BENEFITS OF ADOPTING SYSTEMS ENGINEERING APPROACHES IN RAIL PROJECTS

An abridged version of a thesis submitted to the University of Birmingham for the degree of Doctor of Philosophy

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FOREWORD

In August 2014, after 8 years part-time research at the University of Birmingham in the UK (and after passing my viva), I submitted the final version of my PhD thesis. Anyone can read my thesis, which is available at http://etheses.bham.ac.uk/5322[1].

I carried out the research in the hope of helping people who work on railway engineering projects run those projects better and deliver better systems. I tried to write my thesis in reasonably straightforward English in order make it as accessible to the non-academic. Still, the full thesis is quite long - about 200 pages, excluding appendices – and I have prepared this abridged version for people who do not have time to read it all.

This version is a little under half as long as the main body of my thesis. It covers essentially the same ground but I have cut the detail back throughout and particularly in sections which are of more interest to the academic than the practitioner. The chapters in this document line up with the full thesis so, if you want more detail on one part of this document, you can obtain a copy of the full thesis and turn directly to the corresponding chapter.

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[1] *From 1 December 2014. If you want a copy before that or if the link does not work for any reason, please contact me*

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.

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1 INTRODUCTION

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): a collection of tools, techniques and methods that support the delivery of systems.

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?"*

I embarked upon this research in order to find some sorts of answers to these questions:

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 stated above. 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.

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

Chapter 2, **The nature of the research problem**, contains some reflections upon some aspects of the research objectives the implications for the research.

Chapter 3, **Prior work**, contains a review of the research that has been carried out to date into the benefits of adopting SE approaches.

Chapter 4, **A workable characterisation of systems engineering,** contains an attempt to deliver what is promised in the title. It contains a definition of **core SE**, based upon identifying the types of intellectual products that are at the heart of SE which I argue includes the types of activities that are common to a number of characterisations of SE.

Chapter 5, **The nature of rail systems and rail projects**, contains reflections on the nature of rail projects and some suggestions for how traditional SE practices require adjustment for the rail sector if they are to be effective.

Chapter 6 **A workable characterisation of ‘better** contains a discussion of the difficulties of measure how well a project has taken out. It includes a definition of **change latency** - a measure of the unnecessary delay in taking a decision to make a change – which I argue is a methodologically useful measure of ‘badness’.

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.

In chapter 8, **A case study**, I take one example of the application of SE to a rail project and illustrate how rigorous analysis of cases can produce useful results.

Chapter 9, **A model and tentative theory**, contains what the title suggests.

In chapter 10, **Testing the tentative theory against data collected from projects**, I describe an analysis of data collected from interviews and inspecting project records on five railway projects.

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.

Chapter 12, **Conclusions and recommendations**, also contains what the title suggests.

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. So it is tempting to look at the standards and methods of the natural science as a starting point for my research.

However, the objects in my field of study - **SE**, **projects**, **systems** and the **costs** and benefits associated with projects and systems – are a long way from the objects that physics studies. In particular:

- **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 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. Fuzzy boundaries may also be experienced for systems, projects and the programmes of SE activities within them.

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

  Projects and systems differ 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.

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

  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.
  - 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.

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.

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.

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: 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, contain analyses of information about IT and software development projects. The 2010 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.
- Hertogh et al (2008), reporting findings from a study of large European infrastructure projects, observe that large infrastructure projects *“do not have a good reputation with respect to cost and time control*”, cite facts that justify this reputation and recommend remedies that include some that align with good SE practice in establishing and managing requirements, modelling, simulation and controlling change.
- 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

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 rather than 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, the following three general types of hypothesis may be discerned in the literature. 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. 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 implicit in publications by UK and US engineering institutions (RAEng, 2007; American Society of Civil Engineers, 2009). 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 this can be found in an analysis of very large infrastructure projects (Flyvbjerg, Bruzelius and Rothengatter, 2003) that includes recommendations for procuring against ‘performance specifications’ which allows the system supplier a greater range of solutions to optimise over and an initiative by Dutch government agencies to promote 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 argue that SE will reduce cost by providing information that supports better early decisions.

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. However:

- Hoos (1976), see Beishon and Peters (1976; page 168), notes that SE has been used on a number of well-publicised engineering disasters and wonders whether the *"predominance of systems engineering may have obscured other, perhaps more promising approaches."*
- Some writers question whether the meticulous planning and early decision making that characterises SE always deliver benefits. Weick and Sutcliffe (2001) argue that the 'mindfulness' needed for reliable delivery can be impaired by over-preparation. After studying a number of large engineering projects, Miller and Lessard (2000) assert that, sometimes, it is best to postpone decisions in order to keep options open. However, there seems to be no reason why a thoughtful application of SE should not avoid these pitfalls.

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. 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) describes 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 and ascribes this to the inexperience of the SE practitioners. Honour (2013), when correlating the outcomes of projects with the expenditure on SE, finds that this correlation is stronger if he uses a quality factor to adjust the 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. I conclude that the relationship between the people performing SE and the rest of the project members must affect SE's effectiveness.

  Others agree. A panel discussion at an INCOSE conference (Ade, 007) that came to the conclusion that SE and project management cannot function effectively or efficiently unless the two are integrated. Barker and Verma (2003) describe study of eight IT projects and find provides stronger evidence that SE delivers enhanced productivity if combined with effective project management and test processes than if applied on its own.

- **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.

3.3 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. See (Hoffman and Lawbaugh, 1996; page 18),
- Miller and Lessard (2000) found that the success of 60 large engineering 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.

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 study of three projects at Boeing to develop handling machines which found that the projects that performed more SE delivered better products earlier.
- Gharatya (2006) used a survey to collect data about projects from which he concluded that project cost and schedule improve with the proportion of overall budget spent on SE.
- Kludze (2004) studied projects within NASA and concluded that SE assists in the development of cost-effective systems, reduces risk and has a considerable and positive impact on technical performance.
- Goldenson and Gibson (2003) report results that "*provide credible quantitative evidence that Capability Maturity Model® Integration (CMMI®)-based process improvement*[2] *can result in better project performance and higher quality products*."
- Barker and Verma (2003) studied 8 IT development projects and found that the projects that had adopted more formal approaches to SE and project management enjoyed productivity levels 30% higher than the other projects.
- 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

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[2] *CMMI is a framework for supporting improvement in a range of processes that include SE processes.*

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.

- INCOSE publishes a library of case studies (INCOSE Transportation Working Group, 2013) that illustrate qualitative benefits from adopting aspects of SE on transportation projects.

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 that strengthen this case:

- 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.

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.

3.4 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.

4 PRELIMINARY INVESTIGATIONS

Early in my research, in order 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

I carried out a small survey to improve my 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.

I interviewed 13 people, in the UK, US and Canada, whom I knew and whose opinions I valued, in order to survey their experience of and opinions about the application of SE to projects. 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 for the project and to what degree where they met?
- How did SE relate to the project outcomes?
- Is there anything else?

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 criteria were:

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

I also asked for the interviewee's impression of the performance of the project against these success criteria. Generally, the responses for 'Compliance with written requirements' and 'Actual performance in the field' indicated that performance had met expectations, while the responses for 'Cost to complete project' and 'Time taken to complete project' indicated that performance had fallen below expectations, sometimes significantly.

I sought interviewees' 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.

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

The second preliminary study was designed to explore the relationship between:

- The activities which had figured most strongly in the first study (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 normative content[3] of 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 normative content in its final issue and was subject to

[3] *Excluding front sheets, glossaries, introductions and so on*

three changes in which 1, 2 and 3 pages, respectively, were added or changed, would have a volatility of (1+2+3)/100 = 6%.

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 all suggest that SE should be able to forestall change, because:

- The 'control of complexity' hypothesis 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 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 suggests will accrue from investing in the early stages of a project will be associated with the elimination of latent change.

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?

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 did not find a clear correlation between volatility and the degree of adoption of good practice in the aspects of SE that I asked about but I did find that:

- 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%.

These figures are high but 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.

4.3 The nature of rail systems and projects

One of my generic objectives 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 suggests that a partial and provisional answer is, "*To achieve optimum results in major rail projects, focus SE on avoiding unnecessary costs of change*".

Williams et al (2004) claim a need to tailor SE process for the rail sector and railway organisations such London Underground (Sullivan, 2007) and ProRail (ProRail and Rijkswaterstaat, 2008) do such tailoring.

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 identified the following barriers to the effective and efficient importation of SE ideas into the rail sector:

- Rail projects are better understood in terms of enhancing existing systems than creating new ones because the highly-interconnected nature of railways makes it necessary to consider a significant part of the whole railway, if not all of it, as the system being worked upon when changing part of it.

- The railway must usually continue to operate as it is being changed, which significantly complicates implementation and transition to service,
- Existing rail disciplines already perform tasks that deliver some of the objectives of a traditional programme of SE activities but in different ways.

Although we did not contend that rail systems or rail projects are *fundamentally* different from those in the sectors in which SE has traditionally been applied, we did recommend 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.

5 A WORKABLE CHARACTERISATION OF SYSTEMS ENGINEERING

5.1 Introduction

In order to study the effects of adopting SE approaches on project outcomes, I want 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; and
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

It may help in characterising SE to understand some related things that it excludes.

SE may be seen (von Bertalanffy, 1962) as part of a broader systems movement that includes Operations Research, Human Engineering, cybernetics, information theory, game theory, decision theory and general system theory. It has overlaps (Emes et al, 2005; figure 3) with operations research, project management, systems analysis, system dynamics, control theory, soft systems methodology, industrial engineering, general engineering, information technology and economics, among others.

The systems that SE engineers typically have 'hard', or technical, systems at their core but there Checkland (1999) has developed a soft systems methodology for applying systems thinking to 'human activity systems', which are systems of people working together while others (Buckley , 1968) have attempted to apply systems thinking to societies considered as systems.

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; Hoos, 1976; Honour and Valerdi, 2006).

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, and the only one that meets my criterion (D), 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 that a definition and does not meet my criterion (A).

Having established that there is no definition of SE that meets all my criteria, 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.

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 processes, but, if so, which is the real SE process? There are many different processes. 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.

There have been efforts to harmonise these standards for some time (INCOSE, 2014; Kitterman, 2007) but, in the meantime, practitioners are developing new approaches to SE, see, for instance (Hybertson and Sheard, 2008).

As there is no consensus on which process is the right process, none meets my criterion (D).

Characterising SE as a discipline

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

A recent project has compiled an SE Body of Knowledge as an online encyclopaedia (SEBoK, 2013). In addition, 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. However, given the overlaps between SE and other disciplines, 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 my criterion (C).

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 have used sets of activities as a basis for characterising SE (Honour and Valerdi , 2006; Honour, 2013).

Sheard wrote a pair of papers (Sheard, 1996a, 1996b) in which she characterised SE activities in terms of twelve roles that those performing SE activities might play.

However, none of these characterisations is the subject of broad consensus and none, therefore, meets my criterion (D).

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’ 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 does not meet either criteria (A) and (D).

5.3.1 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. 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

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 1 illustrates. I seek a coherent and principled definition of a set of 'Core SE' activities (as illustrated by the central blue circle in Figure 1) 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.

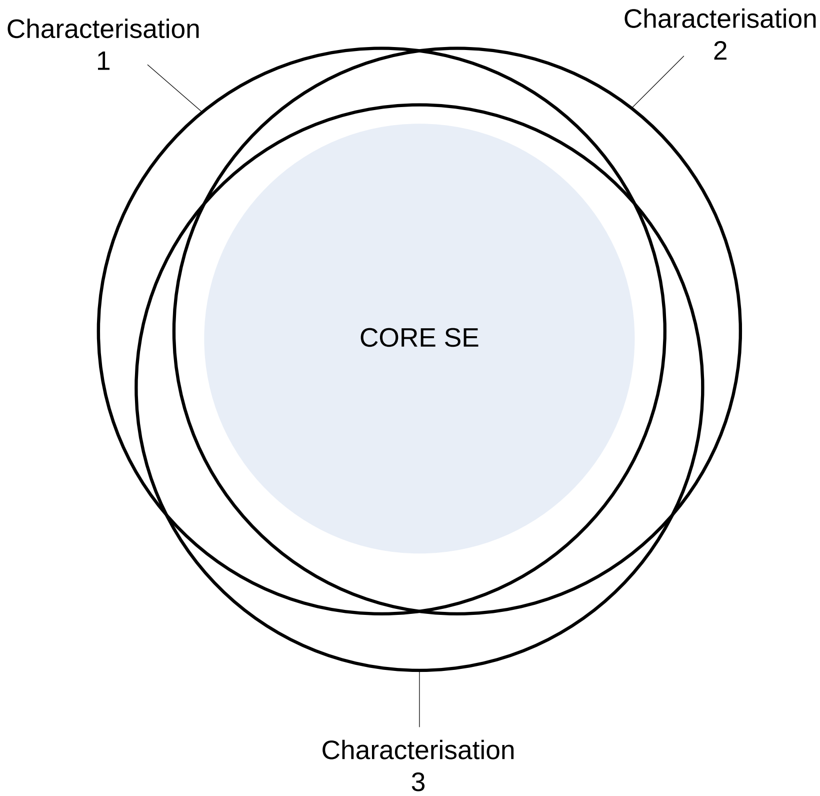

Figure 1: Core SE in the context of other characterisations of SE

My approach to defining core SE is to identify a number of 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.

There is 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.

In presenting a coherent account, I find it convenient to define SE logical artefacts in the context of a number of project management artefacts.

The SE and project management artefacts are illustrated in Figure 2 and listed below.

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.[4]
- 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. I regard the budgets and

[4] *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.*

schedules as **project management artefacts**. That is a common sense definition and one that is consistent with well-used project management methods (Office of Government Commerce, 2002).

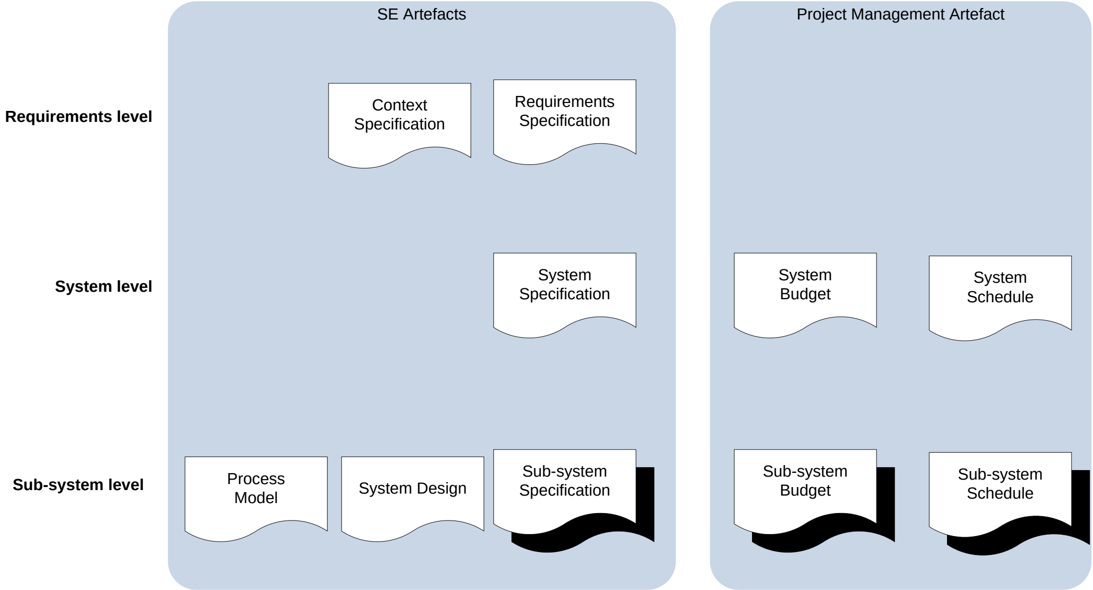

Figure 2: **SE and project management artefacts**

I then define **core SE** to be the totality of all project activities that:

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

I work through this definition 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 1. Table 2 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 1: **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 2: **The relationship between core SE process areas and SE artefacts**

<table>
<tr><th>SE Artefacts</th><th>Create content of artefact</th><th>Check the artefact</th><th>Check system against artefact</th><th>Manage change to artefact</th></tr>
<tr><td>Context Spec.</td><td rowspan="3">Manage requirements and specify the system</td><td rowspan="5">Model, simulate and analyse the system</td><td rowspan="5">Verify and validate the system</td><td rowspan="5">Manage change</td></tr>
<tr><td>Requirements Spec.</td></tr>
<tr><td>System Spec.</td></tr>
<tr><td>System Design.</td><td rowspan="2">Design the system</td></tr>
<tr><td>Sub-system Specs.</td></tr>
<tr><td>Process Model</td><td colspan="4">Model (the project) processes</td></tr>
</table>

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 compared it with two widely-used SE standards: ISO/IEC 15288 (ISO/IEC, 2002) and EIA-632 (EIA, 1998). My comparison showed 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.[5] 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] *Note. There are activities governed by each standard, which do not relate to any core SE process but these 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.*

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 a subjective term. 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.

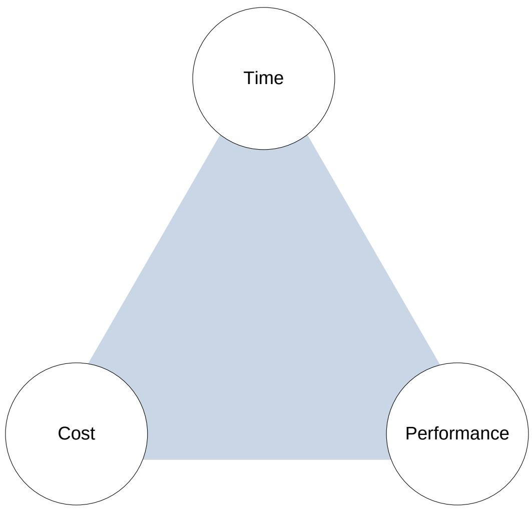

Figure 3: The 'Iron Triangle'

The 13 systems engineers whom I interviewed in my first preliminary study (see section 4.1) chose success factors that relate to time, cost and performance and others carrying out research into the benefits of SE (Elm and Goldenson, 2012; Honour, 2013) have tried to measure project success in these dimensions.

However 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, time, cost and performance are the results of many factors in combination, and 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 and noting that the three most prevalent theories for the manner in which SE can benefit projects (see section 4.2) 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 volatility

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

In my second preliminary study, I found high levels of volatility (see section 4.2). Dale and Plunkett (1999; pages 62-63) have suggested that engineering change within manufacturing companies *"is a sizeable quality-related activity escaping the quality cost net in most organizations*" and a topic worthy of attention.

However, volatility 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.

So, in order to use volatility 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.

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 4. 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.

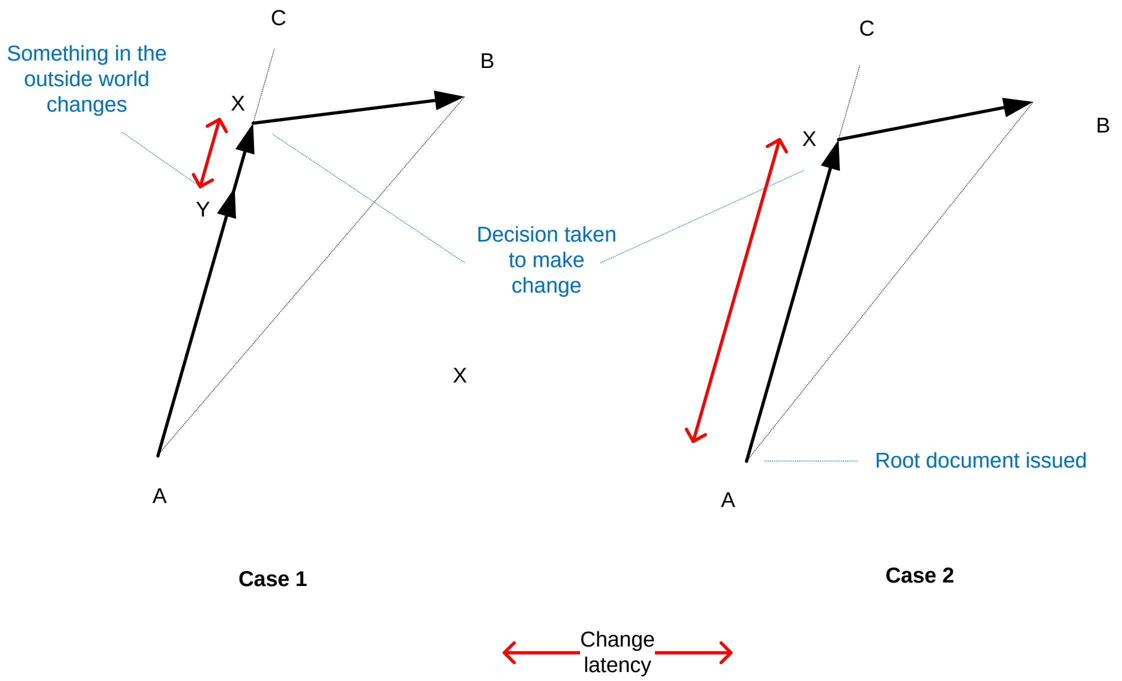

Figure 4: Change latency

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:

Change latency = Detection latency + 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 5, where component changes X1, X2 and X3 are regarded as part of one compound change.

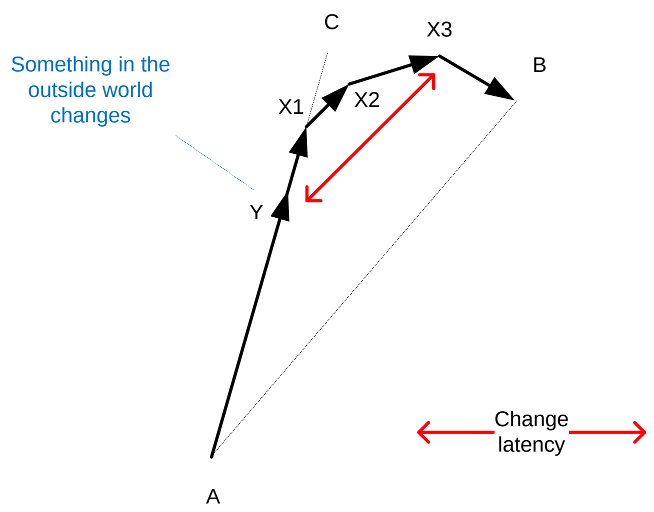

Figure 5: **Latency of a compound change**

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

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

- **Change is expensive**

  Most practising engineers and managers understand that knowledge and options have value and that time is money. Experience (Fricke et al, 2000; Terwiesch and Loch, 1999) suggests that changes consume a significant proportion of the budget of engineering projects.

- **The cost of making a change rises rapidly with time**

  Fricke et al (2000) observe that changing one aspect of the design of system often results in changing other parts. 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.

  Some rules of thumb have been formulated from experience in several domains that suggest that this escalation can be rapid, typically rising by an order of magnitude for each phase of the project lifecycle that passes (Boehm and Basili, 2001; McConnell 2003; page 29; Noland and Pickard 2013; figure 7; Boehm, Valerdi and Honour, 2008; Fricke et al, 2000).

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.
- 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 – a determination which can often be difficult – in order to measure change latency; the measure can be applied to any sort of change.

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.

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.

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 and exhorts researchers to take note of the methods used by the social sciences. I take Brown's advice. In this chapter, I set out the main options and then make a reasoned choice between them.

7.1 Methodological options

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, which I discuss in turn

Realist and interpretive ontological positions

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.

Interpretive methods have been applied in related areas. Checkland (1999) has applied interpretive methods in his research into the application of 'soft systems thinking' to 'human activity systems' in order to resolve certain perceived problems.

However, Checkland is in the minority. Most researchers in the field (Valerdi and Davidz, 2009; Honour, 2013; Elm and Goldenson (2012), take a robustly realist stance. 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.

Qualitative and quantitative methods

Typically, when applying quantitative methods, 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 the following note of warning about the application of quantitative methods to research into the value of SE:

> *"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 grounds for these assertions 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. 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 and Honour (2013) claims 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."*

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) also encourage good case study research into SE, while acknowledging that it is associated with challenges.

Theory-first or observation-first methods

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.

Evaluation and selection

I choose to:

- **Use realist 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.

- **Use both quantitative and qualitative methods**

  Because I believe that they are complementary.

  - Quantitative research can test for the existence of correlations but is of less value in establishing the causal links that produce these correlations.
  - Qualitative research can unravel the causal links and produce theories that quantitative research can test. Or, 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.

- **Use a theory-driven approach**

  Because 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 the researcher may have to be content with making small, preliminary increments to this body of knowledge. 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.

I agree with Boehm, Valerdi and Honour (2008) when they 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 suspect that the lack of theories explains the slower rate of progress in SE research.

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

7.2 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. However refutation is not the same as demolition.

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 → TT → CD → P2

"This schema is to be understood as follows. Assume that we start from some problem PI - 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 → TT1→ CDT → 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.

7.3 Going forward

The final stage 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, from interviews and publicly available reports from and analyse it in order to test the tentative theory.

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 evidence corroborating, contradicting or suggesting refinements to the tentative theory.

The quantitative analysis is focused upon exploring the correlation of 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 chapters 9, 9.4, 11 and 12. 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.

8 A CASE STUDY

In this chapter, I 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 changes made included:

- A "*more intrusive regime of obtaining possession of the track for engineering work through extended blockades*"
- Removing the European Rail Traffic Management System, 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 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.

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

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.
- 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.
- A well-used SE standard, ISO/IEC 15288 (ISO/IEC, 2002) embodies a more complex model of SE as a set of linked processes.
- Another well-used SE standard EIA-632 (EIA, 1998) defines a number of processes, partitioned and shows the main flows of information between them.

However, none 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.

Hypotheses about how SE contributes to project outcomes were reviewed in chapter 3 and categorised into three general types:

- ‘The control of complexity’
- ‘Whole system optimisation’
- ‘Left shift’.

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.

- 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".*
- I define a **sub-system** of a system to be a component of a system that is also a system in its own right.
- I define a **project** to be an activity to deliver a system.[6]
- I define a **stakeholder** in a system to be any individual or organisation with an interest in that system.
- I adopt 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 associated with core SE which were made in chapter 4.

[6] *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".*

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 6). 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.[7]

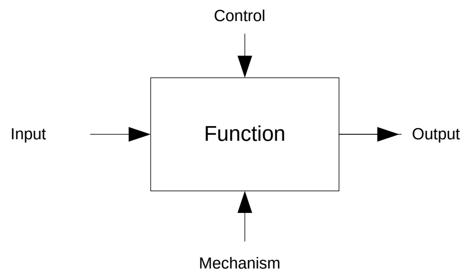

Figure 6: **A key for the IDEF0 notation**

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.

The process 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.

[7] *The notation allows a fifth type of arrow – a 'call' arrow – which I do not use and do not describe.*

The A-0 Context Diagram is shown in Figure 7 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.

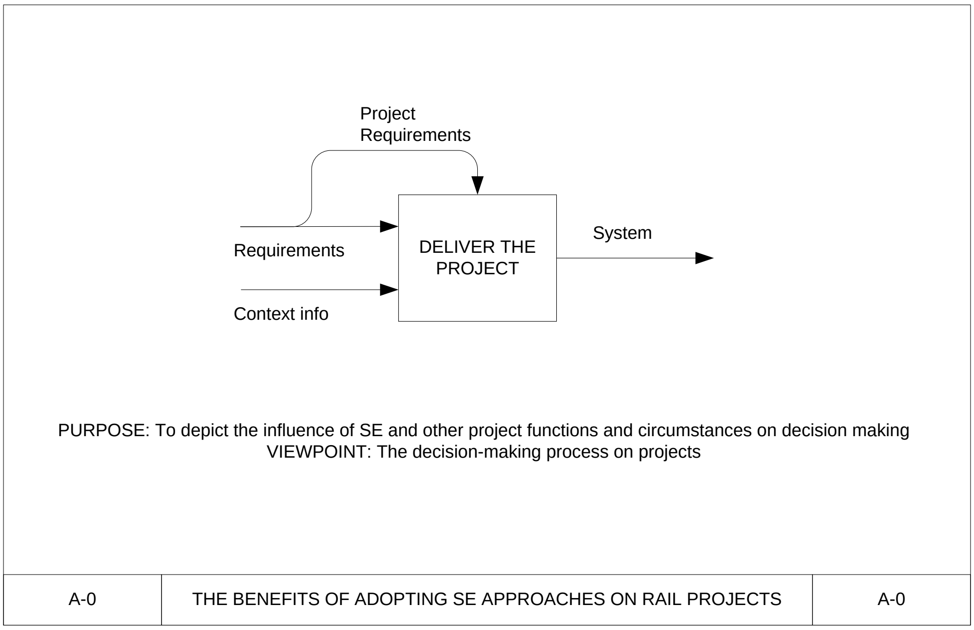

Figure 7: **The A-0 Context Diagram**

The model is strongly focussed on the purpose and viewpoint declared in Figure 7. 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 process map is presented in Figure 8. The mao includes an IDEF0 function for each tof he 6 core process areas into which I partitioned core SE in chapter 5:

- 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

At the very top left, **Model (the project) processes** defines the processes used to perform the other functions and its output is the project Process Model. The Process Model is a control input to all other functions. For clarity, the connections are not shown in full but instead indicated by arrows which are annotated "(2)" and connected at one end only.[8]

The **requirements** and **context info** are inputs to **Manage requirements and specify the system** (near the top left) and the output from this function flows into **Design the system**. Together these two functions generate all the other SE artefacts. These functions must be executed in order to establish a baseline and are then re-executed every time that baseline is changed.

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

The flow continues down and right to **Authorise the system design and process model.** The grey colour of this function indicates that it is not regarded as an SE function. This function authorises the initial system design baseline and subsequent changes. 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.

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 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.

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[8] *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****.*

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.*

A key decision

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

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.

I take the view that this final decision must be regarded as a project governance function and to include it within the scope of SE would leave neither term aligned with the everyday meaning that people attribute to it.

The consequence of this decision 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.
- 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.

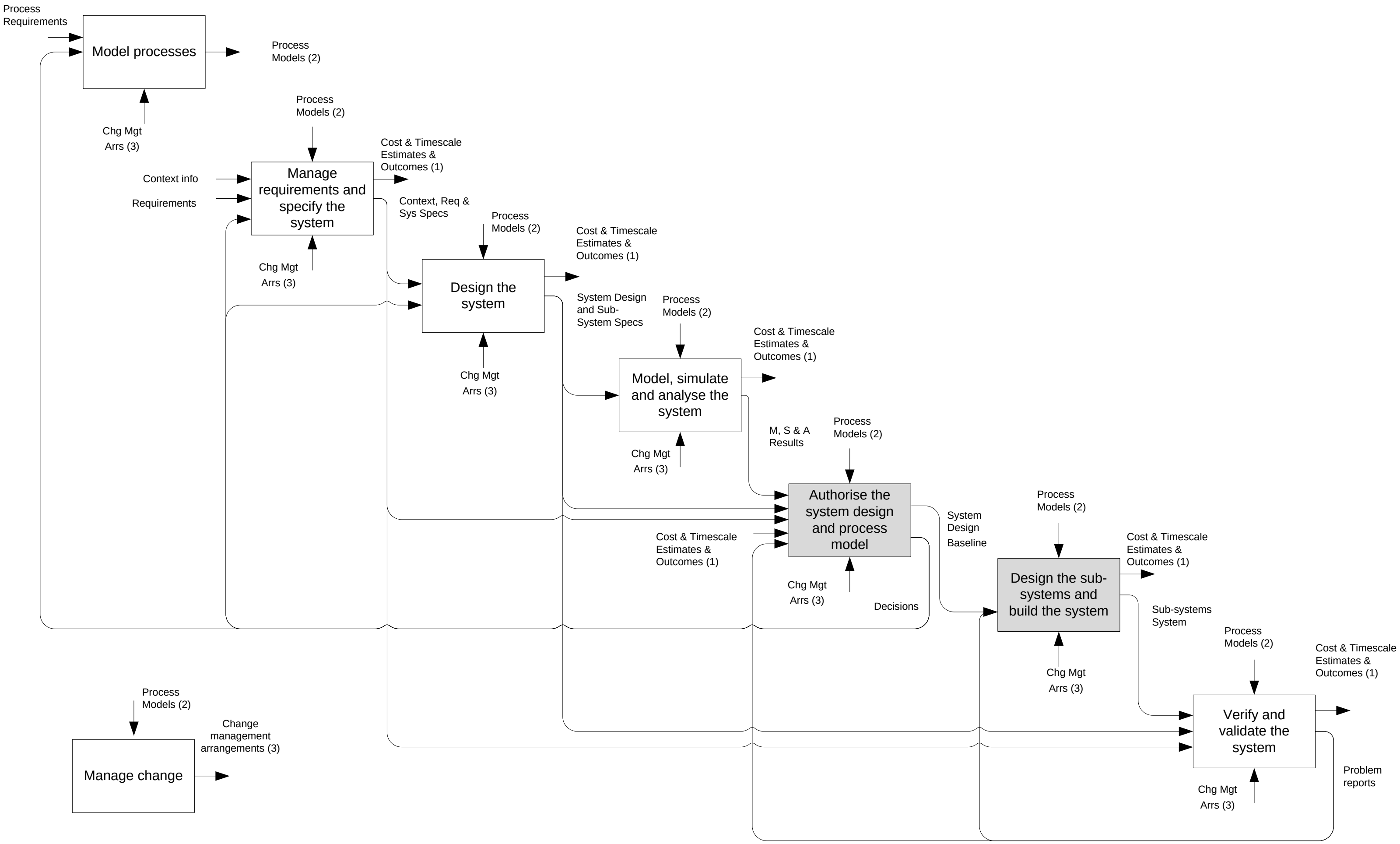

Figure 8: **The process map**

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

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 9 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 3. The serial numbers in Table 3 correspond to the numbers marked on the blue arrows in Figure 9.

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.

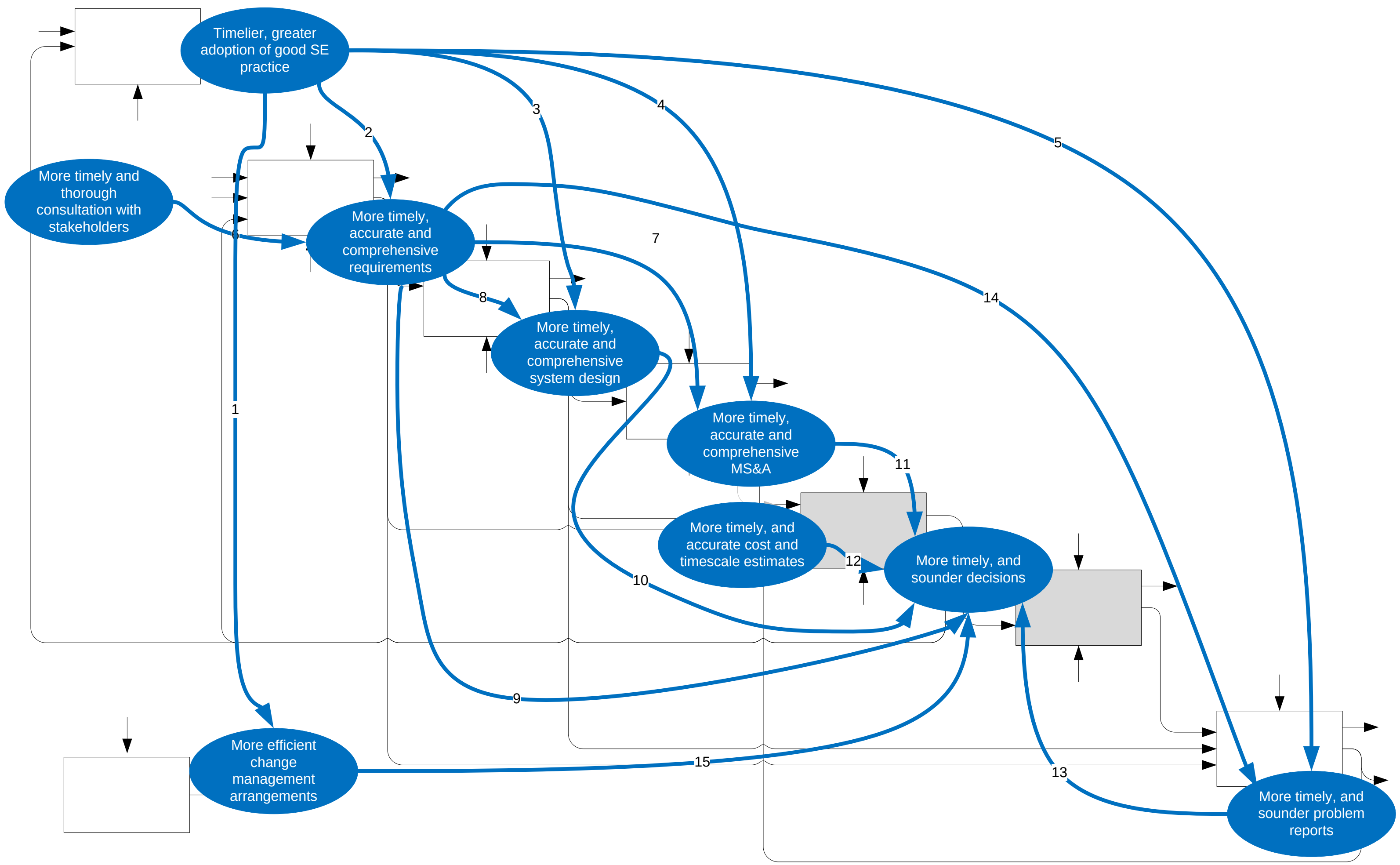

Figure 9: The contribution of SE to reducing change latency in diagrammatic form

Table 3: 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 pursing 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
11	More timely, accurate and comprehensive modelling, simulation and analysis	More timely, and sounder decisions		There is less likelihood of pursing 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 Implications of the tentative theory

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?

The answer must depend upon 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.

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.

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.

I did not collect data on more projects because the logistics of doing so were prohibitive:. 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.

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.

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.

The questions primarily concerned the nature of the project under discussion and the degree to which the project adopted SE practices.

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.

10.2 Data collected about the projects in general

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. The key results from this exercise were:

- 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 a project that was associated with 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.
- No project was clearly associated with significantly higher challenges overall: 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.

10.3 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 were derived from ISO/IEC 15288 (ISO/IEC 2002) and associated with one of the six Core SE processes.

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'.

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.

10.4 Data collected about changes

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 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.

I also noted that some change records 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.

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:

- 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[9]) upon which a decision was made to make the change.

Change latency and its components were then estimated as follows:

Change latency = D4 – D0

Detection latency = D1 – D0

Decision latency = D4 – D1

For each change analysed, I also asked the interviewee why the change was made and whether, in their view it was for the worse overall. None of the responses provided by the interviewees suggested that any of the changes looked at was for the worse, overall.

31 changes were analysed in total. Table 4. Contains the description of the change, the reasons for it and its latency. The changes are tabulated in order of decreasing change latency. In order to respect the confidential nature of the data, 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.

[9] *I had reserved the labels D2 and D3 for another use which I then abandoned.*

Table 4: The reasons for change and the latency of change

Id	Description of change	Reason for change	Change latency (months)
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	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	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	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	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	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	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	54
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	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	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	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	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	29

Id	Description of change	Reason for change	Change latency (months)
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	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.	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.	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	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	24
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	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	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	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	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	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	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	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	13

Id	Description of change	Reason for change	Change latency (months)
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	13
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	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	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)	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	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	5
		AVERAGE	**30.2**

Analysis of the data leads to the following observations:

- **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 that the cost of disruption associated with carrying out unplanned remedial works when the main works found asbestos.

- **Average change latency was 30 months**

  This is a long time - more than a third of the average duration of the projects studied.

- **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.

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

  For 23 of the 31 changes 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.

I asked the interviewees two more 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. 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**)

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.
- 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.

Table 5 summarises the number of changes associated with each generic factor, in decreasing order.

Table 5: 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.

10.4.1 Case study analysis of changes made by the projects

I studied each of the 31 changes listed above and looked for evidence that contradicted, corroborated or suggested refinements to the tentative theory. 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 6 indicates the causal mechanisms corroborated by this process and number of changes that were found to provide evidence of each causal mechanism.

Table 6: Corroboration of causal links

Id	Causal mechanism	Changes
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

10.5 Further quantitative 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).

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. Scatter graphs showing the relationship between the figures of merit on one hand and change latency and its components on the other are shown in the full version of my thesis.

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 these graphs 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 realise that average change latency is a flawed statistic for measuring improvement because process improvements that forestall changes do not necessarily cause it to fall. 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.

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.

10.6 Further qualitative analysis

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.

The 'Manage Requirements and Specify the System' process

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.

These could be aligned with statements about SE good practice that I used in the questionnaire. 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.

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 but that would only have been true if the project had done '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.

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 and found that they fell into the following groups:

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)[10].

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*[10] I consider allocating this time to **MR&StS** but 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.

10.7 Conclusions

I present the results of the other method of testing the tentative theory in the next chapter before drawing overall conclusions in the final chapter after that.

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).

Each section below is devoted to the discussion of one project. Each section has the following sub-sections, which follow the structure of the analysis performed:

- **Introduction**: a top-level description of the project concerned and the scope of the case study.
- **The way in which the project was run**: 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.
- **The changes that were made**: a summary of information about significant changes made on the project.
- **Analysis and conclusions**.

The four projects studied were:

- The West Coast Route Modernisation Project
- The Jubilee Line Extension Project
- The Channel Tunnel Rail Link Project
- Acquisition of High-Output Ballast Cleaning Plant

11.1 Case Study 1: The West Coast Route Modernisation Project

Introduction

This project was already discussed in chapter 8 as an example of the case study method. This section contains a more general analysis.

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'.

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.

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.

In January 2002, the Secretary of State instructed the Strategic Rail Authority to intervene. 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. The NAO concluded that this intervention *“turned around the programme”.*

The way in which the project was run

The NAO report lists five key weaknesses and then describes action taken to remedy them.

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.

11.1.1 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.

11.1.2 Analysis and conclusions

It seems reasonable to conclude that each of the changes listed above 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.

However, since reliably delivering these criteria 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. 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.

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in the tentative theory.

It is considered that there is strong 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.
- 12. More timely and accurate cost and timescale estimates will lead to more timely and sounder decisions.
- 15. More efficient change management arrangements will lead to more timely and sounder decisions.
- 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.

It is considered that there is strong evidence for the following causal mechanisms which were not in the tentative theory but which were suggested by the findings of chapter 9.4:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions.
- X2. Having sufficient skilled people available leads to more timely and sounder decisions.

11.2 Case Study 2: The Jubilee Line Extension Project

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).

The way in which the project was run

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.

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.

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.

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. 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. It is considered that adoption of good SE practice in the area of managing requirements and specifying the system would have revealed the oversight and allowed the latency for this change to have been reduced.

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.

   An option to revert to a fixed-block signalling system was included in the contract to but allowed to lapse. It seems likely that if the London Underground project team had had mechanisms to inform itself better about the state of play, the option would have been exercised. 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 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.

Analysis and conclusions

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in the tentative theory.

It is considered that the case study provides 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.
- 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.
- 10. More timely, accurate and comprehensive system design 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 evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 9.4:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions.

11.3 Case Study 3: The Channel Tunnel Rail Link Project

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.

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 well below those initially forecast (NAO, 2012; page 14).
- After allowing the nature of the terrain over which the lines run, it was significantly more expensive per kilometre than other high-speed lines (Steer Gleave Davies, 2004; page 35)

The way in which the project was run

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.

The project had a very clear and explicit commitment to using proven technology where possible.

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.

The changes that were made

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.

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.

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.

Analysis and conclusions

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.

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.
- The CTRL project was building a new railway rather than upgrading an existing one.
- The CTRL project chose to introduce no new technology.

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 such projects 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. 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.

Nothing has been identified in the case study that appears to corroborate the causal mechanisms in the tentative theory.

It is considered that there is evidence for the following causal mechanism which is not in the tentative theory but which was suggested by the findings of chapter 9.4:

- X1. Efficient, co-operative contractual and quasi-contractual arrangements between the parties involved in a project lead to sounder and timelier decisions.

11.4 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 9.4. 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.

Introduction

This case study concerns the acquisition of a high-output machine to clean ballast[11] and

is drawn from a conversation with an ex-member of the British Rail (BR)/Railtrack project team.

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

[11] *‘Ballast’ comprises the piles of large gravel in which most railway tracks are laid.*

short single line midweek night possessions[12]. 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 supplier had supplied machines of the required type for use in North America but some of the requirements specified by BR had not been met before by the supplier and significant redesign of the machines was required to meet them.

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 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 and reliability requirements. The 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.

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– 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

[12] *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.*

meet the requirements whereupon it is possible that the parties would have agreed to abandon the project.

The changes that were made

There is only one significant change associated with this case study and that is the decision in 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.

Analysis and conclusions

Nothing has been identified in the report that appears to contradict the causal mechanisms postulated in 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 the decision to abandon the project could have been taken earlier. It is considered that there is, therefore, 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.

Nothing has been identified in the report that appears to suggest additional causal mechanisms.

12 CONCLUSIONS AND RECOMMENDATIONS

In this chapter I

- summarise my findings;
- formulate recommendations for researchers investigating the benefits of SE.
- formulate recommendations for people working on rail projects; and
- present my final conclusions.

12.1 Research findings

Findings about changes on railway projects

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 and similar results are reported in other sectors (see chapter 6).
- The latency of changes was high – often well over a year (see chapter 10).
- The majority of significant changes could have been avoided entirely, in principle, if the information available at the outset had been fully exploited (see chapter 10).
- 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 chapter 10).
- Engineering changes were not carefully tracked and engineering change metrics were not calculated (see chapter 10).

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 chapter 6). It follows that reducing change latency could deliver significant potential improvement in rail projects.

Can SE 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 chapter 3).
- There a number of hypotheses that explain why these benefits are to be expected (see chapter 3) 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 7 provides an indication of the strength of the evidence available for each mechanism. The numbers in the **Changes** column indicate the number of changes in the projects which I studied directly that appeared to corroborate that mechanism added to the number of projects for which I inspected published data, where that published data appeared to corroborate the mechanism.

Figure 10 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 7. Figure 10 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 chapter 10):

- 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.

Table 7: **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

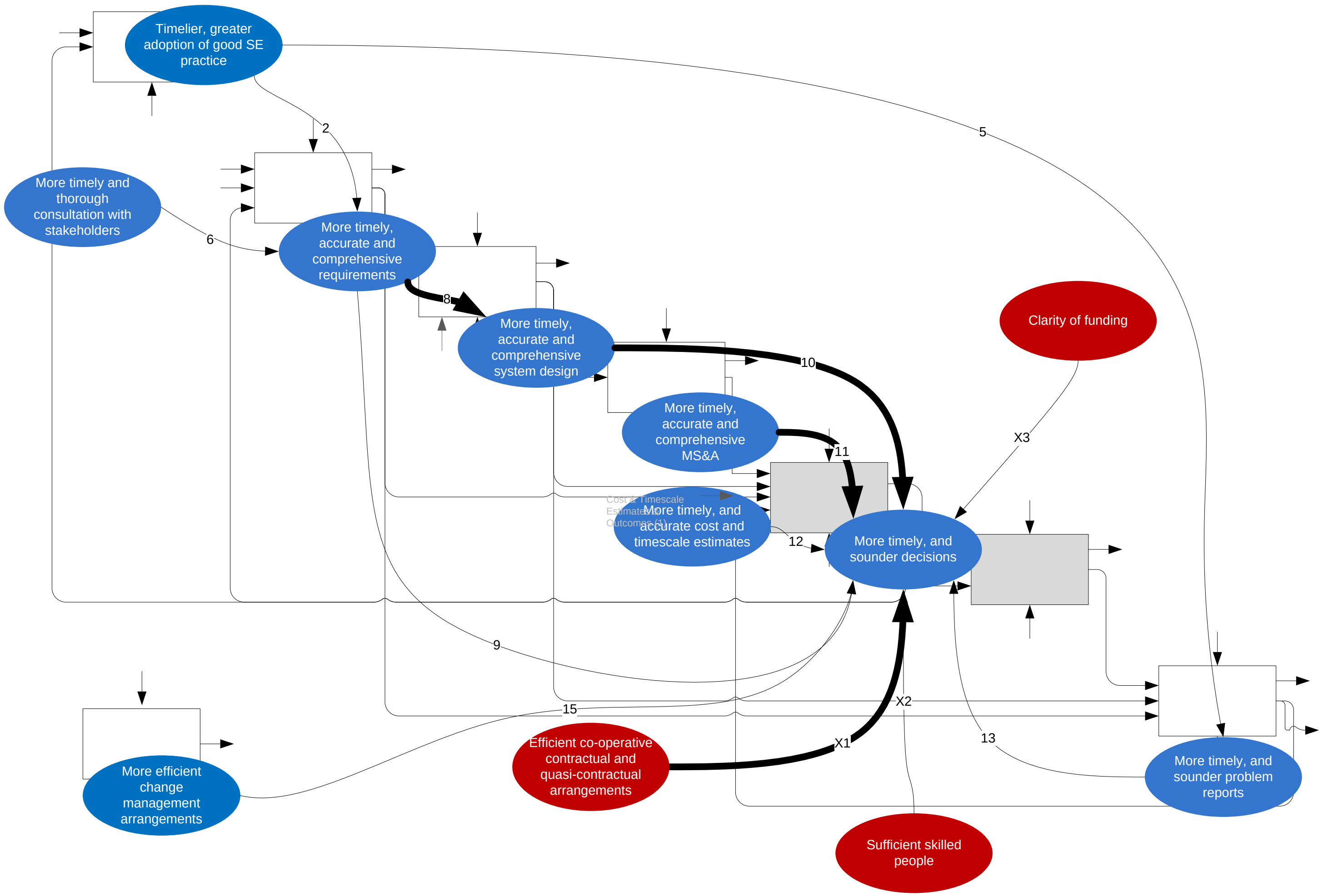

Figure 10: Cumulative evidence for operation of causal mechanisms

The history of the CTRL project (see chapter 10) 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.

How should we adapt core SE to produce the greatest reduction in change latency in major rail projects?

The findings of the research do corroboration of the working assumption that focussing SE upon change latency is valuable. 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 chapter 10) 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 chapter 4) that, 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.

How should we carry out research into the benefits of SE?

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 chapter 10) 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.

12.2 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 chapter 2) 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 chapter 10) 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 chapter 10) 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 chapter 10).

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 0 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 chapter 1). 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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