse Level Plan, FFL 119.340		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	3	01226	01	Oxford Street Entrance	Basement Level Plan, FFL 114.300		1:100				Drawing	5	5.1	5.1.4
		HAG-N105-8742	ARC	D	PLN	2	01227	01	Oxford Street Entrance	Escalator Upper Machine Chamber Level Plan, FFL 121.920 (Including Floor Finishes)						Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	SEC	X	01230	02	Oxford Street Entrance	Section N-N		1:50				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	SEC	X	01231	02	Oxford Street Entrance	Section V-V		1:50				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	SEC	X	01232	02	Oxford Street Entrance	Section Y-Y		1:50				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	SEC	X	01233	01	Oxford Street Entrance	Section W-W		1:50				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	SEC	X	01235	02	Oxford Street Entrance	Section X-X		1:50				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	2	01236	00	Oxford Street Entrance	Floor Finishes Plan, Concourse Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	3	01237	00	Oxford Street Entrance	Floor Finishes Plan, Basement Level		1:100				Drawing	5	5.1	5.1.1
		HAG-N105-8742	ARC	D	PLN	1	01244	01	Oxford Street Entrance	Street Level Plan and Floor Finishes (1:50 Scale Plan)						Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	1	01246	01	Oxford Street Entrance	Reflected Ceiling Plan, Street Level		1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	2	01247	00	Oxford Street Entrance	Reflected Ceiling Plan, Escalator Upper Machine Chamber Level		1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	2	01248	01	Oxford Street Entrance	Reflected Ceiling Plan, Concourse Level		1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	3	01249	00	Oxford Street Entrance	Reflected Ceiling Plan, Basement Level	Sheet 1 of 2	1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	3	01250	00	Oxford Street Entrance	Reflected Ceiling Plan, Basement Level Link Building	Sheet 2 of 2	1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	ELV	X	01255	02	Oxford Street Entrance	Elevations, Interior Concourse		1:50				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	ELV	X	01256	01	Oxford Street Entrance	Elevations, Exterior Street Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	1	01261	01	Oxford Street Entrance	Fire Compartmentation Street Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	2	01262	01	Oxford Street Entrance	Fire Compartmentation Concourse Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	3	01263	01	Oxford Street Entrance	Fire Compartmentation Basement Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	2	01264	01	Oxford Street Entrance	Fire Compartmentation Escalator Upper Machine Chamber Level		1:100				Drawing	5	5.1	5.1.1
	410	HAG-N105-8742	ARC	D	PLN	1	01272	01	Oxford Street Entrance	OSD Interface Street Level Plan		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	2	01273	01	Oxford Street Entrance	OSD Interface Concourse Level Plan		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	PLN	3	01274	01	Oxford Street Entrance	OSD Interface Basement Level Plan		1:100				Drawing	5	5.1	5.1.4
	410	HAG-N105-8742	ARC	D	ELV	X	01279	00	Oxford Street Entrance	Staff Accommodation Concourse, Elevations, Unisex WC and Mess		1:20				Drawing	5	5.1	5.1.4

Figure 68: Snapshot of the DDL Codified by the DBS developed for CS1

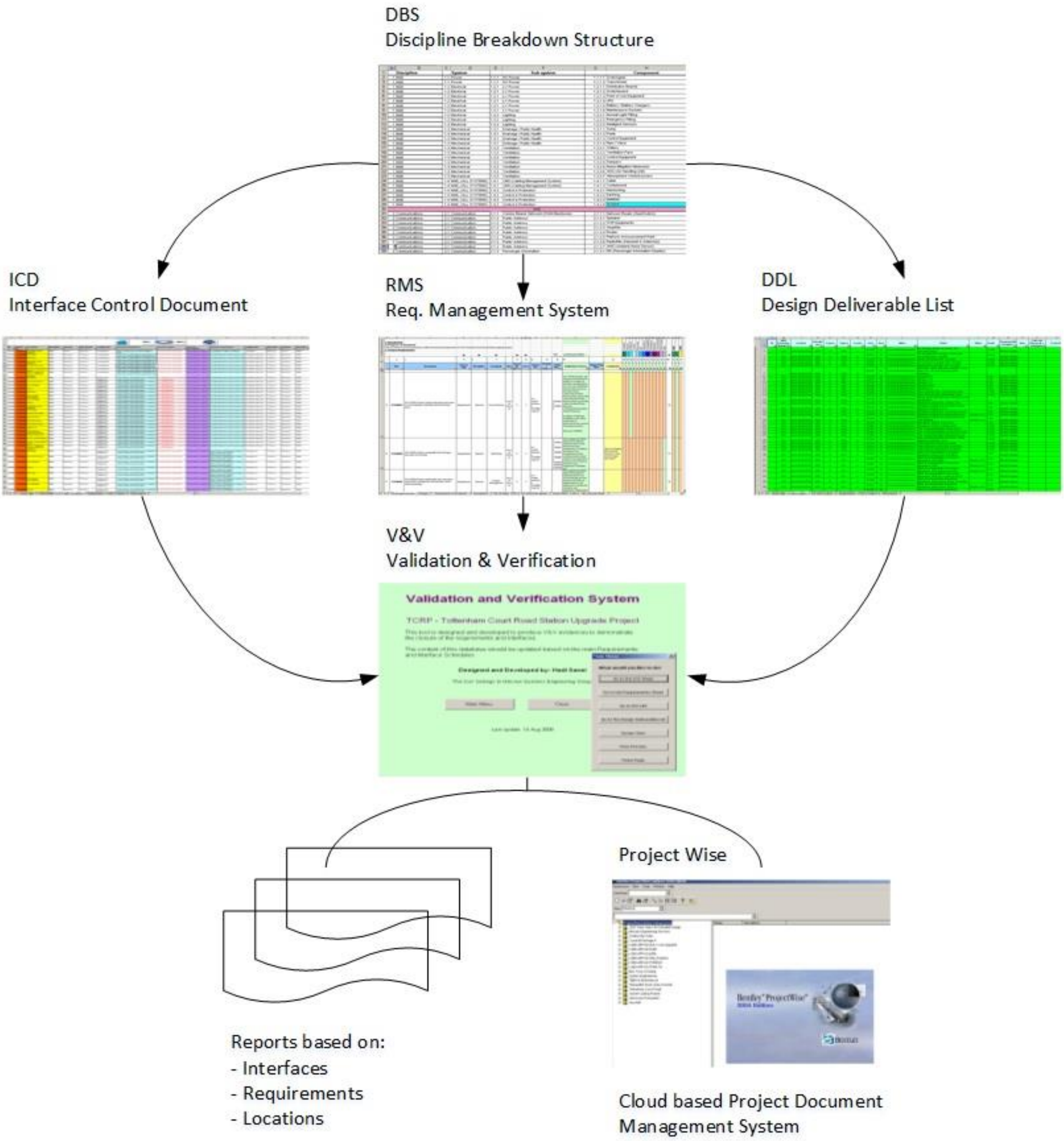


Figure 69: Integrated Management System Architecture Developed for CS1

8.3. CS2 – A Rail Station Upgrade Project in the UK, 2011

8.3.1. CS2 Introduction

CS2 is another design phase for a complex rail station upgrade in central London, contracted to the same major ECF. This project was used as a trial to adopt the DBS concept developed in CS1. The scope of the project is very similar to CS1, and therefore it is expected that the DBS developed for CS1 can be used with minimum alteration.

The DBS developed in CS1 was used as a template to develop an IMS similar to that in CS1. This section discusses the DBS alteration and customisation for the purpose of

CS2 and describes its adaptation to the project. The purpose of this trial was to understand the challenges in using the DBS as a template and developing a new IMS for a new project based on the previous works.

8.3.2. CS2 Systems Engineering Approach

The scope of the SE approach for this project is very similar to CS1, including similar types of tools and documents. Therefore, the ECF-appointed SE team developed various SE activities, including a RMS.

8.3.3. CS2 DBS Development

The proposed DBS for this project was developed based on the concept discussed in Section 7.2.3. Figure 70 is a modified illustration of Figure 50 that shows the DBS development for the purpose of this work for CS2. As Figure 70 shows, the main source to develop the DBS for CS2 was the DBS developed as a template for CS1. Additional project information and documents were used as additional sources in order to identify the gaps in the DBS.

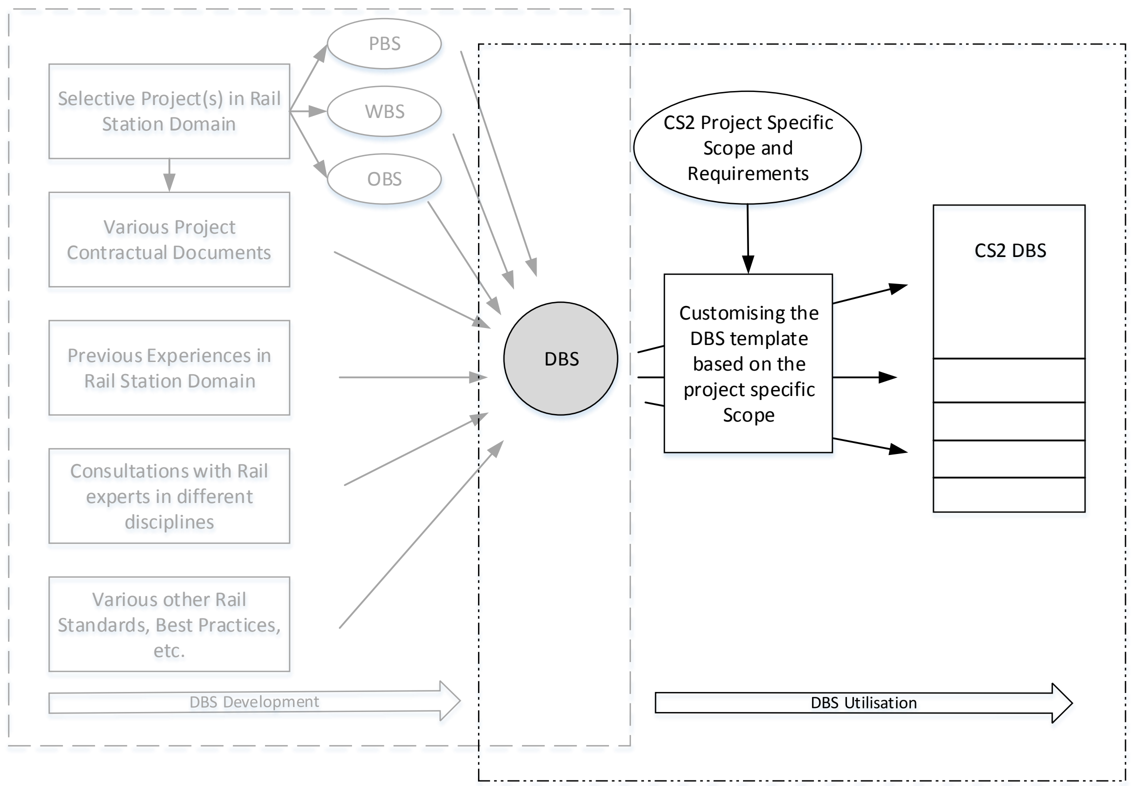


Figure 70: Developing the DBS for CS2 Based on the DBS Template Developed for CS1

In total, 117 items were identified as physical components for the station design-related works among 8 disciplines and under 11 systems and 29 sub-systems. Comparing the DBS used in CS2 with the template DBS developed in CS1 shows that all 106 components of the CS1 DBS were used in the CS2 DBS. One additional sub-system with a single component was added in accordance with the scope of the work for CS2.

8.3.4. CS2 DBS Adoption

Similar to CS1, the customised DBS was used in CS2 for the purpose of IM and RM, as well as developing a project-wide V&V information control system. The main benefit realised from this adoption was that over 99 per cent of the project interfaces pre-existed through the established ICM transferred from CS1. This was a considerable time saver for development of the project interface database and ICDs.

8.4. CS3 – A New Rail Station Design in Canada, 2012

8.4.1. CS3 Introduction

CS3 is the design phase of a major and complex new rail station in the city of Toronto, Canada, contracted to a major ECF. This project was used as another trial to adopt the DBS concept developed in CS1 and refined in CS2. As the project is designing a completely new station, the scope of the work is wider than that of CS1 and CS2 and, therefore, additional systems and sub-systems will be designed in this project.

When the project delivery and the design production started, the author joined the design team to develop a systematic solution based on the proposed DBS to manage the interfaces among various design works. This provides assurance that the design deliverables, including drawings and reports, sufficiently address the interface requirements.

The DBS developed in CS1 was used again as a template in order to develop an IMS similar to that developed in CS1. The following section discusses the DBS alteration and customisation for the purpose of CS3 and describes its adaptation to the project. The purpose of this trial was also to understand the challenges in using the DBS as a template and in developing a new IMS for a new project based on previous works.

8.4.2. CS3 Systems Engineering Approach

The scope of the SE approach for this project is limited to managing the interfaces with other contractors designing other parts of the project and, mainly, the railway system that goes through the new station. The project requirements are mainly managed by the PM team through various scope and requirements schedules based on the project final deliverable list supplied by the client.

The ECF, therefore, appointed a senior systems engineer at the beginning of the project to provide a coordinated approach to the development of an IMS. The PM team also maintains various registers and repositories separately and independently to manage the interface requirements, design risks, technical assumptions, hazards data, etc.

8.4.3. CS3 DBS Development

Similar to CS2, the DBS for CB3 was also developed based on the concept presented in Figure 70. As Figure 70 shows, the main source for developing the DBS for CS3 was the DBS developed in CS1 and refined as a template in CS2. Other project-related documents such as the Project Deliverable List, the PBS, the WBS and the project contractual documents were used to customise the template DBS and select the modules related to this project. They also drove additional items that needed to be included in the DBS template.

As discussed in Chapter 7, several projects were required to be used as case studies in order to build a master DBS that could be applied to other projects in the same sector. Therefore, some alteration to the DBS template developed in CS1 and CS2 was expected in order to make it suitable for CS3. As the scope of the CS3 project is wider than that of CS1 and CS2, it was expected to have many missing items in the DBS template that need to be added.

In total, there are 100 items identified as physical components for the station design-related works among 7 disciplines, 14 systems and 26 sub-systems. Another 41 items were identified under the railway system components that should be supplied by other contractors; these are distributed among 6 disciplines, 18 systems and 23 sub-systems.

8.4.4. CS3 DBS Adoption

Similar to CS1 and CS2, the customised DBS was used in CS3 for the purpose of IM and RM, as well as developing a project wide V&V information control system. The main benefit realised from this adoption was that a large portion of the CS3 DBS was based on the CS1 DBS template. This means that a majority of the project interfaces pre-existed through the established ICM transferred from CS1. This is a massive time saver for the development of the project interface database and ICDs.

8.5. DBS Added Value

8.5.1. CS1 Feedback and Testimonial

The project director for CS1 was interviewed to provide feedback on his observation of the adoption of CS1 and the IMS developed based on the DBS concept. This senior manager also encouraged using the DBS and IMS in many other projects globally in different forms when he was in charge of the rail sector globally in the ECF. Below is a full script of his opinion and feedback in this regard, as provided and confirmed by email in a private communication:

> *"I am writing to offer my experience of the development and application of your Discipline Breakdown Structure (DBS) approach to the management of complex multi-discipline project management in the railway infrastructure project environment.*
>
> *We first used this approach in a major station upgrade project where I was the project director, not just in a massive underground station redevelopment in a major metro in a European capital city, but also as part of [redacted]'s migration towards using the SEM approaches in rail while I was Chief Engineer. This project was not just an exceptionally complex job, but was further compounded by the interface with a major urban metro construction project underneath this critical work. A further major challenge was to undertake this work while keeping this line open and functioning while making huge changes to the structure of the original underground station: a complex project with many interfaces. It was, as you will recall, very effective and proved very attractive to the embedded client assurance team. We*

developed as part of the interface management system approach an interface tool which provided the following:

- *Interface control matrix*
- *Integrated management system*
- *V&V and compliance management system*

We adopted the approaches above and I observed:

- *The DBS gave our team a detailed picture of the skills and activities the project making input and resource planning easier and more efficient and giving a predictable project cost build-up.*
- *The interface matrix which was created and populated based on the DBS could easily be transferred into the project and therefore it was a significant time saving for the project not least because it provided a detailed interface matrix once the project started – Giving a significant time and resource saving. This is because previously we would have needed to spend a lot of time and effort to capture identify and assign the project interfaces.*
- *This integrated application created by Hadi Sanei, provided an easy system for information navigation and V&V and compliance management for the project requirements and interfaces base on the DBS concept.*

Since this project commenced I have rolled out this process with the help of Hadi Sanei I now as a matter of course use the DBS and the interface matrix associated in other projects of the same type with considerable success in South America, S.E. Asia and the Middle East as well as the UK and each time the DBS is applicable to a project with a very small alteration as it is modular and you can pick items related to the project and delete those that are not.

I personally think:

- *This concept can change project management significantly for the better*
- *The DBS idea as a modular standard approach in management can save a massive amount of time and resources in managing projects*

- *I suggest that projects in our sector use and develop this approach further in future projects"* (Project Director for a UK Major Engineering Consulting Firm, 2016)

8.5.2. CS3 Feedback and Testimonial

In developing the DBS concept for the design of this station project, the ECF interfaces heavily with another major firm providing the design for the railway system. The concept of using the DBS was found interesting by their senior management team. The Senior Vice President of that firm, who was in charge of their project to supply design for the railway system, asked his project team to adopt the same concept in their project. He also used the DBS concept and the data developed in CS1 and CS2 for their future projects. An interview was carried out and his testimonial about the DBS concept, as provided to the author in a private communication, is as follows:

"Discipline Breakdown Structure – Developed by Hadi Sanei

As the Senior Vice President for one of Canada's largest construction companies my work includes leading the design effort for very large and complex new Light Rail (LRT) systems. A major risk item for my company in the design of these large LRTs is understanding the skills and activities needed to complete the design. The DBS model developed by Hadi gave us an upfront understanding of what will be required and reduced the uncertainty and risk to the project. We were able to customize the modules to suit our projects with little effort and minimal cost, this provided us with an understanding of requirements prior to the design effort commencing.

We further used the model to address the other major risk associated with LRT Design, that of interface management. The pre-defined matrix that is part of the model allowed as to have a firm understanding of the interfaces that needed to be taken into account. Gave us the knowledge to make sure processes and procedures included the interfaces from the very start of the project (something that would normally have to be developed after the project commenced). This reduced the risk of errors and omissions and in turn the risk of issues arising during construction. This pre-determined knowledge saved my company a large amount of time and advanced the schedule considerably allowing for cost savings in both time and operational cost.

We first used this matrix as a test to determine the benefits it would bring to large project, from this we have since used the same matrix (adapted to suit each project) on two further projects, one of which is the largest LRT to be constructed in Canada with CAPEX cost of over $4.5 billion. The results from the first use of the matrix were so impressive we had no hesitation in using this on our signature project in Canada. We find that one real advantage of the model as a whole is that it allows our design director and his team to pick and choose modular components to suit the project needs with little effort. This has proven to be a valuable advantage as we can split it down in to segments and discipline areas to assist our design segment leads on projects. This is no small feat as these LRT project are extremely complex and have thousands of interfaces and disciplines.

I and my company would highly recommend this DBS system." (Senior Vice President for one of Canada's largest Construction Companies, 2016)

The DBS concept and the IMS based on the DBS for this project were presented to the client's head of the transit rail programme (Ministry of Transportation for the municipal government) in a private meeting with other senior management team members from different stakeholders. The presentation was well received, and the following feedback was provided to the author in a public communication shared with many other senior management team in late 2012:

"I want to thank you for all of the work you put into today's presentation of the Systems Interface Plan for the project. The level of effort was evident, and your understanding of the model and its use on [redacted] *Station was appreciated by both* [redacted] *and* [redacted]*. Some of* [redacted]*'s direct quotes: 'I'm really pleased.'; 'You've hit all of the hot buttons.'; 'I'm very impressed.'; 'I'm thrilled to have you on this project.' and most importantly; 'You've given me more ammunition for maintaining this project as DBB.* [redacted] *has used interface coordination as one of the benefits of using DB procurement; I am now convinced otherwise.'*

This opened up the opportunity for all of us to discuss how beneficial it is to keep us on board for DBB, noting that with the specific station designer focusing on interface coordination, having a sense of responsibility and independence from the systems *contract, while utilizing a tool such as yours, will provide the best design contract coordination for the station.*

Thanks again for demonstrating the mantra of our team, 'exceed the client's expectations', even as an early out-of-sequence snapshot of the deliverable." (Senior Project Manager, 2012)

8.6. DBS Template

8.6.1. DBS Comparison

A like-to-like comparison at the physical component level was conducted among the DBSs developed in CS1, CS2 and CS3, as shown in Figure 71. There is a total number of 116 components in CS1, and CS2 has a very similar work scope. The DBS customised for CS2 based on the CS1 DBS uses 115 items of the CS1 DBS and has an additional item based on the CS2 project-specific requirement. CS3 has slightly different scope meaning wider in some aspects and narrower in others. In total therefore, there are 100 components in the CS3 DBS. Seventy Five of the components come from the CS1 DBS, one from the CS2 DBS and the additional 24 components are captured based on the CS3 project specific requirements.

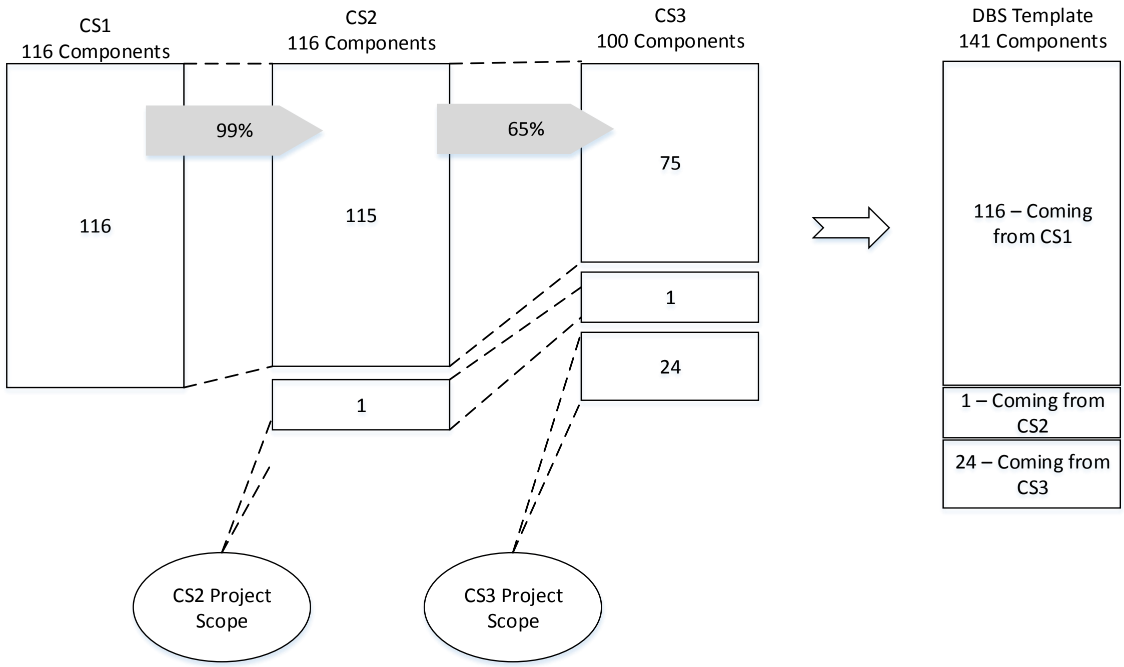


Figure 71: DBS Template Development Comparison

As Figure 71 shows, CS2 used over 99 per cent of the items in CS1, and CS3, with its different work scope, uses over 65 per cent of the pre-existing DBS component. This means that based on the DBS approach, more than two-thirds of the project interfaces, as well as many other management documents, pre-exist. This is a great saving in the time and effort that needs to be put in at the beginning of each project.

Figure 71 also shows that after working on three projects of the same nature, the master DBS database totals 141 items.

8.6.2. DBS Adaptation Tool

As discussed in Section 7.4, the proposed DBS should be formed as a template that can be reused in similar projects within the same domain. In order to put this concept into practice, an application should be developed which works as a database with a user-friendly front end, enabling the user to pick the right modules of a template DBS for the specific project. Meanwhile, the database should hold an ICM for the master DBS items as well as many of the project schedules and documents based on the master DBS.

Developing such an application is beyond the scope of this work. However, the SE team in the ECF, with the help of the author, developed a sample application on the Microsoft Access platform to implement the DBS concept. This application is used as a data store to keep all data related to an IMS. The populated ICM was transferred into the database. Interface search, edit, add and remove are the other facilities provided by this application, as well as providing different reports on interfaces. This application has limited capabilities and requires alterations each time it is used, so is not currently a viable tool to be used in the industry. But it sets some of the key and basic functional requirements required to develop such an application for future related works.

8.7. Conclusion of the Chapter

The proposed DBS concept was applied to three different projects to test and validate the method based on the proposed solution. The projects used as case studies had relatively similar scope but were in different locations and with different project teams and supply chains.

The trial of the DBS concept activities summarised in this chapter demonstrated the following key conclusions:

1. The DBS implementation in CS1 facilitated the identification and assignment of the project interfaces in order to develop an IMS in a multidisciplinary project. The further trials in CS2 and CS3 further demonstrated that regardless of the project-specific team or work streams, the DBS is capable of identifying the areas of interfaces that should be managed to a very detailed level. These case studies also proved that the interface ownership and compliance verification will be improved by using the DBS concept.
2. Application of the DBS in CS1, CS2 and CS3 demonstrated the capability of the DBS to create links among the PM and SE activities in managing such projects. These trials proved that using a DBS provides an integrated approach on managing systems in which interfaces, requirements and deliverables are linked and in which data can be traced and navigated from one to other.
3. The use of the DBS implemented in CS1, and later as a template in CS2 and CS3, demonstrated the management efficiency that the DBS concept can introduce to the projects by saving considerable time and resources as the result of predefined interfaces. This shows that the DBS as a standard and a template in specific domains can save a significant amount of time and resources by generating predefined management baselines for various PM and SE key activities such as project interfaces, risks, costs and activities.
4. The development of an integrated management tool based on the DBS concept for CS1 and the customisation and reusability of that tool in CS2 and CS3 demonstrated the benefit of the DBS concept in implementation of a fully integrated and traceable tool to navigate through the project information within various tools, documents and registers. The tool not only provides various reports and information on the compliances for requirements and interfaces, but also provides a platform to manage the impacts that changes in some parts of the project information have on the other parts.

Chapter 9 CONCLUSION AND FUTURE WORK

9.1. Introduction

This chapter summarises the works conducted in this research and explains the conclusions and outcomes achieved as the result of the research performed. Therefore, the main research scope (MRS) identified in Chapter 1 is recapped and mapped against the outcome of this research.

This chapter also provides an outlook on future work and projects that can be defined based on the outcome of this research.

9.2. Main Research Scope Recap

*The **research scope** of this study is to formulate a **fully integrated** approach to develop a **modular and reusable** solution that creates a traceable **relationship** between a **systems engineering** approach and **project management**, including project delivery tools and documents, in which all changes can be managed **better,** resulting in more **efficient** project management.*

(MRS)

The ultimate goal of this research is to help project management (PM) to be more efficient by using a systems engineering (SE) approach and activities within multidisciplinary projects in rail sector.

The key assumptions made in this research project are as follows:

1. Improving ‘project efficiency’ refers to any effort that can result in saving resources, including time and people.
2. In the type of projects that are the main interest of this research project, the key SE activities are interface management (IM), requirements management (RM) and verification and validation (V&V) (compliance management).
3. Interface management is a key activity of SE in such projects and is targeted to be improved.

The key hypotheses in this research project that were tested through literature review and case studies are as follows:

1. Poor IM and poor RM are key factors that can potentially cause project failure. If they are not managed well, they contribute significantly to project reworks and therefore inefficiency. Therefore, any attempt for improving these activities will potentially improve the efficiency of the PM.
2. In such multidisciplinary projects, PM and SE introduce various activities along with tools and documents. There is no reference in any literature or case studies suggesting a systematic solution to link PM and SE in their physical activities level and not just at the conceptual level. Therefore, a solution that can integrate these activities can form an integrated management system that will make PM more efficient.
3. The PM and SE documents and tools have different layers of information. Therefore, they can be integrated through a solution that has access to different layers of information of a project. Projects tend to use a Work Breakdown Structure (WBS) as a single tree form structure to work with some of the PM and SE activities, mainly commercial and planning/scheduling.

The key activities of this research and the expected outcome are as follows:

1. Studying PM and SE is fundamental to understanding the concept of project, PM and SE, as well as to understanding the activities, tools and documents they introduce in managing a typical construction project.
2. Understanding the importance of IM and RM in PM and their contribution toward project failures.
3. Studying the fundamentals of the WBS and its relationship to the IM and SE concepts and their activities.
4. Designing and developing a new solution to integrate PM and SE activities, tools and documents to form an integrated management system.
5. Testing the new solution in real rail sector projects to realise its applicability, strengths and constraints.

9.3. Research Need Justification

In order to justify the need for this study data was required to understand that:

1. The importance of the IM in such multidisciplinary projects and its impact in project success / failure.
2. How people in industry think about PM, SE and more specifically the common applications such as IM, RM and V&V.

Therefore different types of data gathered through reviewing literatures (mainly statistic reports), conducting case study on a major rail station design project, as well as conducting an industry survey.

Within the literature many examples were gathered to show that projects failed due to poor management of interfaces and requirements. Reviewing the new project procurements strategies in the rail domain revealed the shift toward transferring risk of project delivery from sponsor to the contractors. Contractors are more concerned about project efficiency as they need to manage their project delivery within agreed resources including budget and time. Also as projects are contracted to multiple suppliers, interfacing is becoming a serious issue and therefore improving the management of the interfaces improves management efficiency.

A major railway station design project in central London was approached in order to conduct a case study. Over 7500 line of communication between the project engineering design supplier and the client engineering team gathered and analysed to understand the main reason to generate such communications. The results showed that the poor IM and RM contributed in generating over 50% of this comments, resulting in generating unnecessary works, and therefore use of additional resources (i.e. time and cost).

An industrial survey was conducted in the form of an online questionnaire, targeting mainly project managers and systems engineers with a focus on the main topics that relate to this research including, IM, RM and WBS. The primary result of the survey was the demonstration of a lack of consensus on IM and RM definition and responsibilities among the project team at different levels. The results further showed how poorly functioning IM and RM can impact projects. The survey also demonstrated poor quality of IM and RM according to the industrial experiences. Since the WBS is a structured and layered concept common in Project Management, the survey further looked at the WBS and its possible application in IM. Less than 10% expressed having any sort of experience of using the WBS for the purpose of IM.

The combination of the data gathered as explained above, provided the necessary justification for a need to improve IM by integrating the SE approach and its application into the PM solutions, to improve PM efficiency.

9.4. Solution Development

In this research a simple V life cycle model used for the solution development as explained in earlier chapters. The main requirements for the solution identified are that they must;

- be based on the breakdown structure (divide and conquer)
- integrate SE and PM tools and applications
- provide a systematic way to identify and visualise interfaces
- provide a systematic way to allocate and assign interfaces to relevant parties/owners
- provide a systematic data repository to demonstrate that the project addresses the interface issues and requirements
- create tractability among all other PM documents
- be modular and reusable
- provide time and resource savings

The DBS concept (that, similar to the WBS, PBS, OBS or many other breakdown structure based concepts) is proposed and its use and application in managing projects is explained. It was also further explained that how the proposed approach could not only improve the IM, but also could bring SE and PM tools and functions together at a working level and in an integrated format.

Disciplines can be viewed as more fundamental than work, product or organisations. Disciplines are based on the extant configuration of an industrial capability and are less related to the project unique specification and requirements.

When WBS templates exist, they must be tailored to a particular project and are so not generally fixed. Various factors such as project environment, project nature, organisational culture, personal preference, etc., play key roles in WBS development. WBS is invented for the purpose of planning. Different PMs or project planners plan projects in different ways. There is generally no uniquely ideal plan for project and it is most important that a project has a plan so it can be monitored and measured against.

The Product Breakdown Structure (PBS) is a product oriented breakdown of a project's outcomes. In engineering projects, a PBS shows the deliverables to be developed by the project. The WBS on the other hand structures the work of a project. In such engineering projects, WBS shows the works to be done in the project to develop the PBS products. The proposed DBS is a discipline / knowledge oriented breakdown of the tasks under each disciplines involved in a project. These are the disciplines (typically available with industry) that need to be involved to perform the works under WBS and so to deliver products under PBS.

The proposed DBS can become the source to develop a logical breakdown of the industry knowledge to be used in industry standards, university modules and syllabus, training modules, etc. This could ultimately changes the way of thinking regarding the management and delivery of projects across entire commercial domains.

9.5. Research Key Conclusion Messages

9.5.1. Project Management and Systems Engineering

The literature review of Chapter 3 provided an image of the fundamental definition of project, PM and SE. The review looked into the PM and SE essential activities, tools and processes with a focus on multidisciplinary construction projects with a brief reference to the rail sector. The chapter also investigated and described the SE approach as a discipline and its relationship to PM in different sectors over its history. The SE life cycle, tools and procedures were briefly analysed, and the role of SE in the execution of infrastructure projects was described. The key conclusions of Chapter 3 in the context of PM and SE are as follows:

- All of the activities introduced by SE and PM are defined around different layers of project information in areas like commercial, planning, risk, scope and requirements.
- Integration of SE and PM activities can form an integrated management system, improving PM efficiency.

- Although no specific solution for integrating PM and SE activities in rail projects could be found in the literature, it was explored that the project managers and systems engineers tend to use a WBS as a form of a breakdown structure to categorise the project into smaller parts and manage the processes.

The results of the survey conducted in Chapter 5 clarified further the identity crisis of SE in today's projects and PM. One of the key conclusion from this chapter on this topic is as follows:

- The lack of consensus among the project team people, including management and delivery, on the need for systems thinking and an SE approach in such projects.

9.5.2. Interface Management and Requirements Management

The literature review of Chapter 3 provided a definition of IM from both the PM and SE perspectives. The importance of IM was further investigated by studying new procurement strategies for rail projects that introduce more interfaces among various suppliers. Chapter 3 also reviewed projects that failed as a result of poor IM and RM. Therefore, the key conclusion of this chapter in this context is as follows:

- Interface management is a key function in PM because of the new procurement strategies as well the historical record of project failures related to poor IM.

The survey in Chapter 5 collected data from practitioners on IM and its applications. Key conclusion from the results of the Chapter 5 are as follows:

- Lack of consensus among the project players, including management and delivery teams, about the importance of managing the interfaces and requirements as standalone functions.
- Lack of consensus among project teams on the responsibility of IM (PM view is to manage the interfaces and requirements as natural part of managing a project, while an SE view is to have a standalone and systematic approach, along with its procedures and tools).

- The survey also concluded that because the interfaces and requirements are not being managed well in industry, there is a major risk to the projects as they get larger and more complex. This justifies developing better solutions to enhance and improve IM and RM.

A project case study was studied in Chapter 6 to review the PM performance and the key failure factors in a rail-related project as part of an overall major programme of a railway station modernisation project in central London. The key conclusions from Chapter 6 are as follows:

- Poor management of the interfaces and coordination between different disciplines and parties, as well as poor understanding and management of the project scope and requirements, are the top two reasons that generate a considerable volume of discussions and disagreement among the project parties, which results in generating more work, cost and time.
- This chapter concluded that poor IM and RM together with a poor V&V process make up around 60 to 70 per cent of the additional arguments between a project client and suppliers.

9.5.3. WBS and Its Relationship to Project Management and Systems Engineering

The literature review in Chapter 4 fundamentally discussed the WBS's definition, types, development and applications. Chapter 4 also concluded that the WBS is the main backbone of the PM, playing an essential role in the PM activities, including project resource scheduling; project time scheduling; project cost estimation; budget management; project risk management; and SE activities such as project IM, RM and V&V. The key conclusion messages from Chapter 4 are as follows:

- Work breakdown structures tend to be developed in various ways depending on many different factors, including the type of the project, type of industry, project manager work principle, company regulation and legislation, project environment and parties involved.
- It is not possible to formulate the WBS development in a standard format.

- Improving the quality of the breakdown structure of a project or a system will improve the quality of IM, leading to better, more efficient PM.

9.5.4. Discipline Breakdown Structure

Literature review, survey and project case study provided enough justification for a need for a solution to address the following:

- Improve IM in multidisciplinary projects
- Bridge PM and SE activities to form an integrated management system

Chapter 7, therefore, introduced the proposed Discipline Breakdown Structure (DBS) concept and its applicability. The key conclusions of the chapter are as follows:

- The proposed DBS is a breakdown structure of the disciplines involved in projects within a specific domain. The DBS presents the skills and competencies required by disciplines within an industry sector.
- The proposed DBS is a modular database. Every time it is used in a project, the modules related to the project should be picked and customised based on the project-specific scope and requirements at the early stage of the project definition.
- The proposed DBS improves the project efficiency by providing access to various predefined information when a project starts, such as baselines for risks, requirements and cost elements related to the selected modules of the DBS.
- The proposed DBS creates links between all project activities including PM and SE tools and documents. All other project documents can be related to the DBS on different levels of information to create an integrated information management system.
- The proposed DBS is recommended to become an industry standard for a specific domain.
- The proposed DBS can eventually become a reference for projects in a specific domain. This reference can drive the baseline of what is required for projects supporting both the client and supply chain to identify the project requirements. It can also become a reference for educational purposes in a specific domain.

- The proposed DBS can also eventually become a standard benchmark to score supply chain competency for various purposes including bid evaluation.

9.5.5. DBS Testing – Case Study

The proposed DBS concept was applied to three different projects with relatively similar scope but in different locations and with different project teams and supply chain. The key conclusion messages from these case studies are as follows:

- The proposed DBS has played a key role in developing a structured and traceable Interface Management System (IMS) for the project case studies. The IMS developed in the projects used the DBS in identification of the areas of interfaces in various layers of information from high level to the detailed component level. The DBS also provided interface ownership as well as traceability for the purpose of compliance verification within a V&V tool developed based on the DBS.
- The proposed DBS concept applied as a core to link the key project documents including requirements schedule, interface matrix, interface database, design deliverable register, and document control system as the key PM and SE activities.
- The proposed DBS developed for the first case study was reused as a template in the second and third case studies. This presented the capability of the DBS concept to be used as an industry standard. It also provided evidence on the time and resources that can be saved by creating access to the predefined management baseline information for various PM and SE key activities such as project interfaces. This concept can be expanded to the other key project information including risks, cost and activities.

Further application of the DBS would require the following to be addressed:

- A much more comprehensive data gathering is required to ensure that a fully comprehensive list of assets/skills within a branch of industry is captured before the DBS could be considered as a standard.

- Since technology advances at a fast pace, there is a danger that the data within a developed DBS could become obsolete. Therefore, a timely review cycle needs to be established.
- Non-technical factors (including political and environmental) can impact the project interfaces and architecture. These also need to be included since they are not well captured in the DBS structure.

9.6. Future Work

This research discusses the idea of the DBS and its development. Although the main focus of the author in developing this concept was to develop a systematic solution to manage project interfaces, the results from the trial and the feedback received from various project parties, including client and supply chain, unfolded the potential of the DBS concept in changing the procurement of the multidisciplinary projects in different aspects. Therefore, this is a new path that can generate new work streams and research in developing new solutions, ideas and tools to improve management of the projects in different sectors.

The following section summarises some of the key areas that can be further explored based on the DBS concept.

9.6.1. DBS – an Industry Standard/Database

The DBS should be further developed in different sectors to the level that covers almost all the possible scenarios in different sectors. The development of such a data repository can become an industry standard in different sectors. Like any other standard, the DBS should be updated as technology advances, though the concept remains the same. Such a standard can be developed in a form of a database (data repository), and access can be provided to the projects when it is required.

9.6.2. Integrated Management System Application (Database)

The DBS concept was explained as a core to link PM and SE activities and tools in order to form an integrated management system. The trial of the concept and the project case studies demonstrated the concept applicability in real projects.

Developing a comprehensive PM application database software based on the DBS concept could potentially introduce a new era in management of such multidisciplinary projects. The application should enable the project manager and the project team to access the pre-stored DBS modules (based on the DBS standard developed for specific sector) and select those related to the project and its main scopes. Once this is completed, the software should generate various PM and SE tools and document these with baseline information which is derived from the main data repository according to the DBS modules selected for the project. This application should be a cloud-based application with various access rights for different project team members. Traceability of the information in different registers and tools through the DBS should be developed and maintained in the application. The application could also be equipped with various data analysis engines and reporting tools, helping the project team and other stakeholders.

9.6.3. Project Definition and Initiation

The application of the DBS concept can potentially change the project definition, initiations, costing and procuring. If the DBS becomes an industry standard, the solutions should be developed to initiate the projects based around the DBS. This will help the project sponsor to have a picture of what needs to be done before the project is defined and started. Skills, complexity, cost, interfaces and parties that need to be involved can be better predicted at the very early stages, even before a project is formally initiated. This, however, needs more work and research to refine the DBS concept and its development.

9.7. Dissemination

The concept of the DBS – along with the applications of IMS, Requirements Management System (RMS) and V&V tools developed and used in the project case studies presented in this thesis and many other projects globally – was presented in different forms to various clients and parties. The concept has also been vital in securing a number of major projects based on what was presented in the tender documentations. Therefore, the concept has been presented in the following forms and formats:

- In a form of a proposal as part of the bid documentation to secure major rail projects globally
- In the form of project reports to present the approach adopted in managing major rail projects in the UK, Canada, Malaysia and Brazil
- In the form of presentation in client workshop and conferences in Malaysia, Brazil and Canada
- In the form of a presentation poster for the purpose of business development and marketing

9.8. Conclusion of the Chapter

This chapter is concluded by responding to the project main research question (MRQ) identified and analysed in Chapter 1.

How can SE and PM activities be better integrated to support project managers to manage their multidisciplinary (rail) projects more efficiently?

MRQ

This question has been the source of identification for the MRS, project work packages and activities as well as the specifying the requirements for the solutions that need to be developed in this study.

The SE and PM activities use different tools and documents which generate various information related to the project in different layers. The documents need to inform each other as in many occasions, the information and the changes in one document can impact the other parts of a project. Therefore, these document and tools should be linked and integrated. The best way to integrate a number of documents (mainly in the form of registers) is to have them built around a same concept. The proposed DBS provides what is necessary to form all PM and SE tools and documents around itself, and therefore integrates them in practice.

Improving IM in a multidisciplinary project is vital. Many projects have failed completely or partially due to poor IM. The proposed DBS facilitates the management of interfaces on different levels of a project. Managing the interfaces eliminate project risks.

The projects are managed more efficiently if they can save on resources, including time and people. The proposed DBS saves both time and resources as follows:

- The DBS improves project IM. Therefore it eliminate project rework and reduces the risk of project failure, saving both time and resources.
- The DBS creates access to the predefined information stored in the project database. There will be considerable time and resource savings as a result of having the main baseline of the information in various branches of the PM ready when the project starts.
- The DBS pictures a project in advanced and therefore highlights potential risks and issue. This helps the PM to manage the issues and risks better, and therefore saves project time and resources.
- The DBS, along with the integrated management system application built based on the DBS concept, provides a constructive tool for PM. Traceability of the information through the DBS facilitates change management and impact analysis, saving both time and resources.

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APPENDICES

Appendix 1 Questionnaire/Survey

This appendix provides a full script of the questionnaire provided to conduct the survey detailed in Chapter 5.

Systems Engineering General

The Implementation of 'Systems Engineering' Practice would improve the Effectives of the Project Management in Infrastructure Projects

As part of my PhD research at University College London, Centre for Systems Engineering (UCLse) I have produced this survey which will be used for academic purposes only. All responses will remain confidential and will only be used for data analysis. Your effort is highly appreciated and will be regarded as a great support to my research.

Author: Hadi Sanei

Supervisor: Professor Alan Smith

About you

1. Full Name (optional): -------------------
2. Company (Optional): -------------------
3. We would like to follow-up with some interviews. If you are happy to be contacted please add your email here. No contact details will be passed to any third party or outside the scope of this research.
   Email: -------------------

4. Position in the company (please indicate the title that nearest describe to your role):
   - Business Director
   - Practice Leader
   - Programme Manger
   - Project Manager
   - Systems Engineer
   - Planner / Scheduler
   - Engineer
   - Others (please specify): -------------------

5. Scale of Projects that you are or have been involved with (please indicate which project scales you have been involved with, you may indicate more than one scale):
   - ☐ Major Programme >$100m
   - ☐ Major Project >$20m
   - ☐ Medium Project >$1m
   - ☐ Small Project>$10k

6. Type of Services
   - o Client (e.g. government procurement)
   - o Consultant
   - o Contractor
   - o Manufacturer
   - o Others (Please specify): -------------------

7. Sector (indicated one or more sectors):
   - ☐ Railway
   - ☐ Highway
   - ☐ Bridges and Tunnels
   - ☐ Aerospace
   - ☐ Finance
   - ☐ Healthcare
   - ☐ Academic Research
   - ☐ Energy Oil and Gas
   - ☐ Energy Nuclear
   - ☐ Water
   - ☐ Others (please specify): -------------------

Part 1: Requirements Management

In this part we need to understand your experience in managing the Requirements in your projects. We would like to explore the relationship between Requirements Management and other project management's activities, procedures and documents such as "Scope Management", "Project Objectives", "Deliverables Management", "Interface Management", etc.

---

8. What do you think is/are the main purpose(s) of Requirements Management? (You may choose up to 4 items)
   - ☐ Understanding the scope/ objective of the work
   - ☐ Establish an agreed baseline
   - ☐ Facilitating Change Management/ Claim (meaning protecting both sides of the contract)
   - ☐ Enable the verification of the deliverable`s compliance with the End User Need
   - ☐ Enable the verification of the deliverable`s compliance with the Client Requirements
   - ☐ Traceability of different requirements coming from different sources in different life cycle
   - ☐ Inform design and integration
   - ☐ Minimise reworks
   - ☐ Reducing Cost
   - ☐ Managing crossed requirements/interface requirements across the parties involved
   - ☐ Others (Please specify): -------------------

9. Have you ever used commercial tool for Requirements Management/ Engineering?
   - o Yes
   - o No

10. If you used commercial tools, please name them? -------------------

11. How did you manage the requirements in the absence of a commercial tool? (Brief description of tools developed/used) -------------------

12. Do you think Requirements Management is a natural part of Project Managements and / or Systems Engineering?
    - Project Management
    - System Engineering Management
    - Neither

13. Has there been a quantitative assessment of the value of Requirements Management in your organisation?
    - o Yes
    - o No
    - o Don't know

14. If your answer to previous Question is "Yes", would you be able to share the information? If yes, can you please enter your email here again to arrange a follow up interview? -------------------

15. What type of requirements you mainly work with in your business?
    - Product Requirements
    - Process Requirements
    - Business Requirements
    - User Requirements
    - Functional Requirements
    - Non-Functional Requirements
    - Implementation Requirements
    - Contractual Requirements
    - Legal Requirements
    - Don't Know
    - None
    - Others (Please specify): -------------------

16. Who do you think would benefit the most from Requirements Management?

- End User
- Client
- Contractor/Supplier
- All Stakeholders
- None
- Don't know
- Others (Please specify): -------------------

17. How do you rate the quality of the Requirements Management at your Client Organisation?

- Excellent
- Very Good
- Good
- Average
- Poor
- Very Poor
- Absent
- Not Applicable
- Don't know

18. How do you rate the quality of the Requirements Management at your supplier organisation?

- Excellent
- Very Good
- Good
- Average
- Poor
- Very Poor
- Absent
- Not Applicable
- Don't know

Part 2: WBS- Work Breakdown Structure

In this part of the questionnaire we like to understand your experience in relation to the development of the WBS in your field. We also need to explore the WBS relationship with other tools and documents in a project. The WBS and its application and relationship to Systems Engineering Management is also covered in the section.

---

19. How have you developed WBSs?

- ☐ Used Template
- ☐ Used previous similar project
- ☐ Structured around the project deliverables
- ☐ Structured around the team or discipline
- ☐ Structured around the nature of the work
- ☐ Never developed one
- ☐ Other (please Explain): -------------------

20. Typically how many concurrent versions of WBSs are used within a typical project (differently in your project environment)?

- o 1
- o 2
- o 3
- o >3

21. Once developed which tools incorporated the WBSs?

- ☐ Project Planning Tools
- ☐ Commercial Tools
- ☐ Interface Management Tools
- ☐ Requirements Management Tool
- ☐ Risk Management Tools
- ☐ Resources Management Tools
- ☐ Document Control Management Tools
- ☐ None
- ☐ Don't know
- ☐ Others (Please specify): -------------------

22. How your WBS typically structured?
    - Product Oriented
    - Service Oriented
    - Resources Oriented
    - Discipline Oriented
    - Don’t know
    - None
    - Others (please specify): -------------------

23. How well connected is the WBS to systems engineering management in your opinion?
    - Excellent
    - Very Good
    - Good
    - Average
    - Poor
    - Very Poor
    - Not at all
    - Don’t know

Part 3: Systems Design/ Interface AND Systems Integration

In this section, we want to understand your experience on managing the interfaces between different parties in a project in different phases of a project. We would like to know if you have used or developed any tools or application for this purpose and see how the results have helped your projects to be more efficient.

Interface Management and its relationship to the System Engineering Management in also a topic that we would like to explore further.

---

24. How well are the interfaces managed in your projects? Opinion?
    - o Excellent
    - o Very Good
    - o Good
    - o Average
    - o Poor
    - o Very Poor
    - o Don't know

25. What do you see as the major risks to the project as the results of a poor interface management?
    - ☐ Rework
    - ☐ Project Schedule / Delay
    - ☐ Project cost Overrun
    - ☐ None
    - ☐ Don't Know
    - ☐ Others (please specify): -------------------

26. Have you ever used a commercial tool for interface Management?
    - o Yes
    - o No

27. If you used commercial tool(s), please name them? -------------------

28. How did you manage the interfaces in the absence of a commercial tool? (Brief description of tools developed/ used)? -------------------

29. Do you think interface Management is a natural part of Project Management and/or Systems Engineering?
    - Project Management
    - Systems Engineering Management
    - Neither

30. Has there been a quantitative assessment of the value of interface Management in your organisation?
    - Yes
    - No
    - Don't know

31. If your answer to previous Question is "YES", would you be able to share the information? If yes, please enter your email again to arrange for the follow up interview? -------------------

32. What type of interfaces do you mainly capture in your business?
    - Technical Interfaces
    - Stakeholders Interfaces
    - Contractual Interfaces
    - Human Machine Interfaces
    - None
    - Don't know
    - Others (please specify): -------------------

33. Who do you think would benefit the most from Interface Management?
    - End User
    - Client
    - Contractor / Supplier
    - None
    - Don’t Know
    - Others (Please specify)

34. How do you rate the quality of the Interface Management at your Client organisation?
    - Excellent
    - Very Good
    - Good
    - Average
    - Poor
    - Very Poor
    - Absent
    - Not Applicable
    - Don’t know

35. How do you rate the quality of the Interface Management at your Supplier organisation?
    - Excellent
    - Very Good
    - Good
    - Average
    - Poor
    - Very Poor
    - Absent
    - Not Applicable
    - Don’t know

36. At what stage of the project is integration management important?

- ☐ Feasibility Study
- ☐ Outline Design
- ☐ Detailed Design
- ☐ Implementation
- ☐ Hand over and Commissioning
- ☐ None
- ☐ Others (please specify)

Any other comment?

37. Is there any other comments you would like to share with us in this context?

Thanks you for taking our survey

Appendix 2 Survey Cover Letters

This appendix provides images of the cover letters sent to various parties to communicate the questionnaire to conduct the survey detailed in Chapter 5.

Sanei, Hadi/TOR

From: Sanei, Hadi/LON
Sent: 12 May 2015 11:32
To: 'marketing@apm.org.uk'
Subject: Academic Survey R47006

Dear

As part of my PhD research at University College London, Centre for Systems Engineering (UCLse), we have produced this survey which will be used for academic purposes only. All responses will remain confidential and will only be used for the data analysis. Your effort is highly appreciated and will be regarded as a great support to my research.

The topic is: **The Implementation of 'Systems Engineering' Practice would improve the Effectiveness of Management of Infrastructure Projects**

Link to the Survey: https://opinio.ucl.ac.uk/s?s=37295

Regards, Hadi

Hadi Sanei MSc, BEng, MBCS, MAPM
Associate Director, Rail
Systems Engineering Management

CH2M HILL
Elms House
43 Brook Green
W6 7EF, London, UK
Direct +44 20 3479 8157
Mobile +44 7584 151786
Email hadi.sanei@ch2m.com
www.halcrow.com
www.ch2mhill.com

"You Promised Me Mars Colonies. Instead, I Got Facebook" *Buzz Aldrin (the Apollo 11 moon walking astronaut)*

1

Sanei, Hadi/TOR

From: Sanei, Hadi/LON
Sent: 15 May 2015 17:45
To: 'emmajane@incoseonline.org.uk'
Subject: Survey - Member 25882

Hello Emma

As part of a PhD research I am conducting with UCL centre for Systems Engineering, we are studying the relationship between Systems Engineering Management and Project Management. We have a survey at https://opinio.ucl.ac.uk/s?s=37295 including few questions covering;

- Requirements management
- Interface Management
- Work Breakdown Structure

In the context of Project Management and Systems Engineering.

Please can you kindly assist me with forwarding this link to the INCOSE member? The effort will be highly appreciated and will be great contribution in this study.

Regards, Hadi

Hadi Sanei MSc, BEng, MBCS, MAPM
Associate Director, Rail
Systems Engineering Management

CH2M HILL
Elms House
43 Brook Green
W6 7EF, London, UK
Direct +44 20 3479 8157
Mobile +44 7584 151786
Email hadi.sanei@ch2m.com
www.halcrow.com|
www.ch2mhill.com|

"You Promised Me Mars Colonies. Instead, I Got Facebook" *Buzz Aldrin (the Apollo 11 moon walking astronaut)*

1

Sanei, Hadi/TOR

From: Sanei, Hadi/LON
Sent: 18 May 2015 15:21
To: **[redacted]** **(CH2M Project Management Team)**

As part of the research study we are conducting with UCL Centre of Systems Engineering Management (London, UK), I have a quick survey here at https://opinio.ucl.ac.uk/s?s=37295 to collect your experience, thoughts and ideas in the areas of Project Management and Systems Engineering Management.

I would really appreciate it if you could kindly spend some time filling in this survey and also forward to other Project Managers, Systems Engineers, Planners, and those you think are relevant to this topic. It of course doesn't need to be internal and you may send it to colleagues and friends externally.

Your time and effort is a great contribution in this research and is highly appreciated in advanced.

Regards, Hadi

Hadi Sanei MSc, BEng, MBCS, MAPM
Associate Director, Rail
Systems Engineering Management

CH2M HILL
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"You Promised Me Mars Colonies. Instead, I Got Facebook" *Buzz Aldrin (the Apollo 11 moon walking astronaut)*

5

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Hadi Sanei ... 7mo
Associate Director, Rail at CH2M HILL

Academic Research

Hello

Please can you kindly spend 5 to 10 min of your time and fill in the survey we have created at
https://opinio.ucl.ac.uk/s?s=37295

We are working on a research program in UCL Centre of Systems Engineering and your respond to this survey will be great contribution

Many thanks in advanced for your time and effort.

Regards, Hadi

Survey

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Hadi Sanei
Associate Director, Rail at CH2M HILL · 7mo

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We are working on a research program in UCL Centre of Systems Engineering and your response to this survey will be great contribution.

Many thanks in advanced for your time and effort.

Regards, Hadi

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NCOSE New England Chapter

Unlisted · 34 members

Hadi Sanei ••• 7mo
Associate Director, Rail at CH2M HILL

Academic Survey

Hello

Please can you kindly spend 5 to 10 min of your time and fill in the survey we have created at
https://opinio.ucl.ac.uk/s?s=37295

We are working on a research program in UCL Centre of Systems Engineering and your respond to this survey will be great contribution.

Many thanks in advanced for your time and effort

Regards, Hadi

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Hadi Sanei

Associate Director, Rail at CH2M HILL

7mo

Academic Research

Hello

Please can you kindly spend 5 to 10 min of your time and fill in the survey we have created at https://opinio.ucl.ac.uk/s?s=37295

We are working on a research program in UCL Centre of Systems Engineering and your respond to this survey will be great contribution.

Many thanks in advanced for your time and effort

Regards Hadi

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This is an international networking group for members of ALL organizations that promote support Systems Engineering and for all who want to share their knowledge and exp related to Systems Engineering.

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Associate Director, Rail at CH2M HILL

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Hello

Please can you kindly spend 5 to 10 min of your time and fill in the survey we have created at https://opinio.ucl.ac.uk/s?s=37295

We are working on a research program in UCL Centre of Systems Engineering and your respond to this survey will be great contribution.

Many thanks in advanced for your time and effort.

Regards, Hadi

Survey

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Appendix 3 Survey Report Generated by Opinio

The survey detailed in Chapter 5 was created in Opinio, an online survey tool licensed by UCL. This survey creator generates a full report based on the data stored. This appendix provides as reference a full copy of the report generated by Opinio.

Comment report

Lists all the questions in the survey and displays all the comments made to these questions, if applicable.

Table of contents

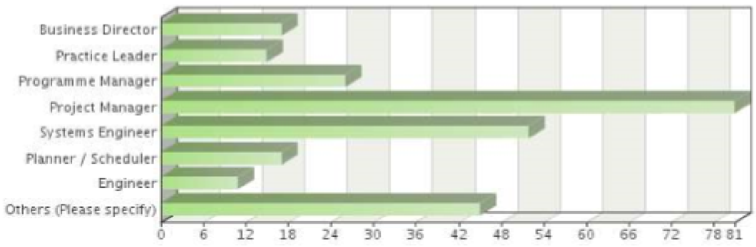
Report info

Report date:	Thursday, October 15, 2015 8:22:43 PM BST
Start date:	Sunday, May 3, 2015 12:00:00 AM BST
Stop date:	Tuesday, June 30, 2015 12:00:00 AM BST

1 / 58

Question 4

Position in the company (please indicate the title that nearest describes your role):



Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Business Director	17	4.06%	6.44%
Practice Leader	15	3.58%	5.68%
Programme Manager	26	6.21%	9.85%
Project Manager	81	19.33%	30.68%
Systems Engineer	52	12.41%	19.7%
Planner / Scheduler	17	4.06%	6.44%
Engineer	11	2.63%	4.17%
Others (Please specify)	45	10.74%	17.05%
Sum:	264	63.01%	100%
Not answered:	155	36.99%	-

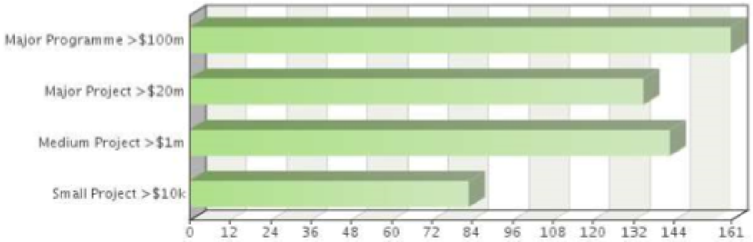
Total answered: 264

Last choice text input
Software developer
researcher
Corporate Chief Systems Engineer
Systems Consultant
Engineering Manager
Requirements Manager
Operations Manager
project control professional
Engineering director
Procurement Director
Project Conrols
Operation Manager / Project Control
Operation Manager / Project Control
Project Controls Specialist
Cost Controls
Project Controls
APR Contracts & Procurement Manager
Commercial Manager
Head of Department
Commercial manager

freelance professor
Project Controls
Head of Operations
Project Controls
Engineering Manager
Chief Systems Engineer (Retired)
Architect
RA
Student
Principal Information Systems Consultant
Head of Software Centre of Excellence
Document Control
Research Fellow
Requirements Manager
Pre-sales Technical Management
Consultant
Manager, Systems Engineering
Principal manager/engineer
Consultant Engineer
Head of Engineering Integration
Project Controls / Commercial Manager
Risk Analyst
Project Architect
General Manager

Question 5

Scale of Projects that you are or have been involved with (please indicate which project scales you have been involved with, you may indicate more than one scale):



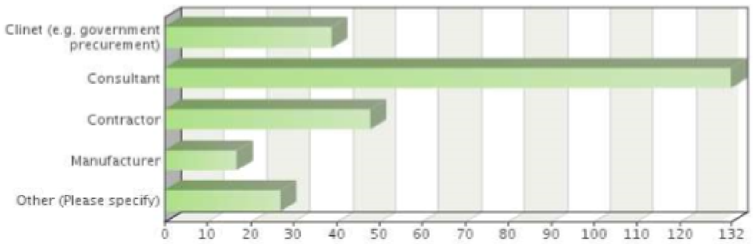
Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Major Programme >$100m	161	30.84%	38.42%	61.45%
Major Project >$20m	135	25.86%	32.22%	51.53%
Medium Project >$1m	143	27.39%	34.13%	54.58%
Small Project >$10k	83	15.9%	19.81%	31.68%
Sum:	522	100%	-	-
Not answered:	157	-	37.47%	-

Total answered: 262

Question 6

Type of Services



Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Clinet (e.g. government precurement)	39	9.31%	14.83%
Consultant	132	31.5%	50.19%
Contractor	48	11.46%	18.25%
Manufacturer	17	4.06%	6.46%
Other (Please specify)	27	6.44%	10.27%
Sum:	263	62.77%	100%
Not answered:	156	37.23%	-

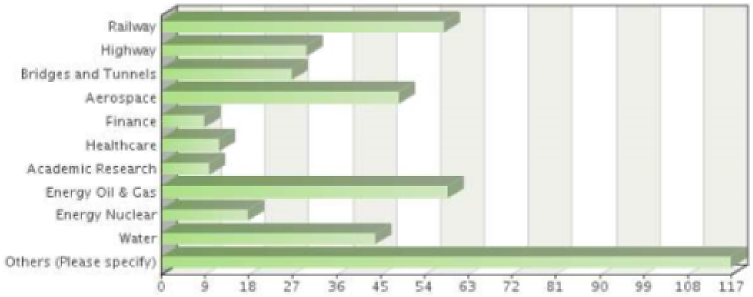
Total answered: 263

Last choice text input
software development
Education
Defence Assurance
All above apply
SAaS software provider
PROJECT DELIVERY
Client's Representative Project manager
EP, EPCM & EPC
General Contractor on Design/Build Projects
EPC and EPCM
Programme Management
Program Management, project management, consultant, contractor, client representative, staff augmentation
Alliance Framework with municpal authorities
Consortium Partner
SYSTEMS DESIGN
Academic Research
Client and Consultant
Educational
Construction Management
Construction and Project Management
Prime Contractor
air navigation service
EPC or EPCm

Vendor
Technical Directorate London Overground
Resource company

Question 7

Sector (indicated one or more sectors):



Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Railway	58	13.39%	13.84%	22.14%
Highway	30	6.93%	7.16%	11.45%
Bridges and Tunnels	27	6.24%	6.44%	10.31%
Aerospace	49	11.32%	11.69%	18.7%
Finance	9	2.08%	2.15%	3.44%
Healthcare	12	2.77%	2.86%	4.58%
Academic Research	10	2.31%	2.39%	3.82%
Energy Oil & Gas	59	13.63%	14.08%	22.52%
Energy Nuclear	18	4.16%	4.3%	6.87%
Water	44	10.16%	10.5%	16.79%
Others (Please specify)	117	27.02%	27.92%	44.66%
Sum:	433	100%	-	-
Not answered:	157	-	37.47%	-

Total answered: 262

Last choice text input
Space Science
Space
Education
Defense
Government Information Systems
Air Traffic Management
defense
Defence Assurance
Trucks
Mining
Renewable Energy
MARINE TERMINALS
Ports
Government
Wastewater

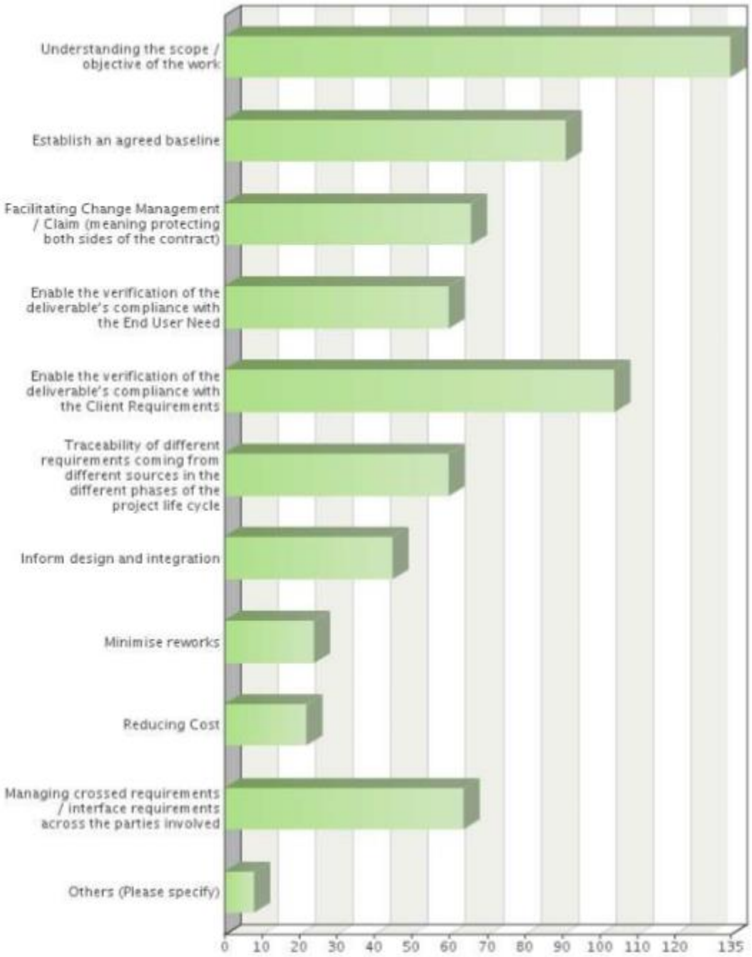
Advanced Facilities
Shipbuilding
Site development infrastructure (Industrial Cities)
Power - hydro
Environmental
Oil & Gas
Environmental
Transportion Business Group
environment
Semiconductor
Mineria, Infraestructura.
Pharmaceuticals, Food & Beverage
Environmental Remediation
Facility O&M
Environmental
Gov't infrastructure
Military
Electric Power
Electric Power
Microelectronics
Environmental; Chem&Pharma
Environmental; Chem&Pharma
Ports, Mining, Bulk Handling
Environmental
contaminated sites
Enviroment
Environmental
Airports
Facilities
Environmental Compliance
Wastewater and Oil and Gas
Environemtnal
Environmental
Emergency response
Emergency Response
Chemical
Info Tech
Aviation
Infrastructure
High Tech and Military
Airports
Ports, Commercial
Ports, Commercial
Environmental/Geotechnical
Environmental/Geotechnical
Environmental Remediation
Transmission
intelligent transportation
Communication/Telecommunications

Telephony
Industrial
Defence
Defence
Environment / waste management
microelectronics, pharmaceuticals, chemicals, aviation, food
Ports & Maritime
Canal
I.T. Services
Defence
Automation
Public Sector
Automotive
Defence
Construction Equipment
Defence
Defence
Industry and Technology
Defence and Government
Defence
Defence
defence
Weather systems
Defence
air traffic management
Defence
Defence
International/Social Development
Security
Ports, Maritine
Maritime
Government
Communications
Defence
Facility Energy studies
Government Facilities
Environment & Nuclear Market
Automotive
Defence
Research & Development
Defence
Environment
Defence
Tunnels
Advanced Electronics and Military Facilities
Public Sector, Telecommunications
IT
Transportation
Industrial and advanced Technologies

Mining logistics
DEfence (All Domains)

Question 8

What do you think is/are the main purpose(s) of Requirements Management? (You may choose up to 4 items)



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Frequency table

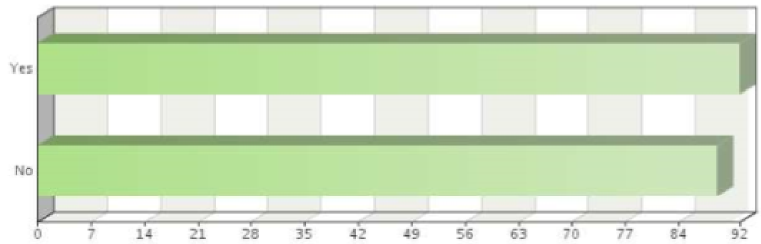
Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Understanding the scope / objective of the work	135	19.88%	32.22%	74.59%
Establish an agreed baseline	91	13.4%	21.72%	50.28%
Facilitating Change Management / Claim (meaning protecting both sides of the contract)	66	9.72%	15.75%	36.46%
Enable the verification of the deliverable's compliance with the End User Need	60	8.84%	14.32%	33.15%
Enable the verification of the deliverable's compliance with the Client Requirements	104	15.32%	24.82%	57.46%
Traceability of different requirements coming from different sources in the different phases of the project life cycle	60	8.84%	14.32%	33.15%
Inform design and integration	45	6.63%	10.74%	24.86%
Minimise reworks	24	3.53%	5.73%	13.26%
Reducing Cost	22	3.24%	5.25%	12.15%
Managing crossed requirements / interface requirements across the parties involved	64	9.43%	15.27%	35.36%
Others (Please specify)	8	1.18%	1.91%	4.42%
Sum:	679	100%	-	-
Not answered:	238	-	56.8%	-

Total answered: 181

Last choice text input
All of the above are important, I am not willing to prioritize without specifying the details of the project
Manage the Contract / identify risk
Resources can be a binding constraint
Ensure the product is completed as specified
Procurement
All of the above. Mgt of requirements ensures change control and traceability and quality of rqts data. Rqts engineering and setting are subtle y different and demand different skills and experience. The question asked tends to miss this.
Define structure of Requiremenst Specifications, Implement an RM Tool, Produce RM Metrics (e.g. Reqs Volatility), Maintain Reqs Baselines
derisk project delivery through identifying progressive acceptance

Question 9

Have you ever used a commercial tool for Requirements Management / Engineering?



Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Yes	92	21.96%	50.83%
No	89	21.24%	49.17%
Sum:	181	43.2%	100%
Not answered:	238	56.8%	-

Total answered: 181

Question 10

If you used commercial tool(s), please name them? >

In-text element ToolUsed

Text input
MS project, CVS/SCCS, UML
RTM
IBM Rational DOORS
DOORS
Doors
DOORS and CORE
DOORS
Doors
DOORS, Caliber RM, Req Pro
DOORS
IBM Rational DOORS
ComplyPro
A-site system
Pipeline tool box, Microsoft Project, Oracle
Primavera P6 Project Management
Cemar
n/a
Tools that were developed by CH2M - PAR, Forecasting, etc.
SmartPlan Matrials
ComplyPro
Primavera, Meridian
SAP de mantenimiento, PACOM, MS PROJECT, S10, AUTOCAD, PRIMAVERA
contracts manager
primavera, prism, PCM
P6, Microsoft Office
MS Project
Primavera P6 and Contract Manager
Snapshot/Insight
P6
DOORS, CORE, ComplyPro
DOORS, CORE, ComplyPro
DOORs, CORE, ComplyPro
Contract Change Management
DOORS, RequisitePro
Pricer, Project Insight
IBM Rational DOORS
Doors
DOORs
PCM, Primavera
Doors, HP ALM
DOORS
DOORS

DOORS
DOORS
Requisite Pro
IBM Rational DOORS
IBM Rational DOORS, MooD
DOORS, Enterprise Architect
DOORS
DOORS
MS Excel, DOORS, Sparx EA, MooD, System Architect
DOORS
DOORS
DOORS, RDD-100, RTM
IBM Rational DOORS
DOORS
Doors
doors
DOORS
DOORS
DOORs
Doors
DOORS, RTM, CRADLE
DOORS
DOORS
DOORS, Sparx Enterprise Architect
DOORS, Enterprise Architect
DOORS, Excel
DOORS
DOORS
DOORS
Doors
Not Applicable
DOORS
DOORS, ENOVIA
Cradle
DOORS, Enterprise Architect
DOORS
Enterprise Architect (as part of my systems training), Excel at my workplace
doors, mood
DOORS
DOORS
DOORS
ComplyPro
Prism
DOORS COMPLY PRO/SERVE
DOORS
DOORS, RDD-100, RTM, GMARC
DOORS, RTM, CRADLE

Question 11

How did you manage the requirements in the absence of a commercial tool? (Brief description of tools developed / used) >

In-text element ReqManTool

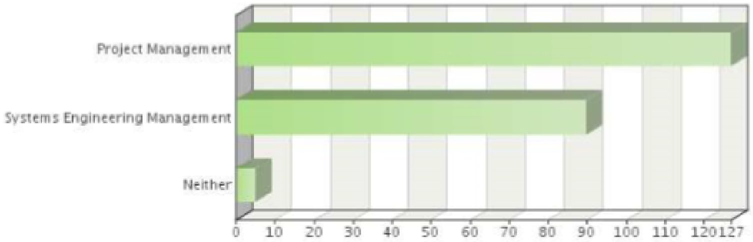
Text input
Excel
Linux tools
with excel and manually
(around 1996) used Excel, email, black board
BA inteviewing users and sponsors and then recording outputs in MS toosl, Word, Excell and Visio for flow diagrams
Excel
Use of spreadsheets under tight document and configuration management control
Have use Microft Office Products (Word, Excel, and Access)
Excle, Word
By means of Excel spreadsheet
old school used paper. Couldn't keep up with change.
Yes. Microsoft Access based proprietary tool
Excel and SharePoint
SYSTEMATIC GATE REVIEWS
capturing the evidence via meeting minutes on document control system
in-house system
Excel and words
Innovation and use other tools for project management
Metodología de Planificación , rastreo e Información de Requisitos; Proceso de priorización de Requisitos; Actividad de gestión de la configuration; Estructura de trazabilidad; Métricas de Producto
Company QA systems
n/a
Excel workbook/Spreadsheet
DATA BASES, EXCEL
Decomposition
Excel Spardsheets
Excel spreadsheets
Formal requirements document
xcel
Remplazando con un ECXEL en macro, Realizar una modificacion de acuerdo al plan solicitado
using excel spreadsheets with macros and also develop programmes in access
created spreadsheets to track deliverables, actual costs and budgets
face to face meetings followed by written documentation
personal spreadsheets and templates for the coompany
Excel Spreadsheet Template - OBS to WBS Matrix
Excel spreadsheets
Listing the requirements along the project into a spreadsheet
Build spreadsheets for scope items. calendars for milestones and deliverable dates
With the technical specification, a compliance matrix, Final Design Reviews, First Article Inspections, Qualification Testing, and then Engineering Change Notices for later improvements and fixes
Deliverables Tracking Table, Other Tracking Spreadsheets in Excel, Compliance Tracker Database (OMI)
stakeholder meetings to understand end user requirements
Scope documents in Word, Excel files of fee and schedule, MS Project for schedule tracking as well

Relied on previously designed and vetted internal standards and templates such Project Execution Plan, Work Plan, etc.
I used no formal process.
Excel
Excel, project developed databases, document control
Used Request for Information (RFIs) to clarify changes and new requirements
Word processing.
crude excel tracking tool which was very inflexible and did not allow audit.
Created a Project Initiation Memorandum (PIM)
Compliance / Deliverable matrix.
Excel Spreadsheets
Office applications
Tables of cross indexes on paper on in spreadsheet table.
spreadsheet tracking (excel)
Produced a master matrix using xl
Identified project specific requirements and tracked their incorporation by Submittal Schedules and similar straightforward tracking
In house documentation and tracking spreadsheets
Documenting all communication, using standard forms for scoping and requirements of the project, relying on regulatory standards
A written document followed by a meeting to verify the requirements, and then the document issued finalizing the info.
chartering, working closely with client, ensuring end user is engaged from the begining
On small projects, I have used spreadsheets
Company practice
spreadsheets, oracle information, etc
Excel and bespoke docs
Excel
Different tools mainly Excel Sheets
Discussions internally with staff and externally with client, documenting and then building into scope
Word document
Sharepoint, Microsoft office
Word, Excel
Excel spreadsheets
Always used DOORS
Microsoft Excel
Excel, Word
Detailed product design specifications
We used text, spreadsheet and database. The text woudl hold the description, the spreadsheet and/or database woudl be used to track them, modification requested, their level or priority etc. with teh adoption of database for larger/longer projects
Spreadsheets
REFER TO MY TEN PUBLISHED PAPERS ON GENERIC SE MODEL
MS Word documents, Excel matrices
word document and data flow diagram
Excel based RVTM
Excel used heavily due to technology restrictions, pivot tables for reporting. Proposed databases and scheduling soft ware never completed
Spreadsheet, Word Table
MS Office based tools such as Excel, Vision or Word
Mainly via manual documentation
Use Cases documented in MS Word
Excel
Spreadsheet

Spreadsheets
Excel Spreadsheet
Excel / word
spreadsheets
use of excel to record, allocate and sort
Excel Spreadsheet. Used Albans Tower to manage relationships
Excel
For very small projects, MS Excel based RM is used
Project plans
Excel Spreadsheets
By using Microsoft WORD or Excel
workshops, design scopes
We don't
Spreadsheets
Structured interviews and systems techniques
Excel
Used Excel with VBA and macros
Developed formats for mobilising personnel, spread sheets for deployment of personnel, templates for employment offers etc.
MS Office i.e. Word, Excel
Excel Spreadsheet and compliance matrix
Usually build a matrix in Excel
Excel
Manual observation and monitoring. Critical requirements addressed in Project Instruction documents
We didn't! Attempted in Excel and Word, but it was never going to work
Development of a user requirement brief
Excel
Ecel and word and used a document management system to control versions
With the statement of work (as sad as it sounds)
Spreadsheets
As well as DOORS, requirements are managed using Word and Excel - especially at a high (user requirement) level and at early concept stages
Schedule &/or spreadsheet
Spreadsheet
excel and access databased developed.
Lean Process
Excel Spreadsheets. Requiirements Documents withrequirements listed and appended.
Excel spreadsheer
20 years ago we used spreadsheets.
Stage gating process identification process phase/definition phase etc each with discrete toll gates

Question 12

Do you think Requirements Management is a natural part of Project Management and/or Systems Engineering?



Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Project Management	127	57.21%	30.31%	74.27%
Systems Engineering Management	90	40.54%	21.48%	52.63%
Neither	5	2.25%	1.19%	2.92%
Sum:	222	100%	-	-
Not answered:	248	-	59.19%	-

Total answered: 171

Question 13

Has there been a quantitative assessment of the value of Requirements Management in your organisation?

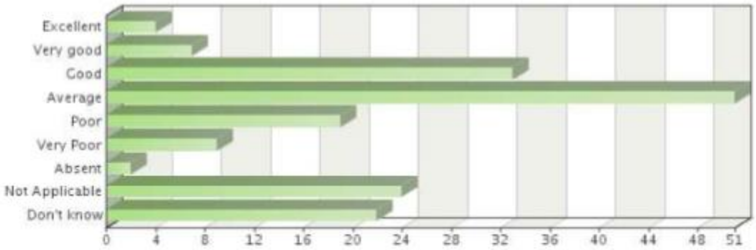
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Yes	19	4.53%	11.11%
No	78	18.62%	45.61%
Don't know	74	17.66%	43.27%
Sum:	171	40.81%	100%
Not answered:	248	59.19%	-

Total answered: 171

Question 18

How do you rate the quality of the Requirements Management at your Supplier organisations?



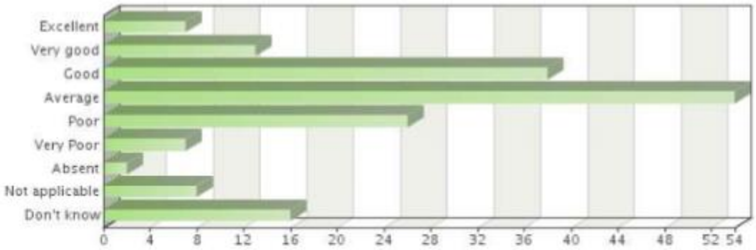
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	4	0.95%	2.34%
Very good	7	1.67%	4.09%
Good	33	7.88%	19.3%
Average	51	12.17%	29.82%
Poor	19	4.53%	11.11%
Very Poor	9	2.15%	5.26%
Absent	2	0.48%	1.17%
Not Applicable	24	5.73%	14.04%
Don't know	22	5.25%	12.87%
Sum:	171	40.81%	100%
Not answered:	248	59.19%	-

Total answered: 171

Question 17

How do you rate the quality of the Requirements Management at your Client organisations?



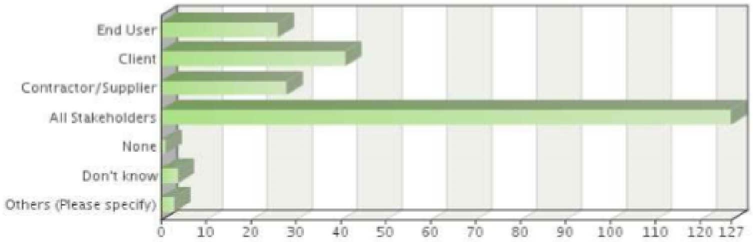
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	7	1.67%	4.09%
Very good	13	3.1%	7.6%
Good	38	9.07%	22.22%
Average	54	12.89%	31.58%
Poor	26	6.21%	15.2%
Very Poor	7	1.67%	4.09%
Absent	2	0.48%	1.17%
Not applicable	8	1.91%	4.68%
Don't know	16	3.82%	9.36%
Sum:	171	40.81%	100%
Not answered:	248	59.19%	-

Total answered: 171

Question 16

Who do you think would benefit the most from Requirements Management?



Frequency table

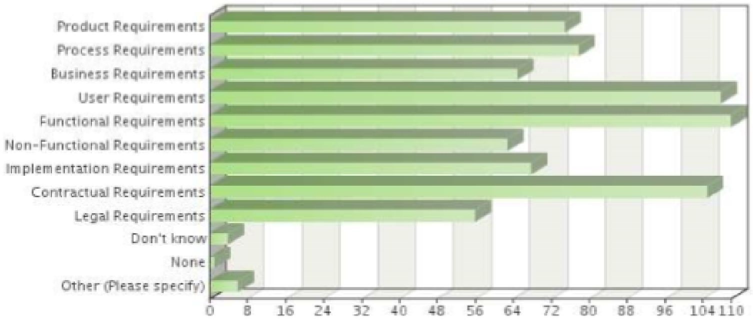
Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
End User	26	11.3%	6.21%	15.2%
Client	41	17.83%	9.79%	23.98%
Contractor/Supplier	28	12.17%	6.68%	16.37%
All Stakeholders	127	55.22%	30.31%	74.27%
None	1	0.43%	0.24%	0.58%
Don't know	4	1.74%	0.95%	2.34%
Others (Please specify)	3	1.3%	0.72%	1.75%
Sum:	230	100%	-	-
Not answered:	248	-	59.19%	-

Total answered: 171

Last choice text input
Project team
management team
Project Management

Question 15

What type of requirements you mainly work with in your business?



Frequency table

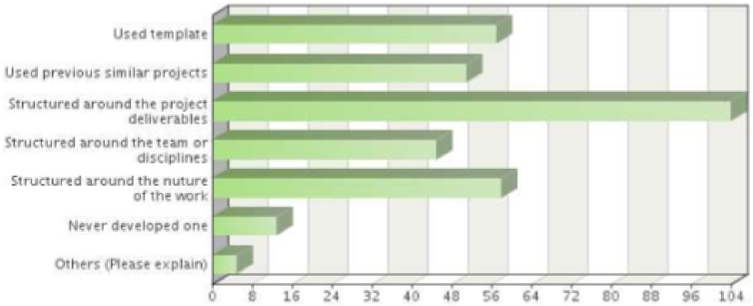
Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Product Requirements	75	10.15%	17.9%	43.86%
Process Requirements	78	10.55%	18.62%	45.61%
Business Requirements	65	8.8%	15.51%	38.01%
User Requirements	108	14.61%	25.78%	63.16%
Functional Requirements	110	14.88%	26.25%	64.33%
Non-Functional Requirements	63	8.53%	15.04%	36.84%
Implementation Requirements	68	9.2%	16.23%	39.77%
Contractual Requirements	105	14.21%	25.06%	61.4%
Legal Requirements	56	7.58%	13.37%	32.75%
Don't know	4	0.54%	0.95%	2.34%
None	1	0.14%	0.24%	0.58%
Other (Please specify)	6	0.81%	1.43%	3.51%
Sum:	739	100%	-	-
Not answered:	248	-	59.19%	-

Total answered: 171

Last choice text input
Use cases
Specification requirements
Field schedule and travel requirements for large crews
Service Delivery requirements
Security

Question 19

How have you developed WBSs?



Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Used template	57	17.12%	13.6%	36.31%
Used previous similar projects	51	15.32%	12.17%	32.48%
Structured around the project deliverables	104	31.23%	24.82%	66.24%
Structured around the team or disciplines	45	13.51%	10.74%	28.66%
Structured around the nuture of the work	58	17.42%	13.84%	36.94%
Never developed one	13	3.9%	3.1%	8.28%
Others (Please explain)	5	1.5%	1.19%	3.18%
Sum:	333	100%	-	-
Not answered:	262	-	62.53%	-

Total answered: 157

Last choice text input
Deliverables and processes
Structured around internal staff resource availability
Structured around a systems approach. A tailoring of ISO 15288:2008
Structured around system architecture and contractual deliverables
Using s standard model across the business

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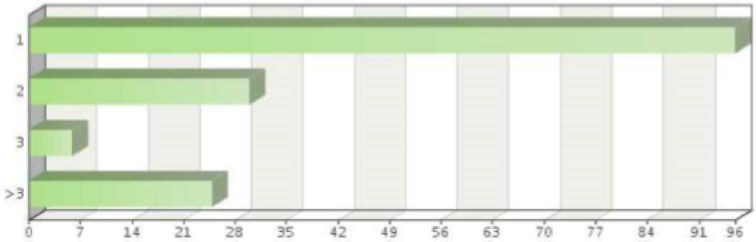
Question 20

Typically how many concurrent versions of a WBSs are used within a typical project (they could be named differently in your project environment)?



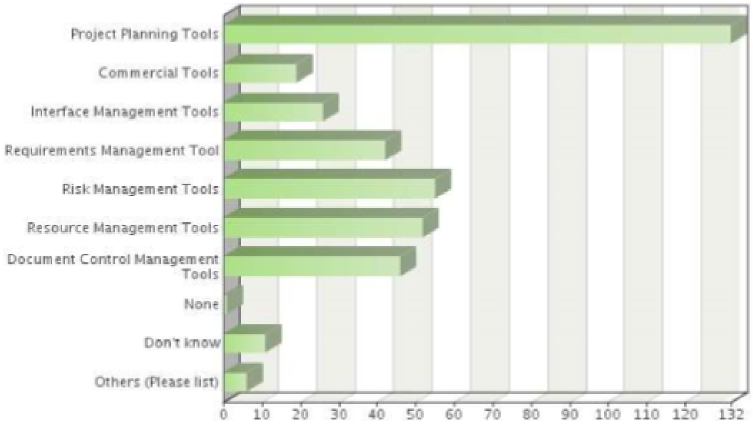
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
1	96	22.91%	61.15%
2	30	7.16%	19.11%
3	6	1.43%	3.82%
>3	25	5.97%	15.92%
Sum:	157	37.47%	100%
Not answered:	262	62.53%	-

Total answered: 157

Question 21

Once developed which tools incorporated the WBSs?



Frequency table

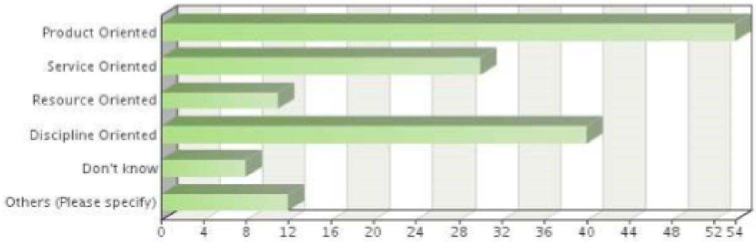
Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Project Planning Tools	132	33.85%	31.5%	84.08%
Commercial Tools	19	4.87%	4.53%	12.1%
Interface Management Tools	26	6.67%	6.21%	16.56%
Requirements Management Tool	42	10.77%	10.02%	26.75%
Risk Management Tools	55	14.1%	13.13%	35.03%
Resource Management Tools	52	13.33%	12.41%	33.12%
Document Control Management Tools	46	11.79%	10.98%	29.3%
None	1	0.26%	0.24%	0.64%
Don't know	11	2.82%	2.63%	7.01%
Others (Please list)	6	1.54%	1.43%	3.82%
Sum:	390	100%	-	-
Not answered:	262	-	62.53%	-

Total answered: 157

Last choice text input
Scheduling
P6, SAP, Unifier
schedule
SAP
Can't answer as I never developed one. Think you need to tweak the logic in your survey form!
Excel

Question 22

How your WBS typically structured?



Frequency table

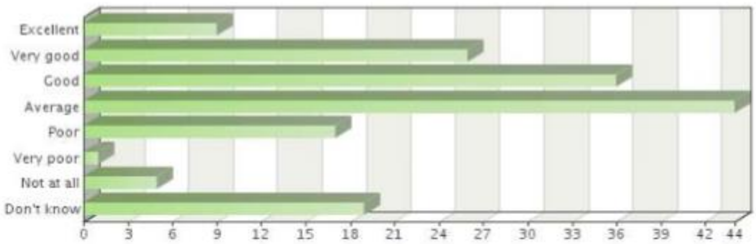
Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Product Oriented	54	12.89%	34.84%
Service Oriented	30	7.16%	19.35%
Resource Oriented	11	2.63%	7.1%
Discipline Oriented	40	9.55%	25.81%
Don't know	8	1.91%	5.16%
Others (Please specify)	12	2.86%	7.74%
Sum:	155	36.99%	100%
Not answered:	264	63.01%	-

Total answered: 155

Last choice text input
Typically Product Oriented but I have developed Service Oriented and Disciplined Oriented structures. Depends on the objective
Deliverable Oriented
Product and service
By Task or Phase of Work
Task oriented
Somewhat based on specification needs and project management reporting needs
project deliverables
Depends
Steps in our systems approach iaw ISO15288:2008
In line with the Contracted Deliverables
Function oriented
Can't answer as I never developed one. Think you need to tweak the logic in your survey form!

Question 23

How well connected is the WBS to systems engineering management in your opinion?



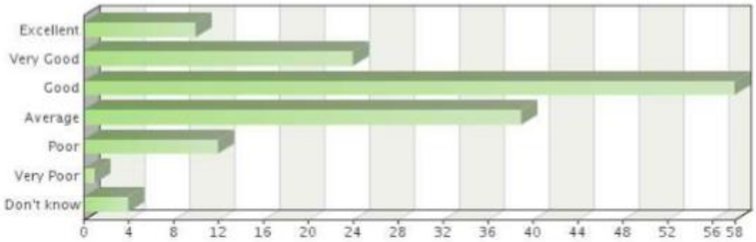
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	9	2.15%	5.73%
Very good	26	6.21%	16.56%
Good	36	8.59%	22.93%
Average	44	10.5%	28.03%
Poor	17	4.06%	10.83%
Very poor	1	0.24%	0.64%
Not at all	5	1.19%	3.18%
Don't know	19	4.53%	12.1%
Sum:	157	37.47%	100%
Not answered:	262	62.53%	-

Total answered: 157

Question 24

How well are the interfaces managed in your projects?



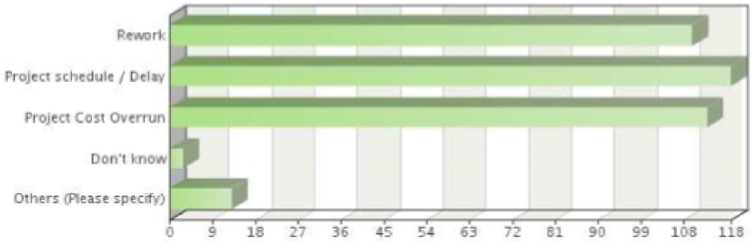
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	10	2.39%	6.76%
Very Good	24	5.73%	16.22%
Good	58	13.84%	39.19%
Average	39	9.31%	26.35%
Poor	12	2.86%	8.11%
Very Poor	1	0.24%	0.68%
Don't know	4	0.95%	2.7%
Sum:	148	35.32%	100%
Not answered:	271	64.68%	-

Total answered: 148

Question 25

What do you see as the major risks to the project as the result of a poor interface management?



Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Rework	110	30.81%	26.25%	74.32%
Project schedule / Delay	118	33.05%	28.16%	79.73%
Project Cost Overrun	113	31.65%	26.97%	76.35%
Don't know	3	0.84%	0.72%	2.03%
Others (Please specify)	13	3.64%	3.1%	8.78%
Sum:	357	100%	-	-
Not answered:	271	-	64.68%	-

Total answered: 148

Last choice text input
loss of product
Poor Performance
reputational if not discovered before work packages are issued
Scope change
Potential confusion and miscommunication between working groups
endless arguing and wasting of time
Security, Legal compliance
Systems Integration issues and inability to provide required functionality
Failure to meet requirements
interfaces not quite working properly with latent errors that surface months after commissioning
eqpt delivery delays
Failure
Performance shortfalls, Integration & Acceptance issues, Operational shortfalls

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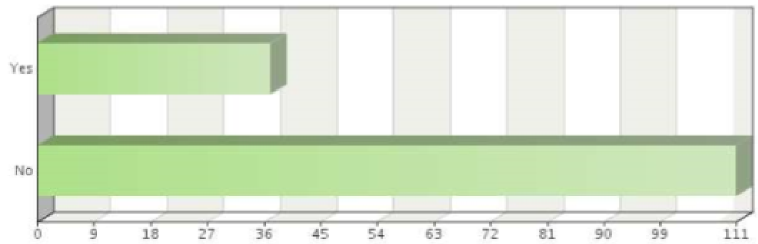
Question 26

Have you ever used a commercial tool for Interface Management?



Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Yes	37	8.83%	25%
No	111	26.49%	75%
Sum:	148	35.32%	100%
Not answered:	271	64.68%	-

Total answered: 148

Question 27

If you used commercial tool(s), please name them?

>

In-text element InterfaceTool

Text input
DOORS
Modeled with CORE; Rational Rose; Arena; and OPNET
ComplyPro
A-SITE
MS-Project; Microsoft Excel
3D drawing packages
Tools developed by CH2M
SmartPlan Materials
Primavera P6
primavera, PCM
MS Project
SharePoint
SharePoint
SharePoint site (not really commercial, but a tool?)
IBM Rational DOORS
DOORS
Enterprise Architect, Rhapsody, MooD, DOORS
ProjectDSM, and LOOMEO commercial tools: Both used mainly for showing dependencies among subsystems of a system.
DOORS, RDD-100
Artisan Studio
DOORS and Traceline
DOORS (requirements), Artisan (modelling, not personally used)
DOORS, Sparx Enterprise Architect, bespoke web based database
DOORS, Enterprise Architect
Project Management Tools - if interfaces between the integrated proejct team, Standrad design tools (e.g. UML and many others) for Product/Design interfaces
ADMIS
Visio and Excel
Not Applicable
Cradle
DOORS, Enterprise Architect
Scheduling Software
ComplyPro
NR Interface Matrices
RDD-100
IME

Question 28

How did you manage the interfaces in the absence of a commercial tool? (Brief description of tools developed / used)? >

In-text element ToolInterface

Text input
linux tools
(NASA, 1996) All interfaces were documented (after negotiation of parties: phone, email), deliverables, exceptions, times, and they were tested in a test environment to reduce risk.
Same as those used by BAs when gathering requirements.
Excel, context diagram, interface control document
Interface Control Documents
Use of spreadsheets under tight document and configuration management control
Microsoft Office Products (Word; Excel; and Access)
Documents
by hand, ad-hock
In-house developed database
ICD Documents
Issue log
PHYSICAL DETAILED REVIEWS
MEETING MINUTES IN DOCUMENT CONTROL SYSTEM
Project Planning Tools and client specified communications. Technical Quiries, RFI's and IDCs
2D Drawings and experience
Excel workbook/Spreadsheet, Primavera Scheduling tools
Decomposition
Matrices using Excel spreadsheets
xcl
excel spreadsheets
created spreadsheets to track deliverables, actual cost and budgets
Consistent Team and Management
face to face team meetings and
project deliverable analysis and required information for the deliverables
Excel
Coordination meetings between parties for defining interfaces, required information from the parties and the strategies to deal with them
Spreadsheets
First Article Inspections and Qualification Testing
Team conference calls to facilitate communication
team meetings
Scopes, regular project coordination meetings - no tools
templates
Informally
Excel, Project database
Developed client specific spreadsheets and databases to meet their end needs
Spreadsheets
Interface plan and diary records/meeting minutes/change orders
Engineering Plan Constraints and Dependencies
Customised systems and client pro formas
Office applications

spreadsheet and meetings

procedures, weekly meetings

good, and constant communication

Interface Control Documents (ICD)

management by walking around. Meetings. Communication

mettings

Spreadsheet

Documents

Using word documents to define teh interface protocols, mails and spreadsheet/database to exchange info register and keep track of events respectively

Word documents

MY OWN -- NOT COMMERCIAL

building models based on data/information flow

Relies on team experience/small team

Spreadsheets

Use standard MS Office tools

A novel tool has been developed i.e. Interface Analysis Template/Table to manage manually and identify the interface requirements (both functional and non-functional) among system and its external interfaces as well as same template to use among chosen su

template based approach controlled by an Excel schedule and governed by a Process

Enterprise architecture tool (Sparx EA) coupled with MS Office for documented and agreed with other parties.

Excel spreadsheets and system diagrams

Management Plan / RASCI Process

MSWord Documents

Using Capability Management toolset such as TEPIDOIL

..

spreadsheets

Excel spreadsheet.

Via good linkages

Excel and Albans Tower

general ICDs

In-House Tool

ad hoc

Excel spreadsheets

By simply using Microsoft Excel

Primavera. Most things i have been involved with to date have been internal interfaces

We don't - but goo dcommunications helps with and without a tool.

Visio and Excel

We have appointed a interface coordinator to do this work. Weekly meetings & follow-up takes place through MOMs.

Document peer review. Also undertaken role-play scenario where people play the role of each side of the interface to identify issues.

Typically each client has its own bespoke Interface Control Document (ICD) template and strategy

Schedule

Regular Expenses At Completion tracking spreadsheets

E-mail, Word, Excel

Brain power!

Excel

Excel and word using interface documents. When strictly adhered to is adequate.

Did not

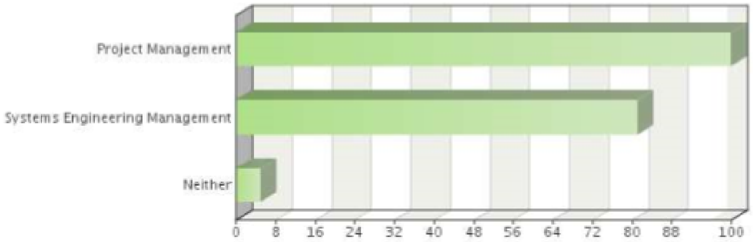
Ad Hoc methods, and the development of a specific management plan.

spreadsheet

Word document
excel
Project Spreadsheets
Excel spreadsheet
Excel spreadsheets and documents
Spreadsheets, drawing tools, documents
Interface management plans and regular interface meetings

Question 29

Do you think Interface Management is a natural part of Project Management and/or Systems Engineering?



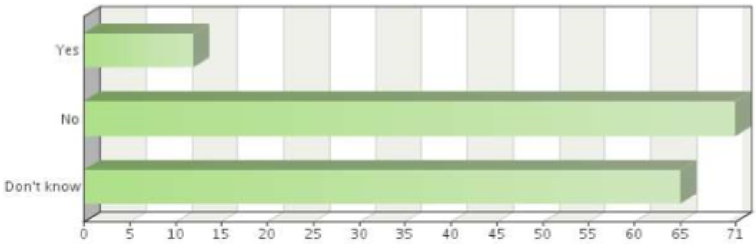
Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Project Management	100	53.76%	23.87%	67.57%
Systems Engineering Management	81	43.55%	19.33%	54.73%
Neither	5	2.69%	1.19%	3.38%
Sum:	186	100%	-	-
Not answered:	271	-	64.68%	-

Total answered: 148

Question 30

Has there been a quantitative assessment of the value of Interface Management in your organisation?



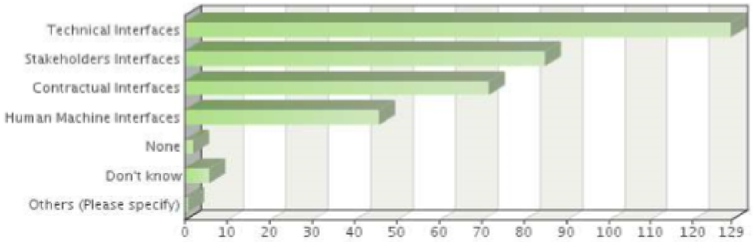
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Yes	12	2.86%	8.11%
No	71	16.95%	47.97%
Don't know	65	15.51%	43.92%
Sum:	148	35.32%	100%
Not answered:	271	64.68%	-

Total answered: 148

Question 32

What type of interfaces do you mainly capture in your business?



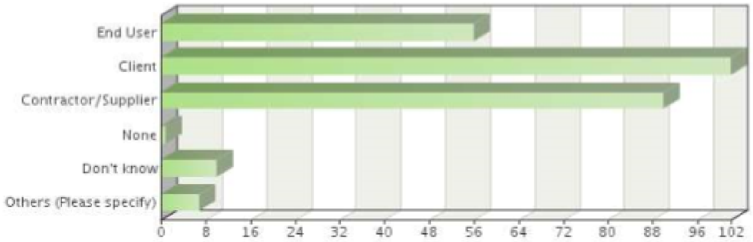
Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Technical Interfaces	129	37.83%	30.79%	87.16%
Stakeholders Interfaces	85	24.93%	20.29%	57.43%
Contractual Interfaces	72	21.11%	17.18%	48.65%
Human Machine Interfaces	46	13.49%	10.98%	31.08%
None	2	0.59%	0.48%	1.35%
Don't know	6	1.76%	1.43%	4.05%
Others (Please specify)	1	0.29%	0.24%	0.68%
Sum:	341	100%	-	-
Not answered:	271	-	64.68%	-

Total answered: 148

Question 33

Who do you think would benefit the most from Interface Management?



Frequency table

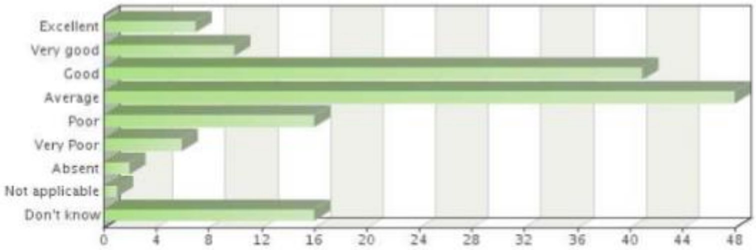
Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
End User	56	21.05%	13.37%	38.1%
Client	102	38.35%	24.34%	69.39%
Contractor/Supplier	90	33.83%	21.48%	61.22%
None	1	0.38%	0.24%	0.68%
Don't know	10	3.76%	2.39%	6.8%
Others (Please specify)	7	2.63%	1.67%	4.76%
Sum:	266	100%	-	-
Not answered:	272	-	64.92%	-

Total answered: 147

Last choice text input
Al stakeholders
stakeholders who rely on the systems for satisfactory performance
Designer
ALL
All Stakeholders
Project Manager
Assuror

Question 34

How do you rate the quality of the Interface Management at your Client organisations?



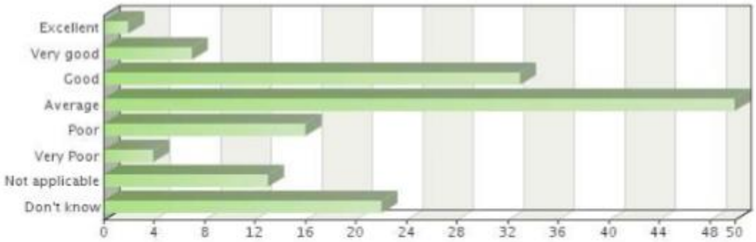
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	7	1.67%	4.76%
Very good	10	2.39%	6.8%
Good	41	9.79%	27.89%
Average	48	11.46%	32.65%
Poor	16	3.82%	10.88%
Very Poor	6	1.43%	4.08%
Absent	2	0.48%	1.36%
Not applicable	1	0.24%	0.68%
Don't know	16	3.82%	10.88%
Sum:	147	35.08%	100%
Not answered:	272	64.92%	-

Total answered: 147

Question 35

How do you rate the quality of the Interface Management at your Supplier organisations?



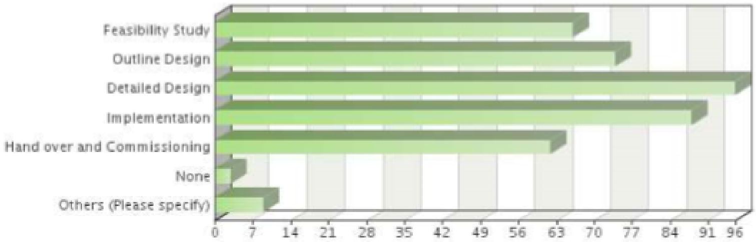
Frequency table

Choices	Absolute frequency	Relative frequency	Adjusted relative frequency
Excellent	2	0.48%	1.36%
Very good	7	1.67%	4.76%
Good	33	7.88%	22.45%
Average	50	11.93%	34.01%
Poor	16	3.82%	10.88%
Very Poor	4	0.95%	2.72%
Not applicable	13	3.1%	8.84%
Don't know	22	5.25%	14.97%
Sum:	147	35.08%	100%
Not answered:	272	64.92%	-

Total answered: 147

Question 36

At what stage of the project is integration management important?



Frequency table

Choices	Absolute frequency	Relative frequency by choice	Relative frequency	Adjusted relative frequency
Feasibility Study	66	16.58%	15.75%	44.9%
Outline Design	74	18.59%	17.66%	50.34%
Detailed Design	96	24.12%	22.91%	65.31%
Implementation	88	22.11%	21%	59.86%
Hand over and Commissioning	62	15.58%	14.8%	42.18%
None	3	0.75%	0.72%	2.04%
Others (Please specify)	9	2.26%	2.15%	6.12%
Sum:	398	100%	-	-
Not answered:	272	-	64.92%	-

Total answered: 147

Last choice text input
all
Planning and Scheduling
ALL
its important at all stages with the focus changing between different types of interface
Pre feasibility
Systems Installation and testing
Testing, verification

Appendix 4 Data Analysis Register

The results of the data analysis of the case study detailed in Chapter 6 were combined into a single register in order to conduct detailed analysis and discussions. This appendix provides a random selection of parts of the overall data analysis register to demonstrate the method of the data gathering and analysis.

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
1	Premises – Name [redacted]	[redacted]	On drawing 08105, number 13 has now been assigned to lift 3 street level.	Please update	CM	Premises	Premises	Late change information from client	4. O
1	Premises - Name [redacted]	[redacted]	On drawing 08100, number 14 has now been assigned to lift 1 street level.	Please update	CM	Premises	Premises	Late change information from client	4. O
1	Premises - Name [redacted]	[redacted]	Sign 326 has had to be split. It is not clear however the space now available for these two individual signs- no being fixed on bulkhead. Please clarify the max. space available so signage can be adapted to suit.	Please clarify	CM	Premises	Premises	Late change information from client	2. Y
2	M&E - Name [redacted]	[redacted]	No CSD's Provided in support of the co-ordination activities this area has been an area of weakness historically. Co-ordination cannot be verified without these deliverables WI chapter 1a section 7.8	Provide co-ordinated CDS's	V&V	Premises	Mechanical	Poor compliance evidence presentation	1. R
2	M&E - Name [redacted]	[redacted]	Messroom / WC co-ordination has not been achieved and the end product is unsatisfactory End user liaison has also not been carried out. WI chapter 1a section 7.4 and 7.8	Co-ordinate and provide an acceptable product	IM	Premises	Mechanical	None compliance with interface requirements / standard / specification	1. R
2	M&E - Name [redacted]	[redacted]	Switchboards are still awaiting manufacturers details. This means co-ordination is incomplete and the risk of rework increased WI chapter 1a section 7.8	Confirm and co-ordinate	IM	Premises	Electrical	Assumption - awaiting for information from other parties	1. R
2	M&E - Name [redacted]	[redacted]	Access to smoke detection. It is evident that access to some detectors will be impossible and this demonstrates that the level of co-ordination is not at a level to install confidence WI chapter 1a section 7.8	Review detection access and co-ordinate solution with Arch	IM	Premises	Electrical	None compliance with interface requirements / standard / specification	1. R
2	M&E - Name [redacted]	[redacted]	The fire drawings do not indicate where cabling is in containment and when in conduit this could well mask an extensive amount of containment that needs to be installed (and co-ordinated) that currently isn't shown and also increases the risk of "make it up as you go along" site works which increases programme risk. WI chapter 1a section 7.8	Detail where fire alarm cabling is routed in trunking and when tubed.	RM	Premises	Electrical	Missing requirement	1. R
2	M&E - Name [redacted]	[redacted]	The fire suppression drawings for Esc are on hold awaiting esc information this is clearly incomplete works.	Either complete the work or cloud the drawings and resubmit the clouded sections at a later date.	IM	Premises	Fire	None compliance with interface requirements / standard / specification	1. R
2	Premises - Name [redacted]	[redacted]	It is to be noted that [redacted] was issued CLOSED, and refers Prestige ticketing elements only. However, these drawings do raise other issues (some previously discussed) hence, will have to be addressed prior to final [redacted] acceptance of these areas.	Ticket hall package to be updated and issued for acceptance.	CoM	Premises	Premises	Poor configuration management	2. Y
2	Fire - Name	[redacted]	On the right-side of the door there shows four	Confirm the other services on the relevant	QM	Premises	Electrical	Poor Quality Check	4. O

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
	[redacted]		penetrations and the tray work is only identifiable on drawing [redacted]	drawings.					
2	M&E - Name [redacted]	[redacted]	When making reference to [redacted] the penetration for the service on grid ref [redacted] will clash with the ceiling. When including the floor finish to maintain the height to the ceiling and the ceiling layer(s) there is a clash with the service .	Review the coordination of this service such there is no compromise of the premises standards.	IM	Premises	Electrical	None compliance with interface requirements / standard / specification	2. Y
2	M&E - Name [redacted]	[redacted]	Sample review on drawings package has shown inconsistencies.	Review the drawing set for coordination with services, ceiling heights and fitting locations in avoidance of install issues.	IM	Premises	Electrical	None compliance with interface requirements / standard / specification	2. Y
2	M&E - Name [redacted]	[redacted]	Confirm that in other design packages that the maintenance of the [redacted] have been considered.	Confirm that the risk of maintenance has been considered as required by CDM regulations, and that the best overall solution is in place.	TQ	Premises	Mechanical	Technical Query / Clarification	4. O
2	M&E - Name [redacted]	[redacted]	Confirm the fans serving the [redacted] are rated no less than 300degC as stipulated in [redacted].	Please confirm.	TQ	Premises	Mechanical	Technical Query / Clarification	2. Y
2	Name [redacted]	[redacted]	Please indicate position of fire alarm interface box for completeness in the [redacted] room	Add this information on the next revision of this drawing or explain which other drawing this information is shown on.	IM	Premises	Fire	Missing interface requirements	4. O
2	Name [redacted]	[redacted]	[redacted] room should be a sloping floor or each [redacted] should be mounted on a plinth. This is probably shown on an architectural drawing.	Add this information on the next revision of this drawing or explain which other drawing this information is shown on.	IM	Premises	Electrical	Missing interface requirements	4. O
2	M&E - Name [redacted]	[redacted]	The drawings specifies a minimum length for the 25mm flexible conduit as 500mm for the double and single socket outlets.	Designer to explain the rational behind using 500mm as the minimum length of the flexible conduit.	TQ	Premises	Electrical	Technical Query / Clarification	3. G
2	M&E - Name [redacted]	[redacted]	The detail does not specify the type of unistrut either heavy or light gauge.	Provide type detail of the supports on the drawing or explain which other drawing this information is shown on.	QM	Premises	Electrical	Poor Quality Check	4. O
2	Communication - Name [redacted]	[redacted]	A number of the back of house rooms are shown with only one speaker is this compliant to [redacted]?	Please confirm with only one speaker in the back of house and plant rooms that the design / install is compliant to [redacted] standards	V&V	Premises	Communication	Poor compliance evidence presentation	2. Y
2	Communication - Name [redacted]	[redacted]	Please confirm where speakers are fitted in false ceilings a secondary means of supporting the speakers has been provided in order to comply with BS5839 Part 8.	please confirm	V&V	Premises	Communication	Poor compliance evidence presentation	2. Y
2	Communication - Name [redacted]	[redacted]	Should there be a speaker in the lobby for Lift 4 in order to comply with the minimum STI levels with standard [redacted].	please confirm	V&V	Premises	Communication	Poor compliance evidence presentation	4. O

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
2	Communication - Name [redacted]	[redacted]	Should speakers be shown in toilet and shower areas?	Please confirm that the design / install is compliant to [redacted] standards	V&V	Premises	Communication	Poor compliance evidence presentation	4. O
2	Fire - Name [redacted]	[redacted]	Confirm that the lift 4 Lobby smoke curtain interface remains.	Clarify	V&V	Premises	Fire	Poor compliance evidence presentation	4. O
2	Premises - Name [redacted]	[redacted]	Bearing in mind the location and size of the existing escalator 3, 4 & 5 trays are being retained,the lengths as shown appear to have been reduced. - See RFI 1358.	Confirm if the existing tray are to be changed and if this change has been coordinated with the maintainer [redacted]. If there is no change, please indicate the correct existing size and location, intrgrated and designed into the proposed ticket hall. Update drawing accordingly.	CM	Premises	Premises	Poor change management and communication	1. R
2	Premises - Name [redacted]	[redacted]	Previous comments raised on handrail size (see [redacted]) in this and a number of packages have not been addressed. Please address and update [redacted], and all other affected drawings showing the 40mm dia. Instead of the 50mm dia..	Please update	CoM	Premises	Premises	Poor configuration management	1. R
2	Premises - Name [redacted]	[redacted]	The [redacted] has been changed to the "Ticket Clerk's Office" and accepted.	Please amend room label as this would impact on the [redacted] labelling. Update drawing.	CM	Premises	Premises	Poor change management and communication	2. Y
2	Premises - Name [redacted]	[redacted]	Please ensure all ceiling fixtures are coordinated with M & E.		V&V	Premises	Mechanical	Poor compliance evidence presentation	2. Y
2	Premises - Name [redacted]	[redacted]	All exposed concrete surfaces in public areas up to 3m high would require anti graffiti coating as per [redacted] standards.	Please ensure this is addressed.	V&V	Premises	Premises	Poor compliance evidence presentation	2. Y
2	Premises - Name [redacted]	[redacted]	On det. 03 for the glass screen, it's not clear if its been designed to meet the relevant required standards in relation to crowd loading and appropriate design loading and impact performance.	Please clarify.	V&V	Premises	Premises	Poor compliance evidence presentation	2. Y
2	Premises - Name [redacted]	[redacted]	It's not clear the threshold detail at all the lift interface.	Please clarify the threshold detail at all the lift interface.	V&V	Premises	Premises	Poor compliance evidence presentation	2. Y
2	Premises - Name [redacted]	[redacted]	Threshold detail at vitrine door doesn't appear to be covered.	Please clarify	V&V	Premises	Premises	Poor compliance evidence presentation	2. Y
2	Premises - Name [redacted]	[redacted]	It appears RFI 1465 had some loading requirements, which had to be taken into consideration, when designing elements incorporated into the escalator enclosure.	Please confirmed if the balustrade proposal has taken into consideration these requirements	CM	Premises	Premises	Poor managing the changes through RFI	2. Y
2	Premises - Name [redacted]	[redacted]	Please confirm that requirements for replacement/removal of balustrade, gaps/joints in balustrade, prevention of sharp corners/edges and	Please provide design in the detailed drawings.	V&V	Premises	Premises	Poor compliance evidence presentation	2. Y

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
			exposed glass edge, will be taken into consideration in the detailed design.						
3	M&E - Name [redacted]	[redacted]	Render to soffit is a poor solution and prone to fail in this situation, it is also problematic and messy on site. Update (08/01/13): Issue closed on the understanding that the contractor has attended to the comment made by [redacted].	review soffit treatment	TS	Premises	Mechanical	Technical Solution Issue / Recommendation	3. G
3	M&E - Name [redacted]	[redacted]	This location may change subject to architecture comments made on [redacted].	Review decision on [redacted].	CM	Premises	Electrical	Late change information from client	4. O
3	M&E - Name [redacted]	[redacted]	The angle bracket is shown to have 2 channels back-to-back to make the necessary length for the hex bolts. It maybe easier if the bracket was placed further towards the socket such a single channel can be used. [redacted] No change.	Review fixing details to make the install easier.	TS	Premises	Electrical	Technical Solution Issue / Recommendation	4. O
3	M&E - Name [redacted]	[redacted]	You can reduce the accessory items if there is a bend in the galvanised conduit such that the flexible conduit can be fixed directly which can reduce the adaptor components.	Review fixing details to make the install easier.	TS	Premises	Electrical	Technical Solution Issue / Recommendation	3. G
3	Premises - Name [redacted]	[redacted]	Speaker locations and accessibilty to cables may not be suitable for delivery into service.	[redacted] to confim that [redacted] have agreements with Maintainer.	TS	Premises	Premises	Technical Solution Issue / Recommendation	2. Y
3	Premises - Name [redacted]	[redacted]	It is noted on drawing to cut glass panel around PHP. Please clarify the need to cut the glass panel. Can PHP not be surface fixed as per Ticket Hall installation?	[redacted] to update as necessary	TS	Premises	Premises	Technical Solution Issue / Recommendation	2. Y
3	Premises - Name [redacted]	[redacted]	On the wall tiling/frieze interface detail shown on [redacted], it appears the face of the tiles and frieze are in alignment. It's noted on [redacted] that, the frieze are faceted in the curved sections of the tunnel.	Please clarify if the wall tiles in the curved sections of the tunnel, would be installed on a faceted wall srface, to pevent a discord between the faceted frieze and the tilled wall.	TS	Premises	Premises	Technical Solution Issue / Recommendation	2. Y
10	Civil Engineering	[redacted]	Please advise whether it has been checked with OSD the construction loads to be allowed for due to OSD construction.	Advise on the approach used or the relevant assurance document to look at.	V&V	Premises	Premises	Poor compliance evidence presentation	3. G
10	Section Manager - Name [redacted]	[redacted]	Drawing 02235 references drawing 02278, which has not been submitted for acceptance. It details the [redacted] structure which is inside the [redacted] boundary	Submit drawing 02278	CoM	Premises	Premises	Poor configuration management	1. R
10	OSD Team	[redacted]	In our comments of September 2009, we asked if insulation could be provided behind the glass panels to	[redacted] believe this may be a change. Please discuss before implementing.	CM	Premises	Premises	Poor communication for the changes with parties	3. G

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
			the walls and soffit, since this will be a party wall with the OSD in the final condition, and the [redacted] entrance space will effectively be external. Can this be provided?						
10	M&E - Name [redacted]	[redacted]	It seems almost all of the comments made by [redacted] previously on the construction issue has not been adressed. [redacted] Provide evidence of the 'agreement'.	When will comments be addressed/incorporated?	CoM	Premises	Mechanical	Poor configuration management	4. O
11	M&E - Name [redacted]	[redacted]	There are routes where only 5 No 150mm dia ducts are being casted with only one spare duct. It is practicable to cast another duct.	Provide spare ducts otherwise a concession will need to be placed against standard [redacted]	TS	Premises	Electrical	Technical Solution Issue / Recommendation	1. R
11	M&E - Name [redacted]	[redacted]	There are routes where only 5 No 150mm dia ducts are being casted with only one spare duct. It is practicable to cast another duct.	Provide spare ducts otherwise a concession will need to be placed against standard [redacted]	TS	Premises	Electrical	Technical Solution Issue / Recommendation	1. R
11	Premises - Name [redacted]	[redacted]	It is not clear how the frieze in the mosaic area meets the WI requirements of the [redacted] signage scheme. The WI signage scheme frieze, consist of the station name/way out signs and directional signs above alternative way out sign. It's also not clear how continuity of the signage requirement of the frieze is achieved between the non-mosaic and mosaic areas.	Please comply with WI design for the frieze height/signage.	V&V	Premises	Premises	Poor compliance evidence presentation	1. R
19	M&E - Name [redacted]	[redacted]	The main earth bar is to be located in the [redacted] transformer room. Most of the connections shown on the main earth bar would be connected to a [redacted] outside the [redacted] transformer room due to the different maintenance responsibilities.	Correct connections on main earth bar and SEB (subsidiary earth bar) in the Powerlink transformer room area.	TS	Premises	Electrical	Technical Solution Issue / Recommendation	1. R
19	Section Manager - Name [redacted]	[redacted]	The document is not signed as having been reviewed and accepted by [redacted] and therefore cannot be accepted by [redacted] [redacted] - sheet signed	In line with the contractual requirements for self assurance, review and accept internally before submitting to the Project Manager for acceptance	CoM	Premises	Premises	Poor configuration management	3. G
19	Section Manager - Name [redacted]	[redacted]	The revision history for earlier revisions has been omitted, please reinstate. [redacted] - reinstated	Please re-instate	CoM	Premises	Premises	Poor configuration management	3. G
19	Project Engineer - Name [redacted]	[redacted]	Will the IP Bosch camera be able to support an uprated recording for events when integrated with verint	please confirm as this is a system requirement. Testing confirmation required that the	V&V	Premises	Communication	Poor compliance evidence presentation	1. R

Data from log books					Data Analysis				
Doc No	**Discipline**	**Section**	**Issue/Comment**	**Required action**	**Fail Factor**	**Party1**	**Party2**	**Note**	**Sens.**
				integration between Verint and Bosch has been successful and the [redacted] statement is correct at 1080p resolution [redacted]					
19	Project Engineer - Name [redacted]	[redacted]	Compliant or non-compliant?	see comment outstanding [redacted]. Closed [redacted] concession requirements to be discussed	V&V	Premises	Communication	Poor compliance evidence presentation	3. G
19	Project Engineer - Name [redacted]	[redacted]	Cable labels confirmed at meeting with [redacted] on the [redacted], document requires update	see comment, Closed on reissue of drawings & schedules[redacted]. Closed[redacted]	CM	Premises	Communication	Late change information from client	3. G
19	Name [redacted]	[redacted]	As discussed, asset labels, cable labelling should be as per previously accepted detail. Asset register data to be agreed with the Maintainer ([redacted]).	see comment. Details agreed with[redacted]	CM	Premises	Communication	Late change information from client	3. G
19	Project Engineer - Name [redacted]	[redacted]	[redacted] comments on [redacted] are still open	see comment	CoM	Premises	Communication	Poor configuration management	2. Y
22	Structures	[redacted]	Comment from previous review on drawing [redacted] not captured or addressed. Cat B comment - drawing missing from submission pack		CoM	Premises	Premises	Poor configuration management	1. R

Appendix 5 Systems Engineering Architecture Based on the DBS

This appendix provides a copy of the poster created to demonstrate the proposed Systems Engineering Architecture. This poster was used to present the concept to large external audiences and for marketing to future clients.

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Appendix 6 CS1 – Discipline Breakdown Structure

This appendix presents a copy of the codified DBS developed for CS1.

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Appendix 7 CS1 – Interface Control Matrix

This appendix presents a copy of a full Interface Control Matrix developed for CS1.

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Appendix 8 CS1 – Interface Status

This appendix provides detail of the interface numbers based on location and discipline for CS1.

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Appendix 9 CS1 – Interface Management System User Guide

This appendix provides a copy of the Interface Management System User Manual that was created for the end users of the system, developed for CS1 and used in CS2 and CS3.

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Appendix 10 CS1 – Validation and Verification System User Guide

This appendix provides a copy of the Validation and Verification Management System User Manual that was created for the end users of the system, developed for CS1 and used in CS2 and CS3.

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Appendix 11 CS1 – Requirements Management System User Guide

This appendix provides a copy of the Requirements Management System User Manual that was created for the end users of the system, developed for CS1 and used in CS2 and CS3.

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Appendix 12 Visual Basic Codes for the Integrated Management System Developed Based on the Proposed DBS

This appendix provides a full script of the Visual Basic code designed and developed for the IMS based on the DBS concept. This tool was developed by the author for CS1 and was modified for further use in CS2 and CS3.

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UNIVERSITY COLLEGE LONDON

LONDON, UNITED KINGDOM

JULY 2016