

**BENEFITS OF ADOPTING SYSTEMS ENGINEERING  
APPROACHES IN RAIL PROJECTS**

**by**

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## **ABSTRACT**

Systems Engineering (SE) is being used increasingly in rail projects, with the aim of creating better systems in better ways, thus generating a return on the effort invested. However, it is not entirely clear what exactly that return will be or how to maximise it. This thesis contains the results of research into the relationship between the adoption of SE in rail projects and project outcomes.

The writer shows that determining the success of a project, and thus the impact of SE, by simply measuring its cost and duration and assessing the performance of the system that it delivers, is problematic. He argues that the adoption of an SE approach can lead to decisions to correct faults in the system design and make other desirable changes being taken earlier, which will improve the outcome in most cases. Theoretical reasons and practical experience lead him to believe that many of the benefits of applying SE on projects will be enjoyed as a consequence of reducing change latency, where change latency is defined to be the unnecessary delay in deciding to make a change. A tentative theory of how SE can reduce change latency is proposed and tested against data collected from nine rail projects. The data corroborate several proposed causal mechanisms in the tentative theory but also suggest that the reduction in change latency achieved depends upon other factors, particularly the contractual and quasi-contractual relationships between the parties to the project.

For practitioners considering whether to apply SE on a project, the research findings provide encouragement but also a warning that the full benefits of applying SE will only be enjoyed if other pre-requisites for sound decision making are in place. The findings also provide guidance on how to adapt SE practices when applying them to rail projects, in order to maximise the benefits enjoyed.

The writer argues that change latency is a valuable metric for both practitioners and researchers and that formulating and refining explicit theories about the manner in which SE delivers benefits can assist researchers investigating these benefits to build upon each other's work.



*This thesis is dedicated*

*to the many men and woman working on railway projects who take pride in  
their work and deserve to be able to take pride in their achievements;*

*to my parents, Jeremy and Elizabeth, who brought my siblings and me up to  
value learning;*

*but above all*

*to my wife, Caroline, without whose support it could never have been written.*

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More than a dozen busy managers and engineers have given up their time to help me collect data about the projects on which they worked. Having promised them anonymity, I cannot name them here, but I wish to record my gratitude to them and also to their employers, where they gave permission for data to be collected for this research. The research would have been impossible without this input and I am grateful to those who provided it. The people who build complex systems are, in my experience, realistic about the chances of encountering disappointment along the way but remain stubbornly keen to learn how to do better. I have been granted access to project data in the belief that I may be able to make a contribution to this cause. I hope that in this thesis I can discharge that trust.

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## ACRONYMS

<b>Acronym</b>	<b>Definition</b>
ANSI	American National Standards Institute
BR	British Rail
CMMI	Capability Maturity Model Integration
CMU/SEI	Carnegie Mellon University Software Engineering Institute
COCOMO	Constructive Cost Model
CTRL	Channel Tunnel Rail Link
DfT	Department for Transport
DtS	Design the System
E&M	Electrical and Mechanical
ECSS	European Cooperation for Space, Standardization
EIA	Electronic Industries Alliance
ERTMS	European Rail Traffic Management System
FoM	Figure of Merit
HS1	High Speed 1
IDEFO	Integration Definition for Function Modeling
IEC	International Electrotechnical Commission
IEE	Institution of Electrical Engineers
IEEE	Institute of Electrical and Electronics Engineers
IET	Institution of Engineering and Technology
INCOSE	International Council on Systems Engineering
IRSE	Institution of Railway Signal Engineers
ISBN	International Standard Book Number
ISO	International Organization for Standardization
JLE	Jubilee Line Extension
JLEP	Jubilee Line Extension Project
LCR	London and Continental Railways
LGV	Ligne à Grande Vitesse

<b>Acronym</b>	<b>Definition</b>
LIP	Large Infrastructure Project
LUL	London Underground Limited
MC	Manage Change
MIT	Massachusetts Institute of Technology
MP	Model (the project) processes
MR&StS	Manage Requirements and Specify the System
MS&AtS	Model, Simulate and Analyse the System
N/A	Not Applicable
NAO	National Audit Office
NASA	National Aeronautics and Space Administration
NETLIPSE	NETwork for the dissemination of knowledge on the management and organisation of Large Infrastructure ProjectS in Europe
NYCT	New York City Transit
ORR	Office of Rail Regulation (previously Office of the Rail Regulator)
PRINCE 2	A project management method
RAEng	Royal Academy of Engineering
RES&COMP	Resourcing and Competence
RLE	Rail Link Engineering
ROI	Return on Investment
SE	Systems Engineering
SEBoK	Systems Engineering Body of Knowledge
SIMILAR	State the problem, Investigate alternatives, Model the system, Integrate, Launch the system, Assess performance, and Re-evaluate
SRA	Strategic Rail Authority
TGV	Train à Grande Vitesse
UCL	University College London
URN	Union Railways North
URS	Union Railways South
V&V	Verification and Validation
V&VtS	Verify and Validate the System
WCRM	West Coast Route Modernisation

<b>Acronym</b>	<b>Definition</b>
WSL	Westinghouse Systems Limited

## SPECIALIST TERMS

Term	Definition
atomicity	When talking about requirements, the condition of being atomic. A requirement is atomic if it cannot be logically decomposed into multiple requirements.
change latency	A measure of the unnecessary delay in taking a decision to make a change.
context specification	A logical artefact that documents all relevant, significant facts and assumptions about the environment in which the system will operate, including the physical, commercial, economic and regulatory aspects of the environment.
core SE	<p>The totality of all project activities that affect or use SE artefacts in at least one of the following ways:</p> <ul style="list-style-type: none"> <li>• they create proposed content of the SE artefacts;</li> <li>• they control change to the SE artefacts;</li> <li>• they check the correctness or assess the implications of the SE artefacts; or</li> <li>• they check the system and its sub-systems against the SE artefacts.</li> </ul>
decision latency	In the context of a change, the time taken to recognise that there is an issue that will require a change.
detection latency	In the context of a change, the time taken from recognising that there is an issue to reaching the decision to make the change.
external validity	The extent to which research conclusions may be generalised to other situations.
internal validity	The extent to which research conclusions are free from the challenge that alternative explanations might have been provided for the same effects.
interpretive	A description of research methods that study the understanding that people have of the world.
left shift	The 'left shift' hypothesis is the hypothesis that effort invested early in a project and, in particular, in the SE activities that occur in early stages will yield savings in effort later in the project that outweigh the investment.
logical artefact	One or more physical artefacts or parts of physical artefacts that contain a defined part of the output of SE activities.



<b>Term</b>	<b>Definition</b>
observation-first	An approach to research in which the researcher allows the theory to arise from observations.
physical artefact	A document, drawing or database that contains the results of SE activities.
realist	A description of research methods that assume an objective world that exists independently of observers and seek objective truth about it.
requirements specification	A logical artefact that documents all project requirements from all project stakeholders, including requirements on the cost and schedule of the project.
root document	When considering the latency of a change, the most basic document in the project hierarchy that must be materially revised in order to implement the change.
snowball effect	The mechanism whereby a change to one part of the design of a system results in many changes to other parts of the design.
sub-system	A system wholly contained within a larger system.
sub-system budget	A logical artefact that specifies a commitment to deliver a sub-system within a certain maximum cost.
sub-system schedule	A logical artefact that specifies a commitment to achieve delivery of a sub-system and, possibly, other intermediate milestones within certain windows of time.
sub-system specification	A logical artefact that specifies what sub-system must be built, including specifications of external interfaces for that sub-system.
system	A combination of interacting elements organised to achieve one or more stated purposes.
system budget	A logical artefact that specifies a commitment to complete the project within a certain maximum cost.
system schedule	A logical artefact that specifies a commitment to achieve completion of the project and possibly other intermediate milestones within certain windows of time.
system specification	A logical artefact that contains a specification of the system to be built. If the system is to be introduced into service in a number of stages then the interim states of the system should be specified as well as the final one.

Term	Definition
Systems Engineering	An interdisciplinary approach and means to enable the realization of successful systems.
theory-first	An approach to research where the research is grounded in theory before data collection starts.
validation	<p><i>Defined in ISO/IEC 15288 (ISO/IEC, 2002) to be:</i></p> <p>Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.</p> <p><i>In this thesis, this is interpreted as referring to confirmation that a system or some part of the system, its design or specification, is consistent with the overall requirements for the system.</i></p>
verification	<p><i>Defined in ISO/IEC 15288 (ISO/IEC, 2002) to be:</i></p> <p>Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled.</p> <p><i>In this thesis, this is interpreted as referring confirmation that some part of the system, its design or specification, is consistent with the requirements placed on the item.</i></p>
Weltanschauung (plural Weltanschauungen)	A world view or philosophy about the nature of the world.



# 1 INTRODUCTION

## 1.1 Background to the research

In 2002, I took a job at Atkins, a design, engineering and project management consultancy, where I was responsible for raising the capability of its rail business in the area of Systems Engineering (SE). I had spent much of the previous 10 years helping the UK rail industry to raise its capability in system safety engineering, through editing a handbook of good practice in this area (Rail Safety and Standards Board, 2007) and delivering associated training and consultancy.

SE is not always well understood and those that do understand it do not always agree about precisely what it is. I devote the whole of chapter 5 to exploring the different characterisations of SE and deciding upon a characterisation to use for research purposes. The reader, however, is entitled to some working definition before we go on. With assistance from my supervisors, I wrote an article in a professional journal to help railway people understand what SE is (Elliott, Roberts, Schmid and Shannon, 2012), during which we concluded that, in a railway context *“SE may be thought of as ‘the business of getting the parts of the railway to work together to do what we want them to’”* and that it *“provides proven and well-grounded methods to put some common-sense ideas into practice and a framework within which to apply them.”* For now, I hope that the reader will find it sufficient to know that SE is a collection of tools, techniques and methods that support the delivery of systems.

For the purpose of this thesis, I consider the deliverables of engineering projects to be systems that are composed of hierarchies of sub-systems. The tools, techniques and methods of SE tend to focus on general, abstract notions such as requirements, functions and interfaces and, it is claimed, complement the tools, techniques and methods of project management and traditional engineering disciplines. In 2002, there had been several decades of experience in applying SE in sectors such as defence and aerospace but very little experience of applying it in the rail sector.

Over time, it became clear to me that the theoretical underpinnings of the venture were shallow and that this would have to be corrected, if progress was to be sustained.

There were two questions in particular that colleagues asked me and that I knew that I could not answer properly:

- "If I apply SE to this project, will I see benefits that justify the cost?"
- "How should I adapt SE practices that have been developed in other sectors to make them work well on my project?"

The questions are linked. The answer to the first question must be, "It depends", because the two extreme positions, firstly, that applying SE can be justified on all projects and, secondly, that it can be justified on none, are both untenable<sup>1</sup>. It follows that achieving a better understanding of the causal mechanisms by which SE delivers benefits or disadvantages would help to answer both questions.

I sought a better understanding of these causal mechanisms in the literature. In 2006, having failed to find what I was looking for and with the encouragement of my manager at the time, Ian Shannon, I embarked upon the research described in this thesis.

## **1.2 Generic objectives for the research**

I set the following two generic objectives at the outset of the research:

- To demonstrate that SE can be used to build better rail systems and to build rail systems better, aiming for measurable improvement.
- To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects.

Making progress towards these objectives would help me provide better answers to the questions stated above. This, admittedly, is true only on the assumption that SE can deliver benefits that justify the cost. That was my belief before I started the research although I did commit myself to adjusting my belief if my findings required that.

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<sup>1</sup> I justify this assertion later.

The generic objectives were intended as general signposts for the direction to be followed and they have served that purpose: the research has remained aligned with them. I acknowledged when I set these objectives that it would be necessary to develop narrower and more refined, specific objectives to guide the research and this is what has happened, as I explain below. In narrowing and refining the objectives my touchstone has been utility to practitioners: I wish to compile knowledge that is useful to people involved in railway projects.

### 1.3 The structure of this thesis

The account of my research is presented in the remainder of this thesis in the following chapters.

In chapter 2, **The nature of the research problem**, I reflect upon the research objectives and observe that all the objects of study are in the field of human activity, may vary from observer to observer and are subject to continual change. I follow the implications of these observations for the research.

In chapter 3, **Prior work**, I look at the research that has been carried out to date into the benefits of adopting SE approaches. This has recently been strengthened by two quantitative studies but I conclude that the prior work does not yet deliver my objectives in full and that further work is required.

Chapter 4 is entitled **A workable characterisation of systems engineering**. In order to proceed with the research, I need a way of characterising SE which is precise enough that I can take any project activity and determine whether it is an SE activity or not. I observe that there are many ways in which people characterise what SE is but I find each of these characterisations fails to meet my needs because it is too imprecise, because it is too broad, because it presumes a certain process or for some other reason. I propose a definition of **core SE**, based upon identifying the types of intellectual products that are at the heart of SE. I argue that this definition is of value because it includes the types of activities that are common to a number of characterisations of SE.

In chapter 5, **The nature of rail systems and rail projects**, I reflect upon experience of rail systems and rail projects. I suggest some ways in which the balance of concerns in rail

projects differs, on the average, from those encountered by projects in the traditional sectors for SE. I do not suggest that the fundamentals of SE vary between sectors but I do suggest that some traditional SE practices require adjustment for the rail sector if they are to be effective in a new domain.

Chapter 6 is entitled **A workable characterisation of 'better'**. I am trying to understand how SE might result in better projects and better systems and in order to explore that I need some objective characterisation of 'better'. Other researchers attempt to do this in terms of the cost and duration of projects and the performance of systems. However, these concepts are hard to evaluate in an objective and standard manner and it is hard to separate the effects of the different factors that influence them. Readings and a preliminary survey lead me to postulate that one of the ways in which SE may deliver benefits is by eliminating changes to project direction or allowing these changes to be decided upon earlier. I define a measure of the unnecessary delay in taking a decision to make a change and I refer to this measure as **change latency**. I argue that this is a useful measure of the potential that SE has to deliver benefits because reduced change latency can contribute to reduced cost and duration and increased performance. I also argue that change latency is a methodologically useful measure.

At this point, my broad objectives, to explore the relationship between SE and project outcomes, can be replaced by specific objectives to explore the relationship between core SE and change latency.

In chapter 7, **Methodology**, I outline my approach to exploring these specific objectives, which is (i) to construct a model of how SE interacts with other project activities, (ii) to construct a tentative theory of how SE can contribute to reduced change latency and (iii) to test this tentative theory, by applying qualitative and quantitative methods to field data collected for the purpose and to published project accounts.

Before describing the results of following this methodology, I look, in chapter 8, **A case study**, at one example of the application of SE to a rail project and illustrate how rigorous analysis of cases can produce useful results – in this case showing that a simple-minded tentative theory about the benefits of SE is untenable and must be refined.

Chapter 9, **A model and tentative theory**, contains a model of how SE interacts with other project activities, presented as a diagram using a process-modelling notation called IDEF0, and a tentative theory of how SE contributes to reduced change latency, presented as conjectures about causal mechanisms associated with the model.

The findings of two exercises designed to test the tentative theory are presented in the next two chapters.

In chapter 10, **Testing the tentative theory against data collected from projects**, I describe an exercise to collect and analyse data about five railway projects and the major changes that occurred on them, via interviews and the inspection of project records.

In chapter 11, **Testing the tentative theory against published data**, I describe an analysis of published data concerning four further railway projects.

In both of these chapters, I reflect upon the extent to which the data confirm the tentative theory, the extent to which they contradict it and the refinements to the tentative theory that the data suggest.

In chapter 12, **Conclusions and recommendations**, I record my findings. I look at the refined research objectives and consider to what extent they have been met. I then relate these to the original research objectives and consider to what extent these have been progressed. I record what has been learnt about SE, about rail projects and about the effects of adopting SE approaches on rail projects. I also reflect on the research methodology, the model and the tentative theory and their value to research of this type. For the researcher I recommend promising directions for future research activity and for the practitioner I suggest ways in which the results of the research to date can be applied.

Some detailed supporting information is provided in appendices and is referred to in the main text.

#### **1.4 A note on style**

Having declared my ambition to compile knowledge of value to people involved in railway projects, I have, I believe, an obligation to present my research in a way that makes it as accessible as I can to people wishing to apply my findings. I have therefore written this thesis



in a style that is nearer to everyday English than is customary for academic documents, in order to make it easier for people outside academia to read it. I hope that readers who are expecting a different style will excuse me.

### **1.5 Key points**

To help the reader follow the logical arguments running through this thesis, I provide a summary of key points at the end of each chapter. I give each point a unique identifier to make it easier to refer to it.

The key points from this chapter are as follows:

1A The research was motivated by the absence of satisfactory answers to the following questions:

- "If I apply SE to this project, will I see benefits that justify the cost?"
- "How should I adapt SE practices that have been developed in other sectors to make them work well on my project?"

1B The outline objectives of this research are:

- To demonstrate that SE can be used to build better rail systems and to build rail systems better, aiming for measurable improvement.
- To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects.

1C I wish to compile knowledge of value that is useful to people involved in rail projects.

## 2 THE NATURE OF THE RESEARCH PROBLEM

I am an engineer and, when I think about academic research, my initial instinct is to take what I know about the development of scientific knowledge as a starting point. I think of Robert Boyle, whose careful measurements resulted in his name being attached to the 'law' that, other things being equal, the volume of a certain mass of an ideal gas varies inversely with its pressure. It is tempting to imagine an 'Elliott's Law', relating the effectiveness of a rail project to some measure of the amount of SE performed on it. I had to discard that vision as an unrealistic ideal but it still held a grip on my thinking for some considerable time as an ideal to be approached, if not achieved.

Gradually, though, it dawned on me that the objects that I was studying were a very, very long way away from ideal gasses. That has important implications for the research methods that I use, as I explain in chapter 7, but, even more profoundly, it affects the sort of knowledge that it is practical to compile. I discuss the objects within the field of study in this chapter and draw conclusions as to what it is possible to know about them.

### 2.1 Observations on the field of study

It is helpful to reproduce my general research objectives. These are:

- To demonstrate that **SE** can be used to build **better** rail **systems** and to build rail systems **better**, aiming for measurable improvement.
- To gain an improved understanding of how to adapt SE to yield optimum results in major rail **projects**.

I have highlighted, in bold type, three nouns – **SE**, **project** and **system** - which are objects within the field of study. For now, the following descriptions will suffice:

- **SE** is a collection of tools, techniques and methods, bound together by some shared ideas<sup>2</sup>.
- A **project** is a social activity in which people work together towards a common goal, which will be taken to be the delivery of a system<sup>3</sup>.
- A **system** is a combination of interacting elements organised to achieve one or more stated purposes<sup>4</sup>.

I have also highlighted the word **better**. ‘Better’ systems and projects are presumably associated with lower **costs**, greater **benefits** or both and so costs and benefits are objects of study.

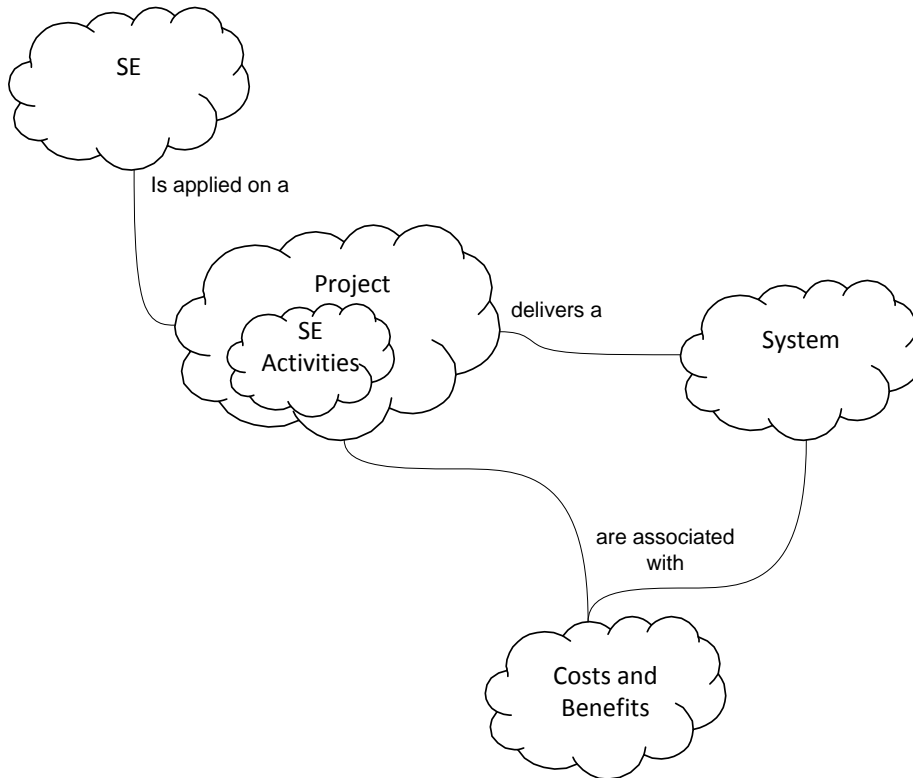
Figure 1 shows the principal objects within the field of study implied by the research objectives.

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<sup>2</sup> This is compatible with the definition provided by the International Council on Systems Engineering (INCOSE, 2010), which is “an interdisciplinary approach and means to enable the realization of successful systems”.

<sup>3</sup> This is compatible with the definition in a manual of project management (Office of Government Commerce, 2002), which is “a management environment that is created for the purpose of delivering one or more business products according to a specified Business Case”.

<sup>4</sup> This is the definition provided in (INCOSE, 2010).



**Figure 1: The main objects in the field of study**

The figure also depicts the principal relationships between the objects:

- The project delivers a system.
- The application of SE to the project results in a set of SE activities which are a subset of the project activities.
- The application of SE to the project will have costs and may or may not result in benefits for the project (which may perhaps be completed more quickly) or for the system (which may please its stakeholders more than it would have done otherwise).

I make four important observations about these objects that have implications for the research:

- The objects in the field of study do not easily permit controlled experiments.
- The objects in the field of study are defined differently by different observers.
- The objects in the field of study are drawn from populations of great variety.
- The objects in the field of study studied are subject to continual change.

I now discuss each observation in turn.

## **2.2 The objects in the field of study do not easily permit controlled experiments**

Boyle could seal a fixed mass of gas within a flexible container, vary the pressure placed on the gas and measure its volume. It is very hard to see how an experimental researcher could run a realistic rail project multiple times with different levels of SE. SE researchers generally have to work with observations of the real world and work with the variation that the real world provides.

The limited role for experiments is recognised in several other fields, including economics, see for instance Mayer (1995; page 20).

## **2.3 The objects in the field of study are defined differently by different observers**

All the objects in the field of study are constructs that people place on the real world and all these constructs may vary from observer to observer. This is most dramatically exemplified in the context of benefits where the general manager of a metro line and a driver on that line may have very different views on the benefits of a project to introduce driverless operation. We shall also see (in chapter 5) that there is a bewildering multiplicity of ways of describing SE.

The fact that systems have a physical reality may suggest that they are more objectively defined. However there is more to a typical system than its physical components and we can still find disagreement about exactly what its components are. Ask different people questions like, “Is the design of the system part of the system?” or “Should the operators and maintainers be considered within the boundary of the system?” and you may receive different answers. The same fuzzy boundaries may be experienced for projects and the programmes of SE activities within them. In organisations that develop products and then use them in projects to build systems, the boundary between product development activity and project activity may also be the subject of dispute. And, if a mechanical engineer is attending an SE workshop to refine requirements, are they doing mechanical engineering or systems engineering?

That is why clouds are appropriate symbols in Figure 1. Ask two people whether there are clouds in the sky and they will probably give you the same answer. Ask the same people how many clouds are in the sky and you may get different answers.

There are research methods, often referred to as ‘interpretive’, which abandon the attempt to compile knowledge about an objective world that exists independently of observers and instead study the understanding that people have of the world – see, for instance, Lings and Lee (2008; page 60). I do not see how such methods may be applied to compile knowledge of the practical utility desired. There appear to be two other strategies to cope with this problem:

- To define objective concepts with some useful relationship with the range of subjective concepts in general discussion and then to discuss the objective concepts.
- If the difference between what different people mean by particular terms is small enough, to use the everyday terms in the conduct of the research and to accept that variation in what people mean by the terms is a source of ‘experimental error’ in any data collected.

In practice, it seems to be necessary to use a mixture of both strategies and that is what I do<sup>5</sup>.

#### **2.4 The objects in the field of study are drawn from populations of great variety**

Finally, projects and systems are drawn from populations of great variety, differing in countless ways.

In practice this makes it virtually impossible to *prove* that a particular cause will always have a particular effect. So a fair answer to the question that I discussed above, “If I apply SE to this project, will I see benefits that justify the cost?” is unlikely to be a definitive ‘Yes’ or ‘No’. The best one can hope for is to be able to say that, on a number of projects that appear to be similar in important respects, the benefits of applying SE justified the cost. That indicates that the benefits are likely to justify the costs for the project in question. However, one can never rule out the possibility that some difference between the particular project and the other projects may impair the ability of SE to deliver benefits to the same degree.

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<sup>5</sup> As we shall see in chapter 3, other researchers working in the area, including Elm and Goldenson (2012) and Honour (2013) take this approach.

This problem is encountered in many other fields, for example, in business studies, where statistical inference is used to draw probabilistic conclusions rather than universal conclusions – see for example Lings and Lee (2008; page 292).

However, being unable to compile definitive, universal knowledge is not an obstacle to compiling useful knowledge. Thoughtfully-analysed, well-grounded knowledge of the type described above is, potentially, of great utility. That utility is increased if researchers take the trouble to identify and document significant features of the sample of projects from which they draw conclusions so that those using these conclusions can judge the relevance to their own situation. That utility is also increased if, when researchers suggest that an application of SE can produce a certain benefit, they suggest the mechanisms by which that benefit is delivered so that practitioners can judge whether these mechanisms are likely to operate on their own projects.

## **2.5 The objects in the field of study are subject to continual change**

Finally, the objects under study are affected by continual change in the following ways:

- SE changes over time as its practitioners work to improve it.
- The values that underpin benefits change over time. For example, it is common at the time of writing to regard a reduction in the cost of materials and labour on a large infrastructure project as a benefit. In the foreseeable future it may become unthinkable to perform this calculation without adjusting for the effect of the project on the natural environment.
- The environment in which projects exist includes the knowledge and beliefs of the people involved and these change over time.

As a consequence, it is not only difficult to reach universal conclusions, it is also difficult to reach timeless ones. Anything that may be concluded about some subset of projects may be rendered untrue, or at the very least irrelevant, by some development in the future.

An interesting example of this limitation encountered in economics is the ‘Lucas critique’ (Stanley, 2000) that *“any change in policy will systematically alter the structure of econometric models”*.

## 2.6 Reflections

The nature of the field of study, then, means that the knowledge that we can compile about it will almost certainly be imprecise, limited in applicability and subject to revision in the light of changing circumstances.

However, this should not stand in the way of accumulating a useful body of knowledge. For that body of knowledge to be truly useful though, it will be necessary to incrementally increase and refine it over time. I acknowledge that I only have the resources to make a limited contribution to that body of knowledge but, in order to maximise the value of that contribution, I set myself a specific research objective to carry out my research in a way that helps others to refine and build upon my findings.

## 2.7 Key points

2A The objects in the field of study are in the realm of human activity and, therefore:

- do not easily permit controlled experiments;
- are defined differently by different observers;
- are drawn from populations of great variety; and
- are subject to continual change.

2B The knowledge that we can compile about the field of study will almost certainly be imprecise, limited in applicability and subject to revision in the light of changing circumstances.

2C I have set myself a specific research objective to carry out my research in a way that helps others to refine and build upon my findings.





### **3 PRIOR WORK**

In this chapter, I review prior research into how SE contributes to project outcomes and some relevant but more general research into project outcomes and the factors that influence them. The review is not restricted to the rail sector.

This chapter does not contain a comprehensive list of the prior work that I refer to. Other chapters draw upon work from a variety of different areas; in this chapter, I discuss prior work that is directly relevant to my research objectives.

I look first at research into the outcomes enjoyed by projects, then at theories about how SE may contribute to projects and then at the empirical evidence for the effect of SE on projects, before, finally, reflecting on the overall state of knowledge.

#### **3.1 The outcomes enjoyed by projects**

There is no difficulty finding evidence that there is scope for improvement in the performance of large engineering projects. In this section I present papers that suggest that a significant number of these projects overrun, deliver systems that do not provide the benefits expected of them or just fail to deliver at all. There is evidence that SE could have prevented some of the disappointments.

The CHAOS reports produced by the Standish Group, for example (Standish Group, 2010), are widely-cited in support of the potential value of SE. The reports contain analyses of information about IT and software development projects. At the time of compiling this thesis, the most recent publicly available report (Standish Group, 2010) contained an assertion that 24% of such projects are failures while a further 44% did not fully meet all their targets. 10 'factors of success' are put forward, which include at least two, 'Clear Business Objectives' and 'Optimizing Scope', that may be delivered through the adoption of SE approaches.

Observers such as Glass (2006) express reservations about the weight that can be given to the CHAOS findings on the grounds that the underlying data are not open to independent scrutiny and that the manner in which projects are selected may favour those that

performed badly. However, even if these criticisms are valid, the conclusion that many projects disappoint survives them. Moreover, other studies reveal that this conclusion is valid in other domains.

For example, Hertogh et al (2008) find consistent results in large European infrastructure projects. They report findings from the NETLIPSE (NETwork for the dissemination of knowledge on the management and organisation of Large Infrastructure ProjectS in Europe) research project. They describe an activity to gather and analyse information on 15 large European infrastructure projects, of which 7 were rail projects, with a total value in excess of €40 billion. Once again there is clearly room for improvement. In section 4.3 of their report, they observe that large infrastructure projects *“do not have a good reputation with respect to cost and time control”* and cite facts that justify this reputation.

They make some attempt to explain the reasons for this and their explanation suggests that SE approaches may have the potential to reduce overruns. They observe that *“the origin of reasons for cost overrun and time delay can more often be found in the planning rather than in the construction phase”* and, amongst these reasons, cite poor definition of requirements, estimates based upon uncertain principles and focussing too little on external stakeholders.

From its research, the project team has formulated 63 findings and 46 *“best practices and lessons learnt”*, essentially, recommendations for future large infrastructure projects. Some of these are in areas such as financial management and contracting, that fall outside SE but others align with good SE practice in establishing and managing requirements, modelling, simulation and controlling change.

More specifically, scope for improvement has been found in the performance of rail projects. Flyvbjerg (2007) studied a number of rail projects and found that:

- they suffered average cost escalation of 44.7%;
- 75% of the projects suffered cost escalations of at least 24%; and
- 25% of the projects suffered cost escalations of at least 60%.

## 3.2 Theories about how SE contributes to project outcomes

### 3.2.1 Theories of how SE delivers benefits

Sheard (1996b) suggests that SE adds value to a project in four ways:

- by activities that contribute directly to the product of the project;
- by increasing efficiency and effectiveness of other people's work through better co-ordination;
- by contributing to setting a vision for the project, and to guiding and leading the project; and
- by reducing risk.

This is a classification of the types of value that are claimed for SE. The first three are associated with better systems or better (that is cheaper and quicker) projects, while the final point reminds us that organisations cannot be certain what the outcomes of their projects will be and a reduction in the variation encountered in any of these dimensions may be considered a benefit even if the mean average is not improved.

However Sheard's categorisation does not of itself constitute a theory of how SE might produce benefits. Given the significant resources expended upon SE, it is surprisingly difficult to find a clear exposition of such a theory. Nevertheless, three general types of hypothesis may be discerned in the literature:

- 'The control of complexity' (RAEng, 2007; American Society of Civil Engineers, 2009; McNulty, 2011). The hypothesis that, it becomes impossible to realise systems that have surpassed a certain threshold in complexity without using SE, at least without unacceptable levels of rework.
- 'Whole system optimisation' (Hitchins, 1998; Flyvbjerg, Bruzelius and Rothengatter, 2003; ProRail and Rijkswaterstaat, 2008). The hypothesis that SE provides a means of optimising the system as a whole that is not provided to a satisfactory degree by other disciplines.
- 'Left shift' (Honour, 2013; INCOSE, 2010). The hypothesis that effort invested early in a project, and in particular in the SE activities that occur in the early stages will yield

savings in effort later in the project that outweigh the investment, presumably because SE pre-empts expensive problems.

Each of these hypotheses is discussed in turn. The hypotheses are clearly not mutually exclusive and to some extent overlap.

### **The control of complexity**

In many different sectors, the systems that people are building are becoming steadily more complicated (RAEng, 2007). We have seen that the projects that deliver these systems are prone to expensive technical hitches. There is a widespread belief that some of these hitches are the consequence of increasing complexity and that some form of systems approach may provide at least partial protection against these problems.

Such a belief is held by UK and US engineering institutions. The UK Royal Academy of Engineering published a paper (RAEng, 2007), 'Creating systems that work: Principles of engineering systems for the 21st century' which espouses an approach to 'integrated system design' that is consistent with many SE approaches. On the other side of the Atlantic, the American Society of Civil Engineers concluded in a recent report (American Society of Civil Engineers, 2009) that, *"Critical infrastructure must be planned, funded, designed, constructed, and operated as a system that is appropriately integrated with all other interdependent systems."* McNulty (2011), reporting the results of a government-funded inquiry into the cost of UK railways, recommends methods for achieving better value for money that include systems approaches.

### **Whole system optimisation**

Hitchins (1998) asserts that trying to maximise the values of individual parts of a system on their own will disturb the other parts and result in a system that has less value than it could have. In his view, SE contributes to better systems, at least in part, by providing mechanisms for finding the best overall system; mechanisms that are not provided by other disciplines.

Some support for at least part of Hitchins's hypothesis can be found in Flyvbjerg's, Bruzelius's and Rothengatter's analysis of very large infrastructure projects (Flyvbjerg, Bruzelius and Rothengatter, 2003). Their recommendations for improving the outcomes of such projects include procuring against 'performance specifications'. A performance

specification is a specification of the performance to be delivered by a system and is contrasted with the traditional practice of specifying the form and function of the system. The benefit of using performance specifications is that this allows the system supplier a greater range of solutions to optimise over.

There is even more explicit support for this hypothesis from the Netherlands. The Dutch government has taken a decision to transfer some responsibility for the design of infrastructure projects to the private sector. In response, ProRail and Rijkswaterstaat, who together manage Dutch railways, roads and waterways, are actively promoting SE because it makes it possible to *“focus the solution on producing maximum performance and quality (efficiency)”* (ProRail and Rijkswaterstaat, 2008; page 13).

### **Left shift**

Honour (2013) presents an orthodox view of the ‘left shift’ hypothesis when he describes the *“intuitive understanding of the value of SE”* in the following terms, *“In traditional design, without consideration of SE concepts, the creation of a system product is focused on fixing problems during production, integration, and test. In a ‘system thinking’ design, greater emphasis on the front-end system design creates easier, more rapid integration and test. The overall result promises to save both time and cost, with a higher quality system product.”*

The International Council on Systems Engineering (INCOSE) is an international professional society for SE. It publishes an SE Handbook (INCOSE, 2010; pages 14ff) that contains a graph which illustrates the hypothesis by showing that, while the costs incurred on a project rise most rapidly in the later stages of the project, the costs committed by decisions rise most rapidly in the early stages. The authors of the Handbook assert that the cost of removing errors is lower if they are removed earlier in the project and argue that SE will reduce cost by providing information that supports better earlier decisions.

### **3.2.2 Theories of how SE might do harm**

One would expect that SE is sufficiently well-established by now that it should have attracted some fundamental challenges. So far, while my literature search has discovered many papers written by authors who believe that current SE practice can be improved upon, I have yet to find an author who believes that the concept is fundamentally flawed and

needs to be thought out again from scratch. The nearest that I can find is Hoos (1976), see Beishon and Peters (1976; page 168), who asserts that SE “cannot claim unqualified success” because it had been used on a number of well-publicised engineering disasters but restricts himself to mild scepticism when he writes that the “predominance of systems engineering may have obscured other, perhaps more promising approaches.”

If direct criticism of SE is hard to find, the existence of some harm associated with applying SE may be inferred from other writers’ work. The SE approach is generally associated with meticulous planning and preparation and, via left shift, with taking decisions earlier than would otherwise be the case. Some writers question whether meticulous planning and early decision making always deliver benefits. After studying a number of organisations that carry out highly reliable operations, Weick and Sutcliffe (2001) ascribe this reliability, in part, to ‘mindfulness’ – a state which they conclude can be impaired by over-preparation. After studying a number of large engineering projects, Miller and Lessard (2000) conclude that taking decisions at the right time is critical to project success and state that, sometimes, it is best to postpone decisions in order to keep options open. These findings might suggest that adopting SE approaches without sufficient thought might do harm, however, there seems to be no reason why a thoughtful application of these approaches should not avoid these pitfalls.

In general, there is little reason to believe that, if applied well, SE is likely to result in harm. The questions upon which a decision about whether to adopt SE are likely to hinge are likely to be, ‘Will the benefits outweigh the costs?’ and ‘Are there other, less-expensive ways of achieving the same benefits?’

### **3.2.3 What else might affect the benefits accruing from using SE?**

In truth, the question is not, “Does SE deliver benefits on projects?” but rather, “On which types of project does SE deliver benefits?” There must be projects on which it delivers benefits. For example, consider a project which, through mistakes in thinking, is building a system that will not solve the problem it is designed to solve. A clear articulation of the requirements may well be sufficient to reveal the mistake and save the project from disaster. Equally, there must be projects that are beyond help from SE. For example,

consider the same project just described but now make the project manager obdurately wedded beyond reasoned argument to the flawed specification. Neither scenario is outside the range of human experience.

So the benefits, if any, that will result from adopting SE on a project must depend upon other factors. I have found four distinct types of factors discussed in the literature:

- How well SE is performed (Kludze, 2004; Honour, 2013);
- The relationship between SE and other project functions (Ade, 2007; Barker and Verma, 2003);
- The motivation of the players (Flyvbjerg, Bruzelius and Rothengatter, 2003); and
- The size of the project (Boehm, Valerdi and Honour, 2008).

Each of these is discussed in turn.

### **How well SE is performed**

It would be extraordinary if the benefits of SE did not depend upon how well it was done. There is published evidence that the benefits of SE do depend upon how well it is done.

Kludze (2004) provides a possible example of poor SE leading to poor outcomes. He describes a study to establish the value of SE within NASA which includes an analysis of a number of case studies from which he concludes that SE assists in the development of cost-effective systems, reduces risk and has a considerable impact on technical performance. However, his case studies include an anonymous NASA project that was delivered a year late at twice the estimated cost, even though the project team performed a lot of SE. Kludze observes that the SE practitioners were inexperienced and hypothesises that a good process in this case did not compensate for a lack in knowledge and skill. If that is the case then presumably this lack resulted in poor execution of SE that, in turn, produced the disappointing outcome.

Honour (2013), when correlating the outcomes of projects with the expenditure on SE, chooses to adjust this expenditure with a quality factor and finds that project success is correlated more strongly with adjusted expenditure than with unadjusted expenditure.



**The relationship between SE and other project functions**

SE is not directly responsible for creating any concrete part of a delivered system; it can only deliver benefits indirectly by helping those who are responsible for these deliveries. Therefore, the relationship between the people performing SE and the rest of the project members must affect SE's effectiveness.

The relationship between SE and project management is of particular interest. Some people think that this relationship has to be sound before the benefits of SE can be fully enjoyed. As an example, Ade (2007) reports on a panel discussion at an INCOSE conference that came to the conclusion that SE and project management cannot function effectively or efficiently unless the two are integrated.

Some empirical evidence for this hypothesis has been reported by Barker and Verma (2003), who describe a comparison of productivity data with data on SE activities from eight IT projects and report that *"Results do not provide conclusive evidence that systems engineering (on its own) enhanced productivity on specific projects. However, preliminary information indicates that application of formal systems engineering practices and methods, in conjunction with effective project management and test processes, can significantly improve development and integration productivity."* These findings appear to corroborate the common-sense view that the benefits of SE must depend on how well it is integrated into the rest of the project.

**The motivation of the players**

One of the ways in which SE may be able to help projects deliver more efficiently is by revealing precisely what needs to be done so that it can be accurately planned and estimated. But the causal link here only works if those in charge are motivated to produce accurate estimates. Flyvbjerg, Bruzelius and Rothengatter (2003) challenge this assumption. They studied a large number of large infrastructure projects and concluded that some of the chronic mismatch between estimated and actual costs and benefits of these projects was the result of deliberate manipulation of the estimates.

### **The size of the project**

In a study of software projects that is discussed in more detail below, Boehm, Valerdi and Honour (2008) find that the effect of variations in the amount of SE performed was greater on very large projects than on small projects.

#### **3.2.4 If SE delivers benefits why is not applied more widely?**

All the theories for the benefits of adopting SE are of a general nature and would predict that these benefits would be enjoyed in a large number of sectors. All the same, SE is only commonly applied in a few sectors. Some writers suggest explanations for the limited adoption in some areas.

Ackoff (2006) suggests reasons why SE is not taken up more. He points out that one must admit to one's mistakes before learning from them. He suggests that Western management and accounting systems measure errors of commission but not of omission and that this predisposes Western management to inactivity. He also suggests that systems engineers are introverted by nature and must learn to talk to its potential users in a language that they understand. I agree with the latter point. Jargon is an obstacle to communication between any pair of communities but it is the responsibility of those selling an idea to speak the language of the prospective customers. I was a member of an international rail SE working group that concluded (Armitage et al, 2008) that excessive use of technical vocabulary by systems engineers was a real obstacle to the uptake of SE.

Adopting SE in areas where it is not traditional requires investment and Sheard and Miller (2000) suggest that an executive under cost pressure will find it hard to adopt a strategy of investing in one area in order to save money overall.

By contrast, Sheard, Lykins and Armstrong (2000) describe six barriers to the adoption of SE ideas that are all associated with flawed thinking or action. These are:

- a tendency for organisations to regard themselves as exceptions to the rule;
- the lack of a generally acknowledged definition of SE;
- working towards the appearance of adopting SE rather than the reality;
- over-reliance on training for process improvement;
- assigning insufficient resources for process improvement; and

- not setting priorities for the introduction of new ideas.

Taken together, these provide sufficient potential obstacles to the migration of SE approaches from sector to sector that the fact that this rate of migration appears to be slow does not undermine any of the theories proposed above.

### 3.3 Empirical evidence

There is increasing empirical evidence for the benefits of SE. Firstly there is evidence in support of some of the underlying theories:

- Werner Gruhl, in the Office of Comptroller at NASA HQ, compiled data from a study of NASA projects that showed a clear negative correlation between the percentage of effort spent in the early phases and cost overruns. These data were originally included in a presentation. I cannot find the original but the data are widely reproduced, for instance by Hoffman and Lawbaugh (1996; page 18), in support of the 'left shift' hypothesis.
- Miller and Lessard (2000) present the findings of a study of 60 large engineering projects. They found that the success of these projects was correlated with (a) investing in the initial, 'shaping' stage of a project and (b) defining the objectives in a manner that creates options about how they can be met. Their findings provide some empirical evidence for the theories of left shift and whole-system optimisation.

To be precise, neither of these analyses provides direct evidence that SE will deliver benefits but, in providing some corroboration for the theories of left shift and whole-system optimisation, they provide indirect support for such a conclusion.

Until recently, evidence of a correlation between the adoption of SE practices and project outcomes has been derived only from studies of small populations of projects:

- Frantz (1995) describes a serendipitous experiment concerning three projects at Boeing to develop handling machines. The projects delivered similar products but happened to employ varying degrees of SE. He found that the project which employed the most SE was completed in a third of the time that the project that employed the least SE took and that the projects that performed more SE delivered

better products. This exercise comes close to the ideal of a scientific, double-blind experiment but the sample size is small.

- Gharatya (2006) used a survey approach to collect data in rail and non-rail projects from which he concludes that project cost and schedule improve with the proportion of overall budget spent on SE, up to an optimum point that appears to be in the range 5-7% for the rail sector. He finds an average of 4.3% spent on SE in the metro rail projects that he looked at, compared with 7.6% in the defence projects looked at. With these data, he succeeds in constructing a business case that satisfies London Underground's investment rules for increasing SE expenditure in some scenarios. Gharatya also finds that the degree of satisfaction of requirements improves with SE expenditure. He acknowledges that, with the survey approach taken, there are concerns about the validity of the (often subjective) data supplied and the representativeness of the sample.
- Kludze (2004) describes a study to establish the value of SE within NASA that includes an analysis of a number of case studies from which he concludes that SE assists in the development of cost-effective systems, reduces risk and has a considerable and positive impact on technical performance. His analysis suggests that SE may shorten or lengthen the duration of the project. Like Gharatya, Kludze collected much of the underlying data by interviewing people and his findings are subject, therefore, to the same reservations about subjectivity. As I have already noted above, his case studies include one, anonymous NASA project that is an apparent counter-example. It was delivered a year late at twice the estimated cost despite performing a lot of SE.
- Goldenson and Gibson (2003) report results that *"provide credible quantitative evidence that Capability Maturity Model® Integration (CMMI®)-based process improvement<sup>6</sup> can result in better project performance and higher quality products."* The data were collected in 12 case studies in different countries, in different sectors and in projects of different sizes, but Goldenson and Gibson acknowledge that the

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<sup>6</sup> CMMI is a framework for supporting improvement in a range of processes that include SE processes.

degree of detail varied between the organisations and I wonder what else might have varied and whether the organisations that took part may have selected themselves on the grounds that their reports were not too negative. It is also acknowledged that this result is limited to software-intensive systems.

- Barker and Verma (2003) describe a study of 8 IT development projects over a period when both SE and project management processes were being improved. They found that the projects that had adopted more formal approaches to SE and project management enjoyed productivity levels 30% higher than the other projects. They conjecture that the improvements in SE and project management produced the rise in productivity but accept that the small sample size does not yield conclusive evidence for this conjecture.
- Boehm, Valerdi and Honour (2008) report a different approach. COCOMO is a parametric model used to estimate the effort required to complete software projects software. It is more than two decades old and is underpinned by a library of data collected from 161 software projects. Some of the parameters for which data was collected may be regarded as indicators of the amount of SE performed on these projects. After normalising for the effect of other parameters, the authors found that these parameters were correlated positively with productivity, measured in lines of code produced per person-day. Moreover, they found that the effect of SE parameters on productivity was greater for the larger projects than for smaller ones.
- I lead an INCOSE group that compiles case studies of the application of SE in transportation. At the time of writing, the published library of case studies (INCOSE Transportation Working Group, 2013) contained descriptions of 11 transportation projects, of which 7 were rail projects. With one exception, which was prepared from public domain sources, these descriptions were written by people not involved in the projects, from the results of interviews with people who had taken part in the projects. Each case study records reasoned beliefs that the adoption of some aspects of SE on the project benefitted the project. There is no suggestion that the sample of projects is representative – on the contrary, the projects were chosen to make the

case for SE – and the conclusions are based upon subjective testimony. However, there is evidence here that SE has been of benefit to the projects in question.

Taken individually, the findings of each of the studies described above must be treated with circumspection because at least one of the following is true:

- the studies looked at a small sample of projects;
- the sample of projects was restricted to one sector;
- the sample of projects was not representative of the wider populations; or
- conclusions are drawn on the basis of people's opinions.

Taken as a whole, though, the studies make a compelling case that adopting SE has been of benefit to projects across a wide range of domains.

Recently two studies with larger samples have been published:

- Elm and Goldenson (2012) present the results of a study containing an analysis of survey data from 148 projects, mostly performed by US defence suppliers, which shows a positive correlation between the adoption of SE practices and project performance.
- Honour (2013) describes the results of a statistical study of more than 90 projects in which he demonstrates a strong correlation between the percentage of the project budget spent on SE activities and certain metrics of project success, with the greatest success associated with projects spending 15-20% of their budget on SE. The projects studied were drawn predominately from the defence sector.

Honour shows that the correlation between the percentage of the project budget spent on SE activities and certain metrics of project success can be improved still further if the measured percentage is adjusted according to other factors that characterise the project. He searches for adjustments that optimise this correlation. He finds that the five changes to factors that most increase the percentage used are:

- more detailed definition at start;
- higher system level of integration;
- more development autonomy;

- smaller system size; and
- greater proof difficulty.

He conjectures that this provides some insight into the factors that affect SE effectiveness.

By selecting a population of projects that is dominated by one or two sectors, the researchers in both studies have reduced one dimension of unwanted variability at the cost of producing results that may not be representative of other sectors. I do not criticise these decisions, indeed, I regard such specialisation as necessary in order to make progress.

Elm, Goldenson and Honour employ fairly standard statistical hypothesis-testing techniques and obtain statistically-significant results but cannot escape the fundamental limitations that are associated with carrying out research in the field and that were set out in the previous section. Both obtain a significant proportion of their data from the testimony of interviewees and survey correspondents and the points of view of the contributors introduce an unknown amount of distortion and inconsistency into the data. The sample of projects studied is drawn predominately from certain sectors and countries and biased to an unknown degree by the fact that it is selected by the organisations concerned and these organisations may prefer to discuss more successful projects.

### **3.4 Reflections on the state of knowledge**

The two larger studies provide corroboration of the conclusion already reached that adopting SE has been of benefit to projects across a wide range of domains.

The studies performed by Honour, Elm and Goldenson also provide some indication of the magnitude of these benefits and some of the factors that influence this magnitude, which could be of real value to someone planning out a new project. However, if I repeat the two naïve questions that initiated this research:

- "If I apply SE to this project, will I see benefits that justify the cost?"
- "How should I adapt practices that have been developed in other sectors to make them work well on my project?"

then it is clear that the studies settle neither question completely. They increase the confidence that the answer to the first question will be 'Yes' and they provide indications of

the circumstances in which this is most likely to be the case. Honour's work could be used to suggest the optimal amount of a project budget that should be spent on SE. However, beyond that, the second question is hardly tackled at all.

### 3.5 Planning a way forward

There is scope, I conclude, to progress the research objectives further than has been achieved so far. However, a plan is needed to make progress. Four preparatory steps are identified:

- to carry out preliminary investigations into the nature of rail systems and projects in order to tighten the focus of the research;
- to achieve a workable definition of what SE is;
- to achieve a workable definition of (some aspect of) what 'better' might mean in the context of 'better rail systems' or 'building rail systems better'; and
- to define an appropriate research methodology.

These points are discussed in the next four chapters, before I proceed to describe the results of applying the methodology chosen.

### 3.6 Key points

3A There is evidence that there is room for improvement in the outcome of engineering projects across a wide range of domains, including the rail sector.

3B There are theoretical reasons for expecting that SE can benefit engineering projects, including the theories of:

- the control of complexity;
- whole system optimisation; and
- left shift.

3C There is empirical evidence that adopting SE has been of benefit to projects across a wide range of domains, including the rail sector.

3D There are theoretical and empirical grounds for believing that the benefits resulting from adopting SE depend upon factors other than the degree of adoption.



3E The research into the benefits of SE that has been carried out to date does not yet achieve the objectives that I have set for my research.

## 4 PRELIMINARY INVESTIGATIONS

When I defined my general research objectives (see key point 1B), I knew that it would be necessary to develop narrower and more refined objectives in order to establish an achievable research programme. I came to the research with prior knowledge of rail projects and systems but, in order to improve this knowledge and to expose my emerging ideas to comparison with the real world, so that they could be refined and developed, I carried out two preliminary studies, early on in the research. I also carried out some investigations into how the nature of rail projects should affect the manner in which SE principles are applied. In this chapter I explain why I carried out these investigations, what I did and what I found.

### 4.1 First preliminary study

In order to make progress towards my generic research objectives, I knew that I needed a better understanding of:

- the nature of SE;
- levels of application of SE;
- which outcomes mattered to project stakeholders;
- a causal relationship between application of SE principles and project outcomes; and
- other factors that affect project outcomes.

In the first preliminary study, I carried out a small survey, acknowledging that this was unlikely to deliver information of sufficient reliability upon which to base conclusions, because it provided an efficient way to advance my understanding in these areas.

I carried out a brief review of good practice in questionnaire-based surveys, looking at guidance published by the Market Research Society (2006) and Peterson (2000). I took this guidance into account when preparing a questionnaire, which I tested on two occasions.

I interviewed 13 people whom I knew and whose opinions I valued, in order to survey their experience of and opinions about the application of SE to projects. Most of my interviewees were current and past colleagues but some were people with whom I had had contact at INCOSE. 11 were based in the UK, 1 was based in Canada and 1 was based in the US.

Interviews were carried out using a questionnaire. In each interview I discussed a particular project on which the interviewee had taken a senior role. During the interview I asked a number of specific questions under five general headings:

- What sort of a project was it [that will be discussed]?
- What SE activities were carried out [on this project]?
- What were the most important success criteria<sup>7</sup> for the project and to what degree where they met?
- How did SE relate to the project outcomes?
- Is there anything else?

The questionnaire used is reproduced in appendix C. In formulating the questions about SE activities, I drew upon Atkins guidance on SE which I had prepared for the business before the start of the research.

Nine of the projects were in the rail sector, two were in the highways sector and two were in the aviation sector.

The responses to the questions about SE activities revealed that the rail projects had a lower uptake of SE practices than the non-rail projects but that the uptake was nonetheless significant: more than half of the activities inquired about were found to be put into practice by more than half of the projects, albeit in some cases with reservations expressed by the interviewee.

When I asked people what the success criteria were for their project, four responses were provided by more than half of the respondents (while no other factor was mentioned more than three times). These success criteria are reproduced in Table 1 below.

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<sup>7</sup> I phrased the question in terms of critical success factors, which was perhaps the wrong term but the examples clarified my meaning and the responses indicated that the interviewees understood what I meant.

**Table 1: Most commonly mentioned success criteria**

Response	Count	Mean Performance
Compliance with written requirements	10	2.5
Cost to complete project	9	0.5
Time taken to complete project	8	1.1
Actual performance in the field	7	2.1

Table 1 also contains a mean average indication of a score for the interviewee's impression of the performance of the project against these success criteria, using the following scoring scheme for the options from which they selected:

**Table 2: Scoring scheme for project performance**

Response	Score
Significantly exceeded expectations	4.0
Exceeded expectations	3.0
Met expectations	2.0
Fell below expectations	1.0
Fell significantly below expectations	0.0

Clearly there was scope for improvement in the perceived cost and time performance.

I asked interviewees how they believed that SE activities related to the project outcomes, seeking their views as to how the SE actually performed had contributed in practice and how more SE could have contributed. Interviewees generally believed that there was a positive correlation between SE activities and project outcomes, particularly for the following SE activities: requirements management; verification and validation; and configuration management / change control<sup>8</sup>.

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<sup>8</sup> By 'requirements management' I mean the activities associated with the 'Stakeholder Requirements Definition' and 'Requirements Analysis' processes in (ISO/IEC, 2002) which comprise activities to compile and structure requirements, resolve problems with them and keep them up-to-date.

Interviewees also believed that there was a positive correlation between project outcomes and:

- how well the SE activities carried out were integrated with other project functions; as well as
- how early they were carried out.

#### 4.2 Second preliminary study

I have already stated that my generic research objectives were too general to pursue in their full breadth and that I needed to define additional specific research objectives. The second preliminary study was designed to explore the relationship between:

- requirements management; verification and validation; and configuration management / change control, as input parameters; and
- the volatility of key project input and output documents, as output parameters.

By the volatility of a document, I mean the sum of the size of all changes made to the document over the period from its first issue as a basis for formal work until the end of the project, expressed as a proportion of the document's final size. So a document which had 100 pages of content in its final issue and was subject to three changes in which 1, 2 and 3 pages, respectively, were added or changed, would have a volatility of  $(1+2+3)/100 = 6\%$ .

In calculating the volatility of a document, I only take account of 'normative' content – content that directly affects the work depending upon the document. I do not take into account front sheets, glossaries, introductions and so on. I measure the content either in number of pages, or, where the document content is expressed as a number of short, numbered clauses, in the number of clauses.

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*By 'verification and validation' I mean the activities associated with the 'Verification' and 'Validation' processes in (ISO/IEC, 2002) which comprise activities to check the system and its documentation against the requirements and design for the system.*

*By 'configuration management / change control' I mean the activities associated with the "Configuration Management" process in (ISO/IEC, 2002) which comprises activities to maintain the integrity of the system and its documentation by establishing baselines and controlling changes to these baselines.*

The volatility of requirements, in the sense described above, is a metric that is collected for software projects for management and research purposes. My definition is consistent with that proposed by Loconsole (2008).

I chose requirements management; verification and validation; and configuration management / change control as input parameters because the first preliminary study suggested that these were the aspects of SE that had the greatest effect on project outcomes.

I chose a measure of change because the rail projects that I worked on had been beset by unnecessary change, some of which I thought could have been forestalled by better SE. Moreover, the three most prevalent theories for the manner in which SE can benefit projects (control of complexity, whole-system optimisation and left shift, see key point 3B) all suggest that SE should be able to forestall change, because:

- The ‘control of complexity’ hypothesis (RAEng, 2007; American Society of Civil Engineers, 2009; McNulty, 2011), which states that it becomes impossible to realise systems that have surpassed a certain threshold in complexity without using SE, at least without unacceptable rework, implies that, without SE, expensive system-level faults will remain in the system and that late changes will be required to remove them.
- The ‘whole-system optimisation’ hypothesis (Hitchins, 1998; Flyvbjerg, Bruzelius and Rothengatter, 2003; ProRail and Rijkswaterstaat, 2008) suggests that SE provides a means of optimising the system as a whole that is not provided to a satisfactory degree by other disciplines and some of these optimisations will result in changes whose desirability would otherwise only have become evident after the system had been realised.
- Some of the savings that the ‘left shift’ hypothesis (Honour, 2013; INCOSE, 2010) suggests will accrue from investing in the early stages of a project will be associated with the elimination of latent change.

I chose volatility rather than the total volume of change because it is a normalised measure which can be compared between projects.

In the second preliminary study, I looked at 6 UK rail projects. I interviewed senior members of each project. Interviews were carried out using a questionnaire, in which specific questions were organised under the headings of five general questions:

- What sort of a project was it [that will be discussed]?
- What requirements management and V&V activities were performed [on this project]?
- What configuration management activities were performed [on this project]?
- How much rework was performed on the project?
- To what extent was the final system fit for purpose?
- Is there anything else?

I prepared the questionnaire and a data collection procedure in advance. The questionnaire used is reproduced in appendix C. In formulating the questions about SE activities, I drew upon an analysis of the relevant parts of an SE standard (ISO/IEC, 2002) and a configuration management standard (ISO, 1997) to prepare detailed questions about the activities performed.

All these projects had maintained registers of changes and I made an estimate of the volatility of input and output documents by reviewing the description of each change, estimating the number of pages or clauses of change to the normative content of the document (excluding document control sections, glossaries and so on), adding up the total volume of change for the whole document and dividing by the total volume of normative content in the final version of the document.

I found no clear correlation between volatility and the degree of adoption of good practice in the aspects of SE that I asked about. This was not surprising, perhaps, given the small size of the sample, the number of confounding factors and the fact that, on one project, volatility had been driven upwards by the fact that the project organisation was learning how to meet new SE requirements from its customer (that is, adding SE to this project increased volatility).

However the volatility figures that I calculated were striking:

- The volatility of input documents varied between 0% and 74%, with a mean of 49%.

- The volatility of output documents varied between 57% and 225% with a mean of 118%.

A mean volatility of 118% for output documents would mean that a normative clause or page from the consolidated set of output documents would have changed at least once, on average, during the course of the project.

A volatility of more than 200% for output documents (and there were two projects that had such a volatility) would mean that a normative clause from the output documents for this project would have changed at least twice on the average during the course of the project.

The estimating method was inexact and some changes to documents may not have been associated with changes to the system being built. Nevertheless, every change to a document must be made by someone and checked by someone and, if the document is being used as the basis of further work, read, understood and acted upon by a number of other people.

At the time I was surprised by how high these figures were but I have since learned that they are not inconsistent with the volume of change experienced in other industries. Pickard, Nolan and Beasley (2010) found that more than half of the requirements for control systems for gas turbines typically change between the first major design review and entry into service. Sterman (2000; pages 58-59) reports on research that found that the fraction of work done correctly first time was 34% for defence projects and 68% for commercial projects.

The levels of volatility, in output documents especially, are high enough to suggest that there was room for significant reductions in volatility on these projects and that such reductions would have resulted in significant reductions in cost.

What the initial study suggested and, as we shall see, what other data will corroborate, is that, on some rail projects at least, change is a significant source of avoidable cost and delay and that, as a consequence, it would be fruitful to explore the potential for SE to reduce this cost. This is in fact the way in which I chose to direct my research, as I describe in chapter 6 below.



### 4.3 The nature of rail systems and projects

One of my generic objectives (see key point 1B) was, *“To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects”*. The high volatility encountered on a small sample of rail projects suggested that this was a fruitful area to research. But the same logic leads to the conclusion that it is a fruitful area for the practitioner to focus SE upon. This suggests that a partial and provisional answer is, *“To achieve optimum results in major rail projects, focus SE on avoiding unnecessary costs of change”*.

Some writers claim a need to tailor SE for the rail sector. Williams et al (2004), describing experience of employing SE in projects undertaken on the London Underground, report as a lesson learnt that *“there is a need to established [sic] a systems engineering model specifically tailored to the railway environment and its supply chain”*. Moreover, Gharatya, as reported in (Sullivan, 2007), states that London Underground had chosen to *“tailor their SE methodology to fit the unique needs of their internal and external stakeholders”*.

It is the case that SE practice in the rail sector is evolving in a manner that departs in some respects from practice in other sectors. For example, a recent set of guidelines on the application of SE to public works, including rail infrastructure, in the Netherlands (ProRail and Rijkswaterstaat, 2008) is based upon an international SE standard (ISO/IEC, 2002) but supplements it with sector-specific guidance.

I drew upon my experience and the experience of colleagues to investigate how the nature of rail systems and projects might make some adaptation of SE practices desirable.

In collaboration with my supervisors and with Anne O’Neil, then Chief Systems Engineer for New York City Transit (NYCT), I published a paper in the peer-reviewed journal ‘Systems Engineering’ with the title, *“Overcoming barriers to transferring systems engineering practices into the rail sector”* (Elliott, O’Neil, Roberts, Schmid and Shannon, 2012). In this paper, my co-authors and I argued that the balance of concerns differs between a typical project in the rail sector and one in the domains in which SE was developed and that this difference, together with a lack of agreement on the scope of SE and differences in tradition between SE and the established rail disciplines, raises barriers to the effective and efficient

importation of SE ideas into the rail sector. My co-authors and I went on to argue SE practices should be adapted in order to overcome these barriers.

The full text of the paper is reproduced in appendix D. In this section, which includes sections of text taken with varying degrees of modification from the published paper, I reflect on the nature of rail systems and rail projects and suggest ways in which this nature may justify adaptations to the SE practices developed in SE's traditional sectors.

Although I do not contend that rail systems or rail projects are *fundamentally* different from those in the sectors in which SE has traditionally been applied, I do argue that the balance of concerns differs between a typical project in the rail sector and one in the domains in which SE was developed because rail projects have to cope with two major complicating factors.

Firstly, rail projects are better understood in terms of enhancing existing systems than creating new ones.

In SE's traditional domains it is often possible to draw a boundary around the system that is being created and to make progress in a self-contained manner, albeit only with the proviso that due attention is paid to the interactions with other systems and with the surrounding environment and respecting the constraints that these interactions impose.

By contrast, railways are highly-interconnected systems. Railway infrastructure components have a myriad of mechanical and electrical connections between them. Moreover, the presence of trains travelling across the network multiplies the complexity by introducing long-distance interactions. Consequently, it is necessary to consider a significant part of the whole railway, if not all of it, as the system being worked upon and, apart from the very rare projects that create brand new railways, rail projects are always changing existing systems.

Secondly, the difficulty of carrying out rail projects is exacerbated by the fact that the railway must usually continue to operate as it is being changed. Mott et al (2005) highlight the importance of this when they assert that *"The trickle of railways requiring upgrades for a variety of reasons has now become a flood, and railway suppliers and authorities worldwide increasingly need to deal with the requirements of metros where signalling and train control has to be upgraded – without stopping the running railway."*

The team for a project that is changing a railway while it remains in service must map out a migration path that splits the overall change down into a sequence of smaller changes, each of which can be accomplished within a short period, a weekend perhaps, and each of which will leave the railway in a state that allows operations to resume.

I identify a third reason why adapting SE practices may be beneficial: Existing rail disciplines already perform tasks that deliver some of the objectives of a traditional programme of SE activities. However, because the rail and traditional SE approaches have evolved separately, they sometimes deliver the same objectives in different ways. For example, it has been common practice in multidisciplinary projects at NYCT and in Britain for some considerable time to subject elements of the design to an 'inter-disciplinary check' – a review by all the disciplines involved. The purpose of this check clearly overlaps the purpose of the design reviews that are common in multi-disciplinary defence projects. Where effective practices already exist, it is likely to be inefficient to change them to fit traditional SE practices and more efficient to adapt traditional SE practices to fit with what is already done.

I argue that, as a consequence of the observations made above, some SE practices that have been developed in other industries require adaptation if the objectives that they serve are to be achieved efficiently and effectively in the rail sector. In particular I suggest that, when taking SE practices developed in another sector and applying them on a rail project, practitioners should:

- look for proven practices in use within the organisation that deliver the same objectives as the 'foreign' SE practices and retain existing practices unless there is a clear benefit in changing;
- be prepared to be flexible about the scope of what is referred to as SE and to exclude functions that are satisfactorily performed by existing rail disciplines;
- plan to expand significantly the 'foreign' functions concerned with migration from one stage to another; and
- take account of the fact that many design decisions about the structure of the system will already have been taken in the context of the railway as a whole (and often recorded in standards) and adjust the 'foreign' design processes to reflect this.

#### 4.4 Key points

4A In a small sample of projects, the most commonly mentioned success criteria were:

- Cost to complete project
- Compliance with written requirements
- Time taken to complete project
- Actual performance in the field

4B In a small sample of rail projects, the volatility of input and output documents was found to be high.

4C The levels of volatility are high enough to suggest that there was room for significant reductions in volatility on these projects and that such reductions would have resulted in significant reductions in cost.

4D It would be fruitful to explore the potential for SE to reduce the avoidable cost of change.

4E Focussing SE on reducing avoidable costs of change may assist with maximising the benefits that it provides to rail projects.

4F Because of the nature of rail projects, practitioners seeking to maximise the benefits that SE provides to rail projects would be well advised to:

- look for proven practices in use within the organisation that deliver the same objectives as the 'foreign' SE practices and retain existing practices unless there is a clear benefit in changing;
- be prepared to be flexible about the scope of what is referred to as SE and to exclude functions that are satisfactorily performed by existing rail disciplines;
- plan to expand significantly the 'foreign' functions concerned with migration from one stage to another; and
- take account of the fact that many design decisions about the structure of the system will already have been taken in the context of the railway as a whole (and often recorded in standards) and adjust the 'foreign' design processes to reflect this.



## 5 A WORKABLE CHARACTERISATION OF SYSTEMS ENGINEERING

### 5.1 Introduction

Opinions vary about what SE is. In order to study the effects of adopting SE approaches on project outcomes, I need a characterisation of SE that meets the following criteria:

- A. it can be applied objectively to divide project activities into SE activities and other activities;
- B. it includes activities that are broadly recognised as SE activities; but
- C. it does not include so much as to draw large areas of what is regarded as project management into the scope of SE

I seek a characterisation that also meets the following additional criterion:

- D. it is the subject of broad consensus.

In this chapter I look for existing characterisations that meet these criteria but, finding none, I define a new characterisation for use in my research. My new characterisation is not itself the subject of broad consensus but there is broad consensus that the activities that it covers are indeed part of SE.

### 5.2 SE in the wider systems movement

Before trying to characterise SE, I look at its relationships with other related areas of activity; it may help in characterising SE to understand some related things that it excludes.

SE has been part of a wider systems movement for a long time. Von Bertalanffy (1962) characterises SE as one of a number of fields of applied system science, together with Operations Research and Human Engineering, which he then contrasts with fields of system theory, including cybernetics, information theory, game theory, decision theory and general system theory. The paper is reprinted in a book (Beishon and Peters, 1981) that is devoted to describing this broad 'systems movement'. See page 61 for the characterisation cited.

Emes et al (2005; figure 3) locate SE in a broader landscape. They draw a map of SE and 'competing' disciplines that shows overlap between SE, on the one hand, and, on the other,

operations research, project management, systems analysis, system dynamics, control theory, soft systems methodology, industrial engineering, general engineering, information technology and economics, among others.

Checkland (1999) delineates one boundary on this map that is of particular interest. He applies his soft systems methodology to 'human activity systems', which are systems of people working together. He distinguishes these systems from 'hard', or technical, systems. He observes that, when dealing with 'soft' systems, one cannot assume a system and a set of requirements for it, albeit initially hidden and to be revealed by discussion. Instead one starts with a problem situation, which may include the fact that different people see different problems; one chooses one or more appropriate systems to work with and then one negotiates agreement on a change to be made. The methodology that he has developed for this purpose looks very unfamiliar to a conventional systems engineer and yet has a record of three decades of application.

There is considerable discussion within the SE community on the application of SE to 'enterprises', that is to say, to organisations. Indeed the September 2007 edition of 'Insight', the newsletter of the society, was devoted to this theme. There is clearly no sharp boundary between 'hard' and 'soft' systems – dealing with the 'soft' issues is a part of every 'hard' systems deployment but there is a general tendency for systems thinking to move further into 'soft' territory.

For example, systems thinking has been applied to considering societies as systems. Buckley (1968) provides a thoughtful review of early attempts to do this. History teaches that a society that persists over any length of time will constantly restructure itself to adapt to changing circumstances. In this field, the focus shifts from studying the structure of the system to understanding the processes that allow it to adapt itself effectively.

### 5.3 Existing characterisations of SE

There is no shortage of potential characterisations to choose from - in fact the abundance of possible characterisations is an acknowledged problem for the practice of SE and research into its effects. Emes, Smith and Cowper (2005) argue that SE *"still doesn't know very well what it is"* and that, if it is to prosper, it should *"take a strategic view on which [...] fields it*

wants to embrace” in order to develop a clear “brand”. Hoos (1976) – see (Beishon and Peters, 1976| page 163) – ascribes a certain amorphousness to the entire systems approach of which SE is a part:

*“[...] both strength and weakness lie in its [the systems approach's] myriad forms and manifestations, the very variety of which is encouraged by the latitude of interpretation as to what actually constitutes the systems approach. There is strength, because a concept so generously dimensioned and so encompassing in scope not only has widespread usefulness in many contexts but, through vagueness, maintains a kind of featherbed resilience against attack and, hence, a marked invulnerability to criticism, But lack of articulation conveys weakness, too, the more so because high among the attributes claimed for the systems approach is its precision, in the designation of parameters, identification of objectives, and measurement of inputs and outputs.”*

Honour and Valerdi (2006) note that this lack of agreement poses a difficulty to the researcher. They write, *“One of the greatest difficulties in quantifying SE is the lack of such a shared conceptualization on the field of study”*.

One obvious way of characterising SE is to look for an agreed definition. Buede (2000; page 9) lists seven different definitions of SE. The SE Handbook published by INCOSE (2010; page 7) lists three definitions.

The common entry in these two lists is INCOSE’s own definition, *“Systems engineering is an interdisciplinary approach and means to enable the realization of successful systems.”* This is more of a description than a definition and does not meet my criterion (A).

In passing, I note that INCOSE’s definition is not wholly consistent with its own usage as the organisation has working groups (INCOSE, 2008) looking at the application of SE to sustainment of successful systems as well as their realisation. This is not a problem in the context of this research, which is however concerned wholly with projects, but further erodes confidence in the definition.



It is clear that there is no definition of SE that meets all my criteria so I look at other approaches to characterising SE. Four further approaches can be identified:

- as a process;
- as a discipline;
- by activities or roles; and
- by principles.

Each is now discussed in turn.

### 5.3.1 Characterising SE as a process

By a 'process', I mean a set of activities together with some indication of how they are ordered or how information flows between them, or both.

SE standards and handbooks describe SE in terms of a process, which might suggest that, at heart, SE can be usefully regarded as a process. But, if so, which is the real SE process? The processes are different.

It is not that there is a shortage of descriptions of SE. More than a decade ago, Sheard and Miller (2001) reported that there was *"a dizzying array of software and system process standards, recommended practices, guidelines, maturity models, and other frameworks."* There remain many descriptions. Some, such as (ISO/IEC, 2002; EIA, 1998; IEEE, 1998; INCOSE, 2010) are independent of any sector while others, such as (ECCS, 2004, London Underground Limited, 2009; ProRail and Rijkswaterstaat, 2008) are specific to a single sector.

INCOSE (2014) publishes a 'Consensus of the SE Fellows' on what SE is, based upon conversations with senior systems engineers and analysis of standard reference books. The consensus is expressed in terms of a process, which is termed SIMILAR from the names of its steps (State the problem, Investigate alternatives, Model the system, Integrate, Launch the system, Assess performance, and Re-evaluate). Presumably this was created to resolve the problem of which process to choose but it just adds another process from which to choose and one that seems to be at odds with other standards in having no home for SE activities that cut across the life cycle.

Wymore (1993) proposes a rigorous set-theoretical treatment of SE as an activity founded on modelling. His description includes an SE process. His approach starts from the premise that a system's interaction with its environment can be usefully modelled as a series of inputs and outputs and that the system can be modelled as a state machine. I am not convinced that this is valid for railway systems. I cannot see how one usefully models as inputs and outputs the gauging and electromagnetic interactions between trains and infrastructure or the interactions between train sub-systems that give rise to power requirements and axle loadings. However, Wymore's approach could be generalised to resolve these concerns. Although Wymore describes an SE process, his approach can be distinguished from those seen so far by the fact that significant intellectual content would remain if the process were to be removed.

There have been efforts to harmonise these standards for some time (Kitterman, 2007) but, in the meantime, there are divergent forces at work. Hybertson and Sheard (2008) distinguish old (mechanistic) SE from a new (organic) SE, which concerns systems that experience continual change, are autonomous and self-organising, and which has a radically different approach to change, risk, uncertainty, control and contradiction. They argue that the two types of SE should be unified, principally through modelling. The papers cited in this section suggest that there is likely to be a backlog for those working on harmonisation for a considerable period of time.

The processes described are not consistent with each other and, as there is no consensus on which process is the right process, it follows that each must exclude approaches to SE that are used in practice. I conclude that there is no characterisation of SE as a process that meets criterion (D).

### **5.3.2 Characterising SE as a discipline**

The relevant definition of 'discipline' in Collins Concise Dictionary is "*a branch of learning or instruction*".

Aslaksen (2007) describes a debate between senior members of INCOSE about aspects of SE, in particular the degree to which it has intellectual content of its own, acknowledging that SE shares a lot of its intellectual content with established engineering disciplines. Aslaksen

argues that SE involves reasoning about requirements and functions as abstractions and that this is something that established engineering disciplines do not do. Wymore (1993) provides examples of such reasoning. I find Aslaksen's argument convincing.

When Honour (2013) writes "*In many ways, however, less is understood about SE than nearly any other engineering discipline,*" he clearly assumes not only that SE is a discipline but also that it is an engineering one. Stoddart (1999) seems to accept that SE is a branch of engineering but questions whether it is a separate discipline.

A recent project has compiled an SE Body of Knowledge as an online encyclopaedia (SEBoK, 2013).

INCOSE publishes a handbook of SE (INCOSE, 2010) and uses this as a syllabus for a program for the certification of SE professionals and several universities offer SE degree programmes, so it is difficult to challenge SE's status as a discipline. It is, however, quite possible to challenge its status as an *engineering* discipline, given that Emes, Smith and Cowper (2005) identify overlaps of SE with operations research, systems analysis and project management, among several other non-engineering disciplines.

Dixit and Valerdi (2007) explore the related question, 'Is SE a profession?' and conclude that it has not yet demonstrated that it meets the criteria for being regarded as a profession but that it may satisfy these criteria in the future.

I do not need to answer the question "Is SE a discipline?" to further the research and I choose to express no opinion on the matter. Given that overlaps between SE and other disciplines have been identified, it is clear that, even if SE were a discipline, attempting to use the coverage of the discipline as a basis for dividing project activities into SE activities and other activities would result in including an excessive amount of activities that common sense would ascribe to other functions, such as project management. These characterisations therefore do not meet criterion (C).

### **5.3.3 Characterising SE by activities or roles**

I am using 'process' to denote a set of activities together with some indication of how they are ordered or how information flows between them, or both. If we remove the indications of ordering and information flows, we are left with just a set of activities. That seems an

attractive approach for my purposes and other researchers into the value of SE have come to the same conclusion. Honour and Valerdi (2006) define a taxonomy (they call it an 'ontology') of SE activities that classifies them under the following headings:

- Mission/purpose definition
- Requirements engineering
- System architecting
- System implementation
- Technical analysis
- Technical management/leadership
- Scope management
- Verification and validation

Honour (2013) uses a small variant on this taxonomy (with 'System implementation' replaced by 'System integration') in his research into the return on investment in SE.

It is still not clear that this taxonomy is sufficiently general to encompass the practice of SE in the rail sector. For example, transition into service, which is a significant SE issue for railway systems, has no clear place in the taxonomy.

Another way of defining the activities associated with SE is indirectly, by defining them to be the activities carried out by people performing certain roles. A discussion on the value of SE, during which the participants seemed to be talking about entirely different definitions of SE led Sheard to write a pair of papers (Sheard, 1996a, 1996b) in which she characterises SE activities in terms of twelve roles that those performing SE activities might play and then explores the way in which each might contribute value to a project. This is an interesting variant on the approach taken by Honour and Valerdi but one on which there is no clear consensus.

So, I find no characterisation of SE by activities or roles that meets criterion (D), although, when I come to creating my own characterisation of SE, I choose to express it in terms of activities.

### 5.3.4 Characterising SE by principles

An interesting and even more abstract way of characterising SE is by articulating the principles that underpin it. In its very early days, INCOSE (1993) published a set of ‘pragmatic principles’, organised under eight headings:

- Know the problem, the customer, and the consumer;
- Use effectiveness criteria based on needs to make system decisions;
- Establish and manage requirements;
- Identify and assess alternatives so as to converge on a solution;
- Verify and validate requirements and solution performance;
- Maintain the integrity of the system;
- Use an articulated and documented process; and
- Manage against a plan.

The principles are statements such as, *“Don't assume that the original statement of the problem is necessarily the best, or even the right one.”* The idea appears to have been abandoned and, in any case, would be difficult to apply to separate SE activities from non-SE activities and so I find no characterisation of SE by principles that meets criteria (A) and (D).

### 5.3.5 Further remarks

It is possible, of course, that the term ‘SE’ might cover more than one thing. Sheard (2000) implies that this is the case when she distinguishes three types of SE, *“**Discovery**, a discipline or specialist type that involves significant analysis, particularly of the problem space; **Program Systems Engineering**, a coordination or generalist type that emphasizes the solution space and technical and human interfaces; and **Approach**, a process type that can (and should) be performed by any engineer”*.

‘Approach’ would occupy the overlap between SE and other engineering disciplines and would, presumably, be practiced by engineers doing ‘Discovery’ or ‘Program SE’ as well. ‘Discovery’ and ‘Program SE’ appear to be discernible flavours of SE and, where the delivery of a system is contracted, to correspond to the activities performed by customer and supplier, respectively.

If one looks at a commonly-used SE standard (ISO/IEC, 2002), for example, one finds that the first process in the SE lifecycle, 'Stakeholder Requirements Definition', includes an activity to elicit stakeholder requirements by talking to stakeholders. This surely is written from the supplier's point of view because it leaves implicit the question of central importance to the customer: which of the many, many things that stakeholders want are we going to try and deliver with this system?

Hitchins (2003) describes an approach to SE that seems to represent the customer's point of view and to align with 'Discovery'. He describes SE in a manner that emphasises its value in terms of defining the optimal system to meet certain general wants and needs rather than in terms of delivering against a specification.

### **5.3.6 Discussion**

The literature makes clear not only that there is no consensus on the precise answer to the question, "What is SE?" but that aspects of the answer are explicitly disputed. No existing characterisation has been found which meets all my criteria.

It is therefore necessary to create a new characterisation to support the research. However, the farther that I depart from the characterisations that are in common use, the less value the research will have and, so, I wish to minimise this distance. Comparison of the characterisations above suggests that if one were to pose the question, 'Which types of project activities are SE activities?' to a number of authorities on SE one might expect there to be a common set of activities that are present in the majority of the answers.

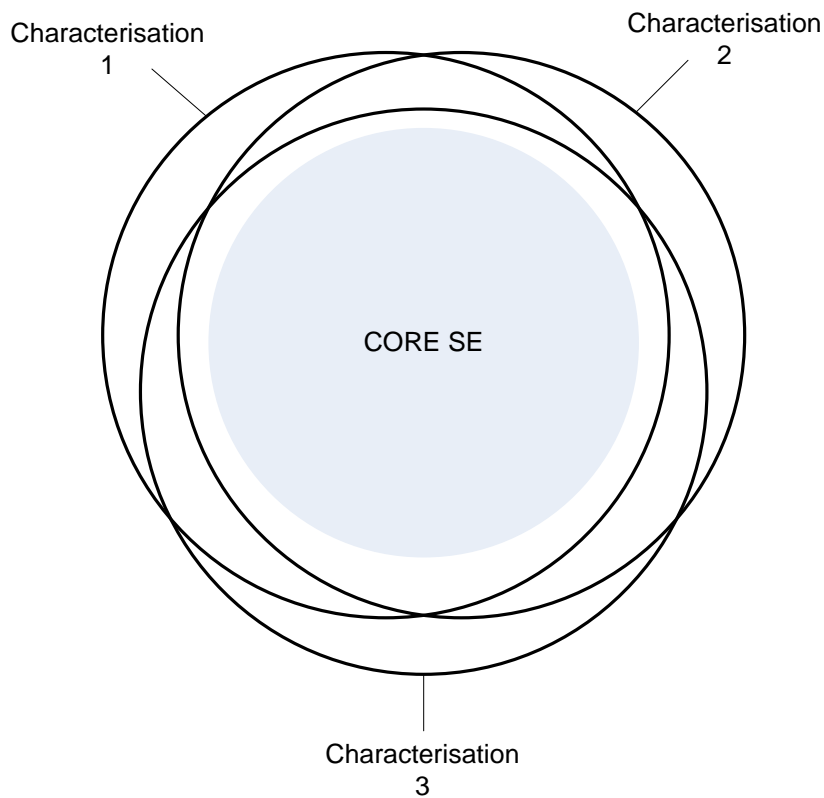
In the next section, I propose a definition of 'core SE' that is designed to capture this common set of activities.

## **5.4 Core SE**

### **5.4.1 Defining core SE**

There may be many different characterisations of SE but they are not completely different. The sets of project activities that they define tend to overlap significantly, with differences at the margin, as Figure 2 illustrates. I seek a coherent and principled definition of a set of 'Core SE' activities (as illustrated by the central blue circle in Figure 2) within that shared overlap.

It would be possible then to claim that there was broad consensus that the core SE activities were SE activities, even if accepted characterisations differed about what other activities should also be regarded as SE activities.



**Figure 2: Core SE in the context of other characterisations of SE**

Software engineers are taught that understanding the data underpinning a programme's operation often provides a quicker, surer and more enduring grasp of the programme than a view focussed on its functionality. The characterisations of SE that I have discussed are generally phrased in a way that is related to what systems engineers do, that is to say, in a way that is related to function.

When transferring ideas from software to project processes, the counterpart of data would be intellectual artefacts (documents, drawings, databases and so on) that are produced, used and updated during these processes. I attempt to define SE in terms of artefacts.

In general terms, my approach to characterising SE is to identify a number of core SE artefacts that I find in the majority of the characterisations of SE that I have seen and then to

define core SE to be the activities that create, change or check these artefacts. However, this simple account of my approach needs to be refined in two ways:

- Firstly, I acknowledge that there is very considerable variation in practice when it comes to deciding how to partition content between physical artefacts (documents, drawings, databases and so on) and so I work with 'logical artefacts', which are defined by their content and which may correspond to one or more physical artefacts or parts of physical artefacts.
- Secondly, in presenting a coherent account, I find it convenient to define SE logical artefacts in the context of a number of project management artefacts.

In the text below, I list the key SE and project management artefacts. I organise the list in three levels that correspond to major phases of a typical project.

The descriptions of the artefacts should be read as definitions of the terms in bold text. If the terms are interpreted on a real project then the extent of the defined logical artefact will be the physical artefact, physical artefacts or parts of physical artefacts that correspond to the definition, no matter what the project members choose to call them.

The SE and project management artefacts are illustrated in Figure 3.

At the **requirements level**, the following logical artefacts exist:

- A **requirements specification**, which is intended to document all the requirements from all the stakeholders. These will include requirements on the cost and schedule for the project.
- A **context specification**, which is intended to document all relevant, significant facts and assumptions about the environment in which the system will operate, including the physical, commercial, economic and regulatory aspects of the environment.

At the **system level**, the following logical artefacts exist:

- A **system specification**, which is a specification of the system to be built. If the system is to be introduced into service in a number of stages then the interim states of the system should be specified as well as the final one.



- A **system budget**, which specifies a commitment to complete the project within a certain maximum cost.
- A **system schedule**, which specifies a commitment to achieve completion of the project and possibly other intermediate milestones within certain windows of time.

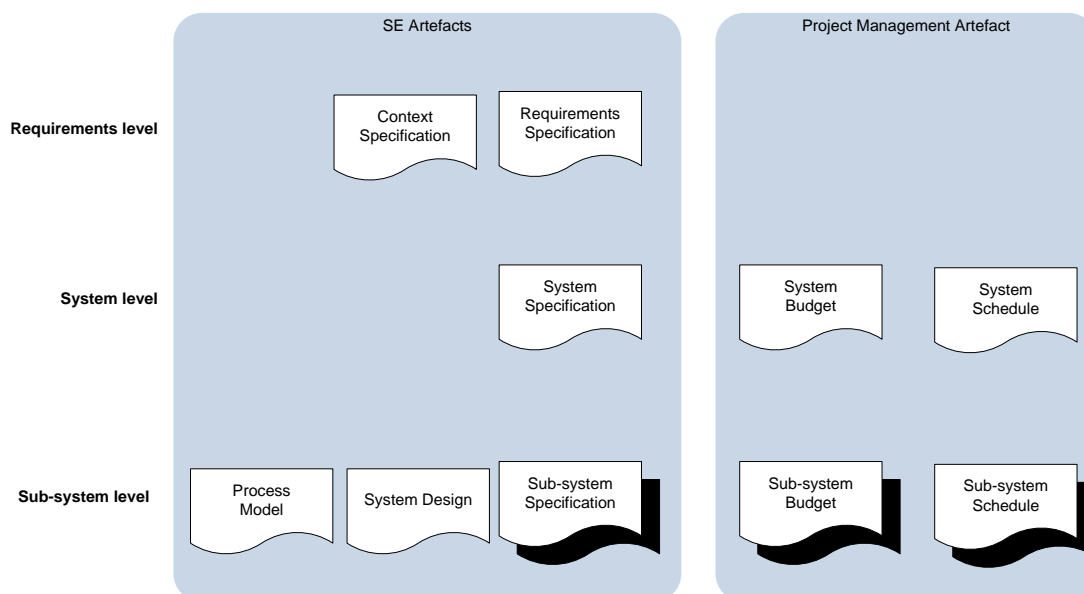
I assume that the system is divided into **sub-systems**. At the sub-system level the following logical artefacts exist for each sub-system:

- A **sub-system specification**, which specifies what sub-system must be built. It is common to create interface specifications to define the interface between two or more sub-systems. For the purpose of this model, I take these as shared components of the specifications of all sub-systems that engage in the interfaces.
- A **sub-system budget** – a maximum cost for the delivery of the sub-system.
- A **sub-system schedule** against which the sub-system must be delivered.

At the sub-system level the following logical artefacts exist for the project as a whole:

- A **system design**, which explains how the sub-systems work together within the environment in which the system will operate in order to achieve compliance with the system specification.
- A **process model**, which describes the definition, design, implementation and transition into service of a system to a level that makes clear the information that must flow between the project teams and delivery functions.

I regard the specifications, the system design and the process model as **SE artefacts**. This classification is consistent with my general understanding of SE and something that I will justify shortly, when I compare core SE with two well-known SE standards. I regard the budgets and schedules as **project management artefacts**. That is a common sense definition and one that is consistent with PRINCE 2, a well-used project management method (Office of Government Commerce, 2002) that includes these items within the Project Plan, a product of applying the method.



**Figure 3: SE and project management artefacts**

I then define **core SE** to be the totality of all project activities that affect or use the SE artefacts in at least one of the following ways:

- they create content of the SE artefacts;
- they control change to the SE artefacts;
- they check the correctness or assess the implications of the SE artefacts; or
- they check the system and its sub-systems against the SE artefacts.

For the purposes of my research, I work through this definition of core SE to produce six core process areas – three that create SE artefacts, two that check them and one that controls change to them. These process areas are defined in Table 3. Table 4 indicates how the process areas cover the range of activities included within the definition above. The partitioning is chosen to align with the division of SE set out in well-used SE standards.

**Table 3: The process areas within core SE**

Core SE Process Area	Description
Model (the project) processes	The preparation and maintenance of the process model.
Manage requirements and specify the system	The preparation and maintenance of the context specification, requirements specification and the system specification.
Design the system	The preparation and maintenance of the systems design and sub-system specifications.
Model, simulate and analyse the system	Modelling, simulation and analysis of actual and potential alternative system designs.
Verify and validate the system	Activities to check the system and its components against the SE documents.
Manage change	Activities to log requests for change, support decisions about what to do and to track the implementation of agreed decisions.

**Table 4: The relationship between core SE process areas and SE artefacts**

SE Artefacts	Create content of artefact	Check the artefact	Check system against artefact	Manage change to artefact
Context Spec.	Manage requirements and specify the system	Model, simulate and analyse the system	Verify and validate the system	Manage change
Requirements Spec.				
System Spec.				
System Design.	Design the system			
Sub-system Specs.				
Process Model	Model (the project) processes			

I have said that I wish the definition of core SE to capture activities that are shared by widely-used characterisations of SE and, in defining SE and articulating its component areas, I have tried to achieve this by keeping these characterisations in mind. To test whether I have succeeded, I compare it with two widely-used SE standards:

- ISO/IEC 15288 (ISO/IEC, 2002) contains definitions of 25 processes. It is, in my experience, the most widely used SE standard – the INCOSE handbook is structured around its processes, for example.<sup>9</sup>
- EIA-632 (EIA, 1998) is another well-established and well-known SE standard. It is the standard that Valerdi and Wheaton (2005) referred to when creating a standard SE

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<sup>9</sup> Actually, to be quite precise, the INCOSE handbook is structured around the processes in the 2008 version of the standard. Both versions remain in use: the 2002 version remained the version adopted as a British Standard at the time of writing. The differences between the lists of processes defined by the two versions are not significant.

work breakdown structure for the purposes of research into estimating methods. It is structured in a slightly different way from ISO/IEC 15288. It contains definitions of 13 SE processes, each of which is associated with one or more requirements. Each requirement, in practice, defines a sub-task within the parent process.

Table 5 identifies the aspects of the two SE standards cited above that are considered to fall within the six core SE process areas.

EIA-632 is structured around a number of requirements and the table lists the requirements (or, in some cases, parts of requirements) that relate to the core SE process area. These requirements are given serial numbers in the standard and the serial numbers are reproduced in the table.

ISO/IEC 15288 is structured around a number of processes and the table lists the processes (or, in some cases, parts of processes) that relate to the core SE process area.

The table also contains, in a row at the bottom, a list of the processes and requirements that were not mapped to any core SE process area.

**Table 5: Mapping the core SE process areas to the requirements of SE standards**

<b>Core SE Process Area</b>	<b>ISO/IEC 15288 Processes</b>	<b>EIA-632 Requirements</b>
Model (the project) processes	System Life Cycle Process Management (as it relates to a particular project) Project Planning	4: Process Implementation Strategy 7: Technical Plans
Manage requirements and specify the system	Stakeholder Requirements Definition Requirements Analysis Verification (of the items above) Validation (of the items above) Transition (as it relates to the migration sequence)	14: Acquirer Requirements 15: Other Stakeholder Requirements 16: System Technical Requirements 25: Requirements Statements Validation 26: Acquirer Requirements Validation 27: Other Stakeholder Requirements Validation 28: System Technical Requirements Validation 32: Enabling Product Readiness (as it relates to the migration sequence)
Design the system	Architectural Design Verification (of the items above) Validation (of the items above)	12: Outcomes Management (Item d: interface management) 17: Logical Solution Representations 18: Physical Solution Representations 19: Specified Requirements 21: Transition to Use 29: Logical Solution Representations Validation 30: Design Solution Verification
Model, simulate and analyse the system	Decision-making Risk Management	12: Outcomes Management 22: Effectiveness Analysis 23: Trade-off Analysis 24: Risk Analysis
Verify and validate the system	Verification (of the system and its components) Validation (of the system and its components)	31: End Product Verification 33: End Products Validation
Manage change	Configuration Management	12: Outcomes Management (Items b and c: configuration management and change management).
<i>None</i>	Acquisition Supply Enterprise Environment Management Investment Management Resource Management Quality Management Project Assessment Project Control Information Management Implementation Integration Operation Maintenance	1: Product Supply 2: Product Acquisition 3: Supplier Performance 5: Technical Effort Definition 6: Schedule and Organisation 8: Work Directives 9: Progress Against Plans and Schedules 10: Progress Against Requirements 11: Technical Reviews 13: Information Dissemination 20: Implementation

It is clear that each core SE process area can be related to activities governed by both standards and I conclude that these process areas describe activities that it is generally agreed fall within SE.

Moreover, the activities in the final row of Table 5, which do not relate to any core SE process are, in my view, generally activities that could reasonably be claimed by management or commercial functions and therefore activities that I do not wish to include within core SE. This is partly the consequence of my defining core SE as a subset of what others choose to regard as SE but also a consequence of the fact that the two standards define the activities necessary to engineer a system and include within these activities that are claimed for project management, for instance by PRINCE 2 (Office of Government Commerce, 2002) and which, in my experience, most systems engineers would regard as falling outside the scope of SE.

Having shown this, I argue that the definition of core SE is useful because, if a correlation can be shown between adopting core SE practices and enjoying benefits then a similar correlation can be inferred between adopting SE practices according to most other common SE characterisations and enjoying benefits.

### **5.5 Good practice in core SE**

I have defined what activities are included within core SE but I also need to be clear what I take as good practice in carrying out these activities. For a statement of good practice one would normally turn to the relevant professional society or to international standards. In this case, the relevant professional society, INCOSE, publishes a handbook (INCOSE, 2010) which is structured around ISO/IEC 15288 (ISO/IEC, 2002). I take these two documents as consistent statements of good practice - ISO/IEC 15288 at a high level and the handbook at a more detailed level.

**5.6 Key points**

- 5A I need a characterisation of SE that can be applied objectively to divide project activities into SE activities and other activities; includes activities that are broadly recognised as SE activities; but does not include so much as to draw large areas of what is regard as project management within the scope of SE.
- 5B There are many characterisations of SE but none meets all the criteria I set for my research.
- 5C I list a number of SE artefacts and define 'core SE' to be the set of activities that create, change or check these artefacts.
- 5D I partition core SE into 6 process areas.
- 5E I show that these process areas correspond to processes or requirements within two well-used SE standards.
- 5F I argue that the definition of core SE is useful because, if a correlation can be shown between adopting core SE practices and enjoying benefits then a similar correlation can be inferred between adopting SE practices according to most other common SE characterisations and enjoying benefits.

## 6 A WORKABLE CHARACTERISATION OF 'BETTER'

One of the objectives for this research is, “to demonstrate that SE can be used to build better rail systems and to build rail systems better, aiming for measurable improvement.” “Better” is of course a wholly subjective term the meaning of which may differ substantially from observer to observer. If the objective is to be met in any useful way, it is necessary to replace the concept with something that can be defined more objectively.

In this chapter, I look at some commonly-used notions of how well a project has turned out but decide instead to define a measure of the delay in taking decisions to make changes, which I term 'change latency', where lower change latency is better.

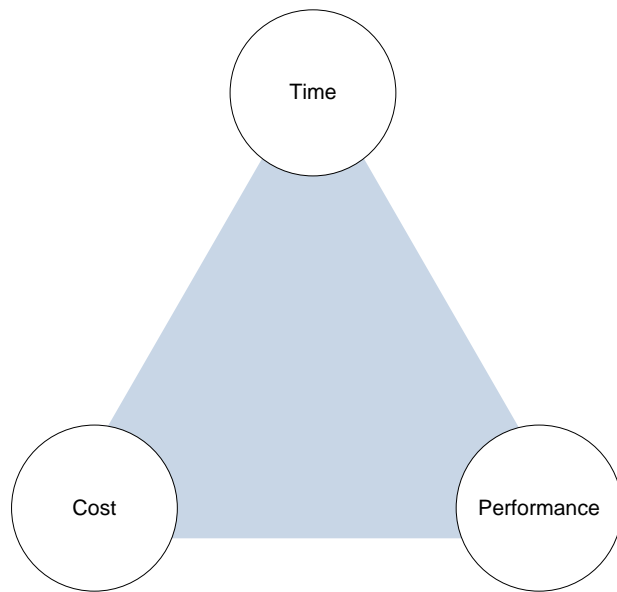
I acknowledge that reduced change latency is not a comprehensive measure of goodness and that it is possible that SE might deliver benefits that are not associated with reduced change latency. I argue however that it is a useful measure for the practitioner, because lower change latency can be used to obtain a range of other benefits. I also explain why it is a useful measure for the researcher.

### 6.1 Characterising 'better' in terms of time, cost and performance

More than forty years ago, Dr Martin Barnes used a triangle with Cost, Time and Quality at its corners to illustrate the space available in which a project manager could trade objectives. Barnes subsequently concluded (The PM Channel, 2013) that the corner that he initially labelled 'Quality' should be labelled 'Performance' instead, indicating the degree to which the deliverable of the project does what it is supposed to do.



In various forms and under various names, including 'The Iron Triangle', this diagram has been reproduced widely since (including to the right) and the notion that the key objectives of a project relate to the cost and duration of the project and the performance of what it delivers has become accepted wisdom within project management, at least as a useful simplification.



**Figure 4: The 'Iron Triangle'**

The 13 systems engineers whom I interviewed in my first preliminary survey (see Key Point 4A) were in broad agreement. The success criteria that they mentioned most often were:

- cost to complete project;
- time taken to complete project;
- compliance with written requirements; and
- actual performance in the field.

Both of the last two points may be broadly aligned with 'performance' and the success criteria are therefore consistent with the 'Iron Triangle'.

This suggests attempting to define 'goodness' as a multi-dimensional parameter where the dimensions are time, cost and performance. This is an approach that has been taken by researchers, including by Elm and Goldenson (2012) and by Honour (2013) but there are problems with creating measures in each of the three dimensions. It is hard to standardise and normalise measures of time, quality and performance in a way that allows meaningful comparisons to be made between projects. One can compare the ratio of the actual cost to the cost outcome but, if this is lower for project A than for project B does this mean that project A was delivered more efficiently or just planned more realistically?

Moreover, and for the purposes of this research most importantly, time, cost and performance are the results of many factors in combination, including the influence of events outside the control of the project. It is very hard to disentangle the contribution of one factor, such as the adoption of SE approaches.

It would be useful to have some measure of 'goodness' that could be more tightly connected with the factors that influence it.

Having found evidence that there is room for significant reductions in avoidable costs of change on rail projects (see key point 4C) and noting that the three most prevalent theories for the manner in which SE can benefit projects (left shift, whole-system optimisation and control of complexity, see key point 3B) all suggest that SE should be able to control these costs, it is interesting to look for measures of 'goodness' that are related to change.

## **6.2 Characterising 'better' in terms of volume of change**

One obvious measure to explore is the volume of change. Change costs time and money and so the volume of change is a candidate measure of 'badness'. Volatility can be defined as a normalised measure of the volume of change which can be compared between projects.

In my first preliminary study carried out early in my research, I found high levels of volatility (see key point 4B).

Others have reached similar findings in related domains. More than 15 years ago, Dale and Plunkett (1999; pages 62-63) suggested that engineering change within manufacturing companies was a topic worthy of attention. They wrote, *"To anyone investigating costs in manufacturing industry, striking features are (a) the large amount of time and money spent on modifications and engineering changes, and (b) an apparent acceptance, in particular amongst design, engineering and technical personnel, that they are facts of organizational life that one must learn to live with. The impression given is that this is the way organizations go about their respective businesses."* They added, *"There can be no doubt that between concessions, modifications and engineering changes there is a sizeable quality-related activity escaping the quality cost net in most organizations."*

However, the volume of change is a problematic measure of 'badness' because it is clear that not all change is bad – some changes are improvements and other project changes are necessary reactions to changes in the outside world. The NETLIPSE report (Hertogh et al, 2008), which was mentioned in chapter 3, contains some remarks about the inevitability of change. For instance, section 4.4 contains the following remarks about Large Infrastructure Projects (abbreviated 'LIPs'):

*“The project has to deal with changes in the context. If there were NETLIPSE researchers who thought at the start of the research that the development of LIPs is linear and can be foreseen beforehand, the NETLIPSE research showed that nothing is less true. LIPs have a 'non-linear' development of the implementation process, as was illustrated by the previous examples. As mentioned, external context factors have a decisive influence on their development. We believe that unexpected or changing conditions, for instance new legislation on fire regulation in runnels or on safety systems on railway lines, will always occur and will impact projects.”*

So, in order to use volume of change as a measure of badness, one would have to find some way of separating those changes that were indicative of things going well from those that were indicative of things going badly. Some distinctions have been proposed that seem to approach this need. For example, Eckert, Clarkson and Zanker (2004) draw a distinction between 'emergent change', caused by problems in the design and 'initiated change', initiated by parties outside the project such as customers or regulators.

However this is still not discriminating enough. If a manufacturer alters its products to comply with new regulations in an orderly and timely manner then that is an initiated change according to the distinction and, presumably, a symptom of healthy processes. If the manufacturer has to recall a product that has been found to be non-compliant with new regulations in order to make the same change, it is still an initiated change but now a symptom of unhealthy processes.

This suggests that what matters is not so much the nature of the change in itself but the manner in which it is implemented and, in particular, the time at which it is implemented.

Miller and Lessard (2000) also take the view that the manner in which a project responds to change is critical to its success. They use the term 'turbulence' to describe the unforeseen events in the outside world that drive much of this change on large engineering projects. In their view, the manner in which these projects handle turbulence is crucial to their success. They observe that successful projects tend to keep useful options open and have flexible contractual arrangements that can tolerate significant change. Their research supports the SE doctrine that time spent at the beginning of a project is repaid later but with a twist. They recommend investing this time as much in setting up robust project arrangements as in defining the final product.

It is this reasoning that leads me to use a measure of the unnecessary delay in making a change as a proxy for 'better' (or more accurately for 'worse').

### 6.3 Change latency

The measure of the unnecessary delay in making a change that I have developed to use as a proxy for 'worse' in carrying out the research is **change latency**. Change latency is a property not of a project but of a change that a project has chosen to make to its technical direction.

The notion is illustrated in Figure 5. In case 1, the project heads off along trajectory AC but, at point Y, something in the outside world changes that makes B a more desirable destination. If the project does not change course until X then the change latency in this case is the period between Y and X. In case 2, the project heads off along trajectory AC but realises at X that B had been a more desirable destination from the outset. The change latency in this case is the period between A and X. In both cases, the fact that the project 'goes the long way around' reflects the fact that proceeding longer than necessary in the 'wrong' direction introduces unnecessary work and rework.

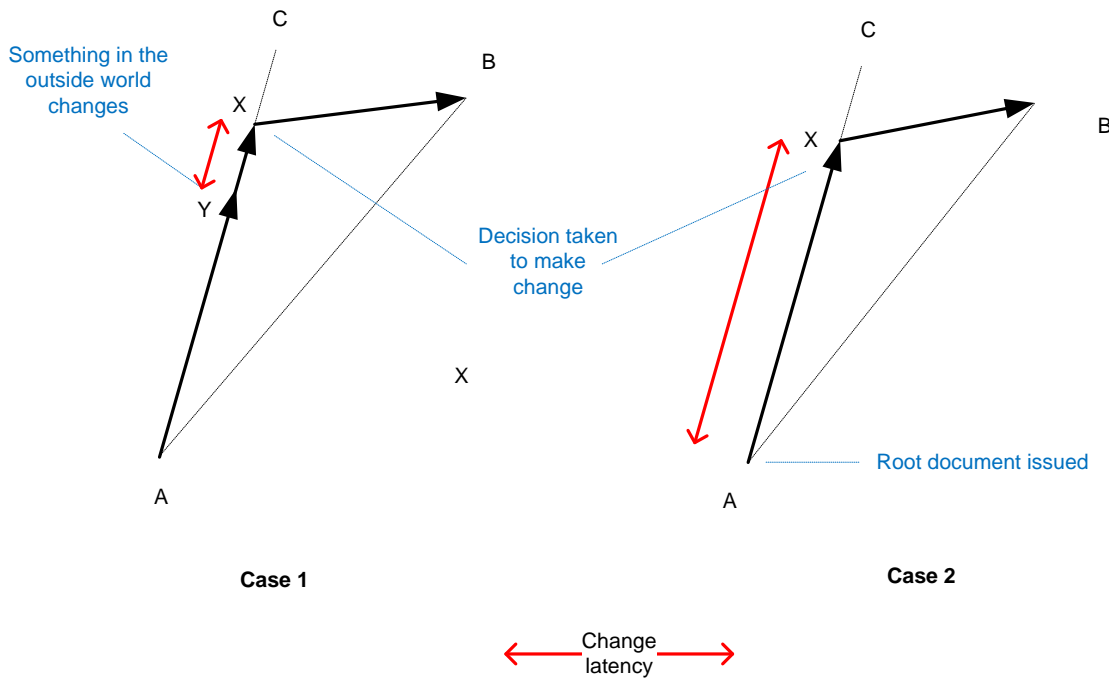
I define the **root document** associated with a change to be the first authoritative specification or plan that committed the project to the course of action being changed.

I define the latency of a change as follows:

- if sufficient information was available to determine that the change was desirable at the point when the root document was issued then the time interval between issuing

the root document and the time when it was actually decided to make the change;  
and

- otherwise, the time interval between the earliest time when sufficient information was available to determine that the change was desirable and the time when it was actually decided to make the change.



**Figure 5: Change latency**

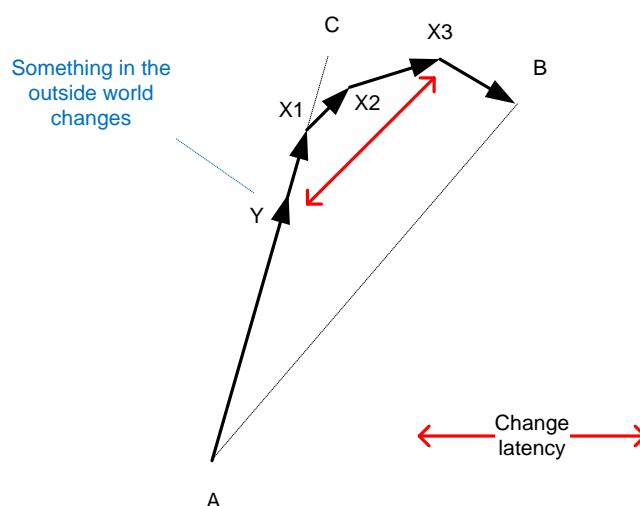
For the purposes of understanding the reasons for change latency, I divide it into two components:

- **Detection latency** is the portion of change latency that elapses before the project explicitly recognises that there is an issue in the area of the change and starts to address it.
- **Decision latency** is the time taken from recognising that there is an issue to reaching a decision to make the change.

By definition, for any specific change:

$$\text{Change latency} = \text{Detection latency} + \text{Decision latency}$$

On occasions where it takes more than one go to resolve an issue, that is to say, where there is a sequence of changes in which the second and subsequent changes are only required because the earlier ones did not resolve the issue that they were designed to resolve, I choose to regard the sequence as one compound change and calculate the latency of the final component change. The situation is illustrated in Figure 6, where component changes X1, X2 and X3 are regarded as part of one compound change.



**Figure 6: Latency of a compound change**

I have not found the concept of change latency defined in this manner elsewhere, but other researchers, for example, Nolan and Pickard (2013), draw  $N^2$  charts, showing the project stages at which faults *are* found and *should be* found, and the change latency is related to the distance of entries on this chart from the diagonal.

#### 6.4 The utility of change latency to the practitioner

A researcher is at liberty to define the concepts into which he or she intends to carry out research as he or she wishes. But a researcher, like me, who has set out to compile knowledge of value to practitioners, has an obligation to show that these definitions do not destroy that value.

Proceeding with the research using reduced change latency as a proxy for 'better' is clearly losing the ability to perceive certain sorts of potential benefits of adopting SE approaches – an example would be if SE resulted in a design with reduced running costs.

Moreover, it is possible to imagine scenarios in which reduced change latency results in worse outcomes for some stakeholders. For example, realising that an expensive change is necessary to make a system work may lead to the cancellation of a project, even though it remains a sound investment. However most of these scenarios involve some degree of irrationality. Reduced change latency is generally associated with improved knowledge about how things are. In most cases, improved knowledge opens up options that may be worth pursuing and that might not otherwise have been considered; it will rarely close off options.

Nonetheless, there are two good reasons for concluding that reduced change latency is a good thing in general:

- Change is expensive.
- The cost of making a change rises rapidly with time.

Both of these reasons are now discussed further.

#### **6.4.1 Change is expensive**

Most practising engineers and managers understand that knowledge and options have value and that time is money. Experience (as reported below) suggests both that changes consume a significant proportion of the budget of engineering projects and that postponing decisions to make changes can be expensive.

For example, Fricke et al (2000) were told when studying German manufacturing companies that about 30% of work efforts are due to changes of all sorts. They found that insufficient communication within these companies contributed both to the number and average cost of changes.

Terwiesch and Loch (1999) report consistent results in another sector. They found that engineering change consumed one third to one half of engineering capacity in automobile development. They found that delays in processing engineering change were not routinely measured and not a priority for some manufacturers. However, they propose a number of principles to be followed in order to reduce the cost of engineering changes and 'reducing delays' is one of these principles. They found five major factors contributing to delay in

processing engineering change: a complex engineering approval process; limits on engineering capacity; setups and batching; the 'snowball effect' and organisational issues.

#### **6.4.2 The cost of making a change rises rapidly with time**

The 'snowball effect', mentioned in the previous section, refers to the scenario whereby a change to one part of the design results in many changes to other parts of the design. Fricke et al (2000) also see this effect, "*A characteristic of changes is that the steps cause-change-effect are not serial, but build a network, where an effect may also be a cause for new changes and all may be somehow interconnected.*" Clearly, this means that the cost of making a change will increase rapidly with time as more and more affected design work is carried out and then has to be reworked later.

There have been attempts to model the 'snowball effect' quantitatively. Clarkson, Simons and Eckert (2004) have attempted to model change propagation in modified Design Structure Matrices. In these modified matrices, the names of the elements of the design are used as both column and row headings and each cell contains an indication of the probability that a change to one element will require a change in the other and an indication of the proportion of the affected element that is likely to be affected. A trial of this matrix on the design of a helicopter predicted results that were similar to those experienced in practice. The probabilities and proportions in the matrix vary significantly, implying significant variation in the degree to which changes propagate through the design. This variation corroborates the common-sense view that the cost of postponing different changes will rise at different rates. The cost of changing the colour of a train may not start to rise until the paint is ordered because there is low change propagation. On the other hand, reducing the maximum axle weight for a train may have high change propagation and require a fundamental redesign of practically everything, with the result that the cost of making this change may rise very quickly indeed.

Even if it is impossible to define a single cost escalation profile for all changes, some rules of thumb have been formulated from experience in several domains that suggest that this escalation can be rapid.



Boehm's studies into the cost of fixing software problems are much quoted. One publication cited is (Boehm and Basili, 2001), which contains the assertion that, "*Finding and fixing a software problem after delivery is often 100 times more expensive than finding and fixing it during the requirements and design phase.*" The factor of 100 is striking but it should be noted that the authors add that, "*For this updated list, we have added the word 'often' to reflect additional insights about this observation. One insight shows the cost-escalation factor for small, noncritical software systems to be more like 5:1 than 100:1.*"

This is consistent with a table of the average relative cost of fixing software defects based on when they are introduced in McConnell (2003; page 29). This contains the entry "10-100" for the same factor. Noland and Pickard (2013; figure 7) suggest that the cost to make a change to the control system software for a gas turbine is 250 times as much after entry into service as it would be if found by initial reviews and modelling.

Boehm, Valerdi and Honour (2008) reviewed data on the cost of fixing software defects and found similar ratios. In particular they found that "*relative to an effort of 10 units to fix a requirements defect in the Code phase, fixing it in the Requirements phase involved only about 2 units of effort, while fixing it in the Operations phase involved about 100 units of effort, sometimes going as high as 800 units.*"

Similar results have been found in other engineering areas. Fricke et al (2000) observe that manufacturing engineers apply 'The Rule of Ten', the rule of thumb that the costs of a change increase tenfold with each phase of the lifecycle. Eckert, Clarkson and Zanker (2004) also found that the costs of change rose when manufacturing products in the aerospace sector. They write, "*As deadlines drew closer and the design problems became more complex, the cost of amending problems rose steadily due to the increase in the number of constraints and the greater degree of integration. The later they occur in the design process the more costly changes can become. This is due to the fact that (a) the process becomes more time critical and (b) the product becomes more integrated.*"

'The Rule of Ten' may have exceptions. It does appear to be possible to control the rate of escalation. Clark and Fujimoto (1991) studied US, European and Japanese automobile manufacturers. They found (Clark and Fujimoto, 1991; page 187) interesting variations

between the costs of engineering changes to the dies used to press bodywork panels. In the US, the cost of these changes was 30-50 per cent of the total cost of a die, whereas in Japan it was at most 20 per cent. They ascribed the lower Japanese costs in large part to a quicker, more collaborative relationship between the manufacturer and tool maker.

### **6.4.3 Conclusions**

I conclude that change latency is a useful concept for practitioners because, in many circumstances, reducing change latency has the potential to deliver significant reductions in the cost and duration of the project, and the released budget and schedule may be used, in some circumstances, to deliver increased performance (or at least to avoid having to reduce performance by cutting out scope).

### **6.5 The utility of change latency to the researcher**

Change latency, has certain practical advantages for the researcher as a measure of outcomes:

- It is a property of a change not of a project and, because one project will typically undergo several changes, this increases the number of opportunities for learning compared with looking at a property of a project.
- It is relatively objective, compared with, for example, a rating of the performance of a system. The date on which a decision was taken to make a change is normally a matter of record and, while different observers may initially disagree about the date on which sufficient information was available to determine that the change was desirable, this disagreement can, in principle, be resolved by rational discussion.
- Because it is a measure of time, a physical quantity, the latencies of two changes may be directly compared and one can calculate mean averages and standard deviations without hesitation if one has the latencies of a number of changes.
- It is not necessary to divide changes into fault corrections and other changes in order to measure change latency – the measure can be applied to any sort of change. That is an advantage because the decision on whether a change is a fault correction or not is often related to the question of who should pay for it and, as a consequence, can be fraught.

## 6.6 Going forward

Having chosen workable characterisations of SE and 'better', it becomes possible to narrow and refine the research objectives. The generic objectives were:

- To demonstrate that SE can be used to build better rail systems and to build rail systems better, aiming for measurable improvement.
- To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects.

The refined, specific objectives become:

- To demonstrate that core SE can be used to reduce change latency in major rail projects.
- To gain an improved understanding of how to adapt core SE to produce the greatest reduction in change latency in major rail projects.

In the next chapter, I describe and justify the research methodology used to tackle these objectives.

## 6.7 Key points

- 6A Time, cost and performance are widely accepted success criteria for projects but are difficult to measure and are the results of many factors in combination.
- 6B The cost of engineering change has been found to be a significant proportion of overall costs in several engineering sectors.
- 6C The cost of making an engineering change has been found to rise significantly with time in several engineering sectors.
- 6D Volume of change is a difficult measure of 'goodness' because it is difficult to separate 'good' change from 'bad' change.
- 6E I choose to use 'change latency' as an indicator of the 'badness' of project outcomes, where change latency is a measure of avoidable delay in deciding to make a change.
- 6F I divide change latency into two components: detection latency and decision latency.

- 6G Change latency is a useful concept for practitioners because, in many circumstances, reducing change latency has the potential to deliver significant reductions in the cost and duration of the project, and the released budget and schedule may be used, in some circumstances to deliver increased performance.
- 6H Change latency has practical advantages for the researcher as a measure of outcomes:
- It is a property of a change, which increases the number of opportunities for learning compared with looking at a property of a project.
  - It is relatively objective.
  - Because it is a measure of a physical quantity, the latencies of two changes may be directly compared and one can calculate mean averages and standard deviations without hesitation.
- 6J My refined specific research objectives are:
- To demonstrate that core SE can be used to reduce change latency in major rail projects.
  - To gain an improved understanding of how to adapt core SE to produce the greatest reduction in change latency in major rail projects.



## 7 METHODOLOGY

In chapter 2, I observed that the field of study presented the SE researcher with a number of fundamental challenges. I argued that these challenges made it impossible to compile timeless, universal knowledge about the benefits of SE.

Other researchers have noted other challenges. Valerdi and Davidz (2009) acknowledge that the relative immaturity of the field, a lack of appreciation of empirical research, the difficulty of accessing data and the lack of accepted metrics raise obstacles in the path of the SE researcher.

In this chapter I describe the methodology that I have chosen to employ and explain how it has been designed to overcome the challenges intrinsic to the field of study while respecting the constraints that my status as a lone researcher places on what I can do.

### 7.1 Methodological options

Because SE generally draws from the traditions of physical science and engineering, it is tempting to adopt the research methods of physical science without exploring the options. Brown (2009) suggests that the exploration of these options by SE researchers is not thorough enough. She argues that *“atheoretical pragmatism”* is not a sustainable position for the SE researcher and that the *“establishment of formal methodologies in systems engineering research is not only important, but that it is critical for the growing maturity and credibility of the discipline”*. She exhorts researchers to take note of the methods used by the social sciences and contrasts the realist and interpretive traditions, but leaves the reader to choose between them. I take Brown’s advice. In this chapter, I set out the main options and then make a reasoned choice between them.

Lee and Lings (2008) provide a readable account of the major options open to a researcher, which, while written for readers carrying out business research, is more generally applicable. From their account, I distil three important choices:

- They distinguish the realist and interpretive ontological positions, which I discuss in the next section.

- They distinguish qualitative research from quantitative research and observe that, while a quantitative approach tends to be associated with a realist one, the realist-interpretive and qualitative-quantitative decisions may be taken independently.
- They encourage the researcher to research existing theories and take a theoretical position before starting to collect data, an approach that I shall label, 'theory-first'. However they observe that there are research methods, such as Grounded Theory, in which the researcher allows the theory to arise from the observations, an approach that I shall label 'observation-first'.

Lee and Lings also define two useful measures of the validity of research methods:

- The 'internal validity' of research is the degree to which conclusions are free from the challenge that alternative explanations may have been provided for the same effects.
- The 'external validity' of research is the degree to which the conclusions may be generalised to other situations.

They observe that the classical experiments of the physical science set the 'gold standard' for internal and external validity but that other fields are forced to settle for methods with lower internal and external validity.

I discuss each of the three main choices listed above in turn.

## **7.2 Realist and interpretive methods**

Realist methods assume an objective world that exists independently of observers and attempt to obtain objective truth about it while interpretive methods study the understandings that people have of the world (Lee and Lings, 2008).

Having observed that concepts such as 'SE' and 'benefits' are subjective, there is a choice to be made between applying interpretive methods to these ideas in people's heads or replacing the subjective concept with more objective concepts in order to apply realist methods.

Other researchers in the field, such as Valerdi and Davidz (2009), take a robustly realist stance. They characterise the three key underlying principles of the scientific process as

empiricism, objectivity, and control and argue that these should be applied rigorously to research into SE.

Honour (2013) and Elm and Goldenson (2012) also follow realist approaches to their research. They create definitions of SE and the value that it adds, either explicitly or implicitly, by defining how they will measure it; establish hypotheses about the relationship between the two and then collect data in order to test these hypotheses using statistical methods. Honour found *“a quantifiable relationship between systems engineering effort levels and program success”* while Elm and Goldenson found *“strong statistical relationships between project performance and several categories of specific SE best practices.”* Anyone making use of this research needs to bear in mind that the relationships found are between SE on the one hand and performance or success on the other, *as the researchers define these things* and check how closely the researcher’s and user’s objectives align and to adjust for any areas in which the project to hand differs from the population studied. Both Honour and Elm and Goldenson acknowledge limitations on internal and external validity but claim real learning, claims that I find convincing.

Interpretive methods have been applied in related areas. Checkland (1999) draws a distinction between ‘hard systems thinking’, which is concerned with delivering an engineered, technical system to meet certain defined objectives and ‘soft systems thinking’ that is concerned with adjusting ‘human activity systems’ in order to resolve certain perceived problems. His research is concerned with methodologies to resolve ‘soft’ system problems.

Checkland (1999; pages 278-280) compares realist and interpretive approaches to this research and declare his sympathies to be with the latter. He declares that his methodology *“accepts that any real-world purposeful human activity will be describable in many different ways within many different Weltanschauungen [world views]”*. He notes that these different descriptions may lead to defining systems in different ways.

From the outset, Checkland chose to carry out ‘action research’ in which the researcher abandons all attempts to conduct research as an independent observer and engages with the objects of study to try both to be of practical use and to learn from the experience.



Checkland observes that, when the objects of study are human activity systems, the states of these systems include the knowledge and beliefs of the people within them and that any research of any value will change this knowledge and these beliefs so that the researcher as independent observer is a chimera.

In trying to be of use in a problem situation, Checkland is quite happy to proceed with multiple, competing definitions of the systems of interest.

I find these conclusions about the nature of 'soft' systems compelling. I wonder whether so-called 'hard' systems are quite as 'hard' as people like to believe but that is of no direct consequence to my research. Even if the products of SE can be considered to be 'hard systems', it is perfectly clear that SE itself, as an object of study, is a soft system.

However, while I have great respect for Checkland's intellectual position, I see no way of applying interpretive methods in a way that will deliver the knowledge of practical utility that I have set out to compile and so I reconfirm my decision to use realist methods in my research.

### **7.3 Quantitative and qualitative methods**

#### **7.3.1 Quantitative methods**

The quantitative methods of the physical sciences are the methods with which most SE researchers will be most familiar. Typically, some relationship between measurable properties of a population of items will be hypothesised and then these properties will be measured for a sample of that population so that statistical methods can be used to test the hypothesis.

Sheard and Miller (2000) sound a note of warning about the application of quantitative methods to research into the value of SE. The abstract of their paper summarises their warning clearly:

*"Many INCOSE members are dismayed that there are no hard numbers to justify implementation of systems engineering process improvement. This paper shows that:*

- 1. There are no 'hard numbers'.*
- 2. There will be no hard numbers in the foreseeable future.*

3. *If there were hard numbers, there wouldn't be a way to apply them to your situation, and*
4. *If you did use such numbers, no one would believe you anyway."*

Their fourth point simply acknowledges that there are always barriers to change rather than questioning the possibility of demonstrating the benefits of SE. Their grounds for the other points are that:

- companies are reluctant to publish bad news and therefore data obtained from them is likely to be biased;
- the supporting data for any demonstration is likely to be confidential;
- data is collected differently in different organisations and it is difficult to compare;
- definitions of SE vary greatly; and
- there is uncontrolled variability in factors other than the manner in which SE is performed on a project.

All these points correspond to real and challenging difficulties. Moreover, if by 'hard numbers' Sheard and Miller mean numbers that could support a quantitative model of the precision and reliability of those underpinning the natural sciences then I would agree that they are unlikely to be obtained. However, the majority of the difficulties set out above also bedevil quantitative approaches to quality improvement, see for instance (Deming, 2000), but nonetheless real progress is made in this field.

Honour (2013) also seems to think that the obstacles posed by Sheard and Miller can be overcome. He concludes at the end of his doctoral thesis that his work "*demonstrates that it is possible to obtain meaningful and quantifiable data about systems engineering and success through empirical methods. The implication of this demonstration is that further empirical research is indeed possible, that can observe the SE discipline to the point of formulating effective underlying theory.*"

### 7.3.2 Qualitative methods

There are alternative qualitative methods, of which one is the rigorous analysis of cases, or 'case study' research. Flyvbjerg (2006) writes an apologia for case study research in which he sets out and refutes five misunderstandings about it:

- General, theoretical knowledge is more valuable than concrete, practical knowledge.
- One cannot generalize from an individual case.
- Case studies are useful for generating hypotheses but not testing them.
- Case study research is biased towards confirming preconceptions.
- It is difficult to develop general theories from specific case studies.

Friedman and Sage (2004) consider the challenges of doing case study research in SE. They acknowledge that it is difficult to achieve high internal and external validity. They also suggest two other challenges. One is to ensure the validity of the concepts used in the case study. The other is to ensure that the methods used are such that different researchers would reach the same conclusions. Nonetheless, their objective is to encourage good case study research into SE, rather than to deter its use and they offer practical advice on responding to these challenges.

### 7.3.3 Evaluation and selection

I am convinced that good case study research is in no sense a second-class research method (the Theory of Evolution rests upon good case study research) and that it has its place in SE research.

So, on this question, I have come to support both options: I believe that both quantitative and qualitative research methods, and specifically case study research, have their place and, indeed are complementary.

Good quantitative research is generally of higher external validity than qualitative research. If one has made a general hypothesis about SE, then, at some point, if it is practical, this hypothesis should be tested in a quantitative study. Nevertheless, if a series of case studies could have contradicted a hypothesis but did not then this does provide some corroboration for the hypothesis. Moreover, as Flyvbjerg (2006) asserts and I show in the next chapter, a single case study can show that a general hypothesis is inadequate.

Quantitative research can test for the existence of correlations but is of less value in establishing the causal links that produce these correlations. In practice, theoretical knowledge is used when interpreting empirical results. From a purely formal point of view, the data accumulated by Honour and by Elm and Goldenson support the alternative hypothesis that project performance/success results in a greater adoption of SE practices. This can be rejected however on the wholly reasonable grounds that an effect cannot be the result of a cause that occurs later.

The internal validity of both quantitative and qualitative methods is generally low when researching the benefits of SE because there are so many other factors that could produce benefits but there are occasions when study of a case study can produce an account of cause and consequence that is so clear cut that conclusions of high internal validity may be drawn from it.

Qualitative research can unravel the causal links and produce theories that quantitative research can test. Or, bearing in mind Flyvbjerg's correction above, it would be more precise to say that qualitative research can unravel the causal links and produce *and initially test theories* that quantitative research can test *further*.

Qualitative case study research also facilitates progress by researchers with limited resources because the quantum of research is a single case rather than a large number of cases.

I use a mixture of quantitative and qualitative methods in my research.<sup>10</sup>

I acknowledge however that the internal and external validity of these methods is limited. This, I argue (see key point 2B), is the consequence of the nature of the field of study, rather than of a flaw in the methods. However, if the methods cannot produce results that are wholly reliable then, it seems to me, that it is of great importance (see also key point 2C) that researchers should carry out their research in a manner that helps others to build upon

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<sup>10</sup> I acknowledge that, as a consequence of the small size of my samples, my research findings derive almost entirely from qualitative methods – the value of the quantitative methods to my research is in demonstrating methods that could be scaled up to larger samples.

and refine their findings. In the next section, I argue that articulation of theories has a part to play in achieving this.

#### **7.4 Theory-first or observation-first**

As I have already noted, Lee and Lings (2008) encourage the researcher to research existing theories and take a theoretical position before starting to collect data. Friedman and Sage (2004) take the same position when discussing case study research. In doing so, these researchers set themselves in opposition to the approach of Grounded Theory, at least as propounded by one of its creators, Glaser (1992), in which it is considered important to let the theory emerge from the observations without preconceptions.

I think it is too late to apply pure Grounded Theory to the benefits of adopting SE approaches. The theories, as was seen in chapter 3, are out in the open now. If they are impairing thinking and crowding out better theories, the damage is done.

More positively, I think that articulating theories is essential to making sustained progress in understanding SE. I have explained why compiling reliable knowledge about SE is difficult and why the researcher may have to be content with making small, preliminary increments to this body of knowledge. However, if the theory underpinning these increments is made explicit then it can serve as the starting point for future research that can refine and correct it.

Lee and Lings (2008; page 123) draw a useful distinction between a theory and a model, *"Theories attempt to explain phenomena, whereas models by themselves are like laws in that they can only describe."* I will use this distinction in the remainder of this thesis. With this distinction, one can say that SE is rich in models – most SE papers contain at least one – but, in my opinion, is poorly furnished with theories.

Perhaps this lack of theories restricts the rate of progress in research into SE. Progress in SE research does seem to be slower than progress of research into related fields. Boehm, Valerdi and Honour (2008) claim that *"Despite its recognition since the 1940s, the field of systems engineering is still not as well understood as the much later field of software engineering."* I think that one can claim that both fields were gestated during the Second

World War, but, as someone familiar with both fields, the suggestion that knowledge of SE has not advanced as fast as knowledge of software engineering rings true.

An example may illustrate the progress made in software engineering. Many of the programmes that people interact with on their computers, tablet and mobile telephones are written in object-oriented programming languages and, if one looks at the structure of these languages one can trace it back to ideas developed over the previous half decade, including:

- the idea that programmes should be structured to make them easy for people to understand, not just for machines to execute;
- the idea that data-processing programmes can be made more maintainable if the structure of their code matches the structure of their data;
- the idea that programming languages should be designed to facilitate detection of programmer's errors; and
- the idea that programmes should be divided into modules in a way that maximises the internal coherence of the modules and minimises the coupling between them.

I struggle to establish such a rich genealogy for modern SE thinking – there are always new ideas but I find it difficult to perceive underlying threads that link these ideas together – and so I find myself in agreement with Valerdi and Honour.

I observe that the 'ideas' in my software engineering example are, in fact, outline theories and I suggest that a greater willingness on the part of the SE community to articulate the theories underpinning its beliefs might allow it to make faster progress.

I choose not only to make my research methods theory-based, but to put theory at the heart of my approach.

### **7.5 Refuting and refining theories**

Some of my peers have criticised my decision to formulate theories on the grounds that a single, repeatable counter-example will refute a theory. This is logically true. A favourite logician's example is the 'theory' that 'all swans are white', which held across Europe, Asia and Africa and the Americas but was refuted when visitors to Australia first encountered a black swan.

However refutation is not the same as demolition. The zoologists do not have to radically rethink their whole approach to swan colour, they simply refine their 'theory' to read 'all swans are white or black'. A small increment has been added to human knowledge and new research questions such as, 'Do swans take other colours and, if not, why not?' emerge.

The theories that I shall be articulating are of the form 'Adopting such-and-such an SE approach on rail projects results in such-and-such a benefit'. If this turns out to be universally refuted then I will have learnt something.

However this is unlikely. What is more likely is to find that the causal link applies for some projects and not others. Analysing the counter-examples may suggest reasons why the causal link did not apply that may in turn suggest conditions that must hold for it to apply. As a result the theory is refined to become 'Adopting such-and-such an SE approach on rail projects results in such-and-such a benefit under such-and-such a set of conditions'.

Such methods fall below the rigour of the methods used in the natural sciences. Popper is often cited as a reference for these methods, although the methods that he prescribed turned out to be too rigorous for even modern physics to use (Lee and Lings, 2008; page 30).

However, Popper believed neither that such methods were appropriate for non-scientific subjects nor that the methods used in other subjects should be completely different. In (Popper, 1994; pages 140-141), he wrote:

*"But almost everyone else seems to be quite sure that differences between the methodologies of history and of the natural sciences are vast. For, we are assured, it is well known that in the natural sciences we start from observation and proceed by induction to theory. And is it not obvious that in history we proceed differently?"*

*"Yes, I agree that we proceed very differently. But we do so in the natural sciences as well."*

*"In both we start from myths - from traditional prejudices, with error - and from these we proceed by criticism: by the critical elimination of errors. In both the role of evidence is, in the main, to correct our mistakes, our prejudices, our tentative theories - that is, to play a part in the critical discussion, in the elimination of error. By correcting our*

*mistakes, we raise new problems. And in order to solve these problems, we invent conjectures, that is, tentative theories, which we submit to critical discussion, directed to the elimination of error. The whole process can be represented by a simplified schema, which I may call the tetradic schema:*

$P1 \rightarrow TT \rightarrow CD \rightarrow P2$

*“This schema is to be understood as follows. Assume that we start from some problem  $P1$  - it may be either a practical, or a theoretical, or a historical problem. We then proceed to formulate a tentative solution to the problem: a conjectural or hypothetical solution - a tentative theory. This is then submitted to critical discussions, in the light of evidence, if available. As a result, new problems,  $P2$ , arise.”*

This accurately describes the method that I use, with the small modifications that (a) critical discussion becomes critical discussion and testing and (b) this yields a revised tentative theory as well as a new problem so that the tetradic schema becomes:

$P1 \rightarrow TT1 \rightarrow CDT \rightarrow P2 + TT2$

My principal objective becomes neither to *prove* nor *disprove* a tentative theory but to *improve* it by exposing it to test and criticism. On the basis of the corroborative and contradictory evidence, the tentative theory is refined.

But there is a danger with refining theories to deal with contradictory evidence and that is to fall into the error of what Popper (1959; pages 61ff) of ‘conventionalism’ – rescuing theories by the ad hoc addition of ‘auxiliary hypotheses’. Popper acknowledges that auxiliary hypotheses are sometimes necessary but recommends that the theorist should observe the discipline of requiring that auxiliary hypotheses should increase the explanatory power of the theory. I follow this recommendation and commit myself to only making changes to my tentative theory which have a sound basis in common-sense situational analysis of projects and which would be generally applicable to projects.

I conclude then that the criticism raised against a theory-based approach is unjustified and persist in my decision to use such an approach.



## 7.6 Going forward – a summary of my research methodology

I have declared that:

- I am using realist methods, to explore the relationship between adopting core SE practices and change latency;
- I am using a mixture of qualitative and quantitative methods; and
- I am formulating an explicit tentative theory to underpin my research.

The final phase of my research has three phases.

In the first, theoretical phase, I propose a tentative theory of how core SE contributes to (reductions in) change latency based upon a model of how core SE contributes to project execution.

In the second, empirical phase, I collect data about real projects and analyse it in order to test the tentative theory. Data is collected from two sources:

- from a number of interviews with senior figures on recent rail projects and from change records on these projects; and
- from publicly available reports on rail projects. I seek the same sort of information from the written reports as I collect from interviews but, of course, I am constrained by what is documented.

I find that these two sources complement each other, particularly as the publicly available reports include some forensic analyses of troubled projects whose members might be reluctant to discuss them in interviews.

Data is analysed in two ways: qualitatively and quantitatively. The qualitative analysis is based upon considering each major change made by a project for which I have data and searching for:

- (a) Any evidence corroborating the causal mechanisms postulated in the tentative theory;
- (b) Any evidence contradicting the causal mechanisms postulated in the tentative theory; and
- (c) Any evidence suggesting additional causal mechanisms affecting change latency.

Evidence of type (b) and (c) is used to refine the tentative theory. Evidence of type (a) is accumulated to allow a picture of the overall strength of the evidence supporting each mechanism to emerge.

The quantitative analysis is focused upon the data collected from interviews. I use these data to estimate the proportion of the change latency attributable to a number of types of cause – some related to the SE performed on the project and some related to other factors. I explore the correlation of apportioned change latency with aspects of the SE performed to see if the relationships suggested by the tentative theory are visible or not.

In the third and final phase, I reflect upon the analysis of the data and formulate conclusions and recommendations for the researcher and for the practitioner in the field of railway SE.

These three phases are discussed in turn in chapters 9, 10 and 11. Before that, I look, in the next chapter, at one particular case study that serves to illustrate the manner in which case studies can help to refine theories.

### **7.7 Key points**

- 7A I choose realist research methods over interpretive methods because I see no way of applying interpretive methods in a way that will deliver the knowledge of practical utility that I have set out to compile.
- 7B I choose both qualitative and quantitative research methods because they seem to me to be complementary and because qualitative methods facilitate progress by researchers with limited resources.
- 7C I acknowledge that my methods have limited internal and external validity
- 7D I choose theory-driven methods because they can compile reliable knowledge over time by allowing incremental refinement of theories.



## 8 A CASE STUDY

In this chapter I look at one application of case study methods and illustrate how rigorous analysis of cases can produce useful results – in this case showing that a plausible tentative theory about the benefits of an aspect of SE is untenable and must be refined.

### 8.1 A common-sense tentative theory

The following tentative theory about the benefits of requirements management is plausible and some version of it is claimed by the vendors of requirements management tools, training and consultancy and is believed by their customers:

*Adopting good requirements management practice leads to more accurate and comprehensive requirements and forestalls significant rework occurring in the later stages of a project and arising from discovering that requirements were wrong or that the scope of the project was not aligned with the requirements.*

### 8.2 The case study

The case under study is the West Coast Route Modernisation (WCRM) project.

The West Coast Main Line connects the UK's largest cities, including London, Birmingham, Liverpool, Manchester, Glasgow and Edinburgh. The WCRM project carried out a significant volume of work on the line between 1998 and 2008, delivering increased capacity and reduced journey times as well as replacing worn-out parts of the railway (NAO, 2006).

The project had a disappointing start. By May 2002 the forecast of its final cost had risen from £2.5 billion (in 1998) to £14.5 billion. In January 2002, the UK Secretary of State for Transport instructed the Strategic Rail Authority (SRA), a UK government department, to intervene (NAO, 2006).

The project and the SRA's intervention were the subject of an investigation by the UK National Audit Office (NAO) which published its findings in a report (NAO, 2006). The report lists areas of weakness in the original project, describes the actions that the SRA took to remedy these weaknesses and contains the following conclusion (NAO, 2006; page 8):

*“The Strategic Rail Authority’s intervention from 2002 turned around the West Coast Programme. It worked with Network Rail [the UK rail infrastructure controller] and the industry to develop a deliverable Strategy and establish appropriate programme management.”*

This case study is valuable because it contains authoritative and independent evidence that, on the same project, a change in practices led to improved outcomes.

The report does not describe the requirements management practice adopted by the project before the SRA’s intervention but an article published by Dick (2000) reports that, in 2000, the WCRM project:

- was trying to apply *“the principles of systems engineering, and particularly requirements management”* and had deployed a proprietary requirements management software package;
- was adopting a *“structured approach”* that included *“establishing clarity of requirements, having traceability, ensuring that we have all the essential elements contributing to business benefits”*;
- was working to *“ensure that high-level business needs were translated into detailed requirements for each system element”*; and
- had determined *“which conditions are essential”* to meet high-level requirements as well as *“those that contributed little and might have been over-specified”* and had been able to *“make adjustments as necessary”*.

That, I conclude, describes a project that has adopted good requirements management and my personal knowledge, derived from discussions with colleagues who carried out WCRM requirements management, corroborates that conclusion.

However the project did carry out significant rework after the SRA intervention that arose from discovering that requirements were wrong or that the scope of the project was not aligned with the requirements. The NAO (2006) reports that the changes arising from the SRA’s intervention included:

- A *“more intrusive regime of obtaining possession of the track for engineering work through extended blockades”* that *“were crucial to delivery of Phase 1 by September*

*2004 as access had been the programme's key constraint and one of the key cost drivers".*

- Removing the European Rail Traffic Management System (ERTMS), new signalling technology, and the Network Management Centre from the scope of the programme, after spending £350 million on these items.
- Identifying *"opportunities to reduce the programme cost by over £4 billion"*, for instance, identifying that *"faster running north of Preston could be achieved without the need to replace the signalling"*.

It is hard to escape the conclusion that, in 2000 and the years immediately afterwards, good requirements management practice was being used to manage the wrong requirements, or at least requirements that did not correctly balance cost with other business objectives.

So, the tentative theory at the top of this chapter is contradicted – good requirements management practice did not forestall significant rework arising from requirements flaws during this phase of the project.

Why not?

Well, the NAO report describes features of the project that together appear sufficient to explain why the potential benefits of adopting requirements management practice were not realised:

- It is obvious from the escalation in the cost of the project that the project was unable to accurately forecast the cost of delivering the requirements that it had established. It would presumably have reached a different balance between aspirations and cost had it had access to accurate forecasts.
- The NAO (2006; page 12) reports that, *"Railtrack [Network Rail's predecessor] lacked the engineering expertise to be able to participate in Alliances as an informed and equal partner and to challenge contractor-developed scope."* Good requirements management practice requires access to competent domain specialists to be effective.
- The NAO (2006; page 11) says that *"Failure to engage stakeholders in support of the programme"* was a key deficiency and noted that *"Railtrack had been unable to*

*persuade train and freight operators to agree to blockades*". It follows that it was known that the optimal strategy involved blockades but the relationships between Railtrack and the operators did not allow this strategy to be put into practice.

As the remedies prescribed by the NAO (2006) included providing "*clear direction to the programme*", engaging "*stakeholders in support of the programme*" and "*tight specification and change control*" – all measures that are consistent with good requirements practice, there is no reason to believe that good requirements management was incapable of delivering benefits on the project (it appears to have helped to formulate the remedies to the problems encountered) but it does appear that its value was negated by poor cost forecasting, lack of access to competent domain specialists and poor stakeholder management

### **8.3 A refined tentative theory**

The initial tentative theory was contradicted. A project that appeared to adopt good requirements practice articulated requirements that did not reflect what was wanted and significant rework ensued.

Deficiencies in aspects of cost forecasting, processes for reviewing requirements and relationships with stakeholders were identified that situational analysis suggests could explain the contradiction and would be likely to produce similar results if repeated on other projects.

The case study suggests that the initial tentative theory should be refined as follows (additions underlined):

*In the presence of accurate cost forecasting, robust and informed processes for reviewing requirements and relationships with stakeholders that allow the solution that is best overall to be adopted,* good requirements management practice leads to more accurate and comprehensive requirements and forestalls significant rework in the later stages of a project arising from discovering that requirements were rework occurring in the later stages of a project and arising from discovering that requirements were wrong or that the scope of the project was not aligned with the requirements.

#### **8.4 Final thoughts**

I find this case study a useful prophylactic against the dogmatic belief that just doing more SE on a project will always yield benefits. The case study strongly suggests that there are circumstances when it is necessary to do other things as well as doing more SE if a proper return is to be seen on the investment in additional SE. However, my main purpose in discussing the study was to illustrate the process by which theories are developed, which I consider in the next chapter.

#### **8.5 Key points**

8A Application of case study analysis to the WCRM programme has shown that a plausible tentative theory about the benefits of adopting good requirements management practice is untenable and has suggested how it should be refined (see section 8.3).





## 9 A MODEL AND TENTATIVE THEORY

To paraphrase Lee and Lings (2008; page 123), models *describe* while theories *explain*. This chapter contains both. It contains a model that describes how core SE interacts with other project activities followed by a tentative theory that purports to explain how core SE contributes to reduced change latency. The model is presented using process modelling notation and the tentative theory is presented as conjectures about causal mechanisms associated with the model.

Before presenting the model, I review prior work in the area of models of SE and theories of how SE delivers benefit.

### 9.1 Relevant prior work

#### 9.1.1 Relevant models

Many of the characterisations of SE that were discussed in chapter 5 are associated with models of SE and, in some cases, with models of all the engineering activities required to produce a system.

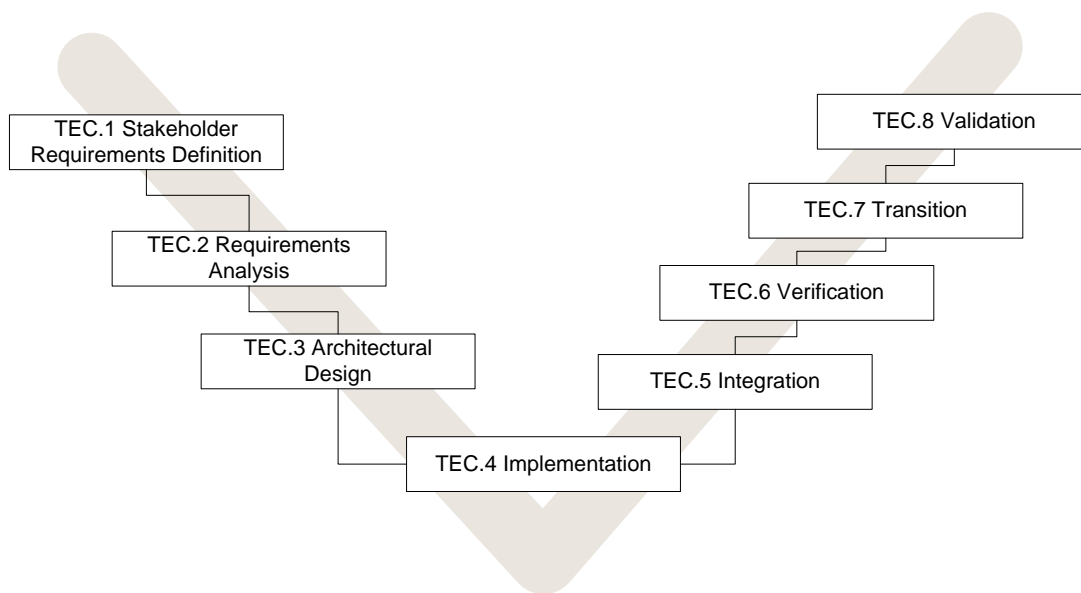
For example, Honour (2013) uses a straightforward breakdown of SE into eight major activities (which I described in section 5.3.3 above).

As another example, Elm and Goldenson (2012) measure the uptake of SE by selecting a number of the work products from Capability Maturity Model Integration - an SE standard – and counting how many can be aligned with the work products produced by a project.

Because Honour, Elm and Goldenson are looking for correlations between the adoption of SE practices and project outcomes, without exploring the detailed causal connections that produce these correlations, they do not need models that describe the interactions between SE activities and other activities. The models of SE underpinning their research are admirably simple – just lists of tasks or work products.

A well-used SE standard, ISO/IEC 15288 (ISO/IEC, 2002) embodies a more complex model of SE as a set of linked processes. The standard requires the execution of 8 technical processes during the project phase of a system lifecycle. These processes are clearly ordered because

each process uses output from the previous processes. Although the standard contains no such diagram, it is common practice to arrange these processes, or similar processes, in a V shape, in which the horizontal axis represents progress on the project while the vertical axis represents the level in the systems hierarchy at which work is being done. The V indicates that design activities become progressively more detailed, working at lower and lower levels and then, after the components have been produced, they are integrated into progressively larger assemblies. The V diagram formed with the 8 project technical processes from ISO/IEC 15288 is shown in Figure 7 below.



**Figure 7: The V diagram**

A richer model that shows the interaction between engineering and management tasks involved in realising a system is provided in EIA-632 (EIA, 1998). The standard defines a number of processes, partitioned into five groups: **Technical Management, Acquisition and Supply, System Design, Product Realization** and **Test and Evaluation**. It also shows the main flows of information between the groups.

However, neither of these models nor any other that I have found is concerned principally with the interaction between SE and other project activities and I therefore conclude that the model that I require will have to be created from scratch.

### 9.1.2 A model of change

Sterman (2000) describes a model of project change, which, while not a candidate for my purposes, is indirectly relevant. The model was used to estimate the consequential costs of changes raised by the customer to a contract. At its heart is a diagram, redrawn in simplified form in Figure 8 below.

The thick lines indicate flows of work between the 'stocks' represented by rectangles, together with some of the influences on the rate of the flow.

The model reflects a different aspect of the mechanisms that I am studying: it is interested in the rates of flow between stocks; I am interested in the time taken to move between stocks. The model is generally consistent with my experience, except that, outside the contractual environment for which the model was created, it would be more appropriate to replace 'customer changes' with 'changes in the outside world' and to acknowledge that these changes can move work really done to undiscovered rework as well as to known rework.

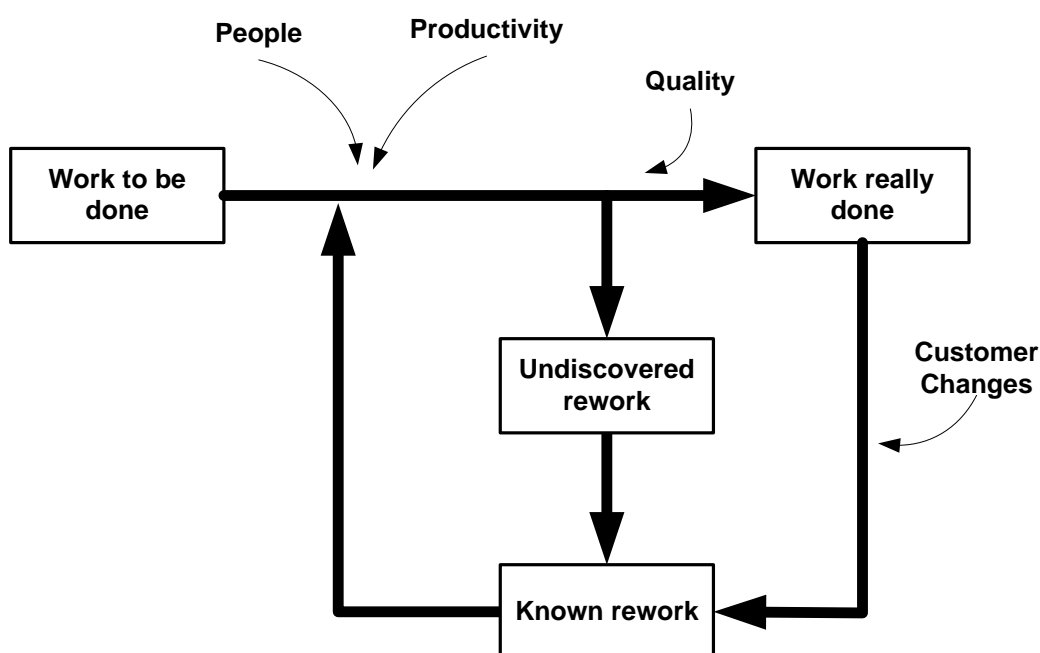


Figure 8: The rework cycle (after Sterman)

### 9.1.3 Relevant theories

Hypotheses about how SE contributes to project outcomes were reviewed in chapter 3. It may be helpful at this point to recall that they were categorised into three general types:

- ‘The control of complexity’. The hypothesis that, it becomes impossible to realise systems that have surpassed a certain threshold in complexity without using SE, at least without unacceptable rework.
- ‘Whole system optimisation’. The hypothesis that SE provides a means of optimising the system as a whole that is not provided to a satisfactory degree by other disciplines.
- ‘Left shift’. The hypothesis that effort invested early in a project, and in particular in the SE activities that occur in the later stages will yield savings in effort later in the project that outweigh the investment, presumably because SE pre-empts expensive problems.

I note that these types are still fairly general and the precise causal links by which SE would produce the benefits claimed remain implicit. I conclude that it is desirable to develop a more detailed theory.

## 9.2 The model

The heart of my model is a process map, but before discussing that, it is helpful to define a few terms so that the process can be presented more precisely.

### 9.2.1 Definitions

I adopt the definition of **system** used in the INCOSE Handbook (INCOSE, 2010): “*a combination of interacting elements organized to achieve one more stated purposes*”. That is a very general definition but still not the most general one in use. Some people use system to cover living organisms that certainly have interacting elements but for which the purpose, if any, may be obscure. The words “*organized to achieve one more stated purposes*” exclude such things from the scope of the word and restrict it to man-made things. However, the definition is from an authoritative source and is general enough to cover those things that I regard as railway systems.

A **sub-system** of a system is a component of a system that is also a system in its own right.

For my purposes, a simple definition of **project** will suffice. I define a project to be an activity to deliver a system.<sup>11</sup>

Some definitions related to requirements help to draw a distinction between SE and project management.

I define a **stakeholder** in a system to be any individual or organisation with an interest in that system. That interest is expressed as one or more **requirements**. I follow the INCOSE Handbook (INCOSE, 2010) definition of a requirement as *“A statement that identifies a system, product or process characteristic or constraint, which is unambiguous, clear, unique, consistent, stand-alone (not grouped), and verifiable, and is deemed necessary for stakeholder acceptability.”*

Requirements may also be categorised as follows:

- A **system requirement** is a requirement on some aspect of the delivered system, for example, to provide certain functionality or to deliver a certain level of reliability.
- A **schedule requirement** is a requirement on the schedule. The simplest example would be a deadline for achieving a certain milestone.
- A **cost requirement** is a requirement on the cost of the project, typically a budget that should not be exceeded.
- A **project requirement** is a requirement on how the project must be executed which is not a schedule or cost requirement. A possible example is a requirement to produce a set of plans in a given format.

For the purposes of the model, I also draw upon the definitions of core SE, requirements specification, context specification, system specification, system budget, system schedule, sub-system specification, sub-system budget, sub-system schedule, system design, process

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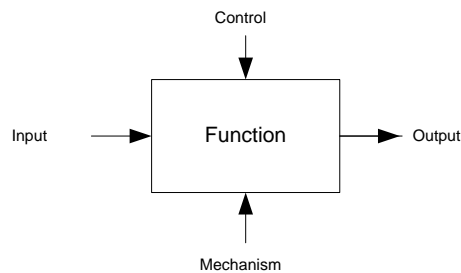
<sup>11</sup> This is broadly consistent with but slightly more specialised than the definition in (Office of Government Commence, 2002; page 7), which is “a management environment that is created for the purposed of delivering one or more business products according to a specific Business Case”.

model, SE products and project management products, which were made in chapter 4 and the definition of change latency, which was made in chapter 6.

### 9.2.2 Notation

The process map is shown using a diagrammatic notation called Integration Definition for Function Modeling or IDEF0, for short. IDEF0 is defined in a draft federal information processing standard (National Institute of Standards and Technology, 1993).

In this notation, functions are shown in rectangles (see the key in Figure 9). The inputs to a function are shown as arrows reaching the rectangle from the left and the outputs are shown as arrows leaving the rectangle from the right. An arrow reaching the rectangle from the top is a 'control input', which governs how the function must be performed. An arrow reaching the rectangle from the bottom is a 'mechanism,' which delivers a resource or some other means required to perform the function.<sup>12</sup>



**Figure 9: A key for the IDEF0 notation**

When an arrow goes from function A to function B, this indicates that there is a flow of information or material from A to B. Note that a function can start as soon as it has sufficient input information or material and so it is quite possible that B may start before A has finished.

The model follows the requirements of the standard fairly closely but I exceed the limit of six rectangles per diagram and there are a few occasions where, to avoid tangling the diagram, I indicate the start and end of an arrow without connecting the two.

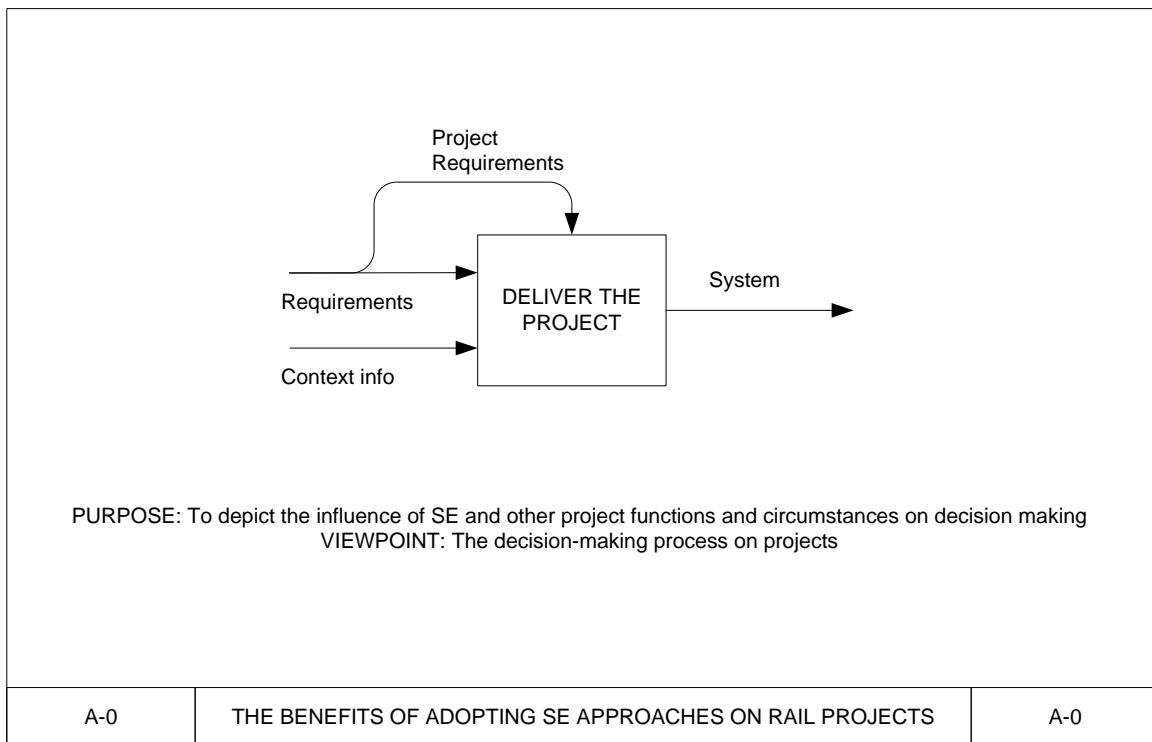
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<sup>12</sup> The notation allows a fifth type of arrow – a 'call' arrow – which I do not use and do not describe.

**9.2.3 The process map – the A-0 Context Diagram**

The first stage in creating an IDEF0 model is to draw an A-0 Context Diagram, which is a depiction of the overall process as a ‘black box’, showing its inputs and outputs. This diagram also contains a declaration of purpose and a viewpoint. In the IDEF0 standard, it is accepted that drawings need not be comprehensive and need only show those functions and flows that are relevant to the purpose and viewpoint.

The A-0 Context Diagram is shown in Figure 10 below. The Project Requirements flow ‘forks’ off from the Requirements flow. This indicates that the Project Requirements are a subset of the Requirements. All Requirements, including Project Requirements, are inputs to the project and are taken into account when designing the system. Project Requirements are also control inputs and are taken into account when designing the project process.



**Figure 10: The A-0 Context Diagram**

**9.2.4 The process map - the project processes used to create a system design baseline**

The model is strongly focussed on the purpose and viewpoint declared in Figure 10. I omit functions and flows that are not relevant to the purpose and viewpoint. For example, money is clearly a resource consumed by project activities but, because it is information about



money and not money itself that plays a part in decision making, I do not show money on the diagram. In addition, I use a single function in the model to represent complex collections of functions where the interactions between these sub-ordinate functions are not relevant to the purpose and viewpoint.

The intention is that the model should be as complex as is necessary to achieve the defined purpose from the defined viewpoint but no more complex. If the model is to do this, then it needs to include the 6 core process areas into which I partitioned core SE in chapter 5. The 6 core SE process areas are:

- Model (the project) processes
- Manage requirements and specify the system
- Design the system
- Model, simulate and analyse the system
- Verify and validate the system
- Manage change

Each of these process areas will be represented by an IDEF0 function. However, it is convenient in explaining the model to start with a simpler model concerned with creating a system design baseline and then to add further functions to cater for change.

The model of the project processes used to create a system design baseline is presented in Figure 11. The grey box is the decision-making process. It is shaded to indicate that it is not an SE function. The other four functions correspond to four of the six core SE process areas listed above.

**Manage requirements and specify the system** and **Design the system** together generate all the SE artefacts listed in chapter 5, except for the project Process Model, which I will return to in a moment. These functions must be executed in order to establish a baseline.

It is considered that all projects must form some idea of what they are trying to achieve and some plan for achieving it, no matter how informal, incomplete, inaccurate or misconceived and consequently all projects must perform these functions to some extent. Sending out a team to dig holes in random places and then fill them in with concrete would fail to meet these criteria but that would be a guerrilla art installation, not a project.

**Model, simulate and analyse the system** is an optional part of the process but, if executed, provides information both for design and decision making.

**Model (the project) processes** defines the processes used to perform the other functions and its output is the final SE artefact: the project Process Model. The Process Model is a control input to all other functions. Note however that, for clarity, the connections are not shown from end to end but instead indicated by arrows which are annotated “(2)” and connected at one end only.

Note. A similar abbreviation is used to indicate that cost and timescale estimates and outturns are outputs from many functions and input to **Authorise the system design and process model**.

The **Decisions** output from the **Authorise the system design and process model** function is the feedback loop in the control process. Decisions may include selecting from options offered and requesting additional options.

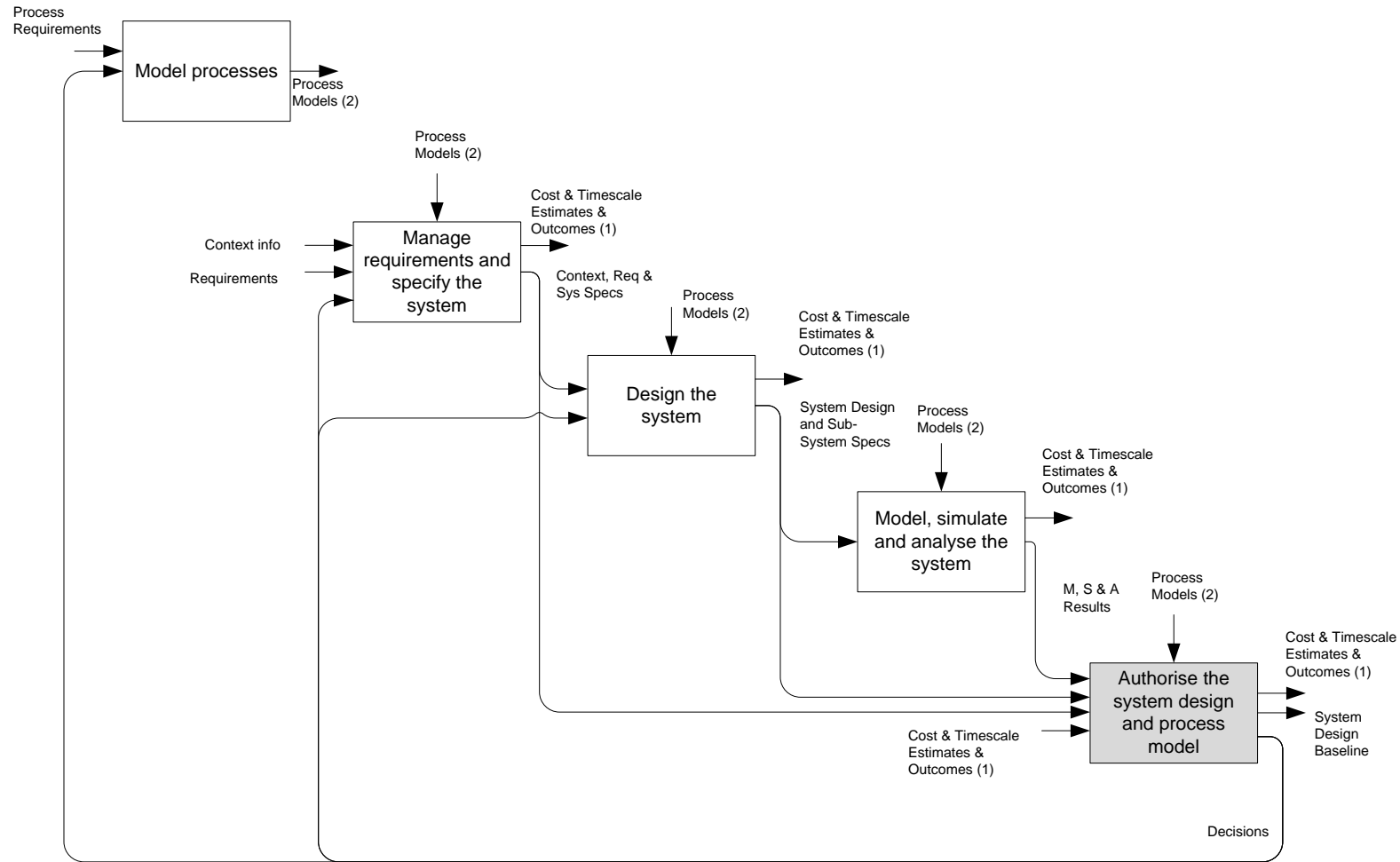


Figure 11: The project processes used to create a system design baseline

### 9.2.5 The process map – discussion of a key decision

The decision not to include **Authorise the system design and process model** within the scope of SE has important ramifications and requires justification.

It may help to be clear that the decision is concerned with the scope of core systems *engineering* and not the responsibilities of systems *engineers*. Members of a project who are called systems engineers may do things that go beyond SE and some SE tasks may be performed by people who are not systems engineers.

Core SE, as I have defined it, clearly includes taking decisions about the system design and process model. However these decisions, as I model the world, are preliminary only. On the real projects with which I am familiar, these decisions are potentially open to challenge by stakeholders and some may be reversed before the project finally approves them, an approval that often takes place at some stage gate review. The final decision, therefore, is taken by the project manager or some sort of project board.<sup>13</sup>

To some extent, this remark applies to anyone with a design role on the project – the decisions that engineers in traditional disciplines take are also open to challenge and revision in principle. In practice it applies with greater force to those doing SE because SE is one step further removed from the realised system than traditional disciplines. The drawings prepared by a civil engineer may be passed directly to the contractor to build whereas an interface description prepared by a systems engineer must be agreed with the designers of the sub-systems that are party to the interface before these designers prepare specifications and drawings for construction or manufacture.

So the decision to exclude **Authorise the system design and process model** from the scope of SE seems consistent with common practice on projects.

It is possible to claim final authority for the system design and process model for SE as a matter of principle, regardless of observed practice. However such a claim seems untenable

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<sup>13</sup> For example, the *PRINCE 2 project management methods* (Office of Government Commerce, 2002; page 273) requires that changes be approved by the Project Board, unless this authority is delegated.

to me. Decisions about the system design and process model almost always have cost and time implications and so have to be fully integrated with budget and schedule decisions. Giving authority for different sorts of decisions to different people makes about as much sense as letting the navigator in a rally car steer while the driver controls the brake, throttle and gear changes.

Some may suggest that this shows that systems engineers should take decisions about budget and schedule as well. I think that *is* a tenable position, although I do not agree with it. But, if systems engineers are given that authority then it seems to me that, when they exercise it, they must be regarded as doing project governance because, to transfer these decisions from project governance to SE leaves neither term aligned with the everyday meaning that people attribute to it.

So in summary:

- I do not think that authorising the system design and process model can be separated in practice from schedule and budget decision, and
- therefore, I regard this authorisation as outside the scope of SE because any other decision would import so much into SE as to leave it unrecognisable.

If I stretch the rally car metaphor a little further, I have prised SE's grip from the car's controls and strapped SE firmly into the navigator's seat. The practical and non-metaphorical consequence of this is that SE can only contribute to the outcome of a project via providing information to other people. In practice, few if any of those other people will be specialist systems engineers. This in turn has two important corollaries:

- To be effective, those performing SE need to prepare the final work products in a way that can be easily understood by the non-specialist. This is a harsher discipline than imposed upon traditional engineering disciplines. A civil engineer on a civil engineering project, for instance, can reasonably assume that the architect, project manager and contractors with whom he or she works can read a standard technical drawing and will understand commonly-used technical vocabulary.

- If the project's decision-making process is broken and it is unable to reach timely, rational decisions about the project then it is unlikely that increasing the effort spent on SE will deliver increased benefits until this process is fixed.

### 9.2.6 The process model - the project processes used to manage system change

The partial model as built up so far describes how the system design baseline is established, but it is not sufficient; the processes involved in design change need to be modelled as well.

The complete model is constructed by extending the partial model.

Three new functions are added:

- **Design the sub-systems and build the system** covers a multitude of detailed design, implementation, installation and commissioning activities which need to be reflected in the model but play a limited role in it. The rectangle is shaded to indicate that it does not depict an SE function.
- **Verify and validate the system** is the fifth core SE process area and covers all activities to check the system and its sub-systems against the SE documents. Where these checks fail, problem reports are raised. For problems requiring localised change, the feedback loop to **Design the sub-systems and build the system** provides a route for local correction of the problem. However, for problems that may require system change, the problem report will be input to **Authorise the system design** that will cause re-execution of **Design the system** and possibly of **Manage requirements and specify the system** as well before a change to the system design is authorised.
- **Manage change** delivers change management arrangements, which are a mechanism for all the other functions.

Note that changes do not 'flow through' the **Manage change** function. The output of this function is a set of change management arrangements. Changes are processed via updates to the data flows that were involved in establishing the baseline. For example, if it is decided to extend the system to deliver a new requirement, that requirement is input to the **Manage requirements and specify the system** function, which may result in updated requirements being input to the **Design the system** and this, in turn, may result in an updated system

design being presented to the **Authorise the system design and process model** function for ratification before being input to **Design the sub-systems and build the system**.

Note, also, that the **Model, simulate and analyse the system** function may continue after the initial system design baseline has been established and is a potential source of system change.

The complete process map is shown in Figure 12. It is considered that this map meets the criteria set for it: it is as complex enough to achieve the defined purpose from the defined viewpoint but no more complex.

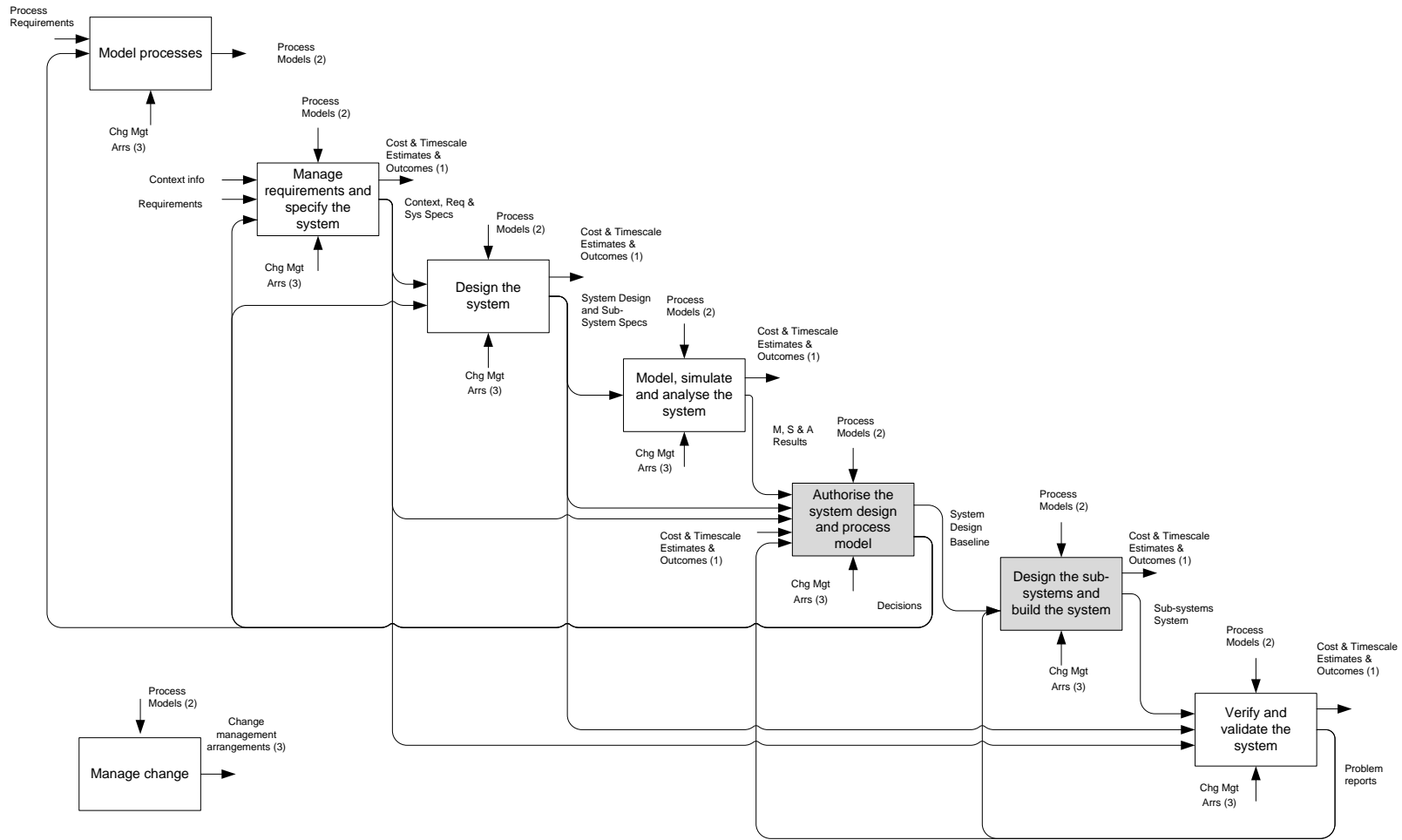


Figure 12: The process map



### 9.3 A tentative theory of the contribution of SE to reducing change latency

The model is not of itself a theory of how SE contributes to reduced change latency but it constrains that theory. Reduced change latency is the consequence of sounder, timelier decisions and these decisions are outputs of the **Authorise the system design and process model** function. The core SE functions provide, as inputs to this function, change management arrangements and information in the form of:

- proposed specifications and designs, for ratification;
- the process model, for ratification;
- modelling, simulation and analysis results; and
- problem reports.

The tentative theory of how core SE contributes to reduced change latency may be summarised as:

*Core SE contributes to reduced change latency by providing the people taking decisions about the system design and process model with timely, accurate and comprehensive information (including proposed specifications, design and process models) and effective change management arrangements.*

The full tentative theory comprises a set of more detailed causal mechanisms through which core SE process areas contribute to reducing change latency by directly or indirectly contributing to *“More timely and sounder decisions”*. These are illustrated in a diagram before being defined in a table.

Figure 13 is just an illustration which may help to read the table. It contains a ‘silhouette’ of the process model, with the text removed, in the background and blue annotations in the foreground. These annotations are associated with flows that are outputs from one function and inputs to one or more other functions and are desirable attributes of these flows.

An arrow between two such annotations asserts the claimed causal mechanism that, all other things being equal. If the attribute at the foot of the arrow is present to a greater extent, then the attribute at the head of the arrow will be present to a greater extent.

The causal mechanisms are articulated in more detail with the justification for believing them in Table 6. The serial numbers in Table 6 correspond to the numbers marked on the blue arrows in Figure 13.

Each row should be read:

**'Cause** will produce **effect** provided that **proviso** because **reason**'.

The theory makes strong predictions: that an effect will certainly be seen if the cause holds and any proviso holds. There are no provisos in the initial tentative theory but it is considered likely that there will be provisos that have not yet been identified and hence unlikely that the theory will be found wholly accurate. Nonetheless, strong predictions of this form provide a sounder basis for the refinement that I wish to see.

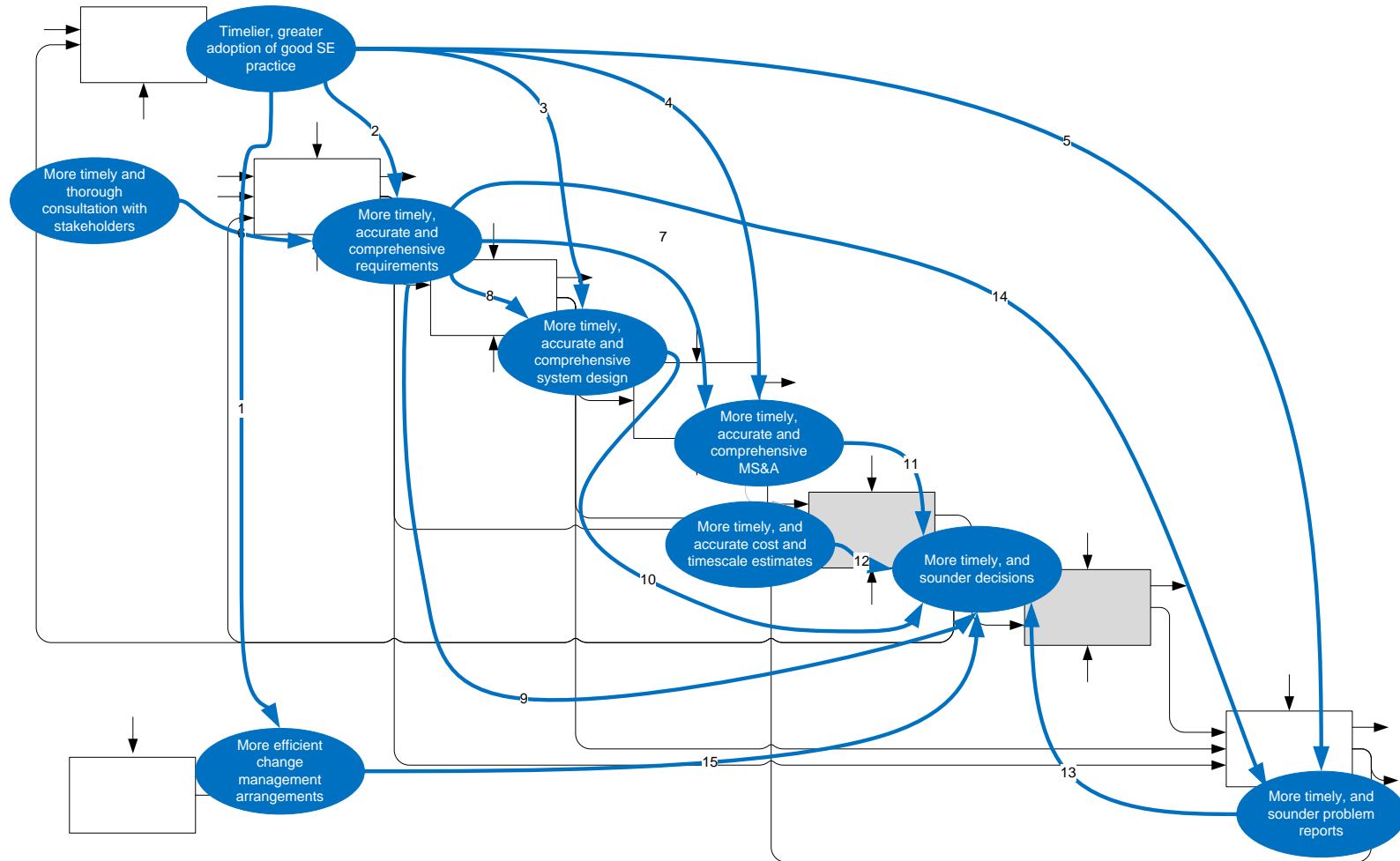


Figure 13: The contribution of SE to reducing change latency in diagrammatic form

**Table 6: A tentative theory of the contribution of SE to reducing change latency in tabular form**

Serial	Cause	Effect	Proviso	Reasons
1	Timelier, greater adoption of good SE practice	More efficient change management arrangements		SE practices are explicitly designed to do this
2	Timelier, greater adoption of good SE practice	More timely, accurate and comprehensive requirements		SE practices are explicitly designed to do this
3	Timelier, greater adoption of good SE practice	More timely, accurate and comprehensive system design		SE practices are explicitly designed to do this
4	Timelier, greater adoption of good SE practice	More timely, accurate and comprehensive modelling, simulation and analysis		SE practices are explicitly designed to do this
5	Timelier, greater adoption of good SE practice	More timely, and sounder problem reports		SE practices are explicitly designed to do this
6	More timely and thorough consultation with stakeholders	More timely, accurate and comprehensive requirements		Because this reduces the number of omissions and misunderstandings
7	More timely, accurate and comprehensive requirements	More timely, accurate and comprehensive modelling, simulation and analysis		The modelling, simulation and analysis can be focussed on the real requirements
8	More timely, accurate and comprehensive requirements	More timely, accurate and comprehensive system design		There is less likelihood of failing to meet a mandatory requirement or of delivering a sub-optimal solution
9	More timely, accurate and comprehensive requirements	More timely, and sounder decisions		There is less likelihood of pursuing options that do not meet the mandatory requirements and can more accurately assess the relative value of options
10	More timely, accurate and comprehensive system design	More timely, and sounder decisions		There is less likelihood of unsatisfactory designs being presented for approval

Serial	Cause	Effect	Proviso	Reasons
11	More timely, accurate and comprehensive modelling, simulation and analysis	More timely, and sounder decisions		There is less likelihood of pursuing options that do not meet the mandatory requirements and can more accurately assess the relative value of options
12	More timely, and accurate cost and timescale estimates	More timely, and sounder decisions		The project is less likely to pursue unaffordable options
13	More timely, and sounder problem reports	More timely, and sounder decisions		Problems can be fixed more quickly and corrected without unnecessary iteration
14	More timely, accurate and comprehensive requirements	More timely, and sounder problem reports		There are clearer criteria for formulating tests and assessing the results
15	More efficient change management arrangements	More timely, and sounder decisions		Delays due to errors and slow administration are reduced

#### 9.4 Beyond the tentative theory

Having articulated a tentative theory, the next stage is to subject it to test against the facts in the real world. In principle these facts may corroborate or contradict the tentative theory. In practice, the most valuable outcome is probably somewhere in between, where the facts generally corroborate the tentative theory but suggest some deficiencies that can be corrected by refining it. Nonetheless, the facts are the facts and I must live with what they are.

The testing that I performed is described in the next chapters. However, the tentative theory can be explored a little in thought experiments first.

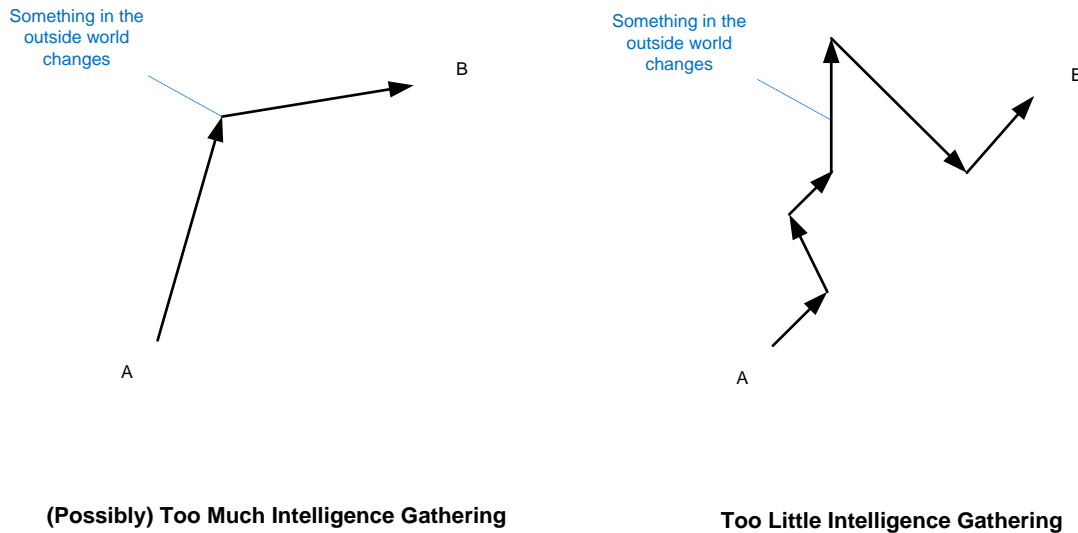
The tentative theory asserts that core SE contributes to reduced change latency by timely, accurate and comprehensive information. So, if that is true, would it mean that a rational manager of a project doing little SE should invest in more SE? There are good reasons for believing that the answer must be, 'it depends'.

One of the things upon which the answer must depend is the relationship between the additional costs of performing more SE and the value of the additional intelligence generated. There must surely be a law of diminishing returns here.

At the extreme end of the application of SE lies a project that defines and analyses everything in such detail that it never has to change unless something in the outside world changes and then it stops work and redefines and reanalyses everything afresh. It completely avoids rework but is likely to proceed along the optimal track so slowly and expensively that a project with a greater tolerance for rework would deliver an acceptable system more quickly and at lower cost. The trajectory of such a project is illustrated in the left hand diagram in Figure 14. Performing more SE on such a project would be a waste of time and money. I have never encountered a rail project of this sort.

At the other end lies a project that proceeds with insufficient intelligence and, as a result, approaches its target along a trajectory that resembles a random walk, as depicted in the right hand diagram in Figure 14. The cost of change on such a project is so large that the benefits of more SE are likely to exceed the costs of more SE.

It follows that, while the theory provide a framework for understanding the likely effects of investing in SE, it is not sufficient on its own to support an investment decision – additional information about the magnitudes of the costs and benefits is required.



**Figure 14: Project trajectories compared**

## 9.5 Key points

- 9A Existing models of SE are focussed on the components of SE but do not make clear how SE contributes to decisions about change.
- 9B A model that describes how SE interacts with other project activities is presented using the IDEF0 notation.
- 9C In this model the function of deciding upon the system design and project process model is not regarded as part of SE because any other decision would import so much into SE as to leave it unrecognisable.
- 9D To be effective, those performing SE need to prepare the final work products in a way that can be easily understood by the non-specialist.
- 9E If a project's decision-making process is broken and it is unable to reach timely, rational decisions about the project then it is unlikely that increasing the effort spent on SE will deliver increased benefits until this process is fixed.

- 9F In summary, the tentative theory proposed is that Core SE contributes to reduced change latency by providing the people taking decisions about the system design and process model with timely, accurate and comprehensive information (including proposed specifications, design and process models) and effective change management arrangements.





## **10 TESTING THE TENTATIVE THEORY AGAINST DATA COLLECTED FROM PROJECTS**

In this chapter, I describe an exercise to test the tentative theory by collecting and analysing data about five UK railway projects and the major changes that occurred on them. The data were collected via interviews and inspection of project records.

Five is a small number. I did not collect data on more projects because the logistics of doing so were prohibitive: the negotiation of access and the collection, checking and analysis of data for one project requires a significant amount of effort and an even more significant amount of time – often as much as six months. This is an intrinsic obstacle to research in this area because organisations have some understandable reluctance to allow access to data that does not always reflect well upon them and because providing such access has a cost to them.

Because the sample was so small, no meaningful conclusions can be drawn from quantitative analysis but I attempt such analysis anyway, in order to indicate how such methods could be usefully applied in later research if larger samples were collected.

Although there were only five projects, these projects provided data on 31 significant changes.

More detailed supporting information about the data collection and analysis is provided in appendix A. This appendix has the same section headings as this chapter. For additional information about any of the sections below, please refer to the corresponding section of appendix A. So, for example, for information on section 10.6, refer to A.6.

### **10.1 Conduct of the survey and data collection exercise**

I contacted a number of people known to me at rail organisations that delivered projects and had an interest in SE. Five interviewees agreed to take part and each provided data on a single UK rail project.

Interviewees were assured that the information that they had provided would not be disclosed beyond the researcher and his supervisors in a form that would allow someone to link it to them or the projects or organisations concerned.

Data were collected at meetings with interviewees by asking questions using a pre-prepared questionnaire and inspecting project records using a pre-prepared data collection procedure. Collection of data for one project took between 4 and 8 hours, typically spread over 2-3 meetings.

Most of the questions were associated with a closed list of possible responses. However, most of these lists included the response, "*Other, please specify*" and interviewees were encouraged to add general remarks, which I recorded.

I sent my notes of interviews to the interviewees and gave them the opportunity to correct any misunderstandings.

The questionnaire was organised using three general questions as headings:

- What sort of a project was it [that will be discussed]?
- To what extent did the project adopt SE approaches?
- Is there anything else?

The first two questions were broken down into more specific questions that were put to the interviewees.

The last question, "*Is there anything else?*" was asked directly to give interviewees the opportunity to add whatever additional information they liked. Not all interviewees took this opportunity and most of the additional information provided comprised clarifications about the project concerned. None of the responses provided is considered significant for the interpretation of the data collected and none is discussed further.

I then worked with each interviewee to review project change records and select a number of changes for analysis. Information was collected for each selected change from project records and the interviewee's memory. This information included a general description of change, historical information that could be used to calculate change latency, and the

interviewee's opinions about the main factors that affected change latency and the main opportunities to reduce change latency on similar projects.

The data collected and the analysis of these data are summarised in the six following sections, which are organised as follows:

- **Data collected about the projects in general** summarises the data collected in response to the question *"What sort of a project was it?"*
- **Analysis of data collected about projects in general** summarises analyses of the data described in the previous section.
- **Data collected about the SE performed on the projects** summarises the data collected in response to the question *"To what extent did the project adopt SE approaches?"*
- **Analysis of data collected about the SE performed on the projects** summarises analyses of the data described in the previous section.
- **Data collected about changes and analysis of these data** summarises the data collected by inspection of project change records as well as analyses of these data.
- **Further analysis** describes further analyses to search for correlations between the different types of data. All quantitative analysis is in this section.

## 10.2 Data collected about the projects in general

In this section, I summarise and discuss the data collected about the projects in general, excluding data about the SE performed on them and the changes made on them.

These data do not directly offer any insight into the benefits of SE but they are important when interpreting other data.

Interviewees were asked to describe the project to be talked about in general terms and were then asked a number of specific questions to establish the status of the project, the parts of the railway involved as well as the size, duration, novelty, volatility and complexity of the project, the experience of those performing SE and the degree to which SE functions were integrated with the rest of the project.

A comprehensive account of the questions and responses is provided in appendix A. In summary:

- The projects are a diverse representation of medium-sized and large projects – probably as diverse as a sample of five projects could be. Three projects were working on metro railways and two were working on mixed-traffic heavy railways. Three projects were delivering infrastructure improvements, one was delivering rolling stock improvements and one was delivering both.
- All projects were at an advanced stage at which non-recurring engineering was largely complete.
- For all projects except one, the part of the lifecycle discussed ran from initial feasibility studies until bringing the new assets into service and decommissioning assets being replaced. The exception was Project 3, which was associated with one change that was of significantly greater magnitude than all other changes made on that project – a decision, part way through design to radically cut back the scope of the project. Knowing that this change would be the focus of the exercise, the survey and data collection for this project were limited to the design phase.
- The duration of the projects varied between 5 and 10 years with a mean average of 7 years.
- Projects were of moderate or large size, 50-199 staff at peak or larger.
- The number of migration stages<sup>14</sup> varied between 2 and 13.
- The experience of the people performing the SE varied significantly between the projects. The degree to which these people interacted with the rest of the project also varied but to a lesser extent.
- Volatility of technical strategy varied significantly between the projects.

Note. Below, I report the finding that the commercial relationships between parties appears have a significant effect on change latency. Because I did not know this when I constructed

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<sup>14</sup> A migration stage is a significant change to the railway after which the railway is returned to service.

the questionnaire and data collection procedure, I did not collect information about this aspect of the projects directly.

### **10.3 Analysis of data collected about projects in general**

I looked out for outliers that could skew the results. One such outlier is immediately apparent: the analysis of Project 3 was restricted to the design phase. This means that the maximum change latency is restricted to the duration of this phase and any changes with greater change latency would not be analysed. As a consequence, I exclude this project from the calculation of correlations between change latency and other parameters.

I carried out analyses in order to determine whether any project was significantly more challenging than the others. These analyses are described in detail in appendix A. No clear outlier was identified – if the challenges faced by one project in one area were above average this tended to be balanced by lower-than-average challenges in other areas. One project, project 5, did appear overall to face greater technical challenges but it also had the most experienced and integrated SE team.

### **10.4 Data collected about the SE performed on the projects**

Interviewees were provided with 51 statements that might or might not have correctly described the SE performed on the project such as, *“The project wrote down a description of the processes used to define, design, implement, build and commission the system”*. The statements and additional detail about the data collected are shown in appendix A. The parameters were derived from the statements used in the second preliminary survey but I returned to ISO/IEC 15288 (ISO/IEC 2002) to create statements reflecting good practice in areas of SE not studied in the second preliminary survey.

For each statement the interviewee was asked to what degree it fairly represented what had happened on the project. Each response provided was converted to a figure of merit (FoM) in the range 0.0 to 1.0, where 0.0 corresponded to the response ‘Wholly untrue’ and 1.0 corresponded to the response ‘Wholly true’. Mean average FoMs were calculated for all 51 statements and these are tabulated in appendix A.

11 of these FoMs were at or above the 80th percentile. They fall naturally into the following groups:

- identifying stakeholders;
- validation; and
- assessing and monitoring risks.

These were the areas where the projects adopted good SE practice to the greatest extent.

A further 11 of these FoMs were at or below the 20th percentile. They fall naturally into the following groups:

- managing interfaces;
- checking and managing requirements;
- tracking the implementation of change; and
- modelling the physical structure of the system.

These were the areas where the projects adopted good SE practice to the least extent.

### **10.5 Analysis of data collected about the SE performed on the projects**

I was interested to see how the degree of uptake in the six core SE processes defined in the model that I presented in chapter 9 above varied between projects. If the degree of uptake was uniformly high or low across the projects, then this would make it difficult to learn whether it affected the outcome.

To explore this, I associated the 51 statements in the questionnaire (apart from one<sup>15</sup>) with one of the six core SE processes. These are listed below with acronyms that will be used below to refer to them:

- Model (the project) Processes (MP)
- Manage Requirements and Specify the System (MR&StS)
- Design the System (DtS)

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<sup>15</sup> The model was revised after the list of questions had been finalised. One question – with identifier C – was subsequently found not to relate to any core SE process.

- Model, Simulate and Analyse the System (MS&AtS)
- Verify and Validate the System (V&VtS)
- Manage Change (MC)

Mean average figures of merit were calculated for each core SE process on each project. An overall average SE figure of merit was also calculated for each project and each core SE process. The results are shown in Table 7.

Highlighting is used in this table to indicate a division of the scores for the core SE processes into three groups:

- Cells containing scores of 0.90 or higher are regarded as significantly better than average and are highlighted in blue.
- Cells containing figures of 0.50 or lower **or** which represent averages of data that include at least one FoM of 0.25 (mostly untrue) or 0.0 (wholly untrue) are regarded as significantly worse than average and are highlighted in pink. The second part of this criterion was included on the basis that omission of or gross deficiency in one aspect of which may undermine the value of the other aspects.
- Other cells are regarded as being approximately average and are not highlighted at all.



**Table 7: Figures of Merit by project and process area**

Core SE process	Project						Overall
	1	2 early	2 late	3	4	5	
MP	0.88	1.00	1.00	0.50	0.63	0.88	<b>0.78</b>
MR&StS	0.83	0.76	0.89	0.40	0.68	0.95	<b>0.72</b>
DtS	0.79	0.46	0.63	0.54	0.75	0.92	<b>0.72</b>
MS&AtS	0.97	0.86	0.86	0.89	0.53	0.86	<b>0.82</b>
V&VtS	0.84	0.84	0.94	N/A	0.81	0.91	<b>0.85</b>
MC	0.95	1.00	1.00	0.35	0.80	0.80	<b>0.78</b>
Overall	<b>0.87</b>	<b>0.79</b>	<b>0.87</b>	<b>0.53</b>	<b>0.70</b>	<b>0.89</b>	<b>0.78</b>

Notes:

- Because I only collected data concerning the design phase of project 3, there was insufficient information to calculate a FoM for V&VtS for this project and this is indicated by showing the cell with a grey background.
- Project 2 carried out a number of similar tasks, grouped into three ‘tranches’. The interviewee on project 2 provided responses for the initial tranche and also indicated where a different response was relevant to the final tranche. This enabled the calculation of separate figures of merit for ‘Project 2 (early)’ and ‘Project 2 (late)’.

All the rows in Table 7, apart from **Verify and validate the system**, contain blue, white and pink cells. The sample then contains examples of low, medium and high uptake of SE practice in five of the six core SE processes, which increases the chances of seeing the effect of variation in uptake, while that chance is reduced for **Verify and validate the system**.

## 10.6 Data collected about changes and analysis of these data

### 10.6.1 An introduction to the data collection

For each project, the interviewee and I reviewed one or more logs of the changes made on that project. With the interviewee’s help, I selected a sub-set of changes that met all the following criteria:

- (a) The change had a significant effect on the cost of the project.
- (b) The change affected either the final built system or the staging of the works. Changes that only affected project processes were excluded.

- (c) The change implied some alteration in direction for the project. Changes that adjusted the requirements to bring them into line with what the project was already doing or planning to do were not included.
- (d) There was sufficient information available to collect the data about the change that I had specified.

The precise interpretation of criterion (a) varied slightly between the projects in order to produce a manageable number of changes to analyse in detail. These criteria are discussed in appendix A but generally included changes that increased or decreased the cost of the project by at least 1% of the final cost.

I observed that, on three of the projects analysed, the change records were incomplete enough that significant changes had to be excluded from the analysis and, on a fourth, criterion (a) had to be applied using the interviewee's judgement because insufficient records were available.

This is a little puzzling because I would expect that adoption of good SE practice would leave sufficient records to apply the data collection procedure fully<sup>16</sup> and the figure of merit for the **Managing change** process only falls below 0.80 for one project. However, closer inspection shows that this average hides significant variation between different aspects of change management and, as I noted above, the figure of merit for tracking the implementation of change falls below the 20th percentile.

I noted when reviewing the change records for some projects that they included entries that supported one contractual variation that, in turn, covered multiple technical changes. I believe change management was used on several of the projects as a commercial tool to document the final outcome of commercial negotiations between the parties rather than as an engineering tool for ensuring that change was consistently applied.

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<sup>16</sup> The requirements for configuration management in ISO/IEC 15288 [ISO/IEC, 2002] include requirements that "Changes to items under configuration management are controlled" and "The status of items under configuration management is made available throughout the life cycle" and these are reflected in statements E, F, G and H in the study questionnaire (see Table 27 in Appendix A).

For each change selected for analysis, the interviewee and I sought the following information from project records and the interviewee's recollection of events in order to estimate change latency, detection latency and decision latency (see key points 6E and 6F):

- The 'root document', by which I mean the most basic document in the project hierarchy that needed to change materially in order to implement the change.
- The date (D0) upon which sufficient information was available to determine that the change was desirable. Where sufficient information was available to determine that the change was desirable at the time that the root document was issued then D0 was taken to be the date of issue of that document.
- The date (D1) upon which someone identified that there was an issue that might require or justify a change and brought it to the attention of those managing the project.
- The date (D4) upon which a decision was made to make the change.

Change latency and its components may then be estimated as follows:

$$\text{Change latency} = D4 - D0$$

$$\text{Detection latency} = D1 - D0$$

$$\text{Decision latency} = D4 - D1$$

Notes:

- These dates were rounded to months before processing and therefore time intervals were estimated in round months. Where the date could not be established to the nearest month, then the rounding that produced minimum values for change latency and detection latency was chosen, that is to say, D0 was rounded to the latest possible month while D1 and D4 were rounded to the earliest possible month.
- If reliable dates could not be established for a change, the change was excluded from the analysis.
- The dates are labelled D1 and D4, because I had originally intended to capture the start and end dates of any change assessment and I had reserved the labels D2 and

D3 for these dates. However, I found that it was not practical to collect reliable data of this sort and abandoned this intention.

For each change analysed, I also asked the interviewee the following questions:

- Why was the change made?
- In your view, was the change for the worse, overall?
- Please tell me in your own words what you consider to be the main factors that determined the latency.
- Please tell me in your own words what could have been done, if anything, to reduce latency.

Note. I asked whether a change was for the worse because, if any changes fell into this category, I would wish to consider them separately. However none of the responses provided by the interviewees suggested that any of the changes looked at was for the worse, overall.

### **10.6.2 Data collected on the reasons for the change and on change latency**

31 changes were analysed in total. Basic data on these changes are presented in Table 8. The **Root** column contains **Yes** if the interviewee said that sufficient information was available to determine that the change was desirable at the time that the root document was issued.

The changes are tabulated in order of decreasing change latency. In order to keep my promise to the interviewees, described above, that the information that they had provided would not be disclosed beyond my supervisors in a form that would allow someone to link it to them or the projects or organisations concerned, the descriptions of the changes have been generalised and the table does not show which project each change was associated with.

It is a long table but I commend it to the reader: reviewing the list of changes provides, in my view, a significant insight into the range of issues that result in change on rail projects.

**Table 8: The reasons for change and the latency of change**

<b>Id</b>	<b>Description of change</b>	<b>Reason for change</b>	<b>Root</b>	<b>Detection latency (months)</b>	<b>Decision latency (months)</b>	<b>Change latency (months)</b>
A.	With regard to one sub-system, the customer needed three in quantity and believed that they had contracted for three but the supplier believed that they had contracted for one only. A contract variation was raised and so presumably there was ambiguity in the contract.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	26	47	73
B.	Buttons which passengers could press to raise the alarm were removed because the dis-benefits of malicious and inadvertent operation outweighed the safety benefits.	In order to deliver increased value to a stakeholder	Yes	51	18	69
C.	The contract included like-for-like replacement of telecommunications facilities while, under another contract, the customer was replacing them with new technology. The like-for-like replacements were not in fact needed but the contract gave the customer no automatic benefit for reducing scope and the facilities were removed from scope after most of them had been installed.	In order to reduce the cost of the project	Yes	27	40	67
D.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	40	19	59
E.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	32	27	59
F.	The cables used allowed potentially dangerous crosstalk and had to be replaced. The crosstalk could have been predicted theoretically.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	51	7	58
G.	Egress doors had to be modified to ensure satisfactory evacuation rates in an emergency.	In order to deliver increased value to a stakeholder through reductions in service delays	Yes	45	9	54

Id	Description of change	Reason for change	Root	Detection latency (months)	Decision latency (months)	Change latency (months)
H.	A scenario was discovered where the system operator could be misinformed in a way that could lead to an accident.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	49	2	51
I.	An option, introduced into the contract at the outset, to extend some train lengths, was taken up.	In order to deliver increased value to a stakeholder	Yes	0	31	31
J.	An option, introduced into the contract at the outset, to provide air conditioning to improve passenger comfort was taken up.	In order to deliver increased value to a stakeholder	Yes	0	30	30
K.	Multiple changes were made to the design of the controls for some equipment in order to deliver something that was operable. The need for change was ascribed to a requirements specification that was unclear and incomplete.	In order to meet the operational needs of the railway	Yes	17	11	28
L.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	2	27	29
M.	The order in which parts of the system were installed was found to be sub-optimal and was changed to minimise delays to the project.	In order to reduce the timescales of the project	No	26	3	29
N.	Multiple changes were made to reduce the transmission of vexatious vibration to neighbours to an acceptable level. The transmission of vibration to neighbours was not initially discussed in the requirements.	In order to avoid an unacceptable nuisance to neighbours.	Yes	17	11	28
O.	Change made to comply with revisions of standards that had been made since the start of the project.	In order to comply with standards change.	Yes	25	2	27
P.	The train roof was lowered because some infrastructure was found to infringe the gauge and changing the train was cheaper than changing the infrastructure.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	No	5	20	25
Q.	An aspect of the system design was found to be more extensive than was required and was cut back to save costs.	In order to reduce the cost of the project	No	15	9	24

Id	Description of change	Reason for change	Root	Detection latency (months)	Decision latency (months)	Change latency (months)
R.	The change added scope to the project in order to remove gaps at the interface between the project and a project to upgrade an adjacent part of the railway.	In order to remove "Scope gaps ", which I consider implies omissions from the scope that must be corrected to deliver a railway that works and meets the overall requirements	Yes	13	10	23
S.	Back-up control facilities were added in order to provide acceptable system resilience.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	3	18	21
T.	The order in which parts of the system were installed was found to be sub-optimal and was changed to minimise delays to the project.	In order to reduce the timescales of the project	No	18	3	21
U.	The system being delivered used different technology from which assumed by the customer's standards and changes to both the system and the standards were required to align them.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	0	18	18
V.	Communications antennae were moved to avoid radio dead spots.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	No	10	6	16
W.	The change concerns adjustments to the outline design, carried out by one contractor, after claims by another contractor performing detailed design that the outline design was not fit for purpose.	The contractor was unable to meet the original programme because of the need to redesign parts of the signalling scheme	Yes	9	6	15
X.	The project was de-scoped because its projected cost exceeded the budget available. This was partly ascribed to inaccurate cost estimates and partly to the fact that the apportionment of the costs between budget holders was unclear and budget holders thought that their shares were lower than they actually were.	In order to reduce the cost of the project	Yes	11	3	14
Y.	The original design would have degraded maintainability and the design was changed to restore maintainability to the levels before the project was made.	In order to restore acceptable maintainability	Yes	9	4	13
Z.	Additional telecommunications facilities were added because the telecommunications needs of another system were found to be greater than anticipated.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	0	13	13

<b>Id</b>	<b>Description of change</b>	<b>Reason for change</b>	<b>Root</b>	<b>Detection latency (months)</b>	<b>Decision latency (months)</b>	<b>Change latency (months)</b>
AA.	Additional telecommunications facilities were added because the telecommunications needs of another system were found to be greater than anticipated.	In order to future-proof the design	No	0	11	11
BB.	The procurement of another system being procured at the same time was cancelled and the contract for the system in question had to be adjusted as a result.	In order to reduce the cost of the project	No	0	9	9
CC.	Distributed control facilities were collected in one place in order to deliver acceptable response times for faults.	In order to deliver increased value to a stakeholder (reduced mean time to repair)	Yes	3	6	9
DD.	Telecommunications facilities were upgraded to give acceptable fidelity.	Because, without the change, the system would not have worked or it would have been unacceptable to a stakeholder	Yes	1	6	7
EE.	Changes to the system being delivered were required because the customer changed the supplier for another system.	In order to deliver increased value to a stakeholder through allowing significant cost savings elsewhere	No	0	5	5
		<b>AVERAGE</b>		<b>16.3</b>	<b>13.9</b>	<b>30.2</b>



One initial finding arises from review of changes I and J:

**Postponing a decision to make a change is a reasonable strategy for some changes and therefore reduced change latency is not always a benefit to projects.**

The decisions to make changes I and J were clearly explicitly delayed. The interviewee believed that it was possible to determine that the changes were desirable earlier than the point at which the decision was made to take them. However, it was not clear when the contract was let that there were sufficient funds to implement the changes and it may not have been *certain* that the changes were desirable.

In addition, one of the interviewees said that, in an infrastructure project, a decision was taken not to carry out surveys to search for asbestos in advance of starting the works because the cost and disruption of carrying out these surveys was, on the average, greater than the cost of disruption associated with carrying out unplanned remedial works when the main works found asbestos.

The change latency figures are striking:

**Average change latency was 30 months, more than a third of the average duration of the projects studied.**

Moreover, average detection latency is a significant proportion of average change latency.

**Average detection latency was more than 50% of average change latency.**

It is one thing to be aware of an issue and to decide to postpone taking a decision about it but it is quite another to be unaware of the issue. One has to assume some seriously dysfunctional decision making if one is to believe that a project will make better decisions in ignorance than if it is fully informed.

Finally, I note that:

**About three quarters (74%) of the changes in the projects studied were latent when the root document was issued.**

23 of the 31 changes have **Yes** in the **Root** column, indicating that, in principle, there was sufficient information available when the project set out on its initial course to determine that another course was preferable even if it is acknowledged that there may have been situations where it was rational to postpone a decision to do something different.

A significant proportion of the major changes made by projects could, therefore, in principle, have been foreseen and incorporated into the original specification and design.

### 10.6.3 Data collected on the factors affecting change latency

As described above, I asked the interviewees two questions about each change:

- Please tell me in your own words what you consider to be the main factors that determined the latency.
- Please tell me in your own words what could have been done, if anything, to reduce latency.

This yielded, for each change:

- A list (possibly empty) of **specific factors** determining actual latency.
- A list (possibly empty) of **specific opportunities** to reduce latency on similar projects.

Although these questions appear to be distinct, in fact the answers provide the same sort of information. Consider, as an example, the following two potential responses to the two questions:

- “Change latency was high because we did not consult sufficiently with maintainers when drawing up the requirements”.
- “Change latency could have been reduced if we had consulted the maintainers better when drawing up the requirements”.

These responses have almost exactly the same logical content and both imply that consultation of maintainers was a factor that affected change latency on the project.

It was valuable to ask both questions because they did not always result in matched answers and therefore asking both questions produced more information. However, having asked the questions separately, I combined the responses before starting to analyse them.

I associated each specific factor and each specific opportunity with one or more **generic factors**.

Six of these generic factors are aligned with the six core SE processes which I have defined and which are as follows:

- Model (the project) processes (**MP**)
- Manage Requirements and Specify the System (**MR&StS**)
- Design the System (**DtS**)
- Model, Simulate and Analyse the System (**MS&AtS**)
- Verify and Validate the System (**V&VtS**)
- Manage Change (**MC**)

A change was associated with one of these processes if a specific factor was associated with some deficiency in that process, or a specific opportunity was associated with a potential improvement to that process, or both.

The remaining specific factors and specific opportunities were inspected and the following common groups were identified and regarded as further generic factors:

- The generic factor **CONTR** covered specific factors and opportunities associated with contractual and quasi-contractual relationships between parties to the project. By 'quasi-contractual relationships', I mean agreements between separately-run departments within one organisation concerning the division of responsibilities between parties and the allocation of funding.
- The generic factor **RES&COMP** covered specific factors and opportunities associated with the number of people available to perform and allocated responsibility for performing tasks, their skill, or their knowledge and understanding of general technical matters. This group included causes of the form, 'No-one was thinking about the issue', on the basis that this suggested that no-one had been assigned responsibility for thinking about the issue.

- The generic factor **COST** covered specific factors and opportunities associated with determining accurate costs of courses of action.
- The generic factor **VALUE** covered specific factors and opportunities associated with value engineering.
- The generic factor **TIME** covered specific factors and opportunities associated with the timing of activities.

This left a few specific factors and specific opportunities that did not occur more than twice, which were placed in an **OTHER** category, which was treated as a final generic factor. The specific factors in the **OTHER** category included the following:

- misjudging the implications of delaying a decision;
- establishing the implications of a change for manufacturing;
- carrying out market research;
- delay in spotting the opportunity;
- underestimation of difficulty; and
- reluctance to change standards.

The specific opportunities in the **OTHER** category included the following:

- more disciplined behaviour by stakeholders; and
- more thorough gate review.

The full results of the analysis are provided in appendix A. Table 9 summarises the number of changes associated with each generic factor, in decreasing order.

**Table 9: The number of changes associated with each generic factor**

Generic factor	Number of changes
MR&StS	16
CONTR	15
MS&AtS	11
OTHER	9
RES & COMP	5
TIME	4
MC	3
COST	2
VALUE	2
DtS	1
V&VtS	1
MP	0

The table paints a clear picture of which generic factors were found to be most significant in determining the change latency of the changes studied. Taking into account the fact that the **OTHER** generic factor is in fact a collection of different, infrequent factors, it can be seen that each of the **MR&StS**, **MS&AtS** and **CONTR** generic factors appears more than twice as often as the next most frequently-occurring factor.

The most important generic factors affecting change latency on the projects studied were therefore found to be:

- the manner in which the **Manage requirements and specify the system** core SE process was carried out;
- the manner in which the **Model, simulate and analyse the system** core SE process was carried out; and
- the nature of the contractual and quasi-contractual relationships between the parties involved.

#### 10.6.4 Case study analysis of changes made by the projects

In the next chapter, I describe analysis of documented case studies that includes tests of the 15 causal mechanisms postulated in the tentative theory and listed in chapter 9. The analysis had three steps:

1. Consider the description of the history of the change and search for evidence that contradicts any of the causal mechanisms listed above.
2. Consider the description of the history of the change and search for evidence of the operation of additional significant causal mechanisms that affect change latency
3. Consider the description of the history of the change and search for evidence that corroborates any of the causal mechanisms listed above.

I applied this process to each of the 31 changes listed above. In summary my findings were as follows:

- None of the 31 changes analysed appeared to contradict any of the causal mechanisms in the tentative theory.
- The following three causal mechanisms, which are not in the tentative theory, were found to have had a significant effect in change latency on at least three of the changes considered:
  - X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to more timely and sounder decisions.
  - X2. Having sufficient skilled people available leads to more timely and sounder decisions.
  - X3. Having clarity of funding for the project leads to more timely and sounder decisions.

Table 10 indicates the causal mechanisms corroborated by this process and number of changes that were found to provide evidence of each causal mechanism.

**Table 10: Corroboration of causal links**

<b>Id</b>	<b>Causal mechanism</b>	<b>Changes</b>
6	More timely and thorough consultation with stakeholders will lead to more timely, accurate and comprehensive requirements.	4
8	More timely, accurate and comprehensive requirements will lead to more timely, accurate and comprehensive system design.	16
10	More timely, accurate and comprehensive system design will lead to more timely and sounder decisions.	15
11	More timely, accurate and comprehensive modelling, simulation and analysis will lead to more timely and sounder decisions.	12
12	More timely and accurate cost estimates will lead to more timely and sounder decisions.	3
13	More timely and sounder problem reports will lead to more timely and sounder decisions.	1
X1	Efficient, co-operative commercial arrangements between the parties involved in a project lead to more timely and sounder decisions.	14
X2	Having sufficient skilled people available leads to more timely and sounder decisions.	3
X3	Having clarity of funding for the project leads to more timely and sounder decisions.	4

The corroborated causal mechanisms are indicated on Figure 15. New mechanisms are highlighted by using red ovals. Arrows for which at least ten changes provided evidence are drawn thicker than other arrows.

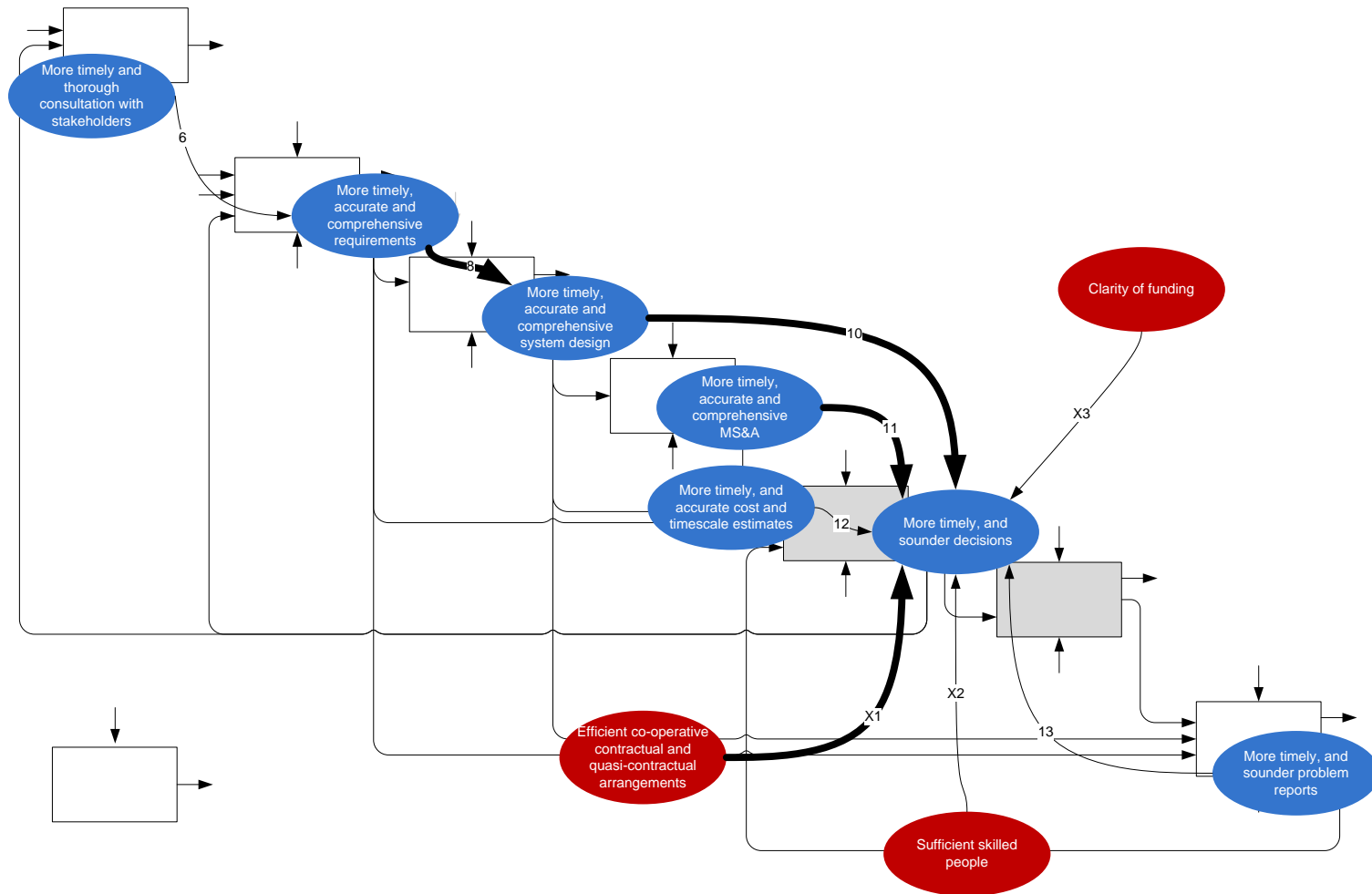


Figure 15: Causal mechanisms corroborated by data collected from projects



## 10.7 Further analysis

The analysis of the previous section suggests that the effect of SE on change latency is principally concerned with two processes:

- Manage requirements and specify the system (MR&StS); and
- Model, simulate and analyse the system (MS&AtS).

In order to investigate the question that I have set for myself, I carried out both quantitative and qualitative analysis into the effects of adoption of good SE practice for these processes on change latency.

### 10.7.1 Quantitative analysis

#### Correlations between adoption of SE and change latency

Under the quantitative heading, I explored the correlations between the figures of merit for **MR&StS** and **MS&AtS** on the one hand and average change latency on the other hand. Of course, because I collected no data that could be used to construct a figure of merit for **CONTR**, I could not explore this quantitatively.

The scatter graphs below between the figures of merit with change latency and with detection latency and decision latency are shown in Figure 16 and Figure 17 below.

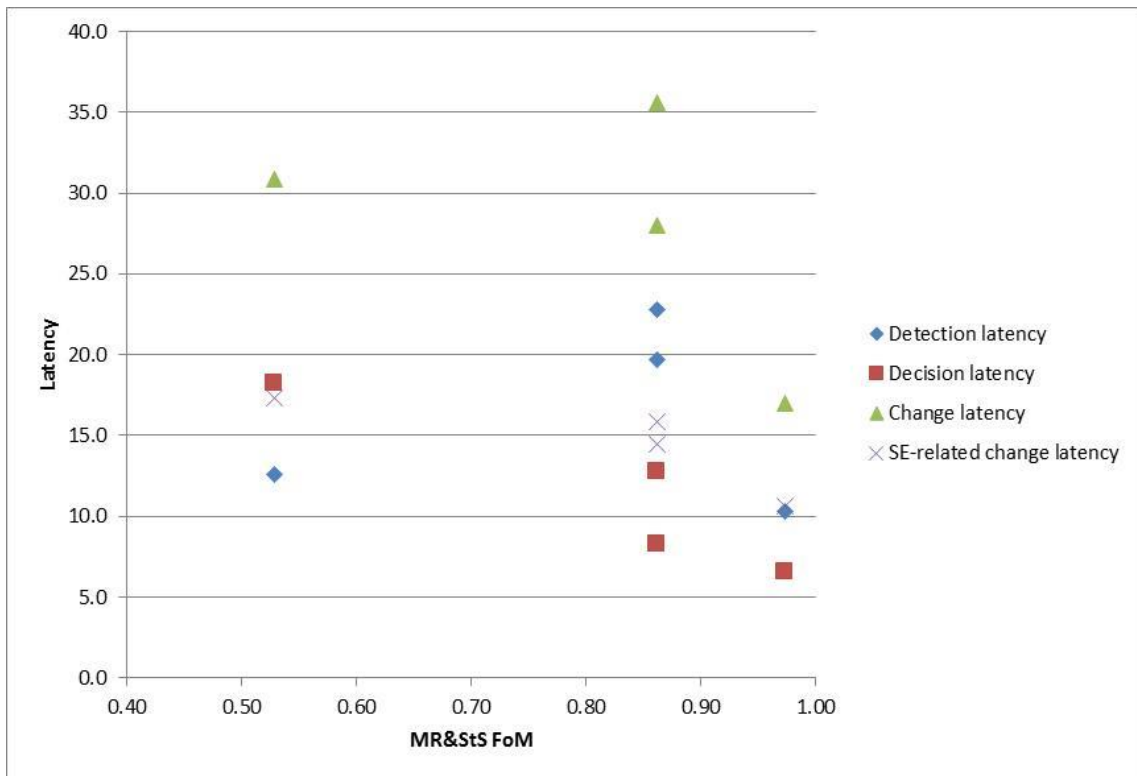


Figure 16: Correlation between MR&StS and change latency and its components

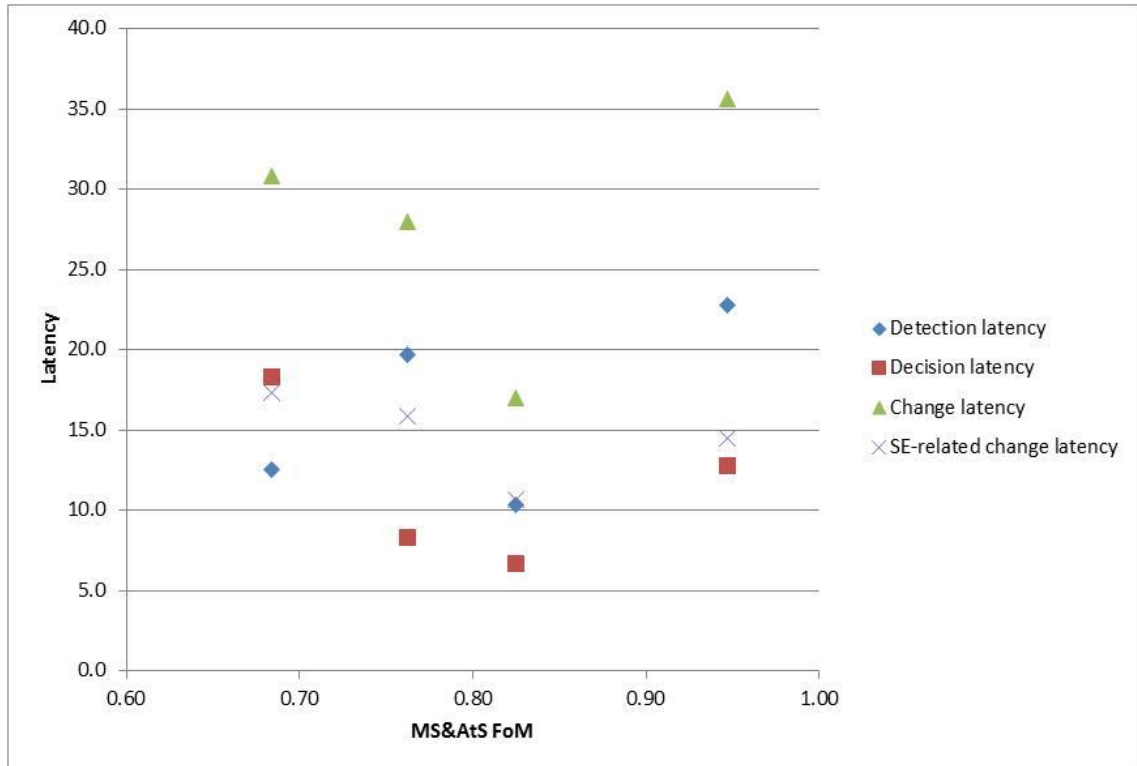


Figure 17: Correlation between MS&AtS and change latency and its components

## Notes.

- I excluded project 3 from the graphs because I only looked at some of its phases. As a consequence change latency was therefore constrained to the length of these phases and its inclusion could have skewed the results.
- I had previously calculated figures of merit for both the initial and final tranches of project 2. As the only change whose latency I was looking was associated with the first tranche, I used the figures of merit for the first tranche in the graphs.

Of course, the number of data points is too low and the number of confounding factors too high to expect to draw any conclusions from this graph and, indeed, there are no compelling correlations visible.

The scattering of the points on the graphs does make clear, if there was ever any doubt, that change latency is a function of other variables in addition to those plotted on the X axes. I suggest that one significant potential value of quantitative analysis of this sort is to allow the principal additional factors to be understood but several dozen data points are required to do this and, if research does continue in this area, I think it will require sponsorship from a rail projects organisation, probably in the context of a process improvement initiative.

Contemplating the absence of any clear correlations has led me to one realisation about the limitations of using average change latency as a measure. That may be most clearly explained by considering a thought experiment. Suppose that we came into possession of some limited form of time travel and chose to use it by going back to the start of one of the projects whose statistics are plotted in Figure 16 and correcting some deficiencies in the way in which it managed requirements. As we watched the effects of this intervention ripple through the time space continuum we would see the project's data point on Figure 16 move to the right because the figure of merit for MR&StS would be increased. But even if the effects on change were beneficial the data point would not necessarily move downwards. It *would* move downwards if the effects of the improvement were to make changes earlier but, if the effects were to forestall changes then the set of changes for which an average change latency is calculated would become smaller and the average might rise or fall.

I do not retract my assertion that change latency is a useful measure for researcher and practitioner alike (see key points 6G and 6H) but when it comes to calculating statistics for the changes undergone by a project, it seems to me that it would be valuable to supplement average change latency by a measure of aggregate change latency, for example the result of summing the change latencies of all changes weighted by their effect on overall cost expressed as a percentage of the total budget for the project. This, admittedly more complex, statistic, is still a quantity with a time dimension and retains the advantages of average change latency but would be guaranteed to fall if change were either accelerated or forestalled.

I did not collect enough data from the projects concerned to calculate aggregate change latency.

### **Estimating the 'reach' of SE**

The project data does provide evidence that SE can reduce change latency but it also suggests that, because there are other factors that affect change latency, no amount of investment in SE could eliminate change latency.

I estimated the proportion of the latency that SE could do away with as  $(l \times m)/n$ , where  $l$  is the change latency for the change,  $n$  is the total number of generic factors for the change and  $m$ , is the number of generic factors for the change that are associated with SE core processes.

On the average, I found that this statistic was 15.0 months, almost exactly half total change latency, suggesting that SE's reach, in terms of the proportion of change latency that it could be used to eliminate, is significant but far from universal.

### **10.7.2 Qualitative analysis**

Under the qualitative heading, I looked at the accounts of the changes for which the **MR&StS**, **MS&AtS** and **CONTR** general factors were found to be causal factors and sought insight into the manner in which the causal mechanisms work.

**Qualitative investigation of the effects of the 'Manage requirements and specify the system' process**

There is evidence that the way in which the MR&StS core process area is implemented affects change latency but the analysis so far has not revealed the mechanisms that produce this effect. To investigate this, I looked at the accounts of the 16 changes for which the MR&StS process was found to be a generic factor and reviewed the specific factors and opportunities related to this generic factor. I found that these specific factors and opportunities were generally concerned with one or more of the following deficiencies in requirements management:

- failure to take proper account of the needs of operators and maintainers;
- failure to take proper account of an external interface; and
- unclear specification.

I reviewed the list of statements about SE good practice that I used in the questionnaire and found items capable of mitigating or eliminating each of these deficiencies<sup>17</sup>:

- N. Stakeholders were consulted to establish their requirements
- U. Scenarios of typical use were defined and used to establish and/or check requirements
- V. Users of the system were identified and treated as stakeholders
- J. Key interfaces between system and external entities were defined and documented
- OO. Each requirement was checked for verifiability, unambiguity and atomicity

I looked at the average figures of merit for these statements and found two of them to be significantly below the overall average for all statements.

I conclude that adopting good SE practices in areas where the current level of adoption was low could have reduced the latency of several changes.

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<sup>17</sup> The initial letters refer to the identifiers of these statements in Table 27 in Appendix A

**Qualitative investigation of the effects of the ‘Model, simulate and analyse the system’ process**

I reviewed the accounts of the 11 changes for which the MS&AtS process was found to be a generic factor and in 10 of these cases the account suggested strongly that further modelling, simulation and analysis could have identified the need for the change earlier.

It is tempting to jump from this finding to the (tentative) conclusion that doing more **MS&AtS** would have been a better strategy for the projects concerned. The conclusion may well be true but it is not a necessary inference from the finding. This is because doing more modelling, simulation and analysis would only have been a better strategy if it had been ‘the right sort’ of modelling, simulation and analysis, that is to say, modelling, simulation and analysis which focussed on the issues that later drove change. The difficulty lies in knowing in advance what the right sort is.

It may be that many rail project changes can be foreseen by modelling, simulation and analysis but the project will not have the time or budget to carry out all possible modelling, simulation and analysis activities and will have to decide which ones to perform before it is known where the issues will be.

The optimal strategy is likely to be risk-based: performing modelling, simulation and analysis in areas where issues are most likely to occur or where their consequences would be most severe, or both.

**Qualitative investigation of the effects of contractual and quasi-contractual arrangements**

There are 15 changes for which **CONTR** was found to be a generic factor. I reviewed the specific factors and opportunities related to this generic factor. I discerned the following general categories (some changes were associated with more than one):

- A. the time taken to conclude contractual discussions (8 occurrences);
- B. lack of clarity about availability or apportionment of funding, including disagreement about who should pay for a change (4 occurrences);
- C. lack of agreement about who was responsible for a technical issue (2 occurrences);
- D. an adversarial relationship between parties (in one case leading to a reluctance to make a change because it might be taken as admitting liability) (2 occurrences);

- E. constraints on the time available for SE in the pre-tender period (1 occurrence);
- F. a contract that meant that no benefit was enjoyed by one party as a result of savings enjoyed by the other party (1 occurrence); and
- G. a contract whose provisions did not align with what stakeholders actually required (1 occurrence).

It is arguable that the item in category G should be allocated to **MR&StS** but, in the case concerned, I concluded that it was a product of the contracting strategy rather than the way in which requirements were set.

Each of these specific factors and opportunities reveals a plausible and general mechanism whereby contractual and quasi-contractual arrangements might be expected to delay decision making and thereby impede the effects of SE on change latency.

## 10.8 Reflections

The data collected from projects have not contradicted any of the causal mechanisms affecting change latency included in the tentative theory and have corroborated several of them. The data have suggested that there are additional causal mechanisms with a significant effect on change latency on the projects studied.

A small subset of the causal mechanisms appears to operate significantly more often than the remaining mechanisms.

The picture in Figure 15 is consistent with the findings of the previous section, which is unsurprising as they derive from the same base data. The picture may be considered as a map of the principal issues that a project manager determined to reduce change latency on a project should tackle.

There are a number of causal mechanisms in the tentative theory for which little or no corroboration was found. With such a small sample, one must be cautious about drawing conclusions from the absence of corroboration. For **Verify and Validate the System**, the fact that there was little variation in uptake of good practice between the projects may have hidden this mechanism. However, if no corroboration was found for a causal mechanism for an extended period, it would be necessary to reconsider that mechanism.

There was no direct corroboration for the causal mechanisms by which greater adoption of good SE practices in core SE processes leads to these processes becoming more effective. This is probably the consequence of the way in which data was collected. Having remarked that change latency was increased by weaknesses in requirements management, or reduced by strengths in requirements managements, an interviewee would have felt no need to point out that requirements management is a part of SE. The interviewees knew that I was looking at the effects of SE on change latency and expected me to look for the causal mechanisms.

In some cases there are good logical arguments from the definition of good practice to believe that the mechanisms operate. There is, also, indirect evidence (see the previous section) that some of these mechanisms operated.

Of course, for reasons explained earlier, these data do not, on their own, allow conclusions to be drawn about the general population of rail projects from the data collected because:

- the sample size is small;
- the sample of projects is not drawn randomly from the population of projects as I knew that the interviewees had an interest in SE and related topics;
- in some cases, the survey process obtains the interviewees' perceptions of the projects rather than the facts directly; and
- in some cases, records were incomplete.

However, despite these limitations it is considered that the data had provided insights of value regarding rail projects and the effects of adopting SE on them.

### **10.9 Key points**

10A The projects studied are a diverse representation of medium-sized and large rail projects – probably as diverse as a sample of five projects could be – and the challenges that they faced were of the same order of magnitude.

10B The areas in which the projects appeared to adopt good SE practice to the greatest extent on average were:

- identifying stakeholders;



- validation; and
- assessing and monitoring risks.

10C The areas in which the projects appeared to adopt good SE practice to the least extent on average were:

- managing interfaces;
- checking and managing requirements;
- tracking the implementation of change; and
- modelling the physical structure of the system.

10D There was significant variation between the projects studied in the uptake of SE practices in five of the six core SE processes – all apart from **Verify and validate the system**.

10E On four of the five projects looked at, the change records were incomplete enough to affect my data collection.

10F Postponing a decision to make a change is a reasonable strategy for some changes and therefore reduced change latency is not always a benefit to projects.

10G Average change latency was 30 months, more than a third of the average duration of the projects studied.

10H Average detection latency was more than 50% of average change latency.

10J About three quarters (74%) of the changes in the projects studied were latent when the root document was issued.

10K The most important generic factors affecting change latency on the projects studied were found to be:

- the manner in which the **Manage requirements and specify the system** core SE process was carried out;
- the manner in which the **Model, simulate and analyse the system** core SE process was carried out; and
- the nature of the contractual and quasi-contractual relationships between the parties involved, including relationships determining the flow of money between separately-run departments within one organisation.

- 10L None of the 31 changes analysed appeared to contradict any of the causal mechanisms in the tentative theory. The changes corroborated some of them (principally those associated with the generic factors listed in the previous point).
- 10M The following three causal mechanisms, which are not in the tentative theory, were found to have had a significant effect in change latency:
- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to more timely and sounder decisions.
  - X2. Having sufficient skilled people available leads to more timely and sounder decisions.
  - X3. Having clarity of funding for the project leads to more timely and sounder decisions.
- 10N The number of data points is too low and the number of confounding factors too high to draw any conclusions from the quantitative analysis carried out but repeating the analysis with a larger data set does offer the prospect of allow the effect of different factors on change latency to be understood
- 10P In carrying out further quantitative analysis, it would be valuable to supplement average change latency by a measure of aggregate change latency, for example the result of summing the change latencies of all changes weighted by their effect on overall cost expressed as a percentage of the total budget for the project.
- 10Q SE's reach, in terms of the proportion of change latency which it could be used to eliminate, is significant but far from universal
- 10R Adopting good SE practices in areas where the current level of adoption was low could have reduced the latency of several changes
- 10S Performing additional modelling, simulation and analysis could have reduced the latency of several changes, but the most cost-effective modelling, simulation and analysis is likely to be one that is risk-based.

10T The responses from the interviewees did not explicitly corroborate the causal mechanisms by which greater adoption of good SE practices in core SE processes leads to these processes becoming more effective, probably as a consequence of how the data were collected. However, there is indirect evidence for these mechanisms.

## 11 TESTING THE TENTATIVE THEORY AGAINST PUBLISHED DATA

In this chapter, I describe an exercise to test the tentative theory by analysing published data concerning four further railway projects (or, in one case, an account of a project provided to me by a member of the project). During the discussion, I reflect upon the degree to which the data confirm the tentative theory, the degree to which they contradict it and refinements to the tentative theory that the data suggest. I summarise these reflections at the end.

### 11.1 Testing the tentative theory using published data on railway projects

Four case studies were analysed. Each section below is devoted to the discussion of one case study as described in one or more public-domain documents, or as arising from an interview.

Each section has the following sub-sections, which follow the structure of the analysis performed:

- **Introduction** contains a top-level description of the project concerned and the scope of the case study.
- **The way in which the project was run** contains a summary of information available on the adoption of SE ideas in the project's processes, supplemented by relevant information about other aspects of the project, focussing on management, governance and contracting arrangements.
- **The changes that were made** contains a summary of information about significant changes made on the project, including a description of each change and, where possible, an indication of its latency.
- **Analysis and conclusions** contains the result of a search for:
  - any evidence contradicting the causal mechanisms postulated in the tentative theory;
  - any evidence corroborating the causal mechanisms postulated in the tentative theory; and

- any evidence suggesting additional causal mechanisms affecting change latency.

Additional sub-sections are added where this helps to clarify the account and supporting detail is provided in appendix B. This appendix has the same section headings as this chapter. For additional information about any of the sections below, please refer to the corresponding section of appendix B. So, for example, for information on section 11.6, refer to B.6.

When I look at the evidence referred to above, I classify it as ‘weak’ or ‘strong’. To be classified as strong the evidence must:

- be more than just the personal opinion of someone directly involved in the project; and
- must show that the upstream parameter was a significant factor<sup>18</sup> for the downstream parameter.

Four cases are studied:

- The West Coast Route Modernisation Project<sup>19</sup>
- The Jubilee Line Extension Project<sup>20</sup>
- The Channel Tunnel Rail Link Project<sup>21</sup>
- Acquisition of High-Output Ballast Cleaning Plant<sup>22</sup>

Each case study is discussed in turn.

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<sup>18</sup> A factor is significant if no other factor has been identified which dominates it.

<sup>19</sup> Drawn from (NAO, 2006; Dick, 2000) and various articles in ‘Modern Railways’ magazine.

<sup>20</sup> Drawn from (Mitchell, 2003; Arup, 2001; UCL, 2009).

<sup>21</sup> Drawn from (Steer Gleave Davies, 2004; NAO, 2005; NAO, 2012) and various articles in ‘Modern Railways’ magazine.

<sup>22</sup> Drawn from an interview with a senior member of the project.

## **11.2 Case Study 1: The West Coast Route Modernisation Project**

### **11.2.1 Introduction**

This project was already discussed in chapter 8 as an example of the case study method. The discussion in chapter 8 was focussed on one aspect of the project. This section contains a more general analysis.

To recap: the West Coast Main Line connects many of the largest cities in the UK including London, Birmingham, Liverpool, Manchester, Glasgow and Edinburgh. The West Coast Route Modernisation (WCRM) project carried out a significant volume of modernisation work between 1998 and 2008, delivering increased capacity and reduced journey times as well as replacing worn-out parts of the railway. The cost of the project rose very significantly during this period and as a consequence the scope of the works had to be cut back (NAO, 2006).

The project appears to be an example of a very problematic project for which the problems were mitigated by remedial actions that included strengthening aspects of project governance and SE. There is clear evidence that change latency was very expensive and some suggestion that weaknesses in project governance and SE in the earlier phases of the project contributed to this.

This case study is drawn from a report into the project published by the UK National Audit Office (NAO) (2006), a magazine article (Dick, 2000), describing the requirements management performed on the project and various articles in the trade magazine, 'Modern Railways'.

The case study is mainly concerned with events in the period 2001 until 2003 inclusive. The following description of this period in the life of the project is adapted from text in the summary of the NAO report.

In January 2002, the Secretary of State instructed the Strategic Rail Authority to intervene and find a way forward for the program to renew and upgrade the West Coast Main Line. The upgrade was being undertaken under a 1998 agreement between Railtrack, the private sector owner and operator of rail infrastructure, and Virgin Rail Group, which operated the West Coast passenger rail franchise, and involved the introduction of new signalling

technology to allow improved services delivered by new trains running at 140 miles per hour.

By 2001, neither the rail infrastructure upgrade nor the new trains were on course for delivery as set out in the 1998 agreement. In October 2001, Railtrack went into Railway Administration and by May 2002 its projection of the programme's final cost had risen from £2.5 billion (in 1998) to £14.5 billion. Railtrack had spent £2.5 billion on the program by March 2002, and had committed some £500 million of further works, but had delivered only a sixth of its scope. There had been substantial abortive costs to the programme.

The Strategic Rail Authority clarified the direction, scope and expected outputs of the program in the June 2003 West Coast Main Line Strategy and the project was completed by Network Rail, the not-for-profit organisation that inherited the railway assets from Railtrack.

### **11.2.2 The way in which the project was run**

Because the NAO report is the principal source for the case study, it is useful to describe how it is structured. The most relevant part of the report is considered to be Part 1, "The Strategic Rail Authority and Network Rail turned around delivery of the West Coast programme". This lists five key weaknesses and then describes action taken to remedy these weaknesses.

The weaknesses were:

1. a lack of clear governance arrangements and direction for the programme;
2. failure to engage stakeholders in support of the programme;
3. a lack of tight specification and change control;
4. the use of untried and unproven new technology; and
5. failure to effectively manage and monitor programme delivery through contractors.

The NAO concludes that these weaknesses had led to "*scope creep*", delays and increase in costs.

The NAO describes improvements resulting from the SRA intervention that included:

- setting a clear direction for the project;
- establishing clear programme governance structures;

- achieving ‘buy in’ from stakeholders to decisions on scope, access and timetables, through better consultation and communication;
- developing a clear, measurable set of programme outputs and a series of functional specifications to translate the programme’s scope into detailed requirements;
- building the internal capacity to write specifications, and to review and approve project designs and then inviting contractors to make fixed-price proposals for completing the design and delivering the physical works;
- appointing Bechtel Ltd to provide “*leadership, direction and clarity*” to the management of programme delivery; and
- restructuring the programme organisation, so that decisions could be taken more quickly.

The NAO concludes that these improvements had led to benefits that included:

- facilitating a more intrusive regime of obtaining possession of the track, which was crucial to delivery of the project; and
- identifying opportunities to reduce the programme cost by over £4 billion.

The project had adopted some aspects of good SE practice before the intervention by the SSRA. Dick reports that, in 2000, the project had adopted the principles of requirements management including the use of proprietary requirements management software, a structured approach, translating high-level business needs into detailed requirements that were traced to business benefits and removing unnecessary requirements. The “*detailed requirements*” to which Dick refers were, however, presumably not detailed enough as the SRA found that it was desirable to prepare more detailed requirements.

### **11.2.3 The changes that were made**

Significant changes made by the project during its lifetime included:

- The increased use of blockades.
- Removing from the scope of the programme the European Rail Traffic Management System (ERTMS), new signalling technology, and the Network Management Centre. This is of itself a major change and one that clearly illustrates the huge potential costs of change latency. The NAO reports that Railtrack had spent £350 million on these



items. Had they been omitted from the start, the cost of the programme would have been reduced by at least this much.

- Identifying that *“faster running north of Preston could be achieved without the need to replace the signalling”*.
- Using a better value solution to the upgrade of the route’s power supply using autotransformers rather than booster transformers.
- Using a different layout at Rugby in which a non-standard arrangement of the traffic across the four tracks was tolerated for a short distance.
- Removing an expensive underpass at Nuneaton station and requiring passengers that would have travelled on trains through this underpass to change trains at Nuneaton.
- Reversing a decision to limit widening in the Trent Valley and reverting to a scheme with four-track line throughout.
- Adopting a simplified layout at Stafford.
- Adopting a change of policy for the Northern section of the line in which the project would try to raise the 90 mph speed limits to 110 mph rather than trying to raise the 110 mph speed limits to 125 mph.

#### **11.2.4 Analysis and conclusions**

##### **Discussion of changes**

It is useful to reflect first upon the changes described in the previous section. In the most general terms, it seems reasonable to conclude that each of the changes was desirable because the previous plans that the project was following failed to meet at least one of the following criteria:

- they could be relied up to support the desired timetable;
- they could be relied upon to be completed by the deadlines defined; or
- there was no cheaper but acceptable alternative.

There is one small caveat to be made regarding this assertion. The removal of the underpass at Nuneaton presumably did not allow the desired timetable to be run. However a saving of tens of millions of pounds was found to outweigh the inconvenience to a limited number of passengers who would now have to change at Nuneaton.

However, since reliably delivering the desired timetable by the defined deadlines at minimum risk was clearly a major part of the underlying objective for the project, it seems reasonable to conclude that the majority of the changes were required because the project was not heading towards this objective. There is no suggestion in the material that I have read that the desired timetable had been subject to fundamental change since the start of the project and, as the NAO report records, aspects of this timetable had been defined in a contract with the Virgin Group. It therefore seems reasonable to conclude that sufficient information was available when the project started to establish that the majority of the changes made in 2003 and 2004 were desirable. Presumably the project took some time to specify exactly what it intended to do but Dick's account suggests that this process was well advanced by 2000 and therefore typical latency for the changes discussed would have been 3 years or more.

#### **Contradiction of the tentative theory**

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in the tentative theory.

#### **Corroboration of the tentative theory**

There is strong evidence from the NAO report that improving the way in which the project drew up specifications of what it was trying to achieve resulted in better specifications that, in turn, resulted in better designs and supported better decisions, contributing to decisions to make changes that had been desirable for some time. The improvements in the way in which the project specified what it was trying to achieve clearly included improved consultation of stakeholders and appeared to include adopting other good SE practices.

It is clear from the project history that Railtrack was unable to obtain accurate cost estimates for the work that it had commissioned and it is likely that Railtrack would have brought forward some of the decisions arising from the SRA intervention if it had had more accurate estimates.

There is some evidence from the NAO report that improving change control resulted in lower cost and reduced timescales and it is considered reasonable to presume that at least some of these benefits are the result of sounder and more timely change decisions.

The decision to replace booster transformers with autotransformers was taken in part, according to the NAO, because the challenge team identified that the booster transformers would have insufficient capacity to cope with future traffic increases, which suggests that Railtrack had insufficient modelling capability in this area.

Given the impartial and authoritative nature of the NAO report, it is considered that there is strong evidence for the following causal mechanisms in the tentative theory:<sup>23</sup>

- 2. More timely and greater adoption of good SE practice will lead to more timely, accurate and comprehensive requirements.
- 6. More timely and thorough consultation with stakeholders will lead to more timely, accurate and comprehensive requirements.
- 9. More timely, accurate and comprehensive requirements will lead to more timely and sounder decisions.
- 12. More timely and accurate cost and timescale estimates will lead to more timely and sounder decisions.

It is considered that there is weak evidence for the following causal mechanisms in the tentative theory:

- 11. More timely, accurate and comprehensive modelling, simulation and analysis will lead to more timely and sounder decisions.
- 15. More efficient change management arrangements will lead to more timely and sounder decisions.

### **Additional causal mechanisms**

It is clear that the decision to adopt a blockade strategy was delayed by dysfunctional relationships between Railtrack and the operators. The NAO report says that changing the programme organisation led to quicker decisions. There is also some evidence from the NAO report that deficiencies in the skills and knowledge of the project team contributed to unsound decisions.

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<sup>23</sup> The initial letters refer to the identifiers of these statements in Table 27 in Appendix A

It is considered that there is strong evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 10:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions.

It is considered that there is weak evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 10:

- X2. Having sufficient skilled people available leads to more timely and sounder decisions.

The conclusions of the previous two sections are illustrated in Figure 18. Corroborated causal mechanisms are shown in blue and additional causal mechanisms are shown in red. Thick lines indicate strong evidence while thin lines indicate weak evidence.

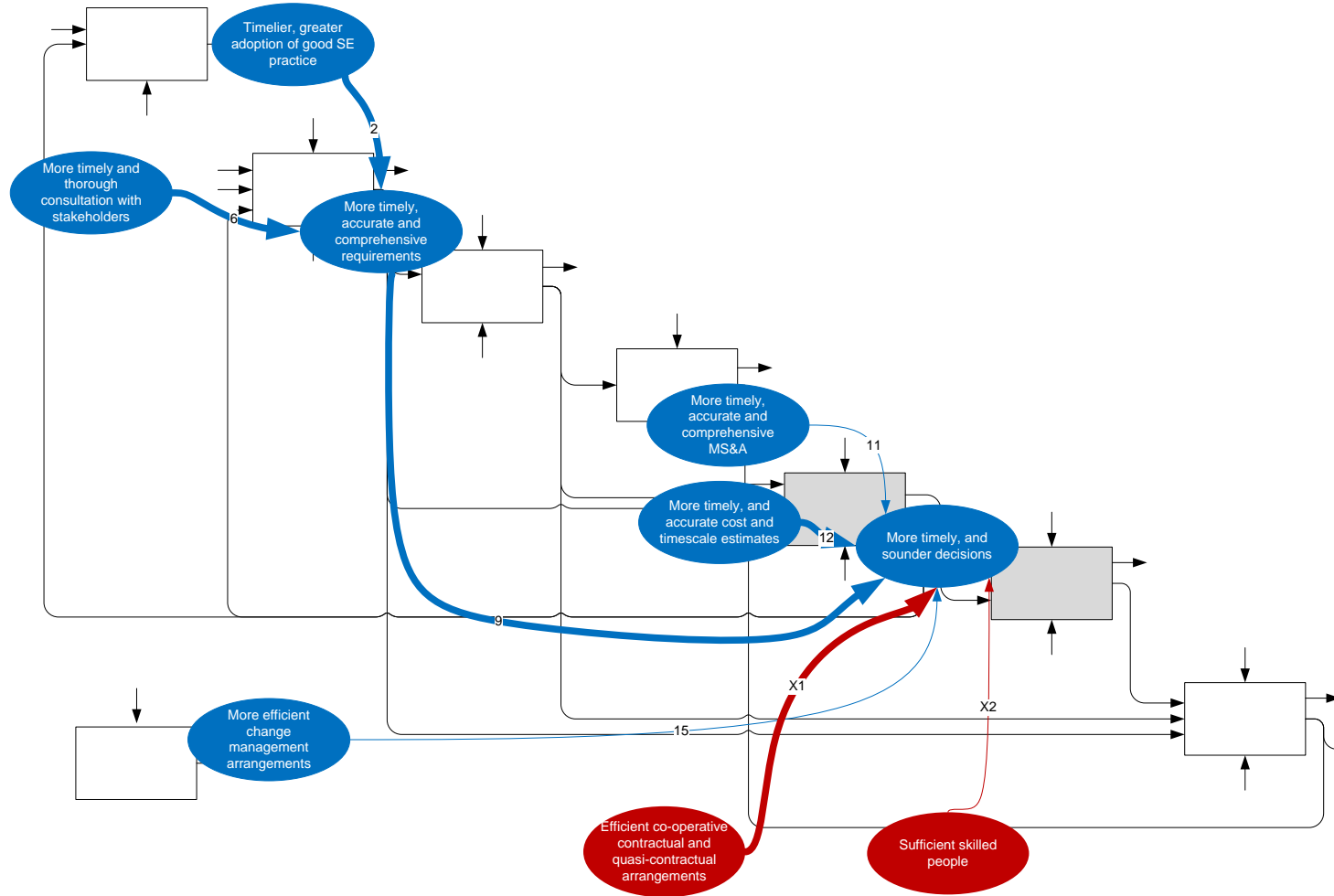


Figure 18: Causal mechanisms corroborated by the West Coast Route Modernisation project case study

### **11.3 Case Study 2: The Jubilee Line Extension Project**

#### **11.3.1 Introduction**

The Jubilee Line Extension (JLE) project extended the Jubilee Line from Charing Cross to Stratford. The project started in October 1993 with a planned timescale of 53 months and an approved budget of £2.1 billion. When it was completed in December 1999, it had taken 74 months and was forecast to cost £3.5 billion. The final cost included some elements not allowed for in the budget and the project was beset by some significant events beyond its control, including:

- The entry into administration of the Canary Wharf developers who, it was planned, would contribute to the cost. This delayed the start of the project.
- A collapse in a tunnel being built by another project using the same tunnelling method. This resulted in an interruption to tunnelling activities.
- The decision by the government to hold national Millennium celebrations in North Greenwich. This placed an absolute deadline of 31st December 1999 on the opening of the line and removed from the project the option of dealing with problems by extending timescales.

This case study is drawn from a report produced by Arup acting as Agent to the Secretary of State for Transport (Arup, 2001), the book 'Jubilee Line Extension from concept to completion' by Mitchell (2003) and a Project Profile for the JLE Project published by University College, London (UCL, 2009).

#### **11.3.2 The way in which the project was run**

##### **Systems Engineering**

I found no use of the phrase 'systems engineering' in any of the three source references above. The project belongs to an age before the phrase entered the railway engineer's vocabulary. The project certainly carried out activities within the scope of the core SE processes that I have defined but these activities appear to have been drawn from the tradition of large civil engineering projects at the time and I have found no evidence of any systematic attempt to adopt good SE practice.

### **Project Management**

There is evidence that weaknesses in project management were causal factors for project problems in general and for change latency specifically. Weaknesses recorded in the source references included:

- letting contracts before the design was complete; and
- reporting on the unduly optimistic basis that historical delays would be made up.

The source references claim that these weaknesses led to delays and an increased volume of change.

### **Contract Management**

Two criticisms of the contractual arrangements have been identified that could have increased change latency:

- Failure by the overall project to put in place adequate mechanisms for co-ordinating contracts. Instead the project required contractors to co-ordinate themselves.
- The use of 'punitive' forms of contract, which created adversarial relationships and created incentives for contractors to avoid co-ordinating their activities with other contractors.

#### **11.3.3 The changes that were made**

In order to identify changes it is necessary to set a baseline. I choose to use as a baseline the scheme defined in the London Underground Bill 1989, as deposited in November 1989. A change, then, must either differ from this baseline or be a deviation from a definite subsequent commitment.

There were a number of changes to the design of the stations but the changes are complex enough and the available information about them is limited enough that I have found it impractical to analyse them.

Leaving these aside, the following five changes are significant enough that their consequences would be readily apparent to a user of the line:

1. The decision to change the route so that it included North Greenwich.

This change was made to promote regeneration of areas of South London. Had the decision been taken by the project in order to meet criteria defined by parliament, this change would have been considered to be of relevance to the research being conducted. However, as parliament was directly involved in the decision, it is considered to fall into the realm of political science rather than project delivery and it is not considered further.

2. The decision to greatly increase the works on the existing portion of the Jubilee Line.

This change appears to have been required because the project regarded its scope as being concerned with building a new line and did not properly consider what work was required on the existing part of the line. Necessary work costing about £100 million was omitted from the original change. The latency for the change to incorporate this additional work was at least 16 months.

The adoption of good SE practice in the area of managing requirements and specifying the system forces consideration of the questions, 'What system are we building?', 'What systems will the new system interface with?' and 'What outcomes do we wish to enjoy as a result?'. It is considered that any serious investigation of these questions would have revealed the oversight and allowed the latency for this change to have been reduced. It is noted (Mitchell, 2003; page 345) that there was no full client brief document until 1995. However, an initial Operating Plan was put together for the extended line in early 1991 (Mitchell, 2003; page 126) so it is possible that the late adoption of some aspects of good SE practice did in fact reveal the omissions.

3. The decision to replace the existing train fleet rather than supplementing it.

The decision was made because replacement was found to be a cheaper way of achieving adequate reliability and conforming to recently introduced safety regulations than modifying the existing fleet. The account suggests that change latency was at least 24 months. It is not clear that greater adoption of SE practices would have reduced this latency nor that the latency had any significant consequences for the project.



4. The decision to open the line in phases.

This decision appears to have been made to increase the manageability of the operational change. It had been championed by operational staff for at least 24 months before the decision was made. It seems likely that better liaison with the operators and better consideration of operational requirements would have reduced the change latency.

5. The decision to abandon the planned moving block signalling system and revert to a fixed-block signalling system with reduced capacity.

It was appreciated at the outset of the project that the technology used for the moving block signalling system was immature and an option was included in the contract to fall back to a fixed block signalling system. After reassurances from the supplier, this option was allowed to lapse in 1996. However, in September 1997, a decision was taken to abandon the moving block solution and fall back to the fixed block alternative. It seems likely that, in 1996, if the London Underground project team had had mechanisms to inform itself better about the state of play, the option would have been exercised at that stage. While good SE practice might have supported such mechanisms, it is not considered that there is evidence that good SE practice on its own could have reduced the latency of this change.

There does appear to have been a great deal of change on the project. Mitchell (2003; page 298) says that 48,000 instruments of change were issued on one contract and Arup (2001; page 7) reports that that 70 per cent of the initial value of the works was accounted for by variations and ascribes this to the incompleteness of the design information issued to contractors. The implication is that further attention to system design activities would have forestalled a great deal of the change described.

The fact that 70% of the initial cost was accounted for by variations does not mean that the cost of the change latency was 70% of the initial cost. If all the changes referred to had been incorporated into the design from the start, then the initial value would have been higher, although presumably not 70% higher.

The accounts of the project do however provide evidence that change latency can be expensive. Mitchell (2003; page 344) estimates that £600 million is attributable to the costs of delay, disruption and acceleration.

However, the costs of change latency are not necessarily the same for all changes. Mitchell (2003; page 194) asserts that, *“The amount of site investigation is always a compromise as the time and cost involved in collecting and interpreting the information has to be balanced against the risk of encountering unknown or unexpected conditions during tunnelling.”* This implies that there are circumstances when the cost of change latency arising from incomplete information is less than the costs of obtaining that information, at least on the average. This corroborates key point 10F, above.

#### **11.3.4 Analysis and conclusions**

##### **Contradiction of the tentative theory**

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in the tentative theory.

##### **Corroboration of the tentative theory**

It is considered that the case study provides weak evidence for the following causal mechanisms for change latency from the tentative theory:

- 2. More timely and greater adoption of good SE practice will lead to more timely, accurate and comprehensive requirements (see change 2).
- 6. More timely and thorough consultation with stakeholders will lead to more timely, accurate and comprehensive requirements (see change 4).
- 9. More timely, accurate and comprehensive requirements will lead to more timely and sounder decisions (see change 2).
- 10. More timely, accurate and comprehensive system design will lead to more timely and sounder decisions (see other changes).
- 12. More timely and accurate cost and timescale estimates will lead to more timely and sounder decisions (see section 11.3.2 and change 5).

**Additional causal mechanisms**

It is considered that there is weak evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 10:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions (see section 11.3.2).

These conclusions are illustrated in Figure 19, using the same conventions as in the previous section.

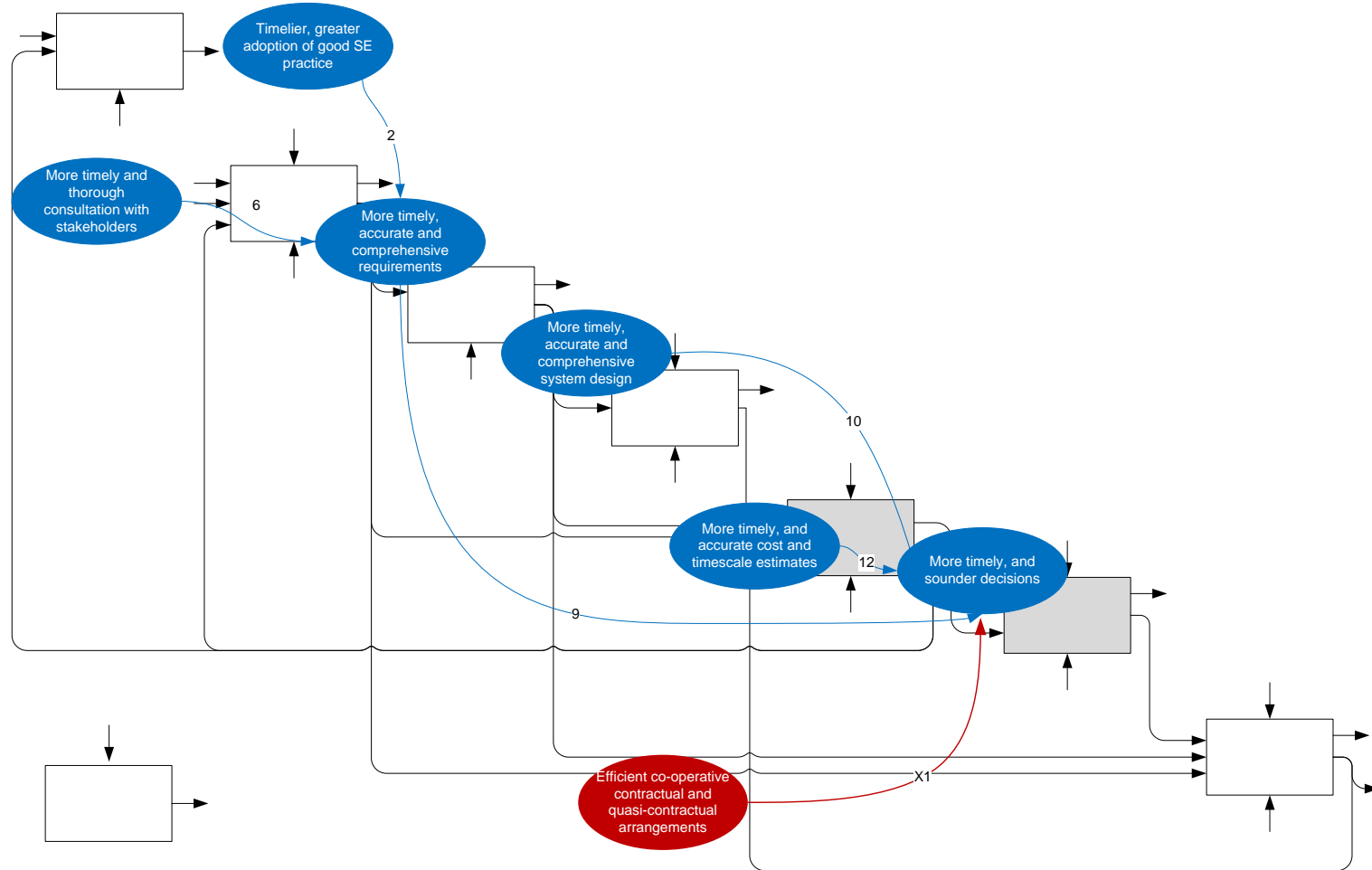


Figure 19: Causal mechanisms corroborated by the Jubilee Line Extension Project case study

**A final thought**

UCL (2009; page 30) states that the JLE project was initially approved with a benefit cost ratio of 0.95 but that, after the project, this ratio was estimated at 1.75. As the costs of the final costs of project were more than 50% higher than those approved, it follows that the benefits must have turned out more than 170% higher than estimated at the time of approval.

The JLE supported the regeneration of East and South East London, facilitated the expansion of London's financial services industry and delivered a very useful link into a network of new transport links. In the long run, it must be regarded as a success.

Had good SE practices been adopted from the start, it should have been possible to produce a far more accurate estimate of the cost at the start. It is intriguing to wonder whether, had that been done, the project would have been approved.

If that leads to questioning the value of accurate estimates, it should be noted that, in the long run, inaccurate estimates are self-defeating. As a consequence of experience on projects such as the JLE project, the UK Department for Transport (2014; section A1.2, paragraph 1.1.2) recommends adding an allowance for optimism bias to cost estimates for transport schemes in order *“to reflect the well-established and continuing systematic bias for estimated scheme costs and delivery times to be too low and too short, respectively.”*

## 11.4 Case Study 3: The Channel Tunnel Rail Link Project

### 11.4.1 Introduction

The project being studied here is the construction of the high-speed rail link between the English end of the Channel Tunnel and London. The case study excludes the construction of the tunnel itself, the procurement of the rolling stock and the works required to allow that rolling stock to run over existing tracks into London.

The information in this case study is drawn from a UCL Project Profile for the CTRL Project (UCL, 2008), two NAO reports (NAO, 2005; NAO, 2012), a report by the consultancy Steer Davies Gleave (2004) and a number of articles in the trade magazine 'Modern Railways'.

The Channel Tunnel opened in 1994. Passenger travel was carried through the tunnel on *Trains à Grande Vitesse* (TGVs) and there was a *Ligne à Grande Vitesse* (LGV) connecting the French end to Paris but construction of a high-speed link to London did not start until 1998. The link was constructed in two sections. Section 1, connected the tunnel to Fawkham Junction, where trains joined the existing network in order to reach Waterloo International station. Section 1 opened in 2003. Section 2 carried the line all the way to St Pancras station, whose reconstruction was included within the project. Section 2 opened in 2007.

Shortly before section 2 opened, the line was rebranded 'High Speed 1' or 'HS1' but, for clarity, I will refer to the project as the 'Channel Tunnel Rail Link' project, or 'CTRL' for short, throughout its lifetime.

The intention was that both sections should be built entirely by the private sector. A private sector company, called London and Continental Railways (LCR), raised funds and contracted another private sector company, Rail Link Engineering (RLE) to build first Section 1 and then Section 2. Section 1 was built under these arrangements and then bought by Railtrack. The collapse of Railtrack forced a restructuring in which public funds had to be made available in order to complete the project.

There were only three rail mega-projects carried out in the UK between 1990 and 2010 and all three are case studies in this report. Case Study 1 – the JLE project – was nearing completion when work started on the CTRL. Case Study 2 – the WCRM project – started and finished around the same time. CTRL is the third member of the group.

JLE and WCRM suffered significant delay and overspend and the scope of both projects was cut back. CTRL is strikingly different:

- Both sections opened within the agreed timescales (NAO, 2005; page 16; NAO, 2012; page 13).
- Section 1 was completed within budget, at a cost of £1.92 billion against a contractual target cost of £1.93 billion (NAO, 2005; page 16).
- Section 2 was completed at a cost of £4.24 billion against a target cost of £3.30 billion (NAO, 2012; page 15). £0.47 billion of this was for extensions to scope (a new depot and additional passenger and retail facilities at stations). The remaining overspend, which was incurred in delivering the originally agreed scope, was less than the contingency reserve held by LCR.
- So, while the CTRL project did exceed its target cost, it did so by a very significantly smaller margin than the JLE and WCRM projects.
- The CTRL project experienced a significantly lower volume of major change than the JLE and WCRM projects and this change did not include any significant reductions in scope.

Moreover, the final product performed well. During 2010-11, only 0.43% of services on the line were delayed by incidents attributable to the infrastructure (NAO, 2012; page 13).

The project, including its initial planning stages, is not however beyond criticism:

- Passenger volumes were significantly below (about half of) those initially forecast, leading the NAO to question whether the project represented good value for the money spent on it (NAO, 2012; page 14).
- It was also very expensive. Steer Gleave Davies (2004; page 35) compared the cost of HS1 against 11 other European and Asian high-speed lines. The authors acknowledge that the cost of high-speed lines is very sensitive to the nature of the terrain over which they run but, even after allowing for that, the authors find that the cost per kilometre of HS1 was about 30% more than that of the next most expensive line and more than three times the cost of a Spanish high-speed line built around the same time.

### **11.4.2 The way in which the project was run**

#### **Systems Engineering and Project Management**

I can find no clear statement of the degree to which the CTRL adopted SE ideas but, from the absence of any evidence of a concerted and explicit attempt to adopt the ideas of SE, I conclude that the project made no such attempt and instead drew upon the traditions of project management alone for its system-level thinking.

The project team certainly put a great deal of effort into meticulous planning and preparation and into consulting stakeholders. So, while the project may not have explicitly adopted SE, it appears to have adopted several of its underlying tenets: 'left shift', the value of stakeholder consultation, the value of meticulous planning and the value of paying attention to interfaces.

#### **General approach to engineering**

The project had a very clear and explicit commitment to using proven technology where possible.

#### **Contract management**

The project team made extensive use of a target-price form of contract that more closely aligned the incentives for client and contractor. The NAO (2005; page 12) reports that LCR and Union Railways considered that the contracting strategy contributed to meeting the budget for Stage 1.

The project created several joint teams in order to reduce the number of interfaces to manage.

### **11.4.3 The changes that were made**

I am not sure at what precise dates the project committed to various aspects of the scheme so I consider changes from the start of construction.

There were at least three major changes.

Firstly, in November 2005, a decision was taken to add the construction of a depot at Temple Mills to the scope of the project. When the Minister for Transport announced this decision,



he said that it had “*always been envisaged as part of the final plan*” for WCRM and that the decision had just been brought forward.

The project had been proceeding under the assumption that trains would continue to be serviced at their existing North Pole depot in West London, even though it was becoming increasingly evident that the increase in traffic resulting from the completion of the London Underground orbital route would not leave enough capacity for the necessary train movements.

I have insufficient information to estimate latency for this change. I suspect that planning for the London Overground orbital route had advanced to the point where it would become clear that there was insufficient capacity for channel tunnel trains to use it before November 2005 but I cannot be sure of this and, in any case, if there was a delay, it may well have been the result of waiting for the completion of political processes that are not susceptible to reduction through SE.

Secondly, significant changes were made to the layout of St Pancras station, which are considered to have improved the passenger experience.

Thirdly, the NAO (2012; page 15) reports that LCR funded investment of £109M on additional passenger and retail facilities at St Pancras, Stratford and Ebbsfleet international stations that were not in the original scope. The project would have created significant retail opportunities and I suspect that this investment represented the decision to exploit some of these opportunities. I do not know when the decision to make this investment was taken and so cannot estimate change latency.

There were also a number of smaller but still significant changes, including:

- changing construction methods to reduce costs;
- raising the maximum line speed in order to increase service reliability;
- changing the tunnel portal design after aerodynamic modelling;
- adding sidings for storing on-track equipment; and
- at St Pancras, changing the rail type.

#### 11.4.4 Analysis and conclusions

##### Discussion of changes

The list of changes above stands in sharp contrast in some ways to the corresponding lists for the JLE and WCRM projects:

- In contrast to the JLE and WCRM projects, none of the changes were made as a consequence of a crisis – they were generally introduced in an orderly fashion and by the existing management without needing to bring in a new organisation to run the project. Several were the result of proactive value engineering.
- In contrast to the JLE and WCRM projects, none of the changes resulted in a visible reduction in the quality of service offered to the users of the railway.
- With the exception of the construction of the Temple Mills depot, where a foreseen addition was brought forward, and the additional passenger and retail facilities, none of the changes were significant enough to figure on the final summary accounts for the project.
- In contrast to the JLE and WCRM projects and with the exception of the construction of the Temple Mills depot, none of the changes resulted in the unexpected demolition or decommissioning of existing assets. Indeed there is no evidence of significant lost work as a result of any of the changes.

##### Contradiction of the tentative theory

The project as a whole does appear to provide a counter-example to the tentative theory as a whole, because:

- there is evidence to suggest that there was scope for the project to adopt SE practices to a considerably greater scope than it actually did, but
- there is no evidence that there was scope for significant reductions in change latency on the project arising from greater adoption of SE practices.

It therefore appears that there are rail projects for which the marginal effects on change latency of adopting SE compared with a rigorous approach to project management are limited. If so, the question arises: what attributes of the CTRL project qualify it for this class?

The following attributes of the CTRL project set it apart from both the JLE project and the WCRM project and are candidate answers to the question:

- The CTRL project made extensive use of a target-price form of contract. We have already seen evidence that contractual relationships are a significant factor affecting change latency and the target-price form of contract, in which purchaser and supplier share overspends and underspends, is designed to improve co-operation and simplify decisions to make changes.
- The CTRL project was building a new railway. This was similar to the JLE but in contrast to the West Coast Main Line, where some changes to the scheme were required in order to balance the conflicting needs of construction and operating the existing railway. It may be noted that the two of the areas where significant change did occur – St Pancras and Temple Mills Depot – were concerned with the points at which the CTRL interfaced with the existing railway network.
- The CTRL project chose to introduce no new technology. It was, to a first approximation, simply an extension of the French LGV on the other side. This was in contrast to both the JLE and WCRM where changes were required because new technology disappointed.

Projects that construct simple, routine, new sections of railway and already adopt good project and contract management practice may see limited benefits in terms of reduced change latency as a result of adopting additional good SE practices because:

- SE delivers benefits, in large part, by identifying and resolving system-level issues;
- a simple section of railway will have fewer systems-levels issues and,
- on a routine project, a greater proportion of these issues will have been encountered and solved before.

This does not mean that they will see no benefits from adopting additional good SE practice because reduced change latency is only one of the mechanisms by which SE may deliver benefits. SE may allow such projects to find and exploit opportunities to increase value for money that they might otherwise have missed.

I note that the CTRL project was well-funded, which arguably allowed it to apply its 'no change' policy to greater effect than the JLE and WCRM projects. It may be noted that the project spent a considerable amount of additional money on building the line to carry freight, see *Modern Railways* (2007; page 45) for example, with no guarantee that this capability will ever be used. Maybe there were changes that a less well-funded project might have sought to make in order to reduce cost but that CTRL could afford to let pass.

### **Corroboration of the tentative theory**

Nothing has been identified in the case study that appears to corroborate the causal mechanisms in the tentative theory.

### **Additional causal mechanisms**

It is considered that there is strong evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 10:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions.

## 11.5 Case Study 4: Acquisition of High-Output Ballast Cleaning Plant

Although information about this project was collected via interview, rather than by inspecting published data, there was no opportunity to structure that interview in the manner described in chapter 10. The nature of the analysis carried out was similar to that for projects investigated via published data and so the project is included in this section.

### 11.5.1 Introduction

This case study concerns the acquisition of high-output plant<sup>24</sup> to clean ballast<sup>25</sup>. The acquisition was eventually abandoned after a significant period of ultimately fruitless endeavour to get the plant to meet its requirements.

This case study is drawn from a conversation with an ex-member of the British Rail (BR)/Railtrack project team. The conversation was held on 14th December 2011. I prepared notes of the conversation which the interviewee reviewed and corrected.

In the mid 1980's British Rail held an ambition to change from the current traditional method of ballast cleaning (and track relaying), mainly at weekends, to a method which used short single line midweek night possessions<sup>26</sup> (each lasting approximately 6 to 8 hours) cleaning up to 1000m of track in each possession. This pattern of work was to be repeated on up to 6 occasions per week. It was also intended to change the crewing from traditional operators to a dedicated crew of maintainer/operators who would travel with the machine throughout the rail network.

For this revised method of ballast cleaning to be successful, the reliability, availability and output of the machines had to be high.

In order to clean ballast on successive nights, the track must be left in a suitable condition to allow trains to immediately run at relatively high speed. The ballast cleaning machine was

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<sup>24</sup> 'Plant' is used here to mean large mobile machines.

<sup>25</sup> 'Ballast' comprises the piles of large gravel in which most railway tracks are laid.

<sup>26</sup> Taking a 'possession' on a part of a railway line means taking it out of use and placing it under the control of maintenance or project staff.

therefore only a part of a total system of work, where all equipment needed to be carefully matched in not only rate of work but also in quality of output.

Achieving this ambition required automation in several areas. This case study describes a project to introduce automation in one area - ballast cleaning.

In 1989, British Rail entered into a contract with a US supplier to develop and supply an automated high-output ballast cleaning machine. The quoted delivery period was about one year.

The supplier had supplied machines of the required type for use in North America. Two separate machines were used in concert and these machines were proven in use and demonstrated to BR. Some of the requirements specified by BR had not been met before by the supplier, for example; self-propulsion at 100 km/h; the ability to feed new ballast into the process; the ability to continuously lift the rail to maintain track height; and profiling of the returned ballast under the sleepers for good geometry behind the machine. Furthermore, the supplier had no experience in designing machines to meet the prescriptive BR rolling stock standards. To fit within the UK loading gauge<sup>27</sup>, the original two machines were to be combined into a single machine comprising six semi-permanently coupled vehicles.

In late 1992, the prototype machine was demonstrated in the US to BR's satisfaction. In early 1993 it was shipped to the UK. It was trialled on the West Coast Mainline but the trials were unsuccessful and it was transferred to the Old Dalby test track for further testing and development. In 1994, Railtrack took over the project and a period of contractual dispute led to a restructuring of the contract in 1995. In 1997, after four years of development in the UK, the machine was handed over to one of Railtrack's track maintenance contractors. However it never achieved its performance requirement to clean ballast at an average rate of 400m/h; the best it could achieve was 300m/h and even at this rate was prone to stoppage. The

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<sup>27</sup> The 'loading gauge' is a profile around the tracks, inside which all rail vehicles must fit. The loading gauge in the UK is unusually small by international standards.

machine was cut up for scrap in 2009. Railtrack acquired a replacement machine from another supplier in 2004, and subsequently purchased more machines from that supplier.

### **11.5.2 The way in which the project was run**

There were a number of differences between the US and UK operating contexts that required changes to the design of the machine. The differences in environment and the differences in design led to a number of practical problems with deployment.

The specification against which the machine was procured was not above criticism but the problems encountered were clearly associated with failures to meet it and so poor specification cannot be regarded as a cause of the problems.

The US trials were intended, of course, to convince BR that the machine was ready to ship to the UK and they were successful in this regard. There is no need to believe that there was any intention to deceive to believe this – the objectives to achieve milestones and to please the customer are perfectly honourable.

BR failed to require a set of tests and checks that comprehensively covered the requirements and did so under realistic conditions (so, for example, night-time operation and remote sensing of conveyors). Had such an approach been taken to the US trials, it is considered that they would have revealed the extent of further development needed to meet the requirements whereupon it is possible that the parties would have agreed to abandon the project.

### **11.5.3 The changes that were made**

There is only one significant change associated with this case study and that is the decision 2004 to replace the machine with a machine from another supplier.

The case study provided by the interviewee provides strong grounds for believing that, in 1992, when the machine was demonstrated to BR, it was possible to establish that the path being followed by the project would not lead to a machine that met all the requirements within acceptable timescales and acceptable cost. This would imply that the latency of this decision was of the order of 12 years.

#### 11.5.4 Analysis and conclusions

##### **Contradiction of the tentative theory**

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in the tentative theory.

##### **Corroboration of the tentative theory**

It is considered that, had good practice associated with the **Verify and Validate the System** core SE process area been adopted during initial field trials, then the magnitude of the inherent problems with the design could have been revealed and this latency could have been significantly reduced.

Note. It is acknowledged however, that the difficulties in proceeding with the project could also have been identified earlier by the application of common sense and good management practice.

It is considered that there is weak evidence for the following causal mechanisms in the tentative theory:

- 5. More timely and greater adoption of good SE practice will lead to more timely and sounder problem reports.
- 13. More timely, and sounder problem reports will lead to more timely and sounder decisions.

The case study is described from the acquirer's view point. It may be suspected that full implementation of core SE processes by the contractor would have reduced change latency. However there is no direct evidence of this.

No evidence has been identified that removing deficiencies in the requirements would have shortened change latency.

##### **Additional causal mechanisms**

Nothing has been identified in the report that appears to suggest additional causal mechanisms.

The conclusions of the previous section are illustrated in Figure 20.



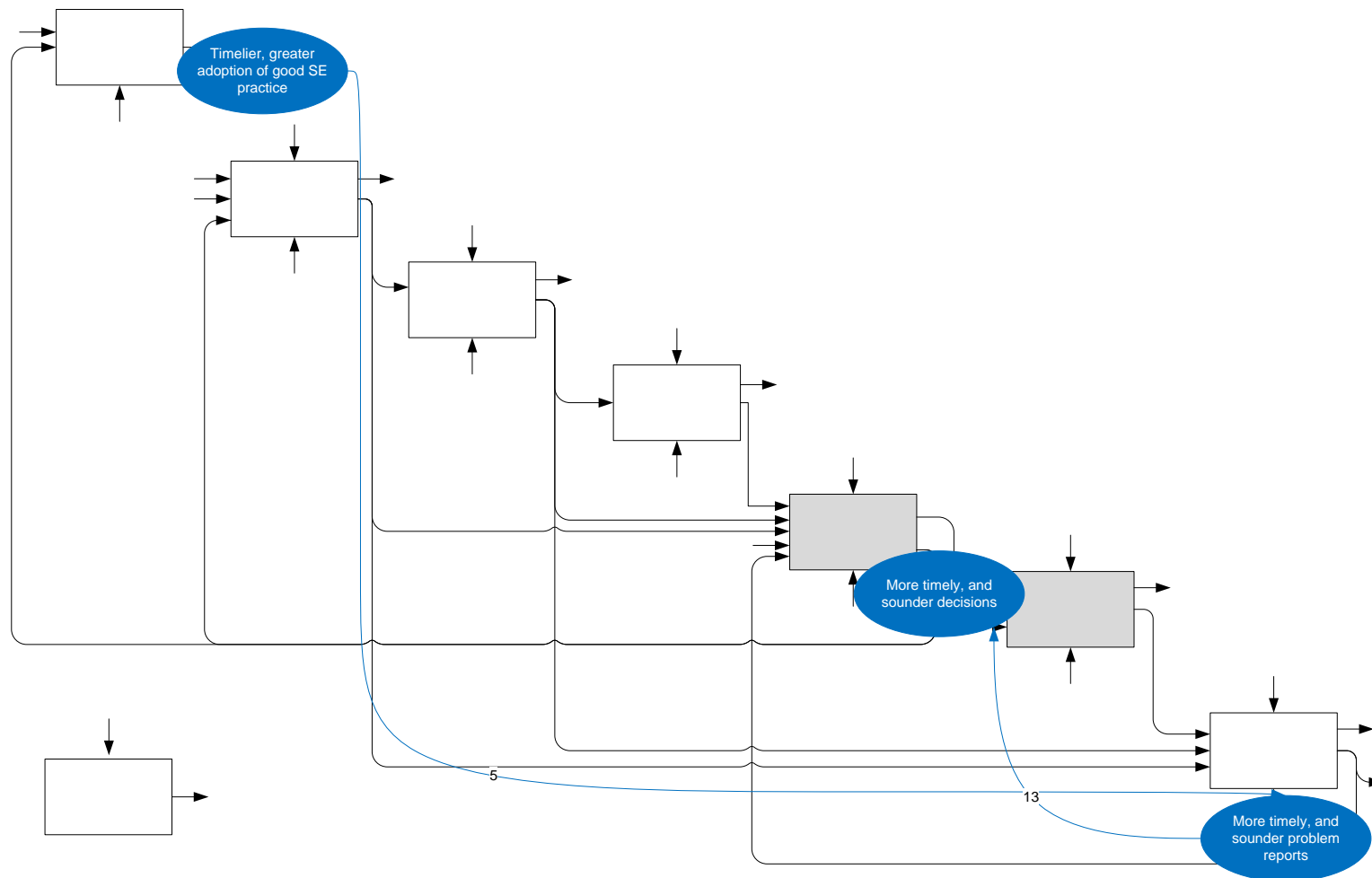


Figure 20: Causal mechanisms corroborated by the Acquisition of High-Output Ballast Cleaning Plant case study

### 11.6 Key points

- 11A Change was pervasive and expensive on two of the projects studied. On JLE, 4,800 instruments of change were issued on one contract, 70% of the initial value of the works was accounted for by variations and an estimate of £600 million is made for the costs of delay, disruption and acceleration
- 11B Change latency was long and expensive on several projects. On a project to acquire high-output ballast cleaning equipment, the decision to abandon the attempt to make one model work had a latency of more than 10 years. Latency for other changes is typically measured in years. On WCRM, £350M had been spent on items that were removed from the project scope.
- 11C Evidence was found to corroborate the mechanisms in the tentative theory numbered 2, 5, 6, 9, 11, 12, 13 and 15.
- 11D Evidence was found for causal mechanisms which are not in the tentative theory, by which change latency can be reduced by:
- Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved
  - Having sufficient skilled people available
- 11E On CTRL, the uptake of formal SE was relatively low and yet there is no evidence that there was scope for significant reductions in change latency on the project arising from greater adoption of SE practices. It is hypothesised that projects that construct simple, routine, new sections of railway and already adopt good project and contract management practice may see limited benefits in terms of reduced change latency as a result of adopting additional good SE practices.



## 12 CONCLUSIONS AND RECOMMENDATIONS

This chapter has four sections:

- In the first section, I recall my research objectives, summarise my findings and assess whether or not I have met my objectives.
- In the second section, I reflect on my findings and formulate recommendations for researchers investigating the benefits of SE.
- In the third section, I reflect again on my findings and formulate recommendations for people working on rail projects.
- In the fourth section, I present my final conclusions.

### 12.1 Research findings and progress against research objectives

#### 12.1.1 Research objectives

I defined two generic objectives for the research (see key point 1B):

- To demonstrate that SE can be used to build better rail systems and to build rail systems better, aiming for measurable improvement.
- To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects.

These objectives were intended as general indicators of the direction to be followed and to be refined later. After preliminary investigations, I defined the following specific objectives (see key points 2C and 6J):

- To demonstrate that core SE can be used to reduce change latency in major rail projects.
- To gain an improved understanding of how to adapt core SE to produce the greatest reduction in change latency in major rail projects.
- To carry out my research in a way that helps others to refine and build upon my findings.

In these objectives:

- ‘core SE’ describes a set of activities that concern the production, update and checking of intellectual artefacts that I consider to be indubitably within the province of SE; and
- ‘change latency’ is a measure of unnecessary delay in deciding to make a change.

### **12.1.2 What I have learnt about changes on railway projects**

Because the specific objectives are focussed on change, I need to discuss what I have learnt about changes on railway projects before I can clearly evaluate progress against these objectives. I have reviewed relevant literature and studied more than a dozen railway projects by interviewing project members, inspecting project records and by reviewing publicly-available accounts of the projects.

I cannot be certain that the sample of railway projects that I looked at is representative of the population of railway projects at large and that my findings can be generalised across the entire population. The projects that I looked at all delivered ‘hard systems’, that is to say engineered, technical systems, and the findings may not generalise to ‘soft’ projects which deliver organisational change. However, the sample does cover a broad range of types and sizes of projects that deliver hard systems and some consistent themes emerge. On the projects that I studied:

- The volume and cost of change was high (see key points 4B, 4C and 11A). Similar results are reported in other sectors (see key point 6B).
- The latency of changes was high – often well over a year (10G, 11A).
- The majority of significant changes could have been avoided entirely, in principle, if the information available at the outset had been fully exploited (see key point 10J).
- About half of change latency was concerned with detecting that some sort of change is required while the other half was concerned with deciding what should be done, obtaining the necessary agreement from interested parties and then deciding to do it (see key point 10H).
- Engineering changes were not carefully tracked and engineering change metrics were not calculated (see key point 10E).

From first principles one would expect that the cost of a change will rise rapidly with delay in deciding to make it and such cost escalation is reported in several engineering sectors (see point 6C).

It follows that reducing change latency could deliver significant potential improvement in rail projects.

### **12.1.3 Progress against objective to demonstrate that SE can be used to build better rail systems and to build rail systems better**

My literature search has revealed that:

- There is a large and growing body of empirical evidence that SE can deliver benefits on engineering projects across a wide range of sectors (see key points 3C and 3D).
- There a number of hypotheses that explain why these benefits are to be expected (see key point 3B) and these hypotheses suggest that some of these benefits should be enjoyed as a result of reduced change latency.

In chapter 9, I presented a model that describes how core SE interacts with other project activities in which SE affects the project primarily by providing information in support of decision making. It follows that, if the decision-making process used on the project is broken and it is unable to reach timely, rational decisions about the project then it is unlikely that increasing the effort spent on SE will deliver increased benefits until this process is fixed. The findings of my studies of rail projects, described shortly, corroborate this (see below).

My tentative theory of how core SE contributes to reduced change latency may be summarised as follows:

*Core SE contributes to reduced change latency by providing the people taking decisions about the system design and process model with timely, accurate and comprehensive information (including proposed specifications, design and process models) and effective change management arrangements.*

The full tentative theory contains 15 more detailed causal mechanisms.

The process of testing the tentative theory against data from real projects has suggested that three additional causal mechanisms should be added and has provided evidence that some of the postulated mechanisms have actually occurred in practice.

Table 11, which is a revision of Table 10, provides an indication of the strength of the evidence available for each mechanism. In Table 10, the numbers in the **Changes** column indicate the number of changes studied in the projects which I studied directly that appeared to corroborate that mechanism. In Table 11, this number has been increased by the number of projects for which I inspected published data, where that published data appeared to corroborate the mechanism.

Figure 21 shows the same information diagrammatically. Arrows for which at least ten changes provided evidence are drawn thicker than other arrows. The numbers on the arrows refer to the serial numbers in Table 11, below and also in Table 6, which contains the original statement of the causal mechanisms

**Table 11: Corroboration of causal links**

Id	Causal mechanism	Changes
2	Timelier, greater adoption of good SE practice will lead to more timely, accurate and comprehensive requirements	2
5	Timelier, greater adoption of good SE practice will lead to more timely, and sounder problem reports	1
6	More timely and thorough consultation with stakeholders will lead to more timely, accurate and comprehensive requirements.	6
8	More timely, accurate and comprehensive requirements will lead to more timely, accurate and comprehensive system design.	16
9	More timely, accurate and comprehensive requirements will lead to more timely and sounder decisions.	3
10	More timely, accurate and comprehensive system design will lead to more timely and sounder decisions.	16
11	More timely, accurate and comprehensive modelling, simulation and analysis will lead to more timely and sounder decisions.	13
12	More timely and accurate cost estimates will lead to more timely and sounder decisions.	5
13	More timely and sounder problem reports will lead to more timely and sounder decisions.	1
15	More efficient change management arrangements will lead to more timely and sounder decisions.	1
X1	Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to more timely and sounder decisions.	17
X2	Having sufficient skilled people available leads to more timely and sounder decisions.	4
X3	Having clarity of funding for the project leads to more timely and sounder decisions.	4

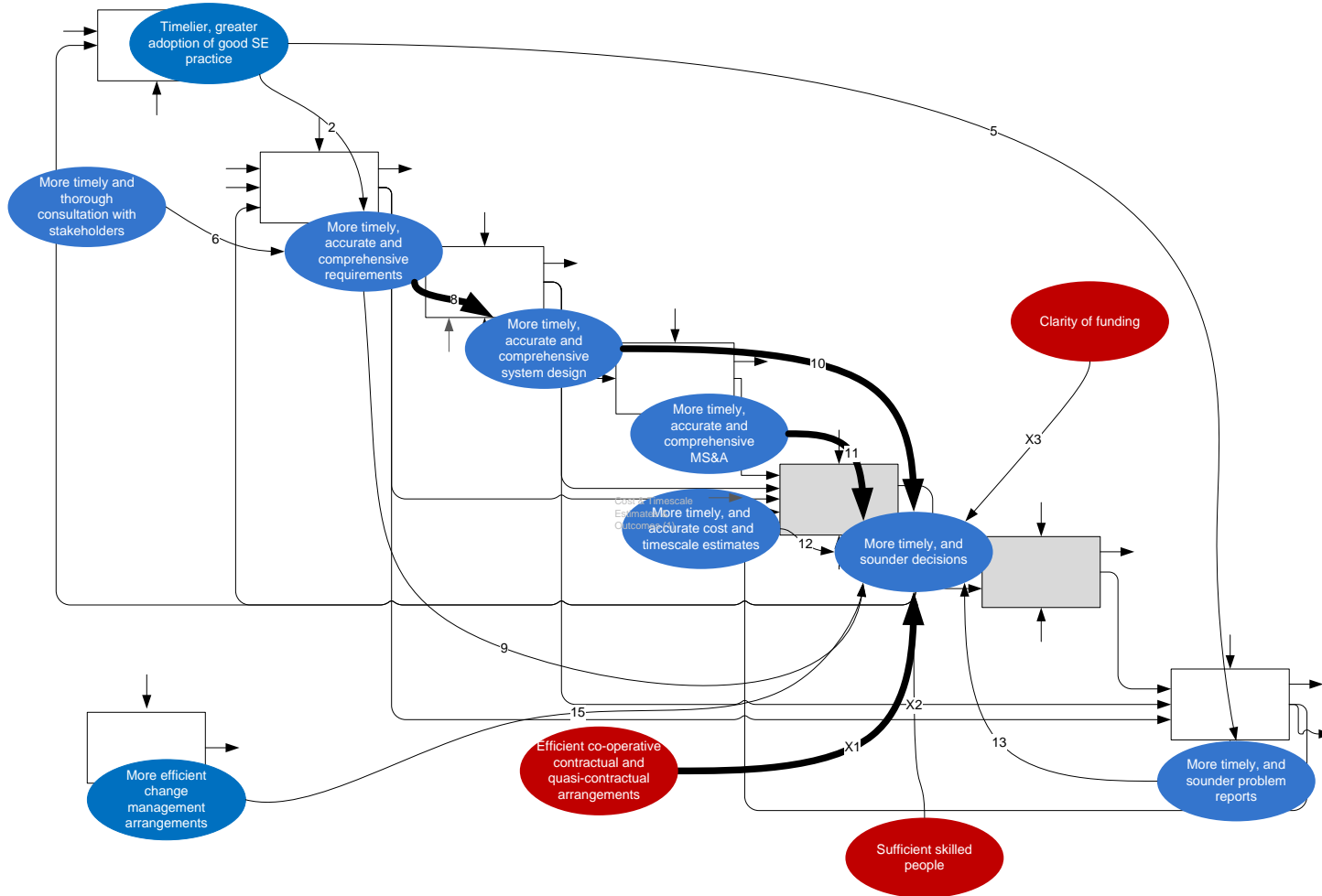


Figure 21: Cumulative evidence for operation of causal mechanisms



Figure 21 highlights graphically that the corroboratory evidence is mostly concerned with a relatively small number of causal mechanisms, suggesting that the primary factors affecting change latency are (see key point 10K):

- the manner in which the **Manage requirements and specify the system** core SE process is carried out;
- the manner in which the **Model, simulate and analyse the system** core SE process is carried out; and
- the nature of the contractual and quasi-contractual relationships between the parties involved, including relationships determining the flow of money between separately-run departments within one organisation.

The history of the CTRL project (see key point 11E) appears to contradict the theory. The uptake of formal SE was relatively low and yet there is no evidence that there was scope for significant reductions in change latency on the project arising from greater adoption of SE practices. It is hypothesised that projects that construct routine new sections of railway and already adopt good project and contract management practice will see limited benefits in terms of reduced change latency as a result of adopting additional good SE practices.

The sample is considered too small to draw firm conclusions from the absence or limited volume of corroboratory evidence for the other proposed mechanisms.

The analysis of the data leads me to conclude that the following refinements to the theory are desirable:

- To add mechanisms X1, X2 and X3 as defined above.
- To add the following additional proviso to mechanisms 9 to 14, inclusive: The project is delivering a system which is not both simple and routine.

#### **12.1.4 Progress against objective to understand better how to adapt core SE to produce the greatest reduction in change latency in major rail projects**

The findings of the research do provide corroboration of the working assumption that focussing SE upon change latency is valuable. While, from a strictly logical point of view, this does not progress the specific objective, *“To gain an improved understanding of how to adapt core SE to produce the greatest reduction in change latency in major rail projects”* it

does progress the generic objective, *“To gain an improved understanding of how to adapt SE to yield optimum results in major rail projects”*.

The research suggests that, for a major rail project employing current practice in SE and project management, the greatest reduction in change latency can be achieved by focussing investment in SE upon requirements engineering and upon modelling, simulation and analysis.

The research suggests (see key point 10Q) that the proportion of change latency that SE could be used to eliminate is significant but well below 100%. Moreover, the research suggests that, in order to maximise the reduction in change latency that SE can deliver, it is important to ensure that the contractual and quasi-contractual relationships between parties to the project, including separately-run departments within one organisation, are set up in a way that allows them to collaborate effectively towards common goals and to take decisions quickly.

The research also suggests that there are intrinsic reasons why core SE practices developed in other sectors should be adapted for rail projects, including the following:

- The rail sector already has established processes that overlap the areas claimed by SE and that should not be unnecessarily disrupted.
- Vehicles traversing across a network introduce long-distance dependencies between parts of a railway and this means that rail projects typically have to think of the whole railway as the system.
- Rail projects typically have to change the railway while it remains in service.

The research suggests (see key point 4F), in order to maximise their effectiveness, core SE practices developed in other sectors should be adapted for rail projects in the following additional ways:

- look for proven practices in use within the organisation that deliver the same objectives as the ‘foreign’ SE practices and retain existing practices unless there is a clear benefit in changing;
- be prepared to be flexible about the scope of what is referred to as SE and to exclude functions that are satisfactorily performed by existing rail disciplines;

- plan to expand significantly the ‘foreign’ functions concerned with migration from one stage to another; and
- take account of the fact that many design decisions about the structure of the system will already have been taken in the context of the railway as a whole (and often recorded in standards) and adjust the ‘foreign’ design processes to reflect this.

#### **12.1.5 Progress against specific objective to carry out my research in a way that helps others to refine and build upon my findings**

I consider that the research approach that I used was appropriate to the nature of the research problem. In particular:

- Formulating a tentative theory helped focus the research and made it possible to combine circumstantial evidence from a variety of sources, including from single case studies. The approach could clearly be continued by other research, building upon what has been achieved so far.
- The construction of a model that is focussed upon the interaction between SE and the rest of the project, rather than upon SE itself, generated useful insights.
- Change latency has been shown to be a fruitful thing to measure. It is a measure that can be applied to all changes, without having to discriminate between those changes that are corrections to faults and those that are improvements or adaptations to external change, which is of value because this discrimination can be fraught.
- Case study analysis was carried out rigorously and delivered understanding of causal mechanisms that quantitative methods generally do not deliver.

The quantitative analysis that I used in the research yielded little value. This was not unexpected, given the small number of projects studied. However I have indicated how it could be usefully applied by researchers who have access to data on larger populations. However, in performing such analysis, it would be important (see key point 10P) to supplement average change latency with a measure of aggregate change latency, for example the result of summing the change latencies of all changes weighted by their effect on overall cost expressed as a percentage of the total budget for the project, in order to be able to measure benefits associated with changes that have been avoided rather than just accelerated.

### 12.1.6 Assessment of progress against the research objectives

The research has substantially met the specific objectives defined.

## 12.2 Recommendations for researchers

I make the following recommendations to readers who are carrying out research into the benefits of SE:

- R1 Face squarely the challenges that the field of study places in the way of research (see key points 2A, and 2B) and consider a broad range of research methods before selecting those that are most appropriate.
- R2 When modelling SE, consider the interactions with the rest of the project as well as the internal structure of SE.
- R3 Consider the use of case study research, which can be applied rigorously but allows small increments in learning to be accumulated over time.
- R4 Articulate a tentative theory before collecting data, in order to focus the collection and to provide a starting point for incremental refinement.
- R5 Consider using change latency as a convenient means of measuring some important effects of SE. Average change latency should be supplemented (see key point 10P) by a measure of aggregate change latency, for example the result of summing the change latencies of all changes weighted by their effect on overall cost expressed as a percentage of the total budget for the project.
- R6 The factors that influence change latency are not yet understood fully and, given the importance of change latency to the outcome of projects, this appears to be a fruitful area for further research and one in which there is synergy with the objectives of practitioners (see recommendation P2 in the next section) that may support collaboration between academia and industry.

### 12.3 Recommendations for practitioners

I make the following recommendations to readers who are taking senior roles on rail projects:

- P1 When thinking about SE, bear in mind that its contribution to project success is by providing timely and accurate information. Although this is not a deep insight, it has corollaries that, in my experience, are not always understood. For instance (key point 9D), those performing SE need to write at least some of their documents in a way that can be easily understood by the non-specialist.
- P2 Calculate statistics for change latency on projects, try to understand the factors that influence these statistics and set targets for reducing these statistics over time. This appears to be a fruitful approach for delivering meaningful process improvement and one in which there is synergy with the objectives of researchers (see recommendation R6 in the previous section).  
*Note. Average change latency is a useful statistic but it should be supplemented (see key point 10P) by a measure of aggregate change latency, for example the result of summing the change latencies of all changes weighted by their effect on overall cost expressed as a percentage of the total budget for the project.*
- P3 If your projects suffer from high change latency then invest in SE.
- P4 In making this investment, focus effort upon requirements engineering and upon modelling, simulation and analysis. The aspects of requirements engineering where uptake of SE is least on rail project appear to be checking and managing requirements (see key point 10C).
- P5 Ensure that the contractual and quasi-contractual relationships between parties to the project, including separately-run departments within one organisation, are set up in a way that allows them to collaborate effectively towards common goals and take decisions quickly.
- P6 Adapt SE practices developed in other sectors for rail projects in the manner described in section 12.1.4 above.

## 12.4 Conclusions

The findings of my research lead me to four principal conclusions:

- There are difficulties in determining the success of a project, and thus the impact of SE, by simply measuring its cost and duration and assessing the performance of the system that it delivers. Change latency is a measure which may be used by researchers and practitioners to make some of the benefits of SE visible in a manner which overcomes these difficulties.
- The volume and latency of change on railway projects is often high and reducing change latency has the potential to deliver significant benefits on these projects.
- Rigorous case study analysis can deliver useful increments in our understanding of causal mechanisms by which SE delivers benefits.
- But these increments are small and sustained improvement in understanding requires that the research community find ways of consolidating these increments. Articulating tentative theories before collecting data provides a basis for this consolidation.

This research was prompted by two questions that I could not properly answer (see key point 1A). I can now offer the following answers to these questions.

**Question:** ‘If I apply SE to this project, will I see benefits that justify the cost?’

**Answer:** ‘You will see benefits if the contractual and quasi-contractual relationships between the parties to the project, including separately-run departments within one organisation, are set up in a way that allows them to collaborate effectively towards common goals and take decisions quickly. The benefits may be lower on projects that construct simple, routine, new sections of railway and already adopt good project and contract management practice but, if your projects suffer from high change latency, the cost of focussed improvements in SE is likely to be justified by the benefits that they deliver.’

**Question:** ‘How should I adapt SE practices that have been developed in other sectors to make them work well on my project?’

**Answer:** ‘To maximise the benefits of SE practices on rail projects, you should maximise their ability to reduce change latency by focussing, at least initially, upon requirements engineering and upon modelling, simulation and analysis and by adapting good SE practice to suit the nature of rail projects, as recommended above’.

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## **A APPENDIX: DETAILED ANALYSIS OF DATA COLLECTED DIRECTLY FROM RAILWAY PROJECTS**

This appendix provides additional information about the exercise, described in chapter 10, to collect data directly from rail projects and to analyse these data.

To make it easier for the reader to cross refer between this appendix and the body of the thesis, this appendix has the same top-level section headings as chapter 10. That is, section A.*n* has the same title as section 10.*n*.

### **A.1 Conduct of the survey and data collection exercise**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **A.2 Data collected about projects in general**

This section records the questions and requests for information made about the nature of the projects investigated (reproduced in bold text) and records the range of responses provided.

**Q1.1.1: Please describe the project that I will talk about. You and I need to be clear about the scope of the project that I are discussing. For instance, if you were working for a supplier or contractor, I need to agree whether I are talking about your organisation's activities only or those of the customer as well.**

The full details are not recorded here, in order to preserve the anonymity of the data providers. However, the following general remarks may be made:

- Project 1, 2 and 3 were concerned with upgrading existing infrastructure while project 4 was concerned with introducing a new fleet of trains.
- Project 2 had to make a number of similar infrastructure improvements at different locations that were grouped, for management purposes, into a number of 'tranches'. Knowing that this opened up the possibility of comparing early and later stages of the project, the survey and data collection was limited to the first and last tranches but data for these tranches were collected separately.

- Project 3 was associated with one change that was of significantly greater magnitude than all other changes made – a decision, taken part way through design to radically reduce the scope of the project. Knowing that this change would be the focus of the exercise, the survey and data collection for this project were limited to the design phase.
- Project 5 carried out an upgrade to a metro line in order to enhance capacity and performance.

**Q1.1.2: Is the project still underway?**

Four projects were still underway but all of these had commissioned deliverables and for all projects the non-recurring engineering was largely complete.

One project was reported as completed but snagging work continued.

**Q1.1.3: Is the project part of a larger programme of work? If so, please explain how its scope relates to the larger whole.**

All projects could be considered as part of larger programmes of work but could also be considered as coherent packages of work on their own.

**Q1.1.4: In what industry sector is the project?**

All projects were in the rail sector.

**Q1.1.5: What sort of railway(s) did it involve? Please select all that apply. Please ignore this question if your project was not a railway project.**

Interviewees were asked to select all responses that applied from a list of alternatives.

Responses were as follows:

**Table 12: Responses to Q1.1.5**

<b>Response</b>	<b>Count</b>
01) Tramway or light rail (eg Docklands Light Rail)	0
02) Metro	3
03) Heavy rail (passenger traffic)	0
04) Heavy rail (freight traffic)	0
05) Heavy rail (mixed passenger and freight traffic)	2
06) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

**Q1.1.6: Which parts of the railway were components of the system? Please select all that apply. Please ignore this question if your project was not a railway project.**

Interviewees were asked to select all responses that applied from a list of alternatives.

Responses were as follows:

**Table 13: Responses to Q1.1.6**

Response	Count
01) Permanent way	3
02) Stations	2
03) Structures (such as bridges, embankments, viaducts)	4
04) Rolling stock	2
05) Signalling	3
06) Electrification	2
07) Telecommunications	4
08) Tunnels	0
09) Lifts and/or escalators	1
10) Level crossings	1
11) Operational procedures	5
12) Maintenance and asset management procedures	5
13) Control facilities	4
14) Other, please specify	3

Note: Other components included mechanical and electrical systems, signalling power supplies and depots.

**Q1.1.7: In which of the following lifecycle stages did or will the project carry out work? Please select all that apply.**

Interviewees were asked to select all responses that applied from a list of alternatives.

Responses were as follows:

**Table 14: Responses to Q1.1.7**

Response	Count
01) Concept and feasibility (initial scoping, exploration of alternatives, establishing feasibility and outline business case)	5
02) Requirements definition	5
03) Design development	5
04) Implementation	4
05) Transition to service	4
06) Operations and maintenance	2
07) Decommissioning and disposal (of system concerned)	0
08) Decommissioning and disposal (of system being replaced)	4
09) Other please specify	0

Note: For reasons described in chapter 10 above, the data collection for Project 3 was restricted to the first three stages and this was reflected in the answer given to this question, although in fact work had continued into stages (4), (5) and (8).

**Q1.1.8: When did the project start? Please answer to the nearest month, if possible?**

**Q1.1.9: When did/will the project finish? Please answer to the nearest month, if possible?**

The duration of the projects varied between 5 and 10 years with a mean average of 7 years.

Note: Some interviewees were unable to provide dates to the nearest month and provided years only. All durations were rounded to the nearest year.

Note: All projects had less than a year to run except for the rolling stock project where the remaining duration was concerned with commissioning of run-on vehicles.

**Q1.1.10: At peak, how many people worked on the project? Please count everyone who carried out activities that fell within the scope of the project as you described it to me in Q1.1.1.**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 15: Responses to Q1.1.10**

Response	Count
01) Less than 10	0
02) 10 to 49	0
03) 50 to 199	3
04) 200 or more	2
05) Other response, please specify	0
<b>TOTAL</b>	<b>5</b>

**Q1.1.11: How many person years were expended on the project? Please count everyone who carried out activities that fell within the scope of the project as you described it to me in Q1.1.1.**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 16: Responses to Q1.1.11**

Response	Count
01) Less than 10	0
02) 10 to 49	0
03) 50 to 199	1
04) 200 or more	4
05) Other response, please specify	0
<b>TOTAL</b>	<b>5</b>

**Q1.1.12: How many stages are involved in the project? (Please select one response.)**

**By a stage, I mean a significant change to the railway after which the railway is returned to service**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 17: Responses to Q1.1.12**

Response	Count
01) 1	0
02) 2-4	2
03) 5 or more	2
04) Other response, please specify	1
<b>TOTAL</b>	<b>5</b>

Note: The “other response” was that there were 13 commissionings in all but none were considered to constitute a significant change to the railway.

**Q1.1.13 Please indicate the degree to which the following statement is an accurate characterisation of the system?**

**“The system relies entirely upon well-tried technology in an application in which it has been used before”**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 18: Responses to Q1.1.13**

Response	Count
1) Wholly true	0
2) Mostly true	3
3) Partly true and partly untrue	2
4) Mostly untrue	0
5) Wholly untrue	0
6) Other, please specify	0
<b>TOTAL</b>	<b>5</b>



**Q1.1.14: Please indicate the degree to which the following statement is an accurate characterisation of the system?**

**“The design, construction, installation and testing methods used on the project were standard methods, used routinely by the organisation performing the project”**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 19: Responses to Q1.1.14**

<b>Response</b>	<b>Count</b>
1) Wholly true	1
2) Mostly true	3
3) Partly true and partly untrue	0
4) Mostly untrue	1
5) Wholly untrue	0
6) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

Note. The ‘Wholly untrue’ response concerned a project that was executed by a newly created organisation. The project members did have some personal experience of the methods used.

**Q1.1.15: How experienced were the people leading the systems engineering functions? (Please select one response. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.)**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 20: Responses to Q1.1.15**

Response	Count
1) The people leading the systems engineering functions included few or no members with at least 5 years of experience performing these function	2
2) A significant proportion of the people leading the systems engineering had at least 5 years of experience performing these functions but in a non-rail context	0
3) A significant proportion of the people leading the systems engineering had at least 5 years of experience performing these functions in a rail context	3
4) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

Note: One interviewee who selected response (3) commented that the situation moved towards (2) as the project proceeded.

**Q1.1.16: To what degree were the systems engineering functions integrated with the rest of the project functions? (Please select one response. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.)**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 21: Responses to Q1.1.16**

Response	Count
1) The people performing the systems engineering functions worked with little or no interaction with the rest of the team	0
2) The people performing the systems engineering functions worked with limited interaction with the rest of the team	2
3) The people performing the systems engineering functions worked as an integral part of team as a whole	3
4) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

Note: Both interviewees who selected response (2) commented that the situation moved towards (3) as the project proceeded.

**Q1.1.17: Please indicate the degree to which the following statement is an accurate characterisation of the project?**

**“The system as built is or will be consistent with the final versions of the design documents and drawings for it”**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 22: Responses to Q1.1.17**

<b>Response</b>	<b>Count</b>
1) Wholly true	4
2) Mostly true	1
3) Partly true and partly untrue	0
4) Mostly untrue	0
5) Wholly untrue	0
6) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

**Q1.1.18: Please indicate the degree to which the following statement is an accurate characterisation of the project?**

**“The technical strategy at the end of the project was substantially the same as the technical strategy at the beginning of the project.”**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 23: Responses to Q1.1.18**

<b>Response</b>	<b>Count</b>
1) Wholly true	1
2) Mostly true	3
3) Partly true and partly untrue	0
4) Mostly untrue	0
5) Wholly untrue	1
6) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

Note: Response (5) was given on Project 3, which was subject to radical reduction in scope as mentioned in the Introduction.

**Q1.1.19: Please indicate the degree to which the following statement is an accurate characterisation of the project?**

**“The project organisational structure was reasonably stable throughout the duration of the project.”**

Interviewees were asked to select one response from a list of alternatives. Responses were as follows:

**Table 24: Responses to Q1.1.19**

Response	Count
1) Wholly true	1
2) Mostly true	2
3) Partly true and partly untrue	2
4) Mostly untrue	0
5) Wholly untrue	0
6) Other, please specify	0
<b>TOTAL</b>	<b>5</b>

### **A.3 Analysis of data collected about projects in general**

I carried out analyses in order to determine whether any project was significantly more challenging than the others. The analyses were in two parts.

Firstly, I looked to see whether any project was significantly more difficult (large, complex or volatile) or easy than the others. If a project was unusually difficult, I might expect it to have a higher than average change latency despite justifying higher than average adoption of SE practices.

I inspected the responses to the following questions, each of which sought information on a parameter that might affect difficulty:

- Q1.1.10. At peak, how many people worked on the project?
- Q1.1.11. How many person years were expended on the project?
- Q1.1.13. Please indicate the degree to which the following statement is an accurate characterisation of the system? “The system relies entirely upon well-tried technology in an application in which it has been used before”

- Q1.1.14. Please indicate the degree to which the following statement is an accurate characterisation of the system? “The design, construction, installation and testing methods used on the project were standard methods, used routinely by the organisation performing the project”
- Q1.1.17. Please indicate the degree to which the following statement is an accurate characterisation of the project? “The system as built is or will be consistent with the final versions of the design documents and drawings for it”
- Q1.1.18. Please indicate the degree to which the following statement is an accurate characterisation of the project? “The technical strategy at the end of the project was substantially the same as the technical strategy at the beginning of the project.”  
Please indicate the degree to which the following statement is an accurate characterisation of the project? “The project organisational structure was reasonably stable throughout the duration of the project.”

I assigned each project a “+” score if the response indicates that, in this dimension, the project is above the median in difficulty and a “-” score if the response indicates that it is below the median.

The scores according to this method are as follows:

**Table 25: Factors increasing and decreasing difficulty.**

Project	+	-
Project 1	0	0
Project 2	1	2
Project 3	2	2
Project 4	1	1
Project 5	4	0

Secondly, I looked to see whether any project team had an SE capability significantly greater or less than the others. This might affect the effectiveness of the SE practices adopted.

I inspected the responses to the following questions:

- How experienced were the people leading the SE functions?
- To what degree were the SE functions integrated with the rest of the project functions?

Project 5 gave a more positive overall response to these questions but there was no significant variation between the other projects.

So there was no overwhelming difference in technical difficulty between projects 1, 2 3 and 4 and project 5, which faced the greatest technical challenges, had the most experienced and integrated SE team. If one takes the common-sense view that the effect of the more experienced and integrated SE team on change latency is to compensate, to some degree, for the effect of the greater technical challenges then it is reasonable to conclude that the sample of projects contained none for which the combined effect of the two factors on change latency was overwhelming.

#### A.4 Data collected about the SE performed on the projects

The following request was made to the interviews.

##### Q1.2.1: Please consider each of the following statements and tell me to what degree they fairly represent what happened on the project

The interviewees were provided with the statements listed in Table 27. For each statement the interviewee was asked:

**Q1.2.1 (cont.): Please select one of the following options. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.**

- 1) **Wholly true**
- 2) **Mostly true**
- 3) **Partly true and partly untrue**
- 4) **Mostly untrue**
- 5) **Wholly untrue**
- 6) **Other, please specify**

**In selecting one of the options above, do not take account of any reservations that you may have had about how the activities concerned were performed. So, if a comprehensive requirements specification was prepared but after the system was built, answer 'Wholly true'.**

The response provided to each statement was converted to a figure of merit (FoM) in the range 0.0 to 1.0 as follows:

**Table 26: Figure of Merit by response**

Response	Figure of Merit
1) Wholly true	1.0
2) Mostly true	0.75
3) Partly true and partly untrue	0.5
4) Mostly untrue	0.25
5) Wholly untrue	0.0



Table 27 also lists the statements whose representativeness for the project interviewees were asked to assess and shows the core SE process to which they are considered to contribute, using the following acronyms:

- MP: Model (the project) Processes
- MR&StS: Manage Requirements and Specify the System
- DtS: Design the System
- MS&AtS: Model, Simulate and Analyse the System
- V&VtS: Verify and Validate the System
- MC: Manage Change

Note. The model was revised after the list of questions had been finalised. One question – with identifier C – was subsequently found not to relate to any core SE process.

Where response (6) was given, no figure of merit was calculated and the combination of project and core SE process was excluded from any subsequent calculation of mean averages.

Project 2 carried out a number of similar tasks, grouped into three ‘tranches’. The interviewee on project 2 provided responses for the initial tranche and also indicated where a different response was relevant to the final tranche. This enabled the calculation of separate figures of merit for “Project 2 (early)” and “Project 2 (late)”.

Mean average figures of merit were calculated across the projects and are presented in Table 27. In the calculation, the early results were used for Project 2 as these are the most comparable with other projects. Across the statements, the average FoM ranges from 0.40 to 1.00. The 80th percentile value is 0.88 and the 20th percentile value is 0.65.

Rows containing figures at or above the 80th percentile value are highlighted in blue. Rows containing figures at or below the 20th percentile are highlighted in pink.

**Table 27: Statements about SE with Figures of Merit and mapping to core SE processes**

	Statement	Ave FoM	Core SE Process
	<b>Process Definition</b>		
A.	The project wrote down a description of the processes used to define, design, implement, build and commission the system	0.75	MP
B.	This description was used as input to the planning of the project	0.80	MP
	<b>Technical Reviews</b>		
C.	The output from each phase of the lifecycle was subject to multidisciplinary review	0.85	<i>None</i>
	<b>Configuration Management and Change Control</b>		
D.	The project placed key documents or components of the system under configuration control	0.85	MC
E.	Once an item was brought under configuration management, all changes to it were done under the authority of an approved change request	0.80	MC
F.	Baselines were established such that each item was placed under formal change control after it was entered in a baseline	0.75	MC
G.	There was a process to define, assess and approve change requests	0.85	MC
H.	There was a process to track the implementation of approved change requests	0.65	MC
	<b>Interface Management</b>		
I.	Key interfaces between components of the system were defined and documented	0.63	DtS
J.	Key interfaces between system and external entities were defined and documented	0.65	MR&StS
	<b>Requirements Management</b>		
K.	The requirements that the system must meet were written down	0.85	MR&StS
L.	Each requirement was given a unique identifier	0.75	MR&StS
M.	Requirements were traced to the sources of stakeholder need	0.65	MR&StS
N.	Stakeholders were consulted to establish their requirements	0.75	MR&StS
O.	Facts about legacy systems and other parts of the environment of the system pertinent to the achievement of the requirements were collected and written down	0.75	MR&StS
P.	Individual stakeholders or stakeholder classes who had a legitimate interest in the system throughout its life cycle were identified	0.90	MR&StS
Q.	Unavoidable constraints (for instance legislation, applicable standards) were identified and recorded	0.85	MR&StS
R.	The scope of the system to be built or changed was defined	0.75	MR&StS
S.	The functions that the system must exhibit were defined together with the conditions under that each function must be available	0.70	MR&StS
T.	The needs of validation were considered as a potential source of system requirements	0.55	MR&StS
U.	Scenarios of typical use were defined and used to establish and/or check requirements	0.80	MR&StS
V.	Users of the system were identified and treated as stakeholders	0.95	MR&StS
W.	Critical requirements (for instance relating to safety) were identified as such	0.70	MR&StS

	<b>Statement</b>	<b>Ave FoM</b>	<b>Core SE Process</b>
X.	Performance measures were defined that would allow the degree to which the system met its needs to be measured.	0.85	MR&StS
Y.	Assumptions relevant to the requirements were written down, checked and tracked.	0.65	MR&StS
	<b>System Design</b>		
Z.	The requirements were used as input to the specification of sub-systems and/or the design of the systems	0.85	DtS
AA.	System requirements were traced to the specification of sub-systems and/or the design of the systems	0.65	DtS
BB.	The design was checked against the requirements as the design process proceeded	0.75	DtS
CC.	Models of the physical structure of the system were created and maintained	0.65	DtS
DD.	Functions of the overall system were allocated to or decomposed into functions of the sub-systems	0.75	DtS
	<b>Simulation and Modelling</b>		
EE.	Simulations or models were made in order to estimate emergent properties of the system (such as reliability and performance)	0.70	MS&AtS
FF.	The results of these simulations were used to improve the design.	0.75	MS&AtS
	<b>Trade-off Analysis</b>		
GG.	A search was made for options that were likely to meet the requirements	0.75	MS&AtS
HH.	The benefits and dis-benefits of each option were assessed	0.75	MS&AtS
II.	The choice between options was informed by an assessment of the benefits and dis-benefits of each option	0.75	MS&AtS
	<b>Risk Analysis</b>		
JJ.	An analysis was done to identify the main risks to the project	0.90	MS&AtS
KK.	The potential severity and likelihood of each risk was assessed	1.00	MS&AtS
LL.	Action was taken to control the risks	0.85	MS&AtS
MM.	The risks were monitored throughout the project	0.95	MS&AtS
	<b>Requirements Validation</b>		
NN.	The requirements were checked for completeness, conflicts, overlap and feasibility	0.50	MR&StS
OO.	Each requirement was checked for verifiability, unambiguity and atomicity	0.40	MR&StS
PP.	There was an explicit process to identify and resolve conflicting requirements	0.40	MR&StS
QQ.	Requirements were checked with stakeholders	0.75	MR&StS
	<b>System Validation</b>		
RR.	Compliance of the built system with each requirement that affected it was checked	0.69	V&VtS
SS.	The method of checking compliance with a requirement was specified at the same time as or shortly after the requirement was written down	0.69	V&VtS
TT.	The results of validation were recorded	0.88	V&VtS
UU.	A strategy for validation was defined	0.94	V&VtS
VV.	There was a programme of activities to ensure that the necessary facilities, equipment and operators to conduct the validation were prepared	0.94	V&VtS

	Statement	Ave FoM	Core SE Process
WW.	Discrepancies and corrective actions arising from validation were analysed, recorded and reported	0.94	V&VtS
XX.	The results of validation contained sufficient information to support the definition of corrective actions	0.88	V&VtS
YY.	The availability of the services delivered by the system that were required by stakeholders was confirmed during validation	0.88	V&VtS

The FoMs that were at or above the 80th percentile fall naturally into three groups as listed below.

- Identifying stakeholders
  - P: Individual stakeholders or stakeholder classes who had a legitimate interest in the system throughout its life cycle were identified
  - V: Users of the system were identified and treated as stakeholders
- Validation
  - TT: The results of validation were recorded
  - UU: A strategy for validation was defined
  - VV: There was a programme of activities to ensure that the necessary facilities, equipment and operators to conduct the validation were prepared
  - WW: Discrepancies and corrective actions arising from validation were analysed, recorded and reported
  - XX: The results of validation contained sufficient information to support the definition of corrective actions
  - YY: The availability of the services delivered by the system which were required by stakeholders was confirmed during validation
- Assessing and monitoring risks
  - JJ: An analysis was done to identify the main risks to the project
  - KK: The potential severity and likelihood of each risk was assessed
  - MM: The risks were monitored throughout the project

The FoMs that were at or below the 20th percentile fall naturally into four groups as listed below.

- Managing interfaces
  - I: Key interfaces between components of the system were defined and documented
  - J: Key interfaces between system and external entities were defined and documented
- Checking and managing requirements
  - M: Requirements were traced to the sources of stakeholder need
  - T: The needs of validation were considered as a potential source of system requirements
  - Y: Assumptions relevant to the requirements were written down, checked and tracked
  - AA: System requirements were traced to the specification of sub-systems and/or the design of the systems
  - NN: The requirements were checked for completeness, conflicts, overlap and feasibility
  - OO: Each requirement was checked for verifiability, unambiguity and atomicity<sup>28</sup>
  - PP: There was an explicit process to identify and resolve conflicting requirements
- Tracking the implementation of change
  - H: There was a process to track the implementation of approved change requests
- Modelling the physical structure of the system

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<sup>28</sup> A requirement is atomic if it cannot be logically decomposed into multiple requirements.

- CC: Models of the physical structure of the system were created and maintained

## **A.5 Analysis of data collected about the SE performed on the projects**

There is no additional information to provide. A full account was provided in the body of the thesis.

## **A.6 Data collected about changes and analysis of these data**

### **A.6.1 The criteria used for selecting changes and the changes selected**

The general criteria used for selecting changes were:

- (a) The change had a significant effect on the cost of the project.
- (b) The change affected either the final built system or the staging of the works. Changes that only affected project processes were excluded.
- (c) The change implied some alteration in direction for the project. Changes that adjusted the requirements to bring them into line with what the project was already doing or planning to do were not included.
- (d) There was sufficient information available to answer the questions about the change that I had asked.

The precise criteria used to select changes for analysis and summary information about the changes selected are provided for each project in the sections following immediately.

### **Project 1**

In interpreting criterion (a), a significant change was taken to be a change with either an increase or decrease in cost that exceeded a threshold set at approximately 1% of the final project cost. Only changes that had been agreed after the start of detailed design were considered for further analysis.

6 changes met the criteria and were selected for further analysis but insufficient information could be identified from the records to perform any meaningful analysis of 3 of these changes so only 3 were actually included in the analysis.

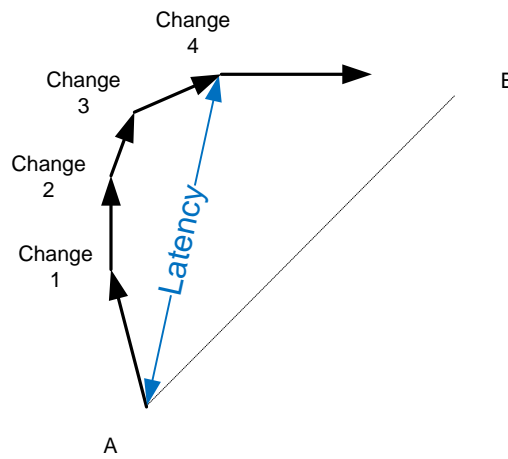
**Project 2**

Project 2 had to make a number of similar infrastructure improvements at different locations, which were grouped, for management purposes, into a number of ‘tranches’. I looked only at the initial and final tranches.

In interpreting criterion (a), a significant change was taken to be a change with either an increase or decrease in cost that exceeded a threshold set at approximately 0.5% of the cost of one tranche.

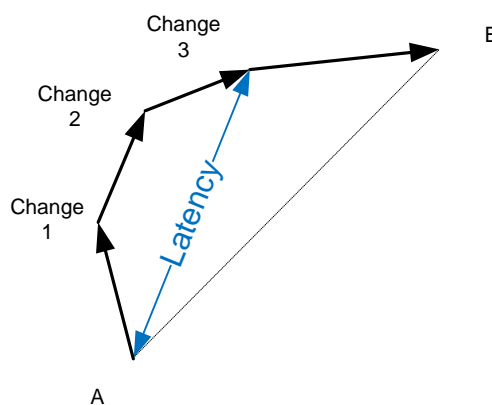
8 changes met the criteria and were selected for further analysis.

4 of these changes concerned consecutive attempts to resolve a problem with transmission of vibration that were, in the end, only partially successful. In accordance with the model that is being used (see section 6.3), these are regarded as one compound change with latency as shown in Figure 22.



**Figure 22: Transmission of vibration**

3 of these changes concerned attempts to resolve problems with the controls specification. These are regarded as one compound change with latency as shown in Figure 23.



**Figure 23: Controls specification**

A final change was analysed separately.

**Project 3**

Project 3 was associated with one change that was of significantly greater magnitude than all other changes made – a decision, taken part way through design to radically reduce the scope of the project. Knowing that this change would be the focus of the exercise, the survey and data collection for this project were limited to the design phase and only this change was analysed in detail. The history of the change was as follows.

The project scope was extended during outline design to deliver some aspirations that were not in the original design. At the stage gate review at the end of outline design, the best estimate for costs was found to be above the target. The cost estimate was discounted on the assumption that future savings would be identified and the discounted figure was presented to the review.

However, the cost estimate rose rather than fell during the course of detailed design for two reasons.

Firstly, additional scope was added. It was appreciated when scope was added that the costs would rise. However, the apportionment of these additional costs between the three budget holders was not made explicit and the budget holders held views of what their shares were that did not add up.

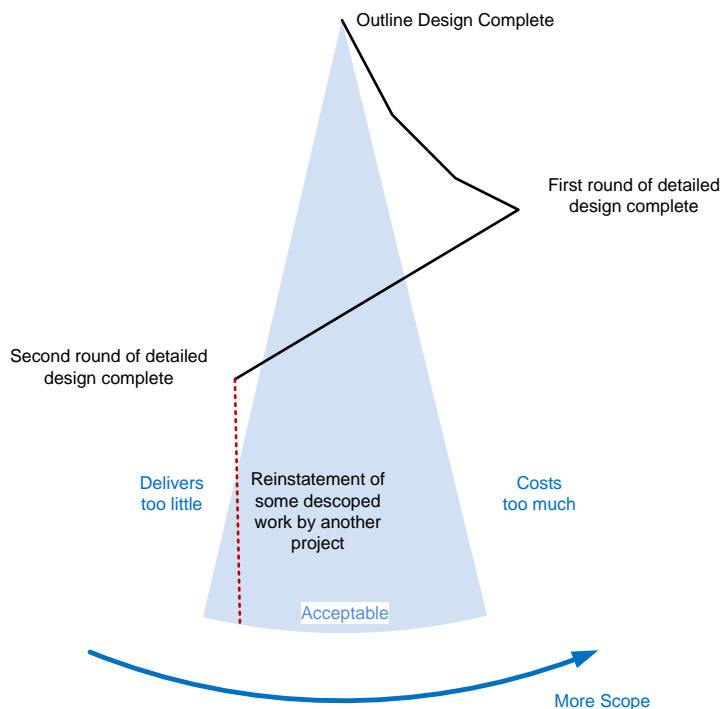
Secondly, the full cost implications of scope decisions that had already been taken emerged during the design process.

When the project completed detailed design, the costs had risen by 50% since outline design. The project was refused authority to proceed as currently scoped. The project was radically de-scoped and detailed design was repeated.

A decision has since been that some of the works that had been removed from the project scope should be carried out as part of a separate project.

The overall trajectory of events is illustrated in Figure 24.





**Figure 24: Increasing, decreasing and then increasing scope**

**Project 4**

The project was delivered by a contractor but the interviewee represented the customer and had access to price rather than cost data. In interpreting criterion (a), a significant change was taken to be a change with either an increase or decrease in price that exceeded a threshold set at approximately 1% of the final price. Design or manufacturing changes found necessary by the contractor in order to meet the specification would therefore be excluded. Only changes that had been agreed at the time of data collection were considered for further analysis.

Note. There were a few occasions when one piece of scope was bartered for another without affecting the price. By definition, the changes concerned could not meet this criterion but the interviewee’s opinion was that none of these changes would have met the price threshold had they been paid for in money.

15 changes met the criteria and were selected for further analysis but insufficient information could be identified from the records to perform any meaningful analysis of one of these changes so only 14 were actually analysed.

**Project 5**

The records available to the interviewee were not sufficient to establish the precise financial impact of each change because contractual variations sometimes covered more than one technical change and because the system integrator's costs, particularly prolongation costs, were not accurately apportioned to changes. The interviewee attempted to apply criterion (a), using his knowledge and judgement to select the changes that were most significant either in terms of changes to the project cost or in terms of work abandoned. It appears that this exercise selected changes that affected the cost of the project by at least 0.2%.

10 changes were selected for further analysis.

**A.6.2 Data collected on the reasons for the change and on change latency**

There is no additional information to provide. A full account was provided in the body of the thesis.

**A.6.3 Data collected on the factors affecting change latency**

Table 28 contains the results of the analysis described in section 10.6.3 to associate changes with generic factors. A '1' is placed in a cell if I found that the generic factor for the column affected the change in the row. The number of times that each generic factor was found to affect a change is shown in a row at the bottom of the table.

**Table 28: The generic factors affecting change latency**

<b>Id</b>	<b>Description of change</b>	<b>MP</b>	<b>MR&amp;StS</b>	<b>DtS</b>	<b>MS&amp;AtS</b>	<b>V&amp;VtS</b>	<b>MC</b>	<b>CONTR</b>	<b>RES &amp; COMP</b>	<b>COST</b>	<b>VALUE</b>	<b>TIME</b>	<b>OTHER</b>
A.	With regard to one sub-system, the customer needed three in quantity and believed that they had contracted for three but the supplier believed that they had contracted for one only. A contract variation was raised and so presumably there was ambiguity in the contract.		1					1				1	
B.	Buttons which passengers could press to raise the alarm were removed because the dis-benefits of malicious and inadvertent operation outweighed the safety benefits.		1					1					1
C.	The contract included like-for-like replacement of telecommunications facilities while, under another contract, the customer was replacing them with new technology. The like-for-like replacements were not in fact needed but the contract gave the customer no automatic benefit for reducing scope and the facilities were removed from scope after most of them had been installed.							1					
D.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.		1										
E.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.		1					1					
F.	The cables used allowed potentially dangerous crosstalk and had to be replaced. The crosstalk could have been predicted theoretically.				1			1					
G.	Egress doors had to be modified to ensure satisfactory evacuation rates in an emergency.		1										
H.	A scenario was discovered where the system operator could be misinformed in a way that could lead to an accident.				1								

<b>Id</b>	<b>Description of change</b>	<b>IMP</b>	<b>MR&amp;StS</b>	<b>DtS</b>	<b>MS&amp;AtS</b>	<b>V&amp;VtS</b>	<b>MC</b>	<b>CONTR</b>	<b>RES &amp; COMP</b>	<b>COST</b>	<b>VALUE</b>	<b>TIME</b>	<b>OTHER</b>
I.	An option, introduced into the contract at the outset, to extend some train lengths, was taken up.				1			1					
J.	An option, introduced into the contract at the outset, to provide air conditioning to improve passenger comfort was taken up.				1			1	1				1
K.	Multiple changes were made to the design of the controls for some equipment in order to deliver something that was operable. The need for change was ascribed to a requirements specification that was unclear and incomplete.		1										
L.	Additional facilities were needed to ensure satisfactory performance at an interface between the system and another system.		1		1								
M.	The order in which parts of the system were installed was found to be sub-optimal and was changed to minimise delays to the project.							1					1
N.	Multiple changes were made to reduce the transmission of vexatious vibration to neighbours to an acceptable level. The transmission of vibration to neighbours was not initially discussed in the requirements.		1		1				1				
O.	Change made to comply with revisions of standards that had been made since the start of the project.												1
P.	The train roof was lowered because some infrastructure was found to infringe the gauge and changing the train was cheaper than changing the infrastructure.							1					
Q.	An aspect of the system design was found to be more extensive than was required and was cut back to save costs.		1						1		1		1

Id	Description of change	MP	MR&SIS	DtS	MS&AtS	V&VtS	MC	CONTR	RES & COMP	COST	VALUE	TIME	OTHER
R.	The change added scope to the project in order to remove gaps at the interface between the project and a project to upgrade an adjacent part of the railway.				1								1
S.	Back-up control facilities were added in order to provide acceptable system resilience.		1					1					
T.	The order in which parts of the system were installed was found to be sub-optimal and was changed to minimise delays to the project.							1					
U.	The system being delivered used different technology from which assumed by the customer's standards and changes to both the system and the standards were required to align them.			1								1	
V.	Communications antennae were moved to avoid radio dead spots.					1				1			1
W.	The change concerns adjustments to the outline design, carried out by one contractor, after claims by another contractor performing detailed design that the outline design was not fit for purpose.				1			1					
X.	The project was de-scoped because its projected cost exceeded the budget available. This was partly ascribed to inaccurate cost estimates and partly to the fact that the apportionment of the costs between budget holders was unclear and budget holders thought that their shares were lower than they actually were.		1				1	1	1	1	1	1	1
Y.	The original design would have degraded maintainability and the design was changed to restore maintainability to the levels before the project was made.		1		1								
Z.	Additional telecommunications facilities were added because the telecommunications needs of another system were found to be greater than anticipated.						1						

Id	Description of change	IMP	MR&StS	DtS	MS&AtS	V&VtS	MC	CONTR	RES & COMP	COST	VALUE	TIME	OTHER
AA.	Additional telecommunications facilities were added because the telecommunications needs of another system were found to be greater than anticipated.		1						1			1	1
BB.	The procurement of another system being procured at the same time was cancelled and the contract for the system in question had to be adjusted as a result.							1					
CC.	Distributed control facilities were collected in one place in order to deliver acceptable response times for faults.		1				1						
DD.	Telecommunications facilities were upgraded to give acceptable fidelity.		1		1			1					
EE.	Changes to the system being delivered were required because the customer changed the supplier for another system.		1		1								
	<b>Totals</b>	<b>0</b>	<b>16</b>	<b>1</b>	<b>11</b>	<b>1</b>	<b>3</b>	<b>15</b>	<b>5</b>	<b>2</b>	<b>2</b>	<b>4</b>	<b>9</b>

## **A.7 Further analysis**

### **A.7.1 Quantitative analysis**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **A.7.2 Qualitative analysis**

#### **Qualitative investigation of the effects of the ‘Manage requirements and specify the system’ process**

There are 16 changes for which the MR&StS process was found to be a generic factor, of which at least one change is associated with each project. I reviewed the specific factors and opportunities related to this generic factor. All concerned deficiencies in the specification. I grouped them into categories and I considered those categories that contained at least two changes. For each such category, I found one or two aspects of good SE practice in this area that I considered had the potential to forestall deficiencies within this category. This was done by reference to one of the statements of good practice used to collect information about the SE performed on the project. A full list of these statements is provided in Table 27. I then looked at the figures of merit associated with these statements for all 5 projects concerned and calculated mean averages for the statements. The results are shown in Table 29 below<sup>29</sup>.

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<sup>29</sup> *The initial letters refer to the identifiers of these statements in Table 27*

**Table 29: Analysis of the effects of MR&StS on changes**

Deficiency	#Changes affected	SE good practice	Average FoM
Failure to take proper account of the needs of operators and maintainers	6	N. Stakeholders were consulted to establish their requirements	0.75
		U. Scenarios of typical use were defined and used to establish and/or check requirements	0.80
		V. Users of the system were identified and treated as stakeholders	0.95
Failure to take proper account of an external interface	4	J. Key interfaces between system and external entities were defined and documented	0.65
Unclear specification	3	OO. Each requirement was checked for verifiability, unambiguity and atomicity	0.40
		<b>Overall average</b>	<b>0.59</b>

The overall average figure of merit for statements J and OO is significantly lower than the average for the process as a whole, which is 0.78 (see Table 7 above). While the average figure of merit for statement N is above the average, a figure of 0.75 suggests gaps in the consultation of stakeholders.

I conclude that there are plausible detailed mechanisms through which greater adoption of SE practice in the MR&StS process areas might, under other circumstances, have reduced the latency of the changes considered.

The contribution of the **Managing Requirements and Specifying the System** process to change latency appeared to be primarily concerned with its ability to avoid the need for changes at all rather than its ability to increase the responsiveness to external changes.

#### **Qualitative investigation of the effects of the ‘Model, simulate and analyse the system’ process**

There are 11 changes for which the **MS&AtS** process was found to be a generic factor. I reviewed the specific factors and opportunities related to this generic factor.

In one case the process was a contributor to change latency – a decision on the change had to wait until a study had completed. Two cases concerned the decision to take up a contractual option. In the remaining eight cases, it was suggested that additional modelling, simulation and analysis could have revealed the need to make a change that was latent at the time that the root documents were issued.



This suggests that a number of the changes made on the projects studied could have been foreseen and incorporated into the original specification and design if more modelling, simulation and analysis had been done.

**Qualitative investigation of the effects of contractual arrangements**

There is no additional information to provide. A full account was provided in the body of the thesis.

## **B APPENDIX: DETAILED ANALYSIS OF DOCUMENTED CASE STUDIES**

### **B.1 Testing the tentative theory using published data on railway projects**

This appendix provides additional information about the exercise, described in chapter 11, to collect data directly from rail projects and to analyse these data.

Four cases are studied:

- The West Coast Route Modernisation Project
- The Jubilee Line Extension Project
- The Channel Tunnel Rail Link Project
- Acquisition of High-Output Ballast Cleaning Plant

Each case study is discussed in a separate section of this appendix. To make it easier for the reader to cross refer between this appendix and the body of the thesis, this appendix has the same top-level section headings as chapter 11. That is, section B.*n* has the same title as section 11.*n*.

## B.2 Case Study 1: The West Coast Route Modernisation Project

### B.2.1 Introduction

There is no additional information to provide. A full account was provided in the body of the thesis.

### B.2.2 The way in which the project was run

#### Before the SRA intervention

Dick (2000) reports that, in 2000, the project:

- had adopted *“the principles of systems engineering, and particularly requirements management”* and deployed a proprietary requirements management software;
- was adopting a *“structured approach”* that included *“establishing clarity of requirements, having traceability, ensuring that we have all the essential elements contributing to business benefits”*;
- was working to *“ensure that high-level business leads were translated into detailed requirements for each system element”*; and
- had determined *“which conditions are essential”* to meet high-level requirements as well as *“those that contributed little and might have been over-specified”* and had been able to *“make adjustments as necessary”*.

The NAO report (NAO, 2006) describes the following conditions before the SRA intervention:

- Key Weakness 1: A lack of clear governance arrangements and direction for the programme

The NAO says that *“The programme lacked direction and leadership. Railtrack had been both commissioner and contractor and did not have a delivery strategy and central point for responsibility and communication across the programme”*.

- Key Weakness 2: Failure to engage stakeholders in support of the programme

The NAO says that, *“There was a lack of openness and communication of the programme to interested parties [...] and a lack of stakeholder management.”* One specific area where stakeholder management is criticised is in the area of

possessions: whether to try and do the work in short periods at weekends and overnight or whether to use blockades, that is to close a part of the line for an extended period to allow work to continue uninterrupted. The NAO notes that, as a result, work on the railway was being performed almost entirely in short possessions.

- Key Weakness 3: There had been ‘scope creep’, arising from a lack of tight specification and change control

The NAO says that changes to scope arose from the lack of *“an agreed specification which matched required outputs with inputs”* and from Railtrack’s *“poor knowledge of West Coast asset condition”*. The NAO concludes that the WRCM alliancing contracts did not work well *“because Railtrack lacked the engineering expertise to be able to participate in Alliances as an informed and equal partner and to challenge contractor-developed scope”*.

- Key Weakness 4: The use of untried and unproven new technology

The NAO says that, *“Technology issues, in particular Railtrack’s decision to replace conventional signalling with unproven moving block signalling, introduced major risk into deliverability and cost before 2002.”*

- Key Weakness 5: Failure to effectively manage and monitor programme delivery through contractors

The NAO says that, *“Railtrack’s programme management was weak, with a lack of senior management skills, too many changes in personnel and ill-defined and fragmented roles and responsibilities”* and that Railtrack *“did not have an integrated delivery plan and had limited oversight of its Alliance contractors”*.

The NAO concludes that these weaknesses contributed to delay and increase in costs.

### **After the SRA intervention**

The NAO report describes the following improvements resulting from the SRA intervention:

- Key Weakness 1: A lack of clear governance arrangements and direction for the programme

The NAO says that the SRA *“set a clear direction for the project [...] specifying what it wanted to achieve”* and put in place *“clear programme governance structures”* with a Project Board and a Project Development Group. The NAO *“found a consensus that the arrangements had worked well”* and concluded that this resulted from board-level engagement, *“continuity of leadership”*, *“having a small, but high calibre, team dedicated to the programme”* and challenge from independent observers on the Project Development Group.

- Key Weakness 2: Failure to engage stakeholders in support of the programme

The NAO says that the SRA *“consulted widely, both formally and informally, to achieve a Strategy which better balanced interests between high-speed long distance trains, local and regional passenger services and freight”* and that stakeholders were kept informed about progress. The NAO found that this engagement with stakeholders *“facilitated the more intrusive regime of obtaining possession of the track for engineering work through extended blockades”*, a regime which was crucial to delivery within time and budget constraints.

- Key Weakness 3: There had been ‘scope creep’, arising from a lack of tight specification and change control

The NAO reports that:

- expert teams were formed to challenge the existing baseline;
- *“a clear, measurable set of programme outputs, along with more detailed infrastructure requirements”* was developed;
- detailed requirements were captured in a series of functional specifications;
- the alliance contracts were progressively replaced with a new contracting approach, which was, where possible, to invite fixed-price tenders against detailed requirements; and
- *“systematic change control and monitoring procedures”* were put in place to control changes to the functional specifications.

- Key Weakness 4: The use of untried and unproven new technology

This was dealt with by removing most instances of untried and unproven new technology from the programme.

- Key Weakness 5: Failure to effectively manage and monitor programme delivery through contractors

The NAO says that

- Bechtel Ltd was appointed *“to provide ‘leadership, direction and clarity’ to the management of programme delivery”*;
- the programme was reorganised *“so that decisions could be taken more quickly and closer to key worksites in the regions;*
- the number of support and technical services staff was increased;
- an integrated plan was created allowing the project management to make informed trade-offs and to prioritise work, and
- Network Rail made greater use of fixed-price contracts, challenged a greater proportion of claims from contractors and introduced productivity incentives into contracts.

### **B.2.3 The changes that were made**

The increased use of blockades was a major change in strategy.

The NAO also reports that *“The 2003 Strategy appropriately removed from the programme the European Rail Traffic Management System (ERTMS), new signalling technology, and the Network Management Centre, on which Railtrack had spent £350 million, to reduce these major risks to programme delivery.”* This is of itself a major change and one which clearly illustrates the huge potential costs of change latency. Had these items been omitted from the start, the cost of the programme would have been reduced by at least £350 million.

The NAO asserts that opportunities were found *“to reduce the programme cost by over £4 billion”*. The report says that these opportunities included:

- Finding a way of allowing trains to run faster north of Preston without replacing the signalling.
- Finding a better way of upgrading the power supply for the route. There is more description of this in Appendix 3 of the NAO Report where it is explained that Railtrack had abandoned its original plan to use an autotransformer system, as used on French high-speed lines, and decided to retain a booster transformer feeder system. However this decision was reversed after a challenge team had identified that an autotransformer system was required in order to support future traffic levels and could be delivered a lower cost than previously thought.
- Remodelling of the track layout at Rugby. The NAO reports that *“constructive challenge”* had led to *“an improved scheme with better outputs than Railtrack’s previously proposed scheme”* and *“which did not require demolition of the station and brought down the project’s planned cost from the original £350 million to £190 million.”*

However, this is clearly not a comprehensive list. For further details, I reviewed the issues of ‘Modern Railways’ magazine in 2003 and 2004. ‘Modern Railways’ is a trade magazine for the UK railway industry and, during this period, carried a series of extended articles describing evolution in the scheme design at a level of detail suitable for the interested enthusiast. The articles make clear that the changes to plans continued to be refined after the period covered by the NAO report.

In the June 2003 edition, Gough (2003) describes the first phase of changes made at Rugby. He writes, *“Work on the preparation of the West Coast Strategy began in April 2002 with a detailed re-examination of existing plans in order to define the exact scope of the specified work and cost that work as accurately as possible. This exercise showed that the project was not only expensive but was also very slow, with an expected completion date of about 2013.”* He goes on to say that, *“examination of the Rugby plans indicated that the expenditure of a great deal of money was going to buy remarkably few benefits. When track speed was matched with signal sighting and overlap questions, it appeared that speed on the through*

*main lines could rise only from 75mph to 85mph, with no change in speeds to and from Birmingham. And although the new layout gave some improvement in capacity, considerable numbers of conflicts remained. Even before the SRA's additional freight objective was taken into consideration, it was clear that neither in terms of line-speed nor in throughput did the planned new Rugby meet the required outputs for the route. This location would remain a low-speed bottleneck. As if all that were not enough, the new layout was going to be difficult to build, and it would probably be quite difficult to own and maintain."*

Gough describes how a more careful analysis led to a different layout in which a non-standard arrangement of the traffic across the four tracks was tolerated for a short distance, the station was demolished and rebuilt to put the through lines where the old platforms were and a flyover viaduct was rebuilt.

Gough's comparison of the old and new ways of working is interesting. He writes, *"This process of starting with a definition of the functionality required and then asking how that can be achieved, rather than adopting the older approach of looking at what is already there and asking how best it can be adapted to get as close as possible to what is wanted, would be normal for projects in many other fields. But it is novel on the railway: this has been partly because of the constraints that have long been imposed by somewhat shorter-term planning and financing."*

Gough is back in January 2004 (Gough, 2004a). He describes how the SRA found that the works planned at Nuneaton station were expensive and would take too long. A proposed underpass was removed from the new layout and a new and cheaper method was found of routing freight traffic that would have used this underpass through the station instead while passengers that would have travelled on trains through this underpass would now have to change trains at Nuneaton.

Gough also describes changes in the Trent Valley. Railtrack had originally planned to make this part of the line four-track throughout but had limited widening as part of a cost-cutting exercise. The SRA reversed this decision *"in the light of its assessment of future needs"*. So, in this case, the SRA added scope.



Gough notes that aspects of the scheme between Stoke and Norton Bridge remained under review by the SRA at the time of writing.

Gough returns again in September 2004 with a pair of articles (Gough, 2004b, 2004c). He discusses further evolution of the plans for Rugby and reports that, with attention to detail, it has been found that it is possible to achieve the desired lines speeds while retaining the existing platforms and parts of the structure of the flyover being replaced, with savings to cost as a result.

At Stafford, Gough reports that, *“a completely new and very much simplified layout”* is being adopted, although he does not describe the reasoning behind the change in detail.

Gough discusses sections further north and writes, *“Over the Lancaster & Carlisle and Caledonian sections the nature of the railway changes completely as it makes its way through the northern fells and then through the lowland hills of Scotland. There are no major schemes. There has, however, been a major change of policy. Instead of trying to bring every possible short section of line up to a 125mph enhanced permissible speed, often giving a saw-tooth speed profile that would be very difficult to drive to, the aim will now be to set a maximum of 110mph on the more curved sections and to bring as much of the line as possible up to that level. It is far better value to bring the 90 speed limits to 110 than to bring the 110s to 125. This decision saves money and accelerates delivery by avoiding a lot of the extra re-laying that would have been required for a 125mph line-maximum.”*

#### **B.2.4 Analysis and conclusions**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **B.3 Case Study 2: The Jubilee Line Extension Project**

#### **B.3.1 Introduction**

There is no additional information to provide. A full account was provided in the body of the thesis.

#### **B.3.2 The way in which the project was run**

##### **Project Management**

There is clear evidence that weaknesses in project management were causal factors for project problems in general and for change latency in particular.

Mitchell (2003; page 298) writes:

*“It was always the intention to have a full 'engineer's design' for the civil works with full working drawings produced to form part of the tender package-albeit contractors were also encouraged to submit alternative design and construction proposals. The very tight timescales for the original design phase and the changing requirements meant this objective was ambitious and, in practice, could not be realised. Consequently the working drawings issued at contract award, despite the moratorium, remained incomplete in terms of both number and substance. This was highlighted on one contract where the contractor stated that they had been issued with 48000 instruments of change by the time the work was complete.”*

It seems as though a high volume of change was the result of incomplete designs that were in turn the result of working towards a programme that was not met and arguably could not have been met. If so, then the project management decision to force the pace early on may well have resulted in the project taking longer than it would otherwise have – a corroboration of the ‘left shift’ hypothesis by counter-example.

Arup (2001; page 8) suggests another deficiency.

*“JLEP’s initial practice of reporting to LUL on progress and cost to date, but not forecasting on eventual programme and budget for completion, was also a shortcoming of this approach to management. Its basis was the premise by JLEP that mitigation and recovery measures, introduced to regain lost time, would work and that,*

*as a consequence, the situation would always improve. We believe this created optimism within LUL and JLEP that was not properly justifiable. This in turn, introduced high risk to both programme and cost targets.”*

The problem is ascribed partially to a lack of expertise and partially to an unwillingness to countenance the possibility of slippage, which appears to be ascribed, in turn, to a lack of independence that was eventually overcome by Bechtel’s “fresh thinking”.

Without accurate cost and timescale forecasts, it must have been difficult to balance options. It seems likely that better cost and timescale forecasting would have resulted in reduced change latency.

### **Contract Management**

Two criticisms of the contractual arrangements have been identified that could have increased change latency.

Mitchell (2003; pages 297ff) criticises the arrangements for co-ordination of contracts when he writes:

*“The Contractor was required to co-ordinate his own work with that of all the Designated Contractors. The Contractor was also required to provide attendance (all reasonable facilities and opportunities for carrying out their work) on the Designated Contractors and any other contractors and workmen of the Employer. The inclusion of this contractual obligation still left the Project team with the sizeable task of managing the interfaces directly and ensuring co-ordination of all the contractors with the overall master programme for the Project. Managing the interfaces was a key factor in the increased costs incurred by the Project as will be seen later.”*

Arup (2001; page 17) corroborates this criticism and provides evidence that it was a source of delay.

*“Works contractors were also procured individually, and management of interfaces between them was not defined. This was particularly relevant to the Railway controls contractors, where absence of early interface management delayed this package by many months.”*

Mitchell (2003; page 306) also reports the following criticism from a civil engineering contractor:

*“The form of contract discouraged collaborative working by being severe and punitive if a party got into trouble. The procurement strategy for the stations was flawed insofar as the form of contract encouraged non-contracting parties to be wary of one another and to leave the co-ordination between the building works and the E&M works to the Project team.”*

Arup (2001; page 17), corroborates this criticism as well with the following observation:

*“The form of contract and the documentation was common to both the Civil and E&M works contractors, and became adversarial under the circumstances under which it was applied and used.”*

### **B.3.3 The changes that were made**

In order to identify changes it is necessary to set a baseline. I choose to use as a baseline the scheme defined in the London Underground Bill 1989, as deposited in November 1989. This is described in Mitchell (2003; pages 329ff). Mitchell (2003; page 19) says when discussing this period that, *“It was always intended to open the extension in one go – the big bang approach.”*

A change, then, must either differ from this baseline or from be a variance from a definite subsequent commitment.

There were a number of changes to the design of the stations but the changes are complex enough and the available information about them is limited enough that I have found it impractical to analyse them.

Leaving station changes aside, the following five changes meet the criteria above and are significant enough that their consequences would be readily apparent to a user of the line:

1. to change the route so that it included North Greenwich;
2. to greatly increase the works on the existing portion of the Jubilee Line;
3. to replace the existing train fleet rather than supplementing it;
4. to open the line in phases; and

5. to abandon the planned moving block signalling system and revert to a fixed-block signalling system with reduced capacity.

Each of these changes is considered in turn followed by some general remarks and conclusions.

### **Change 1: Change of route**

In the scheme originally deposited with the parliamentary bill, the line crossed the Thames twice and remained North of the Thames from Canary Wharf. In May 1991 (Mitchell, 2003; page 33), the House of Commons select committee approved the proposals for the Project but decided upon an alternative route that crossed the Thames twice more in order to connect the Greenwich peninsula to the Underground network and promote its regeneration. The decision took account of the fact that British Gas had also agreed to make a multi-million pound contribution to the scheme if it took the North Greenwich route, including provision of a site for the station at North Greenwich, a worksite and an area for a park and ride facility adjoining the station (Mitchell, 2003; page 333).

### **Change 2: Works on the existing portion of the Jubilee Line**

Mitchell says (2003, p33) that, *“Very little provision had been made in the original Project cost and programme estimates for any works on the basis that the extension was really a ‘bolt-on’ to the existing railway. A figure of £15 million was included for some works at Green Park station to cope with increased passenger flows and some upgrading to the signalling.”*

However, Mitchell (2003, p33) says that, in Spring 1991, the project started to realise that it needed to carry out work on the existing line including:

- Additional signalling equipment;
- A new service control centre;
- Changes to sidings to accommodate longer trains;
- Changes to stations;
- Additional electrical power equipment; and
- Additional communications equipment.

In the final reckoning, according to Mitchell (2003, p33), the works on the existing line cost well over £100 million.

The latency for the change to add the necessary additional works then was at least 16 months. The primary reason for this latency appears to be framing the problem incorrectly and regarding it, as Mitchell is quoted above as saying as “a 'bolt-on' to the existing railway”. Mitchell (2003; page 362) expands on this point later in his book:

*“If the scope of the Project had been considered as the Extended Jubilee Line from the start as opposed to the Jubilee Line Extension, it would have brought about a more holistic approach to planning and design and a more realistic assessment of the costs and risks involved. As it was, the Project team initially took an entrenched view (understandably) that the existing line was nothing to do with them.”*

Arup (2001; page 6) makes a similar point:

*“The fundamental objective that LUL set out to achieve in 1989 was building, equipping, commissioning and opening a new Railway. To achieve this objective, LUL needed to decide not only on the strategy and management structure of the new construction (that is the Project) but, equally important, the strategy and management structure for the delivery of the Railway. The two are not the same. The latter appears to have not been given sufficient consideration when the arrangements were first set up.”*

### **Change 3: Replacing the train fleet**

The original plan was to strengthen the existing fleet of 31½ trains of ‘1983’ stock that had only been in service for two to six years. However in October 1993 (UCL, 2009; page 91), a contract was let to Alstom to supply an entirely new replacement fleet of 59 trains (UCL, 2009; page 9).

The reasons for the change of direction were, according to Mitchell (2003; pages 128ff):

- the need to meet new requirements for fire safety and evacuation following the Fennell report into the Kings Cross fire of 1987 and a serious incident at Bethnal Green in February 1991;

- dissatisfaction with the reliability and doors of the existing fleet; and
- the opportunity to introduce regenerative braking.

The precise point at which there was sufficient information to determine that the fleet replacement was desirable is unclear but Mitchell (2003 page 128) reports that the decision was the result of a “lengthy debate” that “wasn’t concluded for over two years”. If there was a debate then at least one party to the debate must, presumably, have been aware of the benefits of replacing the trains and, as there is no reason to believe that these benefits changed materially during the period leading up to October 1993 so it seems reasonable to conclude that change latency was at least 24 months.

The precise reasons for the latency could not be established but the embarrassment involved in replacing newly-acquired rolling stock may have been a factor. It may be noted (Mitchell, 2003; page 134) that delays in the infrastructure project meant that storage locations had to be found for some of the later trains while they awaited their chance to enter service so it is not clear that the delay in procuring the trains had any significant consequences for the project as a whole

#### **Change 4: Phased opening of the line**

It has already been noted that the original plan was to open the extension in one go.

According to Mitchell (2003; page 147), the General Manager of the Jubilee and East London Lines was never keen on the 'big bang' line opening and the operations business unit came up with its own phased opening plan in late 1996.

According to Arup (2001; page 6):

*“Recognising the importance of access to North Greenwich, JLEP [JLE Project] adopted and published a strategy in December 1997 to open the Stratford to Waterloo section as an ‘incremental railway’, separate from the existing line, in order to meet the then published September 1998 opening date. This was still to be a single event opening. The strategy was again changed in February 1998 with a reversion to an end-to-end Stanmore to Stratford single event opening, but with the opening date deferred to ‘Spring 1999’.”*

In September 1998, after reviewing the project, Bechtel recommended that the opening of the extension should be phased. Bechtel were subsequently hired as project managers for the JLE project and this recommendation was implemented.

I have not been able to establish the precise reasons for this decision. In the UCL report (2009 page 86), the strategy is described as breaking the commissioning schedule into “*three manageable pieces*” suggesting that the ‘big bang’ approach was unmanageable. If so, then this was presumably known by the operations business unit in 2006 in which case, it may be concluded that:

- change latency was about 24 months; and
- this could have been reduced by better liaison with the operators and better consideration of operational requirements.

This, admittedly provisional, diagnosis has further support in Mitchell (2003; page 147) where John Self is reported as saying that “*a breakthrough, in his eyes, was that Bechtel involved the line management much more in project matters and viewed John as the 'ultimate client' - the person who would ultimately have to weld the people, assets and systems into an operational business*” and in (Arup, 2001; page 4), which contains the following observation:

*“LUL lacked the strategy and the structure and continuity of management that would ensure the delivery of a working Railway and not just the construction Project.”*

#### **Change 5: Falling back to a fixed block signalling system**

Mitchell (2003; page 233) notes that there were concerns about whether the moving-block signalling system could be installed within the programme when the signalling contract was let in November 1993 and that LU kept an option to trigger fall back to a fixed block system which was valid until the 23rd month of the contract.

Mitchell continues:

*“By the start of 1996, the Project was expressing concern over the development and testing of the moving block processor and asked for sufficient evidence of progress to be demonstrated to avoid the fall-back solution being instructed. [...] A series of tests*



*were carried out to establish the state of play and the contractor was able to provide sufficient reassurance that development was sufficiently advanced to allow the contractual fall-back solution to lapse.”*

However, in September 1997, a decision was taken to abandon the moving block solution and fall back to the fixed block alternative.

As the concerns of 1993 turned out to be well-founded in 1996, it is hard to believe that the decision to allow the contractual fall-back solution to lapse could have been truly justified by the facts and some degree of wishful thinking must surely have taken place. Others seem to agree. Ralph Mason of Bechtel is reported by Mitchell (2003; page 362) as commenting, *“let the buyer beware’ - ensure you have the mechanisms in place to test that your suppliers are informing you of the true situation with progress at all times.”*

The tentative conclusion is that, had the project had such mechanisms in place, the fall-back decision would have been taken earlier. While good SE practice might have supported such mechanisms, it is not considered that there is evidence that good SE practice on its own could have reduced the latency of this change.

### **Other changes**

There does appear to have been a great deal of change on the project. As has already been noted above, 48,000 instruments of change were issued on one contract.

Arup (2001; page 7) reports that:

*“In the six years of the construction phase between late 1993 and late 1999, there was a significant increase in the estimated final cost of the major construction contracts. This arose from variations to the scope of the works on which the contractors tendered, the instructions issued to accelerate the works and the extended time for completion. The total value of this change amounted to 70 percent of the initial value of the works in 1993 and the administration of this overwhelmed the cost management process, turning it into a ‘catch-up’ monitoring process rather than the advance control process it was intended to be. This high value of change largely came about as a consequence of the incompleteness of the design information issued to contractors for bidding purposes in late 1991. This was governed by the need to meet the then timetabled*

*award of the major construction contracts at the latest by mid-1992. These, and other matters, resulted in JLEP becoming reactive in its management, not the proactive force it needed to be.”*

There is very clear evidence here that further attention to system design activities would have forestalled a great deal of the change described.

#### **B.3.4 Analysis and conclusions**

There is no additional information to provide. A full account was provided in the body of the thesis.

## **B.4 Case Study 3: The Channel Tunnel Rail Link Project**

### **B.4.1 Introduction**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **B.4.2 The way in which the project was run**

#### **Systems Engineering and Project Management**

I can find no clear statement of the degree to which the CTRL adopted SE ideas. However, it does seem reasonable to draw some conclusions from the absence of information in the following channels:

- I have chaired the INCOSE UK Rail Interest Group since 2006, during which time there have been more than 50 presentations to the group, none of which has discussed CTRL. The publications database maintained by INCOSE at an international level contains 45 papers and presentations that contain the word “rail” in their abstracts but none of these discusses CTRL. Nor can I recall any other INCOSE paper or presentation that discussed SE on CTRL.
- Systems engineering is not mentioned in any of the sources referred to for this case study.
- Professor Andrew McNaughton, who became chief engineer and technical director for HS2, the UK’s second high-speed line in 2009, gave a presentation at an IET seminar on railway systems engineering shortly after his appointment. I chaired this seminar. At the seminar, Professor McNaughton asserted that HS2 would follow an SE approach, an assertion that he has subsequently repeated. However I can recall him making no reference to such an approach being used on CTRL and his slides (McNaughton, 2009) contain no such reference.

It seems beyond the limits of plausibility that the CTRL project could have made a concerted and explicit attempt to adopt the ideas of SE and still have missed all these opportunities to tell the SE community about it. This leads me to conclude that the project made no such attempt and instead drew upon the traditions of project management of large civil engineering projects alone for its system-level thinking.

Of course the traditions of SE and project management do overlap. Moreover, the project team certainly put a great deal of effort into the project. Steer Gleave Davies (2004; page 38) reports that professional staff costs, associated with project management, planning, design and legal issues, were estimated to amount to more than 25% of the total cost of the CTRL project. Startlingly, they estimate, on a Spanish high speed line project total project planning and management costs were less than 3% of the total cost of a Spanish high speed line. So the CTRL project invested about eight times as much effort in project management, planning, design and legal issues as the Spanish project did. Some of this effort must presumably have been expended on activities that fall within the scope of the 6 core SE processes that I have defined.

The project team certainly professed a belief in meticulous preparation. In *Modern Railways* (2007; page 40), Mike Glover, RLE's Technical Director is reported as saying, *"one of the underlying principles in our eleven and a half years of work has been to plan, plan and plan again – I wouldn't pretend we haven't had any shocks or surprises, but our planning has thrown up many issues before they really become issues, and helped put any unusual event into context"*.

This commitment to planning seems to have been present from the outset. In *Modern Railways* (2000; page x), Bob Doty, RLE's Contract Manager explains that the absence of storage space on the construction sites require a 'just in time' approach that requires a high level of planning. He is reported as saying, *"We're examining details day-by-day. Over two years ahead [...] we already have daily programmes for all the contractors"*.

However the planning approach appears to have been developed to involve the contractors more over time. In *Modern Railways* (2002; page 36), Roger Picard, RLE's Project Director is reported as saying that, after learning lessons from section 1, RLE had put in place a six-month pre-construction period of planning in conjunction with the contractors during which *"interface and construction design"* were refined. Five years later, In *Modern Railways* (2007), Mike Glover is reported as claiming that this decision was a major factor in the success of the project and saying, *"A conventional client might expect you to be out digging the day after contract signature, and would worry about six months lost on programme [...] but I'd say you've probably gained a year."*

Co-ordination seems to have acquired extra attention over time. Modern Railways (2003; page 45) says that, *“Lessons drawn from Section One are being applied in the way procurement, contracts and management of contractors are handled on Section Two, with URN and RLE taking a much more hands-on, co-ordinating role.”*

Moreover, there does seem to have been consultation with stakeholders where this was required. In Modern Railways (2006; page 46), David Pointon, Managing Director of RLE’s subsidiary, Union Railways, is reported as saying about the new depot at Temple Mills, *“Eurostar [the train operator] have had operational staff working alongside at Temple Mills almost from the start to ensure that they are getting what they want.”*

So, while the project may not have explicitly adopted SE, it appears to have adopted several of its underlying tenets: ‘left shift’, the value of stakeholder consultation, the value of meticulous planning and the value of paying attention to interfaces.

### **General approach to engineering**

The project had a very clear and explicit commitment to using proven technology where possible.

- In Modern Railways (2000; page xiv), Walt Bell, then Managing Director of Union Railways (North) is reported as saying, *“It’s a tenet of this project not to experiment.”*
- In Modern Railways (2002; page 44), it is asserted that *“The logistics of construction have, as far as possible, been carried wholesale from French high-speed lines, and indeed the overhead catenary system and track design are licenced French designs, while the signalling system follows the design used for the June 2001 opening of TGV Méditerranée.”*
- In Modern Railways (2006; page 43), David Bennett, the project’s Implementation Director, is quoted as saying, *“We followed our general principle of trying not to invent anything new, and use proven technology wherever possible.”*
- In Modern Railways (2007 page 37), Rob Holden, Executive Chairman of LCR is quoted as saying, *“The choice of proven French TGV technology was another factor in the success of the railway.”*

### **Contract management**

In *Modern Railways* (2000; page v), Roger Picard is reported as saying that the RLE and URS team had adopted a partnering approach encouraged by an appropriate form of contract, to keep the focus on resolving issues more than contractual battles.

The NAO (2005; page 12), reports that, in the views of LCR and Union Railways, one key factor in bringing Section 1 in on budget was extensive use of a target-price form of contract that had been developed by the Institution of Civil Engineers in consultation with industry experts. Under this form of contract, contractors shared in cost savings or overruns against the target price. The benefits of this were considered to include:

- allowing and incentivising the contractors to propose lower cost methods of construction;
- a significant reduction in the number of contractual disputes compared with the norm;
- encouraging collaboration between contractors; and
- allowing construction to start with some issues unresolved.

In *Modern Railways* (2007; page 45), Brian Sedar, who was RLE's Project Manager for part of the lifetime of the project, is reported as saying that he believed that *"the project's structure, with intermediary client organisations, was conducive to the type of work involved - allowing day-to-day decisions to be taken by the client, which would be difficult for a government agency to take"*.

In *Modern Railways* (2002; page 40), Ian Galloway, RLE's Section Two Operations Manager, describes an initiative to form a joint venture to carry out the works at Stratford, creating a single team for design, procurement and construction because *"With fewer interfaces, you are usually more likely to succeed."*

#### **B.4.3 The changes that were made**

I am not sure at what precise dates the project committed to various aspects of the scheme so I consider changes from the start of construction.

In *Modern Railways* (2007; page 45), Brian Sedar is reported as saying that a ‘no change’ policy was adopted with the principal exceptions of changes that were safety critical or necessary for the opening because “*change could have killed the project if not kept in check*”. In practice, this policy appears to have been flexible – there certainly were changes made that did not fall into the exempted categories. Three significant changes were the addition of a new depot at Temple Mills, changes to the layout at St Pancras and provision of additional passenger and retail facilities at stations. These changes are discussed in the next three sub-sections but there were a number of other changes, which are discussed in the sub-section after that.

### **The Temple Mills depot**

Hansard (House of Commons, 2004) records that, on 15 November 2004, Tony McNulty, the Minister of State at the Department for Transport made the following written statement to parliament:

*“The Department has agreed with London & Continental Railways to bring forward the construction of a Eurostar maintenance depot on existing railway lands at Temple Mills in east London. A depot at Temple Mills has always been envisaged as part of the final plan for the Channel Tunnel Rail Link (CTRL) and bringing it forward will provide for a much more efficient operation of the complete CTRL and the Eurostar trainsets. This decision will enable the new depot to be provided in time for commencement of Eurostar services on CTRL Section 2 in 2007.*

*“Original plans envisaged Eurostar trains gaining access from St Pancras to the existing North Pole International depot via the North London Line, but further investigation indicated that this would require costly and disruptive infrastructure works and significantly reduce capacity on what is already a congested line. Implementing the Temple Mills depot straightaway therefore provides a more cost-effective overall solution.*

*“The Department has agreed in principle with London & Continental Railways to provide the funding for the depot as a Government change to the CTRL development agreement at a total cost not exceeding £402 million including land acquisition and*

*relocation costs, subject to agreement of the detailed financial and contractual conditions.”*

The depot was actually constructed at a cost of £357 million (NAO, 2012; page 15)<sup>30</sup>.

In 2001, Modern Railways (2001; page 38) reported that it was still envisaged that CTRL trains would continue to be serviced at their existing North Pole depot, which would be reached via the North London Line when section 2 opened but that a new depot at Temple Mills was being considered and that *“strategic decisions on the best use of the North London Line’s capacity would be the driver of any change”*.

In 2003, Modern Railways (2003; page 44) reported that a study was underway into the design of a depot at Temple Mills even though no commitment had been made to build one. Again, the capacity of the North London Line was cited as a potential reason for a move.

The main reasons for increased traffic on the North London Line of which I am aware is the completion of the London Overground orbital route created by the North London Line project, which started around 2005, and the East London Line project, which started around 2007.

I have insufficient information to estimate latency for this change. I suspect that planning for the London Overground orbital route had advanced to the point where it would become clear that there was insufficient capacity for channel tunnel trains to use it before November 2005 but I cannot be sure of this and, in any case, if there was a delay, it may well have been the result of waiting for the completion of political processes that are not necessarily susceptible to reduction through SE.

### **St Pancras station**

Modern Railways (2001; pages 44ff) carries a discussion of significant changes to the layout of St Pancras station in which platform 4, which previously ran right into the station, in

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<sup>30</sup> This is shown in the table of final financial figures as one of two items under the heading, *“Work outside original contract scope”*. The other is *“Station fit-out: Passenger and retail facilities at St Pancras, Stratford and Ebbsfleet international stations funded by LCR.”* This item is not commented on in the body of the report, so I assume that it reflects some change in funding arrangements rather than a change in the project’s technical scope.



parallel with the international platforms, was moved back to align with the other regional platforms. This left space to open up 'light wells' in the first floor deck within the existing train shed - a change that is applauded by the magazine.

The magazine ascribes the change to "*reflection*", suggesting that the new layout had always been better than the original one. The point at which the project committed to the original layout is unclear but if it was included in the plans that were in place when construction started then change latency may have been more than two years. However, as the change was made six years before the international station opened, it seems unlikely that the latency had any significant effect on the project.

The CTRL project was responsible for building the box for a new Thameslink station below the main station and there was a change to the method of construction used for that, but that is discussed in a later sub-section.

### **Provision of additional passenger and retail facilities**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **Other changes**

For a project, with a 'no change' policy, there do seem to have been quite a few changes. Several of these were changes to construction methods made in order to save cost and time, including:

- adopting pre-cast roofs for three cut-and-cover excavations (Modern Railways, 2000; page v);
- changing the way in which the Medway viaduct was built (Modern Railways, 2000; page v);
- changing the way in which the tunnel lining was constructed on the North Downs tunnel (Modern Railways, 2000; page v); and
- changing the method of building the box for the Thameslink Station at St Pancras from digging a hole and then covering it to constructing the roof and then excavating below it (Modern Railways, 2007; page 39).

There were also changes to the end-state railway, including the following:

- raising the maximum line speed from 270 km/h to 300 km/h in order to increase service reliability (Modern Railways, 2000; page iii);
- changes in tunnel portal design after aerodynamic modelling (Modern Railways, 2000; page x);
- adding headshunt sidings to freight loops for storing on-track equipment (Modern Railways, 2001; page 37); and
- at St Pancras, changing the rail from standard Railtrack 113lb rail to the new RT60 rail throughout (Modern Railways, 2001; page 44).

#### **B.4.4 Analysis and conclusions**

There is no additional information to provide. A full account was provided in the body of the thesis.

## **B.5 Case Study 4: Acquisition of High-Output Ballast Cleaning Plant**

### **B.5.1 Introduction**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **B.5.2 The way in which the project was run**

The US machine had to be modified to account for differences between the US and UK contexts. These differences included:

- A. Differing climate – it was generally cooler in the UK (especially at night) than was normal in the part of North America where the unmodified machine was operated.
- B. Differing loading gauges - the US loading gauge was substantially larger.
- C. Differing permanent way standards - US track tolerances were suited to freight railways operations and the US track bed geometry and were unacceptable in the UK.
- D. Differing health and safety standards.
- E. A requirement in the UK to for the machine to move under its own power between stabling and the work site.
- F. The need to operate at night.

These gave rise to significant design differences between US and UK machines:

- a. Whereas the US machine comprised two vehicles travelling in convoy, the UK machine comprised six vehicles coupled in a rake [because of B and E].
- b. The UK machine had significantly smaller conveyors and drive sprockets [because of B].
- c. The UK machine was fitted with additional guards to protect workers on the track side [because of D].
- d. The cab was air-suspended to reduce vibration [because of D].

The differences in environment and design led to a number of practical problems with deployment. These included the following:

- The conveyors' capacity was marginal [because of b]. The equipment was hydraulically powered and pressure in the hydraulic system was used for control purposes. However, because temperatures were lower [because of A] and hydraulic lines were longer [because of a], the delay in the control loop was increased. As a result the equipment frequently stalled. This was overcome by increasing hydraulic pressure but at a cost in energy efficiency. Later, relay equipment was replaced by programmable logic control with a fibre-optic data bus.
- The guards initially fitted to the machine [c] were destroyed within a few minutes of operation and it was obvious that mechanical guards could not be made to work in close proximity to the excavating wheels.
- The machine could not initially meet UK standards for track [C] until the excavating equipment and ballast distribution system was redesigned.

The specification against which the machine was procured was not above criticism. It included a requirement that the machine should be capable of moving (without cleaning ballast) under its own power at 60 mph, which added significant cost but proved unnecessary - the machine was always hauled by a locomotive. With hindsight, it is considered that the specification was overly prescriptive in some areas while the performance requirements were limited.

Nevertheless, the specification was such that the problems listed above were clearly associated with failures to meet it. The US trials failed to make these problems visible to BR.

### **B.5.3 The changes that were made**

There is no additional information to provide. A full account was provided in the body of the thesis.

### **B.5.4 Analysis and conclusions**

There is no additional information to provide. A full account was provided in the body of the thesis.



## **C APPENDIX: QUESTIONNAIRES USED FOR PRELIMINARY SURVEYS**

The questionnaires used for the first and second preliminary surveys are reproduced in this appendix. The questions are introduced with a prefix starting with the letter 'Q'. Other text comprises section headings and explanatory notes.

### **C.1 Questionnaire used for first preliminary survey**

#### **What sort of a project was it?**

*I ask about this in order to see whether there is any evidence that the benefits of systems engineering vary between types of projects.*

Q1.1.1 Please describe the project that we will talk about. You and I need to be clear about the scope of the project that we are discussing. For instance, if you were working for a supplier or contractor, we need to agree whether we are talking about your organisation's activities only or those of the customer as well.

Q1.1.2 At peak, how many people worked on the project? (Please select one response.)

- 01) Less than 10
- 02) 10 to 49
- 03) 50 to 199
- 04) 200 or more
- 05) Other response, please specify

Q1.1.3 Is the project still underway?

- 01) Yes
- 02) No

Q1.1.4 In what industry sector is the project?

- 01) Rail
- 02) Other, please specify

Q1.1.5 What sort of railway(s) did it involve? Please select all that apply. Please ignore this question if your project was not a railway project.

- 01) Tramway or light rail (eg Docklands Light Rail)
- 02) Metro
- 03) Heavy rail (passenger traffic)
- 04) Heavy rail (freight traffic)
- 05) Heavy rail (mixed passenger and freight traffic)
- 06) Other, please specify

*From now on, I will use the word "system" to describe whatever the project was ultimately concerned with building or changing.*

Q1.1.6 Which parts of the railway were components of the system? Please select all that apply. Please ignore this question if your project was not a railway project.

- 01) Permanent way (track)
- 02) Stations
- 03) Structures (such as bridges, embankments, viaducts)
- 04) Rolling stock
- 05) Signalling
- 06) Electrification
- 07) Telecommunications
- 08) Tunnels
- 09) Lifts and/or escalators
- 10) Level crossings
- 11) Operational procedures
- 12) Maintenance and asset management procedures
- 13) Other, please specify
- 14) Other, please specify

Q1.1.7 What stages in the system lifecycle were involved? Please select all that apply.

- 01) Concept and feasibility (initial scoping, exploration of alternatives, establishing feasibility and outline business case)
- 02) Requirements definition
- 03) Design development

- 04) Implementation
- 05) Transition to service
- 06) Operations and maintenance
- 07) Decommissioning and disposal (of the system)
- 08) Decommissioning and disposal (of equipment being replaced)
- 09) Other please specify

**What systems engineering activities were carried out?**

*I ask about this because I am trying to understand what current systems engineering practice is and because I am looking for correlations between systems engineering activities that were carried out and how successful the project was.*

*I have a number of more specific questions about some activities which I think are at the heart of systems engineering.*

Q1.2.1 Were you given or did you produce any of the following? Please indicate all that apply.

- 01) A definition of the requirements of the system that you were building or changing in terms of its effects on the wider world (for example reduced journey times, increased service reliability, increased capacity; improved ambience for passengers and so forth)
- 02) A specification of the form and function of the system that you were building or changing
- 03) A compilation of significant facts about the environment in which the system must operate (for example train characteristics for an infrastructure project; infrastructure characteristics for a train project and so on)
- 04) An explicit decomposition of the whole system into parts

*From now on, let us refer to these parts of the system as “sub-systems”*

- 05) Specifications of the form and function of the sub-systems
- 06) Specifications of the interfaces between sub-systems
- 07) A description of how the sub-systems worked together and fitted together to deliver the requirements placed on the system



08) A mapping between the statements in the system specifications and the statements in the specifications of the sub-systems and the interfaces between them Q1.2.2 To what extent was the material listed above kept up-to-date during the project?

Q1.2.3 Did you or someone else check, for instance by multi-disciplinary review, that the design of the overall system was consistent and correct?

Q1.2.4 Did you or someone else check, through testing, inspection, analysis or some other means, that the system met each requirement placed on it?

Q1.2.5 Did you or someone else plan the introduction of the system into service?

Q1.2.6 Before introducing the system into service did you or someone else plan out any migratory stages that it must pass through?

*By "migratory stage" I mean a stage where the system is returned to service although not yet complete.*

Q1.2.7 Before introducing the system into service did or someone else check that the operator was ready for it? (for instance, that is that they had sufficient trained staff, procedures were in place and so on)

*I am also interested in some other activities*

Q1.2.8 Please indicate which of the activities from the list below were carried out on the project.

- 01) Planning systems engineering activities
- 02) Change control
- 03) Configuration management
- 04) Managing assumptions
- 05) Resolving critical technical issues
- 06) Electromagnetic Compatibility analysis
- 07) Life cycle costing analysis
- 08) Reliability, Availability and Maintainability analysis
- 09) Safety analysis
- 10) Non-safety risk analysis

- 11) Systems modelling
- 12) Systems prototyping
- 13) Systems simulation
- 14) Trade-off studies

Q1.2.9 Please tell me about any other systems engineering activities which were carried out on the project but which we have not discussed.

*I ask about your systems engineering responsibilities because I am interested to see if people with different roles on projects have different views on systems engineering.*

Q1.2.10 Please outline for me your responsibilities on the project for planning or carrying out the activities that we have been discussing in questions 1.2.1 to 1.2.9.

*I seek your views on the practical value of systems engineering reference documents.*

Q1.2.11 What reference sources (standards, handbooks, manuals, reference books) if any did you use for defining your systems engineering processes?

Q1.2.12 For each reference source that you used, please tell me how useful you found it.

**What were the critical success factors for the project and to what degree where they met?**

*I ask about this in order to understand what “success” means and to explore the correlation between systems engineering and success.*

Q1.3.1 Please indicate what were the critical success factors for the project, selecting from the list below and/or adding as necessary.

Q1.3.2 For each of the critical success factors, please indicate how the project performed against it using the following scale.

- A) Significantly exceeded expectations
- B) Exceeded expectations
- C) Met expectations
- D) Fell below expectations
- E) Fell significantly below expectations
- F) Other, please specify

*Critical success factors*

- 01) Cost to complete project
- 02) Time taken to complete project
- 03) Whole lifecycle cost of system
- 04) Compliance with written requirements (in contracts, standards and so on)
- 05) Actual performance in the field
- 06) Other, please specify
- 07) Other, please specify
- 08) Other, please specify

**How did systems engineering relate to the project outcomes?**

*The next two general questions go directly to the heart of my research.*

Q1.4.1 Please tell me in your own words how the systems engineering activities which were actually carried out contributed to the project outcomes (whether positively or negatively).

Q1.4.2 Do you think that systems engineering activities could have contributed to a better project outcome if carried out differently and, if so, how?

**Is there anything else?**

Q1.5.1 Is there anything else which I have not asked about but which you think that I ought to take into account?

## **C.2 Questionnaire and data collection procedure used for second preliminary survey**

### **C.2.1 Questionnaire**

*The questions concern a specific project and it is necessary to choose a project before proceeding.*

*Even when the question has a list of possible answers you are welcome to make additional comments if you think that something is important and I will record them.*

#### **What sort of a project was it?**

*I ask about this in order to see whether there is any evidence that the benefits of systems engineering vary between types of projects.*

Q1.1.1 Please describe the project that we will talk about. You and I need to be clear about the scope of the project that we are discussing. For instance, if you were working for a supplier or contractor, we need to agree whether we are talking about your organisation's activities only or those of the customer as well.

Q1.1.2 Is the project still underway?

01) Yes

02) No

Q1.1.3 Is the project part of a larger programme of work? If so, please explain how its scope relates to the larger whole.

Q1.1.4 In what industry sector is the project?

01) Rail

02) Other, please specify

Q1.1.5 What sort of railway(s) did it involve? Please select all that apply. Please ignore this question if your project was not a railway project.

01) Tramway or light rail (eg Docklands Light Rail)

02) Metro

03) Heavy rail (passenger traffic)

04) Heavy rail (freight traffic)

05) Heavy rail (mixed passenger and freight traffic)

06) Other, please specify

*From now on, I will use the word 'system; to describe whatever the project was ultimately concerned with building or changing.*

Q1.1.6 Which parts of the railway were components of the system? Please select all that apply. Please ignore this question if your project was not a railway project.

01) Permanent way (track)

02) Stations

03) Structures (such as bridges, embankments, viaducts)

04) Rolling stock

05) Signalling

06) Electrification

07) Telecommunications

08) Tunnels

09) Lifts and/or escalators

10) Level crossings

11) Operational procedures

12) Maintenance and asset management procedures

13) Control facilities

Other, please specify

Q1.1.7 In which of the following lifecycle stages did or will the project carry out work? Please select all that apply.

01) Concept and feasibility (initial scoping, exploration of alternatives, establishing feasibility and outline business case)

02) Requirements definition

03) Design development

04) Implementation

05) Transition to service

06) Operations and maintenance

07) Decommissioning and disposal (of the system)

08) Decommissioning and disposal (of equipment being replaced)

09) Other please specify

Q1.1.8 When did the project start? Please answer to the nearest month, if possible?

Q1.1.9 When did/will the project finish? Please answer to the nearest month, if possible?

Q1.1.10 At peak, how many people worked on the project? Please count everyone who carried out activities that fell within the scope of the project as you described it to me in

Q1.1.1.

01) Less than 10

02) 10 to 49

03) 50 to 199

04) 200 or more

05) Other response, please specify. (If an accurate figure is available from project records, please enter it here).

Q1.1.11 How many person years were expended on the project? Please count everyone who carried out activities that fell within the scope of the project as you described it to be in

Q1.1.1.

01) Less than 10

02) 10 to 49

03) 50 to 199

04) 200 or more

05) Other response, please specify. (If an accurate figure is available from project records, please enter it here).

*For some projects, the process of getting the railway from the state it was before the project to the final state delivered by the project can be complex. The next question is designed to assess that complexity. It counts 'stages' that the implementation of the system requires. By a stage, I mean a significant change to the railway after which the railway is returned to service*

Q1.1.12 How many stages are involved in the project? (Please select one response.)

- 01) 1
- 02) 2-4
- 03) 5 or more
- 04) Other please specify

*The next two questions are designed to assess how much novelty was involved in the project technology and processes*

Q1.1.13 Please indicate the degree to which the following statement is an accurate characterisation of the system?

“The system relies entirely upon well-tried technology in an application in which it has been used before”

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

Q1.1.14 Please indicate the degree to which the following statement is an accurate characterisation of the system?

“The design, construction, installation and testing methods used on the project were standard methods, used routinely by the organisation performing the project”

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

Q1.1.15 How experienced were the people leading the systems engineering functions? (Please select one response. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.)

- 01) The people leading the systems engineering functions included few or no members with at least 5 years of experience performing these functions.
- 02) A significant proportion of the people leading the systems engineering had at least 5 years of experience performing these functions but in a non-rail context
- 03) A significant proportion of the people leading the systems engineering at least 5 years of experience performing these functions in a rail context
- 04) Other please specify

Q1.1.16 To what degree were the systems engineering functions integrated with the rest of the project functions? (Please select one response. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.)

- 01) The people performing the systems engineering functions worked with little or no interaction with the rest of the team
- 02) The people performing the systems engineering functions worked with limited interaction with the rest of the team
- 03) The people performing the systems engineering functions worked as an integral part of team as a whole
- 04) Other please specify

*I ask the next question in order to assess the degree to which measurements of the amount of change in project documents are likely to be correlated with amount of change in the as-built system.*

Q1.1.17 Please indicate the degree to which the following statement is an accurate characterisation of the project?

“The system as built is or will be consistent with the final versions of the design documents and drawings for it”



- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

Q1.1.18 Please indicate the degree to which the following statement is an accurate characterisation of the project?

“The technical strategy at the end of the project was substantially the same as the technical strategy at the beginning of the project.”

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

Q1.1.19 Please indicate the degree to which the following statement is an accurate characterisation of the project?

“The project organisational structure was reasonably stable throughout the duration of the project.”

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

**What requirements management and V&V activities were performed**

*I ask these questions because I am trying to understand the relationship between these activities and project outcomes.*

*Please answer these questions using your knowledge about what was done on the project even if you or your organisation did not do it?*

*I am using 'V&V' to refer to all checking activities on the project including review, testing, inspection, survey and demonstration. It does not matter, for the purposes of this questionnaire which of these activities are put under the heading 'validation' and which are put under the heading 'verification'.*

Q1.2.1 Please consider each of the following statements and tell me to what degree they fairly represent what happened on the project

Please select one of the following options. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

In selecting one of the options above, do not take account of any reservations that you may have had about how the activities concerned were performed. So, if a comprehensive requirements specification was prepared but after the system was built, answer 'Wholly true'. If you answered (01) or (02) above, please go on to select one of the following options:

- 07) I have no reservations about how the activity concerned was performed
- 08) I have minor reservations about how the activity concerned was performed
- 09) I have major reservations about how the activity concerned was performed untrue
- 10) Other, please specify

*Statement**Requirements and their structure*

- A. The requirements that the system must meet were written down
- B. Each requirement was given a unique identifier
- C. Requirements were traced to the sources of stakeholder need

*Requirements elicitation*

- D. Stakeholders were consulted to establish their requirements
- E. Facts about legacy systems and other parts of the environment of the system pertinent to the achievement of the requirements were collected and written down
- F. Individual stakeholders or stakeholder classes who had a legitimate interest in the system throughout its life cycle were identified
- G. Unavoidable constraints (for instance legislation, applicable standards) were identified and recorded
- H. The scope of the system to be built or changed was defined
- I. The functions that the system must exhibit were defined together with the conditions under which each function must be available
- J. The needs of V&V were considered as a potential source of system requirements
- K. Scenarios of typical use were defined and used to establish and/or check requirements
- L. Users of the system were identified and treated as stakeholders
- M. Critical requirements (for instance relating to safety) were identified as such
- N. Performance measures were defined that would allow the degree to which the system met its needs to be measured.

*Management of requirements*

- O. Assumptions relevant to the requirements were written down, checked and tracked.

*Use of requirements*

- P. The requirements were used as input to the specification of sub-systems and/or the design of the systems
- Q. System requirements were traced to the specification of sub-systems and/or the design of the systems

*V&V Coverage*

- R. Compliance of the built system with each requirement that affected it was checked
- S. The design was checked against the requirements as the design process proceeded
- T. The requirements were checked for completeness
- U. Each requirement was checked for atomicity
- V. Each requirement was checked for verifiability
- W. Each requirement was checked for unambiguity
- X. The requirements were checked for conflicts
- Y. The requirements were checked for overlap
- Z. The requirements were checked for feasibility
- AA. There was an explicit process to identify and resolve conflicting requirements and infeasible requirements
- BB. Requirements were checked with stakeholders
- CC. The method of checking compliance with a requirement was specified at the same time as or shortly after the requirement was written down

*V&V management*

- DD. The results of V&V were recorded
- EE. A strategy for V&V was defined
- FF. There was a programme of activities to ensure that the necessary facilities, equipment and operators to conduct the V&V were prepared
- GG. Discrepancies and corrective actions arising from V&V were analysed, recorded and reported
- HH. The results of V&V contained sufficient information to support the definition of corrective actions
- II. The availability of the services delivered by the system which were required by stakeholders was confirmed during validation

**What configuration management activities were performed**

*I ask these questions because I am trying to understand the relationship between these activities and project outcomes.*

*Please answer these questions using your knowledge about what was done on the project even if you or your organisation did not do it?*

Q1.3.1 Please consider each of the following statements and tell me to what degree they fairly represent what happened on the project

Please select one of the following options. If your answer would depend upon what time in the project that you considered, answer for the end of the project start-up phase and describe in your own words how things varied over time.

- 01) Wholly true
- 02) Mostly true
- 03) Partly true and partly untrue
- 04) Mostly untrue
- 05) Wholly untrue
- 06) Other, please specify

In selecting one of the options above, do not take account of any reservations that you may have had about how the activities concerned were performed. So, if a comprehensive requirements specification was prepared but after the system was built, answer 'Wholly true'. If you answered (01) or (02) above, please go on to select one of the following options:

- 07) I have no reservations about how the activity concerned was performed
- 08) I have minor reservations about how the activity concerned was performed
- 09) I have major reservations about how the activity concerned was performed untrue
- 10) Other, please specify

#### *Statement*

#### *Planning*

- A. A plan was prepared containing a programme of configuration management (CM) activities
- B. The project explicitly defined a set of items to place under CM ('Configuration Items' or 'CIs')
- C. Requirements were placed under CM

- D. Key design documents and drawings were placed under CM
- E. Key physical elements of the built system were placed under CM
- F. Software components of the built system were placed under CM
- G. The project defined a structure showing the relationship between configuration items

#### *Data storage*

- H. A CM repository was maintained containing data about CIs and the CIs themselves, if they were data items
- I. Project staff worked from data held in the CM repository
- J. Each version of each CI was given a unique identifier
- K. It was possible to obtain reports on the status of CIs

#### *Change control*

- L. Once a CI was brought under change control, all changes to it were done under the authority of an approved change request
- M. Baselines were established such that each CI was placed under formal change control after it was entered in a baseline
- N. There was a process to define, assess and approve change requests
- O. There was a process to track the implementation of approved change requests
- P. It was possible to obtain reports on the status of change requests

#### *Audit*

- Q. The CM system was subject to audit

#### 1.4 How much rework was performed on the project?

We define “rework” to be work done to change a document, drawing or other item of data after it has been released to be used as a basis for other work or work done to change a component of the delivered system after first delivery

Q1.4.1 In your judgement, what percentage of the overall effort expended on the project was expended on rework

- 01) Less than 5%
- 02) 6-10%

03) 11-20%

04) 20-40%

05) More than 40%

06) Don't know

07) Other please specify

Q1.4.2 How do you come to that judgement?

1.5 To what extent was the final system fit for purpose?

Q1.5.1 In your judgement, to what extent was the system fit for purpose (Please select one response.)

01) Completely

02) Mostly

03) Partly

04) Not at all

05) Don't know

06) Other please specify

Q1.5.2 How do you come to that judgement?

Q1.5.3 Has the end-customer made any statements concerning their satisfaction with the system or their perception of its fitness for purpose? If so what have they said?

Q1.5.4 Were any measures made of the performance of the system? If so, please describe the measures and the results?

Q1.5.5 What post-implementation changes to the system have been made or are being considered or planned?

*Is there anything else?*

Q1.6.1 Is there anything else which I have not asked about but which you think that I ought to take into account?

## **C.2.2 Data Collection Procedure**

### **Estimate of rework by change to key documents**

Pre-requisites for employing this procedure are access to a project repository which contains all issue versions of all key project documents and the means to mechanically mark revisions between documents.

1. Obtain a document tree showing the principal requirements and design documents or drawings on the project, and the relationships between them. If this is not available, work with the project representative to draw such a tree.
2. Select up to 10 documents drawn randomly from across the project lifecycle, including at least one at the most 'upstream' end and at least one at the most 'downstream' end.
3. Obtain all issues of these documents which were provided for further work. Note the names of the documents and number of issues of each.
4. Take the final issue of each document and estimate the number of pages of content. Ignore front pages, informative introductions, glossaries, contents list, indices and lists of abbreviations. For each partially-printed page, estimate the proportion of the page printed upon to the nearest 0.1 page.
5. Obtain a copy of each issue of the document, apart from the first, with revision marked relative to the previous issue. Estimate the number of pages of changed content, using the same counting rules as for step 4.
6. Estimate the percentage rework on the project as  $(\text{Grand total changed pages}) / (\text{Grand total pages in final versions})$

### **Estimate of rework by reference to change records**

A pre-requisite for employing this procedure is access to change records which contain an estimate of the effort expended on each change. Note that the 'change records' may be described as test logs, fault management records, contract variations or some combination thereof. It is possible to perform this procedure if an estimate of the costs of each change is available together with an estimate of the cost of a day's effort.



1. Obtain access to project change records.
2. Establish what types of changes were recorded in this system
3. Make an estimate of the proportion of rework which is capture in the change records. If the procedure in the previous section has been followed, take a random selection of changes and establish what proportion can be related to an entry in the change record systems
4. Total the effort recorded for each change, or, if this is impractical, select a random sub-set of the change, total the effort for these changes and adjust pro rata
5. Estimate the percentage rework on the project as  $(\text{Estimated effort for changes}) / ((\text{estimated effort for project}) \times (\text{proportion rework capture in changes}))$

## **D APPENDIX: PUBLISHED PAPER: OVERCOMING BARRIERS TO TRANSFERRING SYSTEMS ENGINEERING PRACTICES INTO THE RAIL SECTOR**

The text of (Elliott, O'Neil, Roberts, Schmid and Shannon, 2012) is reproduced, with the permission of the copyright holder, John Wiley and Sons, on the following pages.

My co-authors provided advice and criticism during the preparation of this paper and provided photographs and information about NYCT SE practices. Apart from this, I wrote the paper myself.

























