Systems Engineering in Transportation Projects
A Library of Case Studies

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Introduction

The Transportation Working Group has recognized that there is a need on the part of practicing systems engineers for a library of case studies of the application (or sometimes the lack of application) of Systems Engineering (SE) to transportation projects in order to learn from the experiences of others and to make a case for investing in SE.

This document contains such a library. This library will grow over time as we add further case studies. We hope that, as it grows, clear themes will emerge that the reader may discern and turn to advantage on their own project, even if it differs in some significant respects from the projects described below.

In this issue, there are thirteen transportation case studies:

1. West Coast Route Modernisation Project in the UK
2. SkyTrain control center upgrade and expansion in Vancouver, Canada
3. Prestwick Air Traffic Control Centre in the UK
4. Docklands Light Railway Expansion in London, UK
5. NETLIPSE, a European research project studying large infrastructure projects
6. Upgrade of the East London Line in London, UK
7. Santa Clara County Traffic Operations System and Signal Coordination Project in the USA
8. Extension of the Jubilee Line in London, UK
9. Upgrade of the Jubilee Line and Northern Line in London, UK
10. Replacement of the CityLink Control System in Melbourne, Australia
11. Network Rail Performance Modeling in the UK
12. The California High-Speed Rail Project in the USA
13. Denver Regional Transportation District CAD/AVL and Radio Replacement in the USA
14. Pasadena Adaptive Traffic Signal System in California, USA

For contrast, we also include a case study from outside the transportation sector, which we think provides useful context. The topic of this case study is:

X1. Construction of a Simulator for the Detroit Edison Fermi Nuclear Power Plant

Each case study has been prepared either from authoritative documents in the public domain or by interviewing senior members of the project and checking the written case study with them. However, to ensure objectivity and a degree of harmonization, each case study was written up by a member of the Transportation Working Group who was not involved in the project.

The Transportation Working Group continues to seek further potential case studies. If you can suggest possible further case studies, or if you have any comments on this library, please contact Bruce Elliott, at bruce.elliott@arbutus-tc.co.uk.

Transportation Case Studies

Systems Engineering Case Study #1 UK West Coast Route Modernisation Project

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Configuration Management

Background to the Project

The West Coast Main Line is the busiest mixed-use railway in the UK, connecting 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 modernization work between 1998 and 2008, delivering increased capacity and reduced journey times as well as replacing worn-out parts of the railway. The cost of the project rose very significantly during this period and as a consequence the scope of the works had to be cut back.

This case study is drawn from a report into the project published by the UK National Audit Office (NAO)[1] with additional input from a published article.

The case study illustrates the dis-benefits of embarking on a project with inadequate requirements management and configuration management and the benefits of correcting this.

Description of the Challenges Faced

By 2001, neither the rail infrastructure upgrade nor the new trains were on course for delivery as set out in the original plans. In October 2001, Railtrack went into Railway Administration and by May 2002 its projection of the program'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.

Description of the SE Performed

In January 2002, the Secretary of State instructed the Strategic Rail Authority to intervene and find a way forward for the program to renew and upgrade the West Coast Main Line. The upgrade was being undertaken under a 1998 agreement between Railtrack, the private sector owner and operator of rail infrastructure, and Virgin Rail Group, which operates the West Coast passenger rail franchise, and involved the introduction of new signaling technology to allow improved services delivered by new trains running at 140 miles per hour.

[1] "The Modernisation of the West Coast Main Line", Report by the Comptroller and Auditor General , The Stationery Office, 22 November 2006

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 organization that inherited the railway assets from Railtrack.

The NAO's analysis identifies a number of deficiencies in the way that the project was being run before this intervention. These deficiencies include some, such as unclear project governance, which are not considered to be associated with SE. However the deficiencies also include a lack of direction for the program, a lack of stakeholder management and a lack of tight specification and change control, and all of these are considered to fall within the domain of SE.

It may be noted that by 20002, the project had adopted some important aspects of good practice in requirements management and had established a comprehensive hierarchy of requirements, maintained in a special-purpose database, with traceability maintained between the levels. However, the NAO report clear reveals that not all aspects of good practice had been adopted by 2003

The NAO report concludes that the identified deficiencies had already contributed to delay and cost overruns.

The actions taken by the SRA to remedy the situation included several which align with good SE practice, including:

- setting a clear direction for the project, in its June 2003 West Coast Main Line Strategy, specifying what it wanted to achieve;
- establishing a clear, measurable set of program outputs, along with more detailed infrastructure requirements, which were then subject to systematic change control and monitoring procedures
- fixing scope, and then inviting contractors to tender to complete detailed designs and deliver the work to a fixed price;
- instituting clear program governance structures; and
- consulting widely with stakeholders and keeping them informed.

Outcome

The NAO report concludes that the new arrangements worked well and that the benefits included:

- facilitating a more intrusive regime of obtaining possession of the track for engineering work through extended blockades, which was crucial to delivery as access had been the program's key constraint and one of the key cost drivers; and
- identifying opportunities to reduce the program cost by over £4 billion

The opportunities to reduce the program cost included removing new signaling and train control systems and a Network Management Center from the scope of the project but, by then, £350 million of abortive costs had been incurred.

[2] "DOORS ® for West Coast Route Modernisation Programme", Jeremy Dick, Railway Strategies, Winter 2000

The NAO report summarizes the outcome as follows:

> *"The Strategic Rail Authority's intervention from 2002 turned around the West Coast Programme. It worked with Network Rail and the industry to develop a deliverable Strategy and establish appropriate programme management. Network Rail improved the management of the projects and, so far, has delivered the Strategy outputs to schedule. The Strategy has delivered passenger benefits from a modernised track. But value for money for the programme in its entirety has not been maximised: there were substantial early abortive costs to Railtrack in the programme to 2002; and there remains uncertainty about the expected lifespan of some of the equipment on the upgraded line."*

Conclusion

The NAO report provides an independent and authoritative perspective on a large and difficult rail project. It provides direct evidence that a program of action that included adoption of good SE practices in the areas of requirements management and configuration management led to significant reductions in cost and timescales.

The project had already adopted some good SE practices in the areas of requirements management. It is possible that this had delivered some benefits already and likely that it significantly facilitated the programme of action described above, but there is no direct evidence of this.

It seems very likely that, had good practice in requirements management and configuration management been adopted from the start, significant further cost savings would have been enjoyed.

Systems Engineering Case Study #2 Vancouver, BC, SkyTrain control center upgrade and expansion

Keywords: Implementation; Integration; Verification; Transition; Validation; Operation; Project Planning; Project Control; Decision-Making; Engineering Environment; Risk and Opportunity Management; Configuration Management; Information Management; Systems Analysis

Background to the Project

Vancouver SkyTrain is a fully-automated elevated light rapid transit system, in operation since 1986. There are three lines: the Expo Line opened in 1986 with further extensions, and the Millennium Line extension in 2002. A separate fully automated transit system, the Canada Line, opened in 2009. In each case, the trains are driverless with no on-board operator. All control of the trains is carried out at one central control center. Therefore the availability and reliability of the control center are critical to the operation of the system.

The upgrade and expansion of the SkyTrain control center, which is the subject of this case study, was carried out as part of the construction and integration of the Millennium Line. The existing facility was to be refitted with new and upgraded equipment, and would also include the additional staff and equipment necessary to support the extension. System construction began in 1999 and was completed in 2002.

The control center upgrade involved constructing a temporary control center close to the existing center, transferring operation to the temporary center while the existing facility was completely refurnished, then cutting over operations to the upgraded center, with no loss of functionality and no interruption to regular revenue service.

The main players were:

- British Columbia Rapid Transit Corporation (BCRTC), SkyTrain Operations division – project owner
- Rapid Transit Project Office (RTP2000) – owner's project management organization
- Bombardier Transportation – supplied and installed all electrical and mechanical systems, including vehicles, systems and track, but were not responsible for civil works
- The project replaced the operation control center in the location of the existing facility and brought into service a new line with 14 stations, while continuing revenue operations without interruption. This case study covers the planning, design, construction and commissioning of a temporary operations center and a new replacement operations center.

This case study is drawn from an interview carried out in January 2011 with a senior member of the project team.

Description of the Challenges Faced

At the outset, it was envisioned that only modifications and upgrades would be required. However, only after a period of investigation was the full extent of the required work understood, to replace equipment, accommodate additional staff, provide more ergonomic consoles, and address the obsolescence of the existing equipment.

The basic requirements set for the interim facility were that it must be as reliable as the existing facility with no reduction in control performance and functionality. Full functionality of the existing facility had to be maintained until the interim facility could be confirmed to be fully operational. The same applied to the eventual cut-over to the final, upgraded facility.

Description of the SE Performed

System engineering practices were employed comprehensively, including: detailed requirements analysis, detailed risk analysis and risk management planning, detailed system configuration management. The operators' responsibilities were examined and the manner in which operators and supervisors cooperated and worked collaboratively under various situations and scenarios was documented. This led to detailed consideration of the ergonomics of the operation and to a layout in the final design that was more efficient and effective than the existing layout. It also provided a basis for deciding what compromises would be acceptable during the period of operation of the interim facility.

This review led to clear requirements for both the temporary and final facilities in the following categories:

- Ergonomics: including viewing angles, lines of sight, communications with neighbors and supervisors, noise; the ability for audio recording of conversations on telephones and radios, human health.
- Equipment: what equipment is needed at a workstation in order for the operator to perform the required tasks.
- Interfaces: between the equipment within the control room and other locations, such as cable routing grounding of devices.
- Mechanical and electrical interfacing: focusing on the requirements for cut-over and cut-back, including for example, pre-wired modularity.

The approach developed to deliver these requirements was to modify a training facility to become a temporary operations facility that was suitable for the operators to maintain their current performance level, with equipment that would be reliable and comfortable within the timeframe (several weeks only), and to provide a set of modular interfaces that could be quickly connected to the outside world, with only a short downtime once the existing facility was disconnected.

A risk analysis was performed which was used to choose between migration approaches. The process studied the feasibility of each approach, undertook a risk analysis, and involved detailed consultations with the operators and system owner, suppliers and the installation team.

Detailed testing and verification plans were developed and both the interim facility and the final facility were subjected to full testing and commissioning prior to the cutover their operation. This meant that only minimal testing and verification at the interface level was required to confirm each facility was ready to go live at the end of the cutover.

Outcomes

The whole process implementation was extremely successful. There was no unplanned downtime during the cutover or the cutback. The key ingredient to the success of the activities was the level of detail of the planning. This required a great deal of coordination and communication, but since all the players were able to clearly see the planned activities of all participants and their dependencies, the plan was subjected to very little deviation as the work progressed.

The success of the implementation, with few unexpected situations and no delays to the schedule, indicates that the correct solutions were applied and that they were applied correctly.

The risk analysis undertaken at an early stage highlighted the severe implications if the cutover and cutback did not go smoothly, such as loss of revenue, delay to cutover, delay to cutback which would have increased the length of time staff were operating in a less satisfactory environment). Since all the risks were identified, each was avoided (through the selection of the approach) or mitigated with contingency plans (such as backup equipment) in place.

Configuration Management was also extremely important. Drawings and documents identified the state of equipment that would be expected at each phase of the work, which minimized the need for decisions on the fly and unexpected interim connections.

Conclusion

This project was undertaken in an environment in which failure would have severely impacted the operation of the client, with implications of lost revenue and significant inconvenience to the public. While the requirements were unclear at the beginning, good application of SE during the preliminary design adequately identified all the requirements, and the application of SE practices during the implementation ensured a successful outcome.

Systems Engineering Case Study #3
NATS Prestwick Air Traffic Control Centre

Keywords: Requirements management; Integration; Verification; Validation; Project Control; Engineering Environment; Risk and Opportunity Management; Configuration Management; Information Management; Systems Analysis

Background to the Project

NATS, formerly National Air Traffic Services, provides air traffic control (ATC) services to aircraft flying in UK airspace and over the eastern part of the North Atlantic. ATC had been provided through four regional Centres. In the late 1990's, it was decided to consolidate air traffic control into two Centres, with one at Swanwick, Hampshire, and one at Prestwick, Ayrshire. The Prestwick Centre was to incorporate the airspace managed by the Scottish and Manchester Centres. However, due to a falling demand in air travel, the Prestwick Centre Project was not started in earnest until 2007. The new Centre was completed and became fully operational in January 2010.

This case study concerns the design, implementation, test and commissioning; and acceptance of the Prestwick Centre. The Project was managed by NATS, who performed the systems integration task. Contractors were used for specific aspects.

This case study is drawn from an interview carried out in February 2011 with senior members of the engineering team.

Description of the Challenges Faced

The major challenges were:

- A challenging and immutable deadline, driven by public commitments made by NATS;
- The need to achieve safety acceptance of the new system by the CAA, the UK regulator;
- Significant personnel issues arising from the need to relocate staff;
- Changes in scope during the project, for example, the incorporation of Oceanic control, which had been scheduled for a later implementation; and
- Uncertainties in costs, for example, the unexpected rise in the cost of some materials and labor.

Description of the SE Performed

NATS had mature SE processes but used IEC standard 15288, "Systems and software engineering -- System life cycle processes" as a checklist, to ensure that best SE practices were followed. System engineering practices and tools were employed comprehensively, including: detailed requirements analysis, detailed risk analysis and risk management, configuration management and information management working in tandem with Quality Assurance and Safety Assurance.

The stakeholder requirements were gathered and these comprised mainly strategic requirements of a business nature, for example, the requirement for a 30% system and operations expansion capability,

An ATC System is a system of systems, and so the Centre design began with the examination of the Centre architecture and data flow between the various systems. This was used to develop a logical model of the Centre using the Unified Modeling Language (UML). Business requirements were translated into requirements for both the facilities and the systems. Where possible, existing systems were re-used to reduce the project risks. Analysis of the Centre showed that certain functions were duplicated between the systems that NATS already used, and so by modification to certain systems, others could be eliminated.

A web-based document control system was employed whereby several hundred project documents were managed, and could be uploaded, controlled and accessed remotely. A web-based issues and actions system was also employed.

A requirements management tool was used to identify, allocate and manage system requirements through to verification and validation. Requirements were captured and traced only to the level necessary, for example, where a legacy system was used without significant modification, then it was not necessary to go to the level of software requirements.

Testing included functional, overload and failure mode testing. Systems were tested in isolation before being combined into facilities before testing at the level of the Centre as a whole.

Proprietary tools were used for life-cycle modeling and to justify the required spares holding and to manage the configuration management for system parts and spares.

Risk management techniques were employed to identify and to mitigate risks as early as possible in the project, for example by the use of simulator tools to test individual subsystems and interfaces in the development environment.

The manner in which SE processes were implemented took full account of human factors. For example:

- The High Level System Design Document was deliberately kept to within one hundred pages so that it would not only be easy to manage, but also so that it would be read and understood by all team members;
- Simple and regular communication channels between project leaders and team members were put in place;
- Regular meetings with senior management ensured that key decision makers were fully informed and involved throughout the project and could provide assistance where and when necessary;
- Engineering management provided genuine leadership and ensured that all project decisions were fully informed by engineering considerations.

Outcomes

The project was implemented on time and £9M under budget. The new Prestwick Control Centre became fully operational without any interruption to air traffic control. A senior airline manager rang NATS to inquire when the switchover was due to occur only to be told that it had happened the previous week!

It had been planned to incorporate Oceanic control into the Centre after it had gone live but the project’s progress allowed this to be brought forward so that Oceanic control could be provided from the start.

NATS is now leading the way in Europe's agreed strategy of concentrating ATC in a small number of large centers.

The logical model allowed the removal of at least three systems from the Centre resulting in significant savings in whole-life costs.

The project drew upon established NATS practices and improved upon them. It has advanced and continues to advance good practice within NATS

- NATS have developed Systems Architecture Development (SAD) processes, using UML, that will be applied to future System projects;
- NATS provides an Engineering Product Design Life-Cycle (EPDL), two-day, in-house training course to all Engineers to ensure all Engineering staff have a common understanding of the NATS processes and procedures for System projects;
- A lessons Learned database has been established, whereby lessons learned can be captured to avoid recurrence of issues on future projects, and ensure best practices are developed and followed;
- Standard templates have been developed to ensure Engineering documents follow a consistent and comprehensive approach from one project to another; and
- A 'Coaching for Performance' process has been implemented to develop the 'soft skills' of all staff involved in such projects.

Conclusion

This project was undertaken in an environment in which failure would have severely impacted operations, with implications of lost revenue and significant inconvenience to the public. Good application of SE during initial design adequately identified all the requirements so that NATS, acting as System Integrator, was able to implement the project on time, within budget and to the level of performance required.

Systems Engineering Case Study #4 Docklands Light Railway Expansion

Keywords: Requirements Analysis; Architectural Design; Integration; Configuration Management; Systems Analysis

Background to the Project

The Docklands Light Railway (DLR) is a driverless light transit railway which covers regenerated parts of East London that are not well served by the Tube. The DLR now runs trains over a significant network but, in 1992, it was a small operation running 11 vehicles over two short routes.

In 1992 the railway's owner, the London Docklands Development Corporation, let a contract for a significant upgrade to build a new extension, increase the vehicle fleet to 70 and replace the train control system. A fixed-price contract was awarded to a joint venture formed by Booz Allen Hamilton and Brown & Root to perform the roles of prime contractor and systems integrator, and to deliver the upgrade. This contract included requirements for the performance of the completed railway and payments contingent on meeting these requirements. The new trains were supplied by Bombardier and the train control system was supplied by Alcatel, both under contract to the joint venture. The contract was completed in 1996.

This case study is drawn from an interview carried out in March 2011 with a senior member of the project team.

Description of the Challenges Faced

By the time that the project was complete, only a small fraction of the railway was as it had been before and many of the changes were of a fundamental nature. Not only had the train control system been replaced but a two-route railway now had multiple-routes, switched at several complex junctions.

The consortium inherited several existing contracts for the vehicles, train control system and an extension, which had not benefited from the adoption of a full SE approach.

There was significant innovation involved. The train control system had never been used on complex junctions before and required enhancement to its logic to cope. Moreover the train control system, which must control the position of trains very accurately not only for safe train separation, but also in order to ensure that trains are adjacent to a platform when the doors open, had only previously been used with trains powered by linear motors; it now had to control new trains powered by more traditional, rotary motors, introducing slip/slide issues.

All this had to be accomplished in a regulated, safety-critical industry with only short interruptions to the operation of the railway and under a contract that transferred a significant amount of risk to the prime contractor/systems integrator.

Description of the SE Performed

It was apparent to the prime contractor/systems integrator from the outset that the project could not be delivered successfully without an SE approach.

Systems requirements were articulated and, from them, requirements were derived for the vehicles, the train control system and the interface between them. An operational simulator, using Monte Carlo algorithms, and models of reliability, availability, maintainability and performance, were built in order to check whether the design would deliver the contractual requirements and, where there was a shortfall, to prioritize cost-effective changes to remedy it.

The operations and maintenance requirements were translated into system requirements which allowed co-ordination between development of the technical system and the development of the operations and maintenance procedures.

A comprehensive series of integration tests was specified and performed at the manufacturers' facilities and on the delivered railway itself, with additional testing defined as part of the requirements management process.

All of this was thoroughly documented, with traceability between the documents, and was maintained under configuration control.

Outcome

The upgrade was delivered within the agreed fixed price and the performance requirements were fully met by the end of the contract, so not a penny of the performance-based payments remained unpaid. The SE documentation provided the technical input for preparing a comprehensive safety case for submission to the safety regulator, who gave approval to place the new system into service.

Sound foundations were laid for the future. Several significant further extensions and upgrades have since been carried out and the system now carries almost 70 million passengers a year with consistently high levels of reliability and passenger satisfaction.

Conclusion

The system integrator's clear opinion is that the project could not have been delivered without an SE approach. Not only did the SE approach support successful delivery but it assisted in delivering a well-performing and extendable railway system which is one of Britain's great transport success stories.

Systems Engineering Case Study #5 NETLIPSE

Keywords: Stakeholder Requirements Definition; Requirements Definition; Risk and Opportunity Management; Configuration Management; Systems Analysis

Background to the Project

NETLIPSE stands for "NETwork for the dissemination of knowledge on the management and organisation of Large Infrastructure Projects in Europe". It is a research project set up with the following objectives:

- *"Setting up a continuous and interactive knowledge network.*
- *Gathering information on best practices and lessons learnt in the management and organisation of 15 Large Infrastructure Projects in Europe.*
- *Disseminating the knowledge gathered and promoting the research results.*
- *Translating the best practices into an evaluation and monitoring tool that will allow for the quick and effective implementation of new policies."*

This case study is drawn from a report published by the project[3]. This describes an activity to gather and analyze information on 15 large European infrastructure projects, with a total value in excess of €40 billion.

Although the project is a research project rather than a delivery project, useful conclusions may be drawn from its study of large infrastructure projects (or LIPs for short).

Description of the Challenges Faced by Large Infrastructure Projects

The report makes very clear that LIPs encounter significant problems in meeting their cost and time targets. The authors observe that, "*LIPs in general, do not have a good reputation with respect to cost and time control*" and record that "*In the NETLIPSE research batch, the projects researched also encountered cost overruns and time delays*."

[3] "Managing Large Infrastructure Projects: Research on Best Practices and Lessons Learnt in Large Infrastructure Projects in Europe", M Hertogh, S Baker et al, 2008, AT Osborne BV.

The authors ascribe these problems in part to deficiencies in requirements, stakeholder management and response to change when they say:

> *"We noticed repeatedly, that the technical, environmental and engineering or constructional requirements and scope have been ill-defined at the initial stages of a project and publicly stated cost estimates have been given, based on these uncertain principles. Many project organisations initially focussed too much on the 'internal world of shareholders' - on issues such as design and organising formal legal consents - and too little on the 'external world of stakeholders' such as collaboration with stakeholders and exploring opportunities. The observed focus often leads to a slow reaction to context changes."*

The report has some interesting things to say about the inevitability of change. For instance, section 4.4 contains the following:

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

Findings and Recommendations

The authors have formulated 63 findings and 46 "best practices and lessons learnt", essentially, recommendations for the execution of future large infrastructure projects.

The first finding of the report is a clear endorsement of a systems approach:

> *"Projects must be conceived, managed and operated as an integrated whole, with the prime purpose being the user and economic benefits derived from a new or improved transport link, rather than the completion of a physical project as an end in itself. Where the success of the outputs depends on operational interfaces as well as infrastructure construction, these must be managed from the outset and integrated into the programme management of the whole project.*

Several of the findings corroborate the value of performing requirements analysis and configuration management. For example:

- Requirements Analysis

  Finding 10 includes the conclusion that*, "It is essential that major infrastructure projects are properly defined against a specific output requirement and strategic purpose."* Finding 15 is that, *"Clear project objectives, if defined at the early stage, can be very helpful for the project delivery organisation in defining design parameters and project specification as well as in undertaking consultation and staff communication."* Finding 16 recommends that, *"The project objectives should be clearly translated into a functional output specification. The functional specification should be translated to required technical outputs, scope of work, work packages and milestones."*

- Configuration Management

  Finding 18 recommends that, "Tight arrangements should be in place for scope management and control between the Project Delivery Organisation and the client/sponsor" and one of the identified good practices is to "Use configuration management to assess the impact of scope changes."

There is an endorsement of the value of system modeling in principle that is implicit within the following criticism of how it is performed in practice:

> *"Major infrastructure projects have been similarly criticised for over estimation of benefits, possibly so that schemes can be given authority and funding to proceed. One of the key findings of this NETLIPSE research in relation to those projects which have been fully or partially completed is that conventional modelling tools are unsuitable for use where new infrastructure links are created by a project or where a step-change improvement in connectivity is obtained. In these cases, within this research, traffic results for the completed or partly completed projects studied, in some cases have been greater than conventional forecasts would have suggested. The original project justifications have therefore been over cautious and not, as some have claimed, ambitious."*

There are also clear recommendations to invest in comprehensive, open communications with stakeholders and in thorough systematic risk and opportunity management.

Conclusion

The findings of the NETLIPSE research project corroborate the view that investment in several aspects of SE good practice, including Stakeholder Requirements Definition, Requirements Definition, Risk and Opportunity Management, Configuration Management and Systems Analysis, is positively correlated with the success of large infrastructure projects. In particular, they note that changes in major external constraints are the norm for large infrastructure projects and that good SE practices provide a robust framework within which to deal with these changes.

Systems Engineering Case Study #6
East London Line

Keywords: Stakeholder Requirements Definition; Requirements Definition; Verification; Validation

Background to the Project

The East London Line project modernized and extended a former London Underground line to provide better connection between the north and south sides of the Thames River on the eastern side of London, and made the line part of the London Overground network. The project used existing and redundant lines with 300m of new route to produce the new train service and in this upgraded track, signaling, power, communications and signage to mainline railway standards. Four new stations were constructed and several existing stations reconditioned. New rolling stock was also procured.

This case study is drawn from an interview carried out in January 2011 with the project's Head of Engineering and Systems Integration Manager.

Description of the Challenges Faced

The major challenges faced by the project were:

- Uncertainties and changes to funding in the early stages of the project;
- Constructing a new, modern railway on Victorian infrastructure in a dense urban environment;
- Interfacing the new railway to other existing railways;
- The application of new safety regulations, introduced part way through the project; and
- Two changes to the infrastructure manager and the ultimate operator of the railway during the project.

The civil engineering designers and contractor were used to working in an environment where the majority of work elements are governed by existing standards, and they were not familiar with operating under a requirements-driven contract approach.

Description of the SE Performed

System engineering was central to the entire project. The senior members of the Transport for London project team were experienced system engineers. They did not form a separate system engineering team, but rather committed the project to "*engineering in a systematic way*". Rather than prepare a 'System Engineering Management Plan', they wrote an 'Engineering Management Plan'. This avoided the perception that the application of system engineering was something apart, and helped to focus the entire team on using a requirements-driven approach to their activities. In addition, the requirements writers were at the heart of the project team, not a separate group at the side of what was regarded as the main activity.

The requirements management tool DOORS was used by the requirement authors in the client team to document the technical requirements, which were disseminated around the project as conventional documents and formed part of the contractual works information. The main works contractor used management tools which directly interfaced to the client's DOORS data and distributed relevant requirements to his supply chain. All assurance reports (approximately 300) produced by the contractors were linked directly to requirements.

Verification tests were all structured to document satisfaction of requirements in a progressive way. The project manager monitored delivery of verification test reports (assurance reports) against a complex schedule that provided a structured, pre-planned sequence of reports. This allowed the team to better handle perturbations in schedule, allowing them to continue acceptance of track elements when stations were not ready. The assurance cases were structured into levels. Level 3 related to individual deliverables, Level 2 encompassed the major sub-systems (Infrastructure, rolling stock and operations), while Level 1 covered the whole railway.

Because the requirements were embedded in the contracts, changes to the contract could be accommodated when a requirement was changed. Conversely, contractual issues were easily traced back to identify affected requirements.

When asked what they would do differently if given the opportunity, the interviewees considered that development of the contract documents would have been smoother in the early stages if the decision to use requirements as the basis of the contract had been made 6-12 months earlier.

There were approximately 1600 to 2000 requirements. During the course of the contracts, there were approximately 140 groups of requirement changes. Some of these related to additions to scope that it was known would be required before the main contracts were let: the addition of a depot and added escape routes.

Interfaces were controlled by placing requirements on the contractors on either side of the interface.

Outcomes

During the course of both the design and construction, scope creep was controlled because every contract requirement was linked to a business requirement or an external constraint, and contract changes were directly related to requirements.

The project met all the requirements, and provided all required functionality. It has received twelve important awards, including 2011 Greatest Contribution to London award, and 2011 National Rail Project of the Year.

The railway was opened for revenue service five weeks ahead of schedule.

During the design phase, detailed operations models were used to compare the expected operation with the network reliability targets, and the findings were incorporated into the requirements. The actual reliability experienced (97% of arrivals within four minutes of scheduled time) has exceeded the target (92%).

The other rail systems with which this system would eventually interface maintained full operation during the project.

Conclusion

The adoption of SE practices allowed a complex and difficult project to be delivered successfully and on-time. The underlying principles of SE were adopted in a manner that was integrated with existing practices and that was presented as a systematic way to do the engineering with which the various designers and constructors were already proficient, rather than as a new method of working. This allowed the principles to be successfully implemented by a supply chain that was not generally familiar with formal SE.

Systems Engineering Case Study #7 Santa Clara County Traffic Operations System and Signal Coordination Project

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Verification; Risk and Opportunities Management; Validation

Background to the Project

Santa Clara County is located at the southern end of the San Francisco Bay in California. It includes several cities, the largest of which is San Jose, the eighth largest city in the USA. The road infrastructure includes freeways managed by Caltrans, city streets and highways managed by the individual municipalities, and an overlay of limited-access highways with widely-spaced signalized intersections, managed by the County.

Santa Clara County is a member of the Silicon Valley Intelligent Transportation System (SVITS) forum, which provided a means of coordinating with other Intelligent Transportation System (ITS) projects. An earlier feasibility study had developed a system architecture, including identifying system interfaces, for an ITS together with upgrades to the Traffic Operation Center (TOC), traffic signal system, communications, and CCTV surveillance at intersections, and upgrades to center-to-center communication links with other municipal control centers. The project began in 1998 and was fully operational within the legislated timescales and budget, covering a period of seven years.

This case study concerns the design, implementation, testing and commissioning of the Traffic Operations System and Signal Coordination Project for Santa Clara County. It is drawn from an interview carried out in July 2011 with a senior member of the project management team, and focuses on the communication system, the CCTV surveillance used for traffic monitoring, and the signal control elements of the project.

Description of the Challenges Faced

The major challenges experienced during the design and implementation phases were:

- Rapid changes in the technology for video cameras and video transmission suitable for traffic surveillance;
- The availability of new technologies to allow traffic signal and ITS communication systems to transition from analog to digital using internet protocol (IP);
- The ‘dot.com’ boom had generated many major technology projects affecting the supply and delivery of fiber optic cables; this led to an 18 month delivery schedule and a potential doubling of costs with a corresponding risk to the schedule and budget.

SE Performed

This case study is an example of a project that adopted SE practices, although the main participants did not specifically cast it as an SE-driven project. The process closely followed the 'Vee diagram' model of SE. It included the following major steps:

- A clear statement of the operational concept;
- Development of system requirements;
- Selection of a procurement model;
- Controlled revision of the requirements during both the design and construction phases to accommodate changes in technology;
- Clear statement at the design stage of verification tests to be used for acceptance of sub-systems; and
- Early definition of measures of performance to be used in system validation.

While not necessarily part of SE, the project was strengthened by strong risk management planning. This highlighted the significant risk to the project delivery posed by the shortage of fiber optic cable, as a result of the 'dot.com' boom, with expected delivery times in excess of 18 months. So as soon as the communications requirements were considered to be stable, procurement of the fiber was initiated by the client, and processes put in place to successfully incorporate the cable into the construction contracts as 'client-furnished materials'.

Even though many of the senior staff (both client and consultant) were involved in the earlier feasibility study, it proved very useful to explicitly review the user requirements and revise the concept design during the design and implementation phase. This gave the opportunity to remove some technological biases in the requirements, which in turn made it easier to accommodate some of the later technology revisions.

Outcomes

The project was implemented within the established timescales and budget. During implementation, major changes in technology were accommodated without significant disruption to the schedule. Twelve years have elapsed since the start of the project and the communications protocols have been changed. The modularity of the design has allowed this to occur in stages, without changing equipment before its useful life has expired and without changing any of the underground communication infrastructure at all.

A key outcome of the careful attention to the user requirements was the specification of multiple fixed CCTV cameras at each intersection, rather than using pan-tilt-zoom (PTZ) cameras as has been commonly used by many similar operations. This satisfied user requirements to simultaneously observe traffic passing through multiple intersections in both directions, which could not have been achieved as efficiently and effectively with PTZ cameras. This requirement evolved because of the unusually long distances between signalized intersections and the resultant difficulty in observing and fine-tuning signal coordination in the field.

In addition to the documents and processes used during this project, a requirements traceability matrix (RTM) would have been prepared if the project team had formally followed the SE Vee. The project team members believe that if that process had been used, it would have been easier to accommodate the technology decisions that were made during the construction phase, therefore reducing the number of small change orders that followed a major decision as its implications unfolded in the field. The use of a formal Systems Engineering Management Plan (SEMP) would also have provided a better structure within which to incorporate the Risk Management Plan, the Value Analysis, and the Configuration Management Plan. In addition, a SEMP have more closely integrated the system and sub-system acceptance tests and the system validation. While each of these was done and effectively managed, the SEMP would have provided a clear framework and avoided the need to separately justify undertaking each of these activities.

Conclusion

The use of SE practices (even though they were not explicitly recognized as such at the time) resulted in a successful project that met all of Santa Clara County's expectations and was delivered on time and within budget. The success was further enhanced by some far-sighted purchasing decisions that grew out of rigorous application of project risk management practices. There is potential to further improve similar projects by adopting additional SE practices.

Systems Engineering Case Study #8 Jubilee Line Extension

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Interface Management

Background to the Project

The Jubilee Line forms part of the London Underground network. In 1979, when it opened, it ran from North West London into the center of the city. However, in 1993, the Jubilee Line Extension Project (JLEP) was started with the objective of extending the line by 16km to reach east London via two busy mainline termini. The route ran through disused dockland areas which were in the early stages of regeneration when the project started, but have now been transformed. The regenerated areas include Canary Wharf, which has become a major financial center to rival the City of London. An evaluation after the project had finished[4] found that the project had delivered an estimated benefit cost ratio of 1.75. The project has left London with some handsome stations which have won several awards. The extension was completed without a single loss of life.

However, these achievements are tempered by significant cost and time overruns. 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 had cost £3.5 billion, despite the fact that some signaling capability had been removed from the scope.

The project has been well documented. This case study is drawn from a report into the project published by Arup[5], which had acted as agent for the UK government during part of the project, and a book about the project written by Bob Mitchell[6].

The project overruns could not have been eliminated by better SE alone. The sources cited above include criticisms of some aspects of project management. The project was also victim to external events beyond its control including the financial collapse of a developer investing in the project, which delayed the start of construction, as well as the physical collapse of a tunnel being bored by another project using the same methods as the JLEP, which caused a pause in tunneling on the JLEP. This case study presents evidence from these sources that the project's performance against schedule and budget could have been significantly improved by taking a whole-system view from the outset, by improved treatment of operational factors and by improved interface management.

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[4] "Project Profile: UK Jubilee Line Extension", The Omega Centre at University College London, 2009, downloaded from www.omegacentre.bartlett.ucl.ac.uk

[5] "The Jubilee Line Extension: End-of-Commission Report by the Secretary of State's Agent; Summary Statement", Ove Arup Partnership Ltd, 2000)

[6] "Jubilee Line Extension: From Concept to Completion", Bob Mitchell, 2003, Thomas Telford Publishing, ISBN 978-0727730282

A Whole Systems View

Mitchell notes that, *"Very little provision had been made in the original Project cost and programme estimates for any works on the basis that the extension was really a 'bolt-on' to the existing railway. A figure of £15 million was included for some works at Green Park station to cope with increased passenger flows and some upgrading to the signalling."* He goes on to record that, in Spring 1991*, "The extent of work needed on the existing Jubilee line between Charing Cross and Stanmore began to be realised".* In the final reckoning, the works on the existing line cost well over £100 million.

The primary reason for this appears to be framing the problem incorrectly and regarding the project's deliverable as "a 'bolt-on' to the existing railway". Mitchell comments on this point later in his book:

> *"If the scope of the Project had been considered as the Extended Jubilee Line from the start as opposed to the Jubilee Line Extension, it would have brought about a more holistic approach to planning and design and a more realistic assessment of the costs and risks involved. As it was, the Project team initially took an entrenched view (understandably) that the existing line was nothing to do with them."*

Mitchell may find the project team's view understandable given the objectives given to them but with hindsight, it is clear that these objectives were not fully aligned with the objectives of the business. Arup expands on this:

> *"The fundamental objective that LUL [London Underground Limited] set out to achieve in 1989 was building, equipping, commissioning and opening a new Railway. To achieve this objective, LUL needed to decide not only on the strategy and management structure of the new construction (that is the Project) but, equally important, the strategy and management structure for the delivery of the Railway. The two are not the same. The latter appears to have not been given sufficient consideration when the arrangements were first set up."*

The adoption of SE good practice in the area of managing requirements and specifying the system forces consideration of the system to be built, the systems with which the new system must interface and the desired outcomes of running the new system in its environment. The evidence cited above suggests that adopting good SE practice in these areas would have revealed the oversights and allowed a more realistic scoping of the works on the existing line.

Operational factors

Mitchell quotes the General Manager of the Jubilee and East London Lines business unit as saying that it was not until the latter stages of the project that the project team "*involved the line management much more in project matters and viewed [him] as the 'ultimate client' - the person who would ultimately have to weld the people, assets and systems into an operational business".* Arup makes a similar point, *"[London Underground Limited] lacked the strategy and the structure and continuity of management that would ensure the delivery of a working Railway and not just the construction Project*." An Operating Plan for the extended line was not put together until January 1991; more than a year after the project had started.

There were a number of significant changes to the project that were made after the initial project had been defined in order to meet operational requirements:

- A radical change to the service reversing facilities was agreed in February 1991, which included the introduction of a third platform at two stations.

- A decision was made to start operations in a phased manner in late 1998; two years after the business unit had proposed such an approach.

The evidence cited above suggests that, had the project followed good SE practice in the elicitation and formulation of operational requirements, it would have been possible to have brought these decisions forward significantly.

Interface Management and Co-ordination

Mitchell is critical of the arrangements for co-ordination of contract and management of interfaces when he writes:

> *"The Contractor was required to co-ordinate his own work with that of all the Designated Contractors. The Contractor was also required to provide attendance (all reasonable facilities and opportunities for carrying out their work) on the Designated Contractors and any other contractors and workmen of the Employer. The inclusion of this contractual obligation still left the Project team with the sizeable task of managing the interfaces directly and ensuring co-ordination of all the contractors with the overall master programme for the Project. Managing the interfaces was a key factor in the increased costs incurred by the Project as will be seen later."*

Arup corroborates this criticism and provides evidence that it was a source of delay:

> *"Works contractors were also procured individually, and management of interfaces between them was not defined. This was particularly relevant to the Railway controls contractors, where absence of early interface management delayed this package by many months"*

The evidence cited above suggests that, had good SE practice in interface management been adopted from the start, the project might have enjoyed significant time and cost savings.

Time is Money

Mitchell reminds us that "*time is money*" and goes on to conclude that "*it is estimated that something like £600 million of the £1.36 billion [overspend] is attributable to time-related causes, be it claims for delay and disruption, acceleration measures instructed by the Client or extensions of time awarded by the Engineer along with the prolonged resourcing of the Project team*".

Conclusions

The JLEP was ultimately a successful project that delivered improvements to London's transport infrastructure that justified the considerable investment made in them. The evidence from authoritative accounts of the project suggests that, had the JLEP adopted good SE practice from the start, the project could have avoided some of the problems listed above on the way to delivery. It also suggests that adopting good SE progress could have avoided a number of late changes and delivered savings in both project timescales and budget.

Systems Engineering Case Study #9 Jubilee Line and Northern Line Upgrade Project

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Configuration Management; Interface Management; Architectural Design; Project Control; Validation

Background to the Project

The Jubilee Line and Northern Line are parts of the London Underground network. When this case study began, a Public Private Partnership (PPP) contract was in place whereby two franchisees were responsible for maintaining and upgrading the network. The maintenance and upgrade of the Jubilee Line and Northern Line were the responsibility of Tube Lines Limited. Under the terms of the PPP contract, the upgrades were privately funded and the investors would recoup their outlay by receiving regular payments which would increase in line with improvements in metrics of service performance and reliability. The principal such metric was journey time capability (JTC) which was based on a weighted average of customer journey times from station entrance to station exit

In 2004 an upgrade program was initiated for both the Jubilee and Northern Lines. The program began as part of the PPP and its principal objective was initially to deliver improved JTC. However over the course of the program the franchises were returned to London Underground and London Underground took over as the customer for the program. The objective of the program remained to increase capacity but this was now phrased in terms of train throughput

The initial upgrade was made to the Jubilee Line, and this was completed in July 2011 in time for the London Olympics. The main improvements to the Jubilee Line accrued from replacing the existing conventional, track-circuit based signaling system with a communications-based, moving block train control system and by adding a seventh car to every train. Some changes to operational practices were made as a consequence of adopting new technology and civil and electrical works were also required to remove speed restrictions and provide the necessary additional power.

While the initial conceptual design for the Northern Line Upgrade began in parallel with the Jubilee Line Upgrade in 2004, the later stages of the lifecycle only began in earnest after the completion of the Jubilee Line Upgrade; and the Northern Line Upgrade was completed in 2014 The primary targets for the Northern Line Upgrade were to improve train throughput by at least 20% in the central branches, to return the line to a state of good asset condition and to improve reliability. The benefits were realized principally by replacing the existing conventional, track-circuit based signaling system with the train control technology used on the Jubilee Line. This new technology also required changes to operational practices. Some civil and electrical works were also required to remove speed restrictions and provide the necessary additional power.

On both lines, Thales provided the new signaling and Alstom modified the existing trains. London Underground remained the system operator throughout.

As a matter of policy, the Northern Line Upgrade project used the same technology, system design and operating practices as the Jubilee Line Upgrade project unless there was a good reason to do otherwise. However, some functions of the system that had proved of limited value on the Jubilee Line were removed from the Northern Line system scope.

This case study was developed from interviews with senior members of the project team.

Description of the Challenges Faced (Jubilee Line Upgrade)

The PPP contract provided Tube Lines with considerable technical freedom in how they met the objectives but also meant that any delay or shortfall in delivering the JTC enhancements would have direct financial consequences.

The moving block signaling system employed was very different from the existing conventional fixed block system and it was difficult to meld existing operational practices and signaling principles with the new technology. This was also not a conventional application of the moving block signaling technology and substantial modifications to the baseline product were required.

The Jubilee Line remained in operation throughout the project and it was difficult to obtain the necessary access to the line for installation and test. The differences in technology meant that in-house simulation capabilities were limited. At the time, the project also had limited test track facilities and therefore had to perform a significant amount of testing on the line in competition with routine track maintenance activities. Disruptions to passenger service became an issue for London politicians which exacerbated the challenge for the project.

Description of the SE Performed (Jubilee Line Upgrade)

Considerable effort was expended on requirements management, developing the systems architecture, interface management and configuration management.

An Operational Concept was provided by LU which together with the JTC targets formed the basis of the stakeholder needs and requirements. A formal requirements baseline was established by Tube Lines and Thales and managed in a requirements database. A decision was taken that Tube Lines would focus upon the specific requirements for the project and those relating to new technology because this was where the primary risk was considered to lie. Requirements to follow established standards (for example, building standards) were managed outside the database. Thales managed all its requirements, most of which were relevant to safety, within its requirements database, which was shared with Tube Lines.

Signaling principles were articulated and converted into functional requirements for the signaling system, with special attention paid to failure and degraded modes of operation.

No system architecture had existed previously for the Jubilee Line but one was developed iteratively and the level of detail increased with the evolution of the system design.

Based on the system architecture, interfaces were defined and formally managed. Interface specifications were created and cited in the scopes of work for the parties to the interfaces. Interface specifications were reverse-engineered at interfaces with legacy systems, such as those at depots.

The requirements, architecture and interface specifications were maintained under configuration management. A formal change control process was used to track and manage changes.

Outcome (Jubilee Line Upgrade)

The upgraded line is operational. Initial reliability was disappointing but a focused improvement program resulted in achieving the performance and reliability targets in time for the London Olympics. The target delivery date was not met – an initial performance upgrade was delivered in December 2010 with the final upgrade delivered in July 2011. The delay was the result of the need to rework some novel parts of the system and challenges posed by some interfaces, for instance, the complex interface with Stratford Market Depot. The rework was almost entirely within individual sub-systems – there were no significant changes to the top-level system requirements and architecture.

Description of the Challenges Faced (Northern Line Upgrade)

The Northern Line Upgrade shared with the Jubilee Line Upgrade the challenges of:

- introducing new technology, which in turn required the introduction of new operational practices;
- managing multiple stakeholders; and
- carrying out the works while the line remained in operation, with minimal impact on passenger service.

The first challenge was significantly mitigated by the experience gained on the Jubilee Line Upgrade and the decision to use the same technology, system design and operational practices finally implemented for the Jubilee Line.

The second challenge was mitigated by subsequent organizational changes arising from the abolition of the PPP, after which LU took direct control of the project.

The principal challenge facing the Northern Line Upgrade was to improve upon the Jubilee Line Upgrade in the following areas where the latter had disappointed:

- cost and timescale;
- initial reliability; and
- disruption to passengers.

A comprehensive 'lessons-learned' exercise was carried out at the end of the Jubilee Line Upgrade and this informed some adjustments to the SE and project management practices used on the Northern Line upgrade, as described in the next section.

Description of the SE performed (Northern Line Upgrade)

The Northern Line Upgrade adopted the SE practices that had been used on the Jubilee Line Upgrade, including:

- developing an Operational Concept;
- establishing a formal requirements baseline and managing it in a requirements database;
- developing functional requirements;
- developing a system architecture and interface specifications;
- maintaining the requirements, architecture and interface specifications under configuration management; and
- using a formal change control process to track and manage changes.

There were some differences in the top-level requirements, which were phrased in terms of trains per hour rather than Journey Time Capability. However, the principal technical differences to the systems development activities were concerned with system testing, which was restructured in order to deliver increased initial reliability with reduced disruption to services as follows:

- A new approach was adopted for this project; Performance Monitoring, whereby systems were run in shadow mode (systems operating passively with no control), before final systems tests and cut-over into service. This allowed growth in both hardware and software reliability. It was possible during these periods to gather system data, particularly on the use of the axle counters and the data communication subsystem, analyze the data and system performance, and where necessary make changes.
- More work in the field was done during the routine night-time breaks in service rather than through closures.
- Improvements were made to test tools.
- More use was made of a test track at Highgate.

The project management and systems assurance processes were significantly overhauled:

- A 'one team' approach in which the client's and principal contractor's teams were located in the same office and shared a single set of project management and progress data with complete transparency.
- The systems assurance processes were streamlined. For example, Thales certified its own installations.

Outcome (Northern Line Upgrade)

The Northern Line Upgrade was completed in June 2014, ahead of schedule and within budget. Performance and reliability targets were met from day one. The targets for minimizing passenger disruption were met: the project was delivered with less than half the line closures that were initially planned and an order of magnitude fewer than were required for the Jubilee Line Upgrade.

Conclusion

Previous projects that had attempted to introduce new technology to existing railway lines had encountered problems that required fundamental changes to the system being delivered. Both the Jubilee Line Upgrade and the Northern Line Upgrade succeeded in avoiding such problems. The application of requirements management, systems architecture and interface management headed off this risk – the system as designed met its requirements without requiring significant change. Problems were encountered on the Jubilee Line Upgrade, but at the sub-system level.

The Jubilee Line Upgrade illustrates clear benefits of investing in good SE practice in the left-hand side of the V diagram but also illustrates that these techniques cannot forestall all project problems and suggests that a balanced investment in both sides of the V diagram, as was made on the Northern Line upgrade, is likely to yield the best return.

Although the Jubilee Line Upgrade project was ultimately a success, there were some disappointments along the way. The Northern Line Upgrade project benefited from the experience gained from the Jubilee Line Upgrade project and was an unqualified success.

Although, the Northern Line Upgrade project made improvements in the SE practices, particularly in the area of validation, the principal difference between the manners in which the two projects were executed concerned project management and governance. It is concluded that the benefits of good SE and good project management and governance are not independent of each other and that the greatest benefits are obtained when both are in place.

The success demonstrated the importance of making use of the lessons learned at the completion of a project, with real actions resulting from analysis of the previous project's experience. The application of SE practices alone is not sufficient to guarantee success without a coherent and unified organization committed to the delivery.

Systems Engineering Case Study #10 CityLink Melbourne Control System Replacement

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Decision-Making; Risk and Opportunity Management

Background to the Project

Several tolled freeways and tunnels in Melbourne, Australia are operated and maintained by CityLink Melbourne Limited, a subsidiary of the Transurban Group, under a concession agreement with VicRoads, the road authority in the state of Victoria.

The financial success of CityLink depends on maximizing toll revenues while minimizing operation and maintenance costs. The reliability and safety of the roadway are major factors in this equation. From the beginning, Transurban understood that effective use of computer control technology would be needed to achieve this. The operators make significant use of computer systems for monitoring and controlling traffic in order to maximize traffic flow and safety. There are some long tunnels and the ability of the computer systems to facilitate a rapid response to incidents within these tunnels is very important to safety.

The CityLink tunnel has been operational since 2000. The CityLink Central Computer Control System (CCCS) became operational at the same time. From the start, CityLink operations were predominately focused on managing traffic control and ancillary power and ventilation systems in the tunnels. Over time, however, it became apparent that an active traffic management strategy on the open road portions of the CityLink network would be needed, and that the original computer control system could not be cost-effectively enhanced and expanded to meet the emerging new requirements. In 2006 Transurban began the search for a replacement system.

In March 2007, Transurban contracted Transdyn to replace the existing CityLink Central Computer Control System. This replacement system provided the following functions:

- Monitoring and control of air quality and tunnel facilities, including fire, ventilation, pumping and electrical supply systems;
- Advanced traffic management functions, including management of CCTV, radio and telephony equipment, tunnel lane control signals, control of dynamic message signs and incident response management;
- Traffic data monitoring and collection;
- Operations data archiving and reporting; and
- Real time data interchange with VicRoads regional computer system.

The contract required that several functions of the replacement system should be identical to those of the existing system but that most functions should be “equivalent to” existing functions.

Transdyn planned to meet the contract using its existing DYNAC software product. Both Transurban and Transdyn were keen to use as much of the existing DYNAC functionality as practicable and to also incorporate any new functionality into the DYNAC product baseline.

Description of the Challenges Faced

The challenges faced were largely associated with functionality as implemented in software – the provision of the hardware was relatively straightforward.

The precise interpretation of "equivalent to " was potentially the source of conflict between the parties but it also provided them with the opportunity to meet their aim of maximizing software re-use – both re-use of existing product software by the project and re-use of software developed by the project in later releases of the product.

Transurban specified in their contractual statement of work a traditional "V" Model system engineering process. Project milestones, and associated payments, were based on a single pass through the "V". On the other hand, Transdyn's software product development approach was based on an agile, iterative development approach.

Description of the SE Performed

A co-operative approach between Transurban and Transdyn underpinned the SE performed on the project. The parties worked together to merge the traditional "V" Model with Transdyn's working practices. Transurban agreed that the software would be delivered in increments with multiple passes through the "V" and adjusted milestone payments to mitigate cash flow problems for Transdyn. Transdyn adjusted their approach to ensure that system engineering discipline was maintained throughout the project by all parties and to respect the formal entry and exit criteria for each phase of the process.

Considerable time and effort was invested on requirements analysis. Transdyn staff sat with CityLink staff in order to understand current operating processes and the functionality of the existing system and. At the same time, Transurban system engineers worked with Transdyn to gain an understanding of DYNAC software design and functionality. A demonstration system was provided onsite for CityLink stakeholders to interact with DYNAC functions.

From these interactions the design of the DYNAC enhancements emerged. Storyboards, which documented operational scenarios with the new system, were developed collaboratively and then used as the basis of software requirements specifications which defined the new functionality to be introduced. During this process it became clear that, while there were occasions when the operator had a genuine need for functionality that was very similar to that which they already enjoyed, there were other occasions where they could be much more flexible. Transurban gave one of its senior managers the responsibility for ensuring that any remaining conflicts were efficiently resolved.

Decision making was focussed on controlling risk. Transurban was open to consideration of alternative technical and process approaches when these improved outcomes and controlled technical or program risks. This approach permitted flexibility and led to objective and easily understood decisions.

Outcome

The initial system implementation was completed in March 2009, within the delivery timeframe required by Transurban, and in time to support a major expansion of the system to support active traffic management on the southern portion of the CityLink roadway network.

The control system is operational, technical and support objectives were fully achieved and the new system has been successful in operation.

Transurban and Transdyn were able to exploit the work done on this project on further projects for customers in Sydney and New Zealand.

The practices employed on the Melbourne project for managing requirements, managing progress through the lifecycle and risk management were used as the basis for follow-on projects. Areas where further improvement was possible were identified:

- Providing training to customer staff on the existing product would have made the process of requirements elicitation more efficient. Such training is now offered routinely on similar projects.
- On the Melbourne project, it had only been possible to integrate the components of the system with each other and with external systems towards the end and this had meant that some issues had not been discovered until late in the process. For the Sydney project, Transdyn invested in enhanced development and test facilities. This included setting up servers at Sydney that could provide realistic external interfaces and that could be accessed remotely from Transdyn's development facility in California. This contributed to the Sydney project experiencing a significantly lower volume of integration and configuration issues that needed to be addressed in the latter stages of the project.

Conclusion

Traditional SE practices sometimes appear to assume that each system is being delivered from scratch. In reality, many systems are created by adapting existing systems and products, as was the case with this project. This case study demonstrates that SE practice can be successfully applied to adapting existing systems.

The "V" lifecycle is sometimes interpreted to require each phase to be completed before the next phase can be started. This case study demonstrates that the lifecycle can be adapted to retain rigorous and disciplined control of an incremental development process.

The modified SE processes contributed to making ensure that the system was delivered on time and fully met its requirements.

A rigorous approach to risk management was not only successful in managing risk – it also provided an objective and understandable approach to taking decisions.

A collaborative approach between the parties to the contract and some flexibility in adjusting and interpreting the contract was an essential ingredient in the success of the approach taken.

Systems Engineering Case Study #11 Network Rail Performance Modeling

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Systems Analysis

Background to the Project

Most of the case studies in this library describe the benefits of SE activities carried out as part of specific projects to improve transportation systems. This case study describe the benefits of a project carried out by Network Rail, the owner and operator of the UK's railway infrastructure, to refine and exploit models of the performance of the UK railway system. This case study shows the benefits of an aspect of SE at the enterprise level.

This case study is derived from a paper presented by Network Rail at the 2012 INCOSE International Symposium[7] and an interview with the leader of Network Rail's modeling team.

Description of the Challenges Faced

Most of the things that people want from a railway system, such as reliability, capacity and low journey times, are properties of the railway system as a whole. As the demands on railway systems increase across the world, significant sums of money are being invested in enhancing these systems. However the precise effects of technical changes to railway systems upon reliability, capacity and journey times are often not understood in full when these enhancements are specified. As a consequence, railway systems tend to evolve in response to problems that have already occurred rather than to forestall future problems and there is doubt about whether the best value for money is being obtained.[8]

Description of the SE Performed (Creating the Model)

In order to provide a more rational basis for taking investment decisions, Network Rail has invested in developing models of the performance of the whole railway system over a period of more than a decade. It started with a fragmented set of models and techniques which looked at localized aspects of railway performance. It integrated these into a whole-railway model which, using Monte Carlo simulation, could model not just behavior in the fault-free case but also the effects of faults and other perturbations on reliability. It developed this model to cover the range of items of interest to investment decisions and calibrated the model until it reached a high degree of fidelity.

Figure 1 shows the cumulative percentage of trains arriving at their destination within a specified time before or after their scheduled arrival date on part of the West Coast Mainline – the busiest mixed-use railway in the UK. The blue line shows performance forecast by the model and the red line shows actual performance. The close match shows how well calibrated the model is.

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[7] "UK Railway System Reliability - Modelling the Future – a Case Study", N Best, B Hyland, S Waters

[8] See, for instance, "Realising the potential of GB rail" by Sir Roy McNulty, published in 2011 by the UK Department for Transport

Notes:

- *The 10 minute "PPM" threshold referred to in Figure 1 is a "Public Performance Measure" figure used in the UK for reporting train service performance. It is not significant to this case study.*
- *Figures 1 and 2 are reproduced with permission from the paper by N Best, B Hyland and S Waters referred to above.*

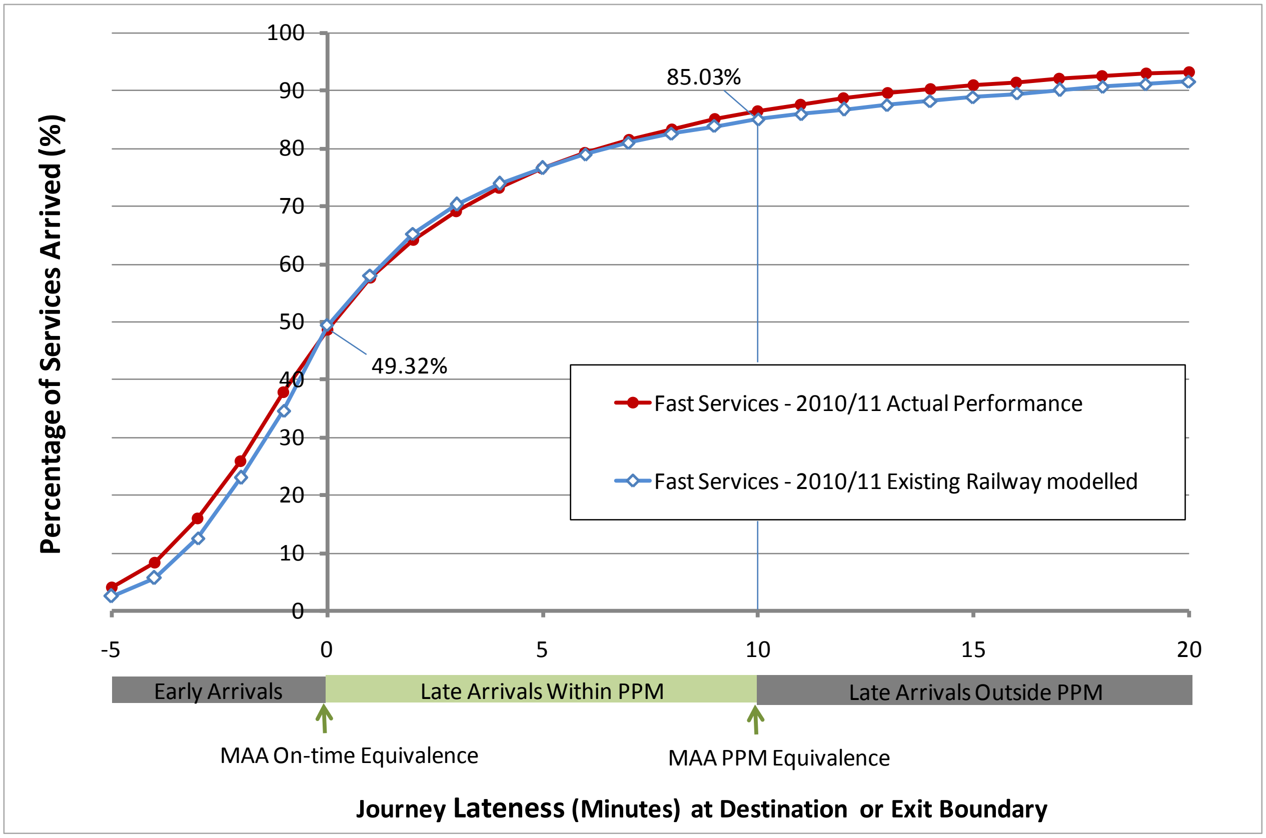

Figure 1: Forecast and actual distributions of lateness

Description of the SE Performed (Exploiting the Model)

Traffic on the UK network is increasing and, to explore the value of the model, it was used in a study to predict what the reliability of services on the West Coast Mainline would be if twice as many trains were to be run without changing anything else. Of course the model predicted what everyone knew would be the case, which is that reliability would fall to quite unacceptable levels. The model was then used to establish what would need to be done to restore an acceptable level of reliability with this level of traffic.

The companies that run trains on the UK's infrastructure are separate from Network Rail and the train companies pay each other penalty charges for delays that they introduce. Penalties are only calculated for delays of three minutes of more in order to reduce the administrative burden. As a consequence only delays above this 'attribution threshold' have traditionally been monitored and taken into account in reliability improvement actions.

Equipment failures are a major source of delays above the attribution threshold while driving style is a significant source of perturbations from the timetable which are below this attribution threshold.

Simplifying slightly (for more detail see the paper referred to above), the study team looked at the effects of:

(a) Addressing the source of delays above the threshold, principally by improving equipment reliability until the law of diminishing returns started to operate; and

(b) Doing this and addressing sub-threshold events as well.

The results are shown in Figure 2. The green line is the base case – increased traffic with no action to restore reliability. The red line is shows the results of case (a) and the purple line shows the results of case (b). Clearly, both the red and green lines are unacceptable while the purple line represents a level of reliability which is better than that currently experienced.

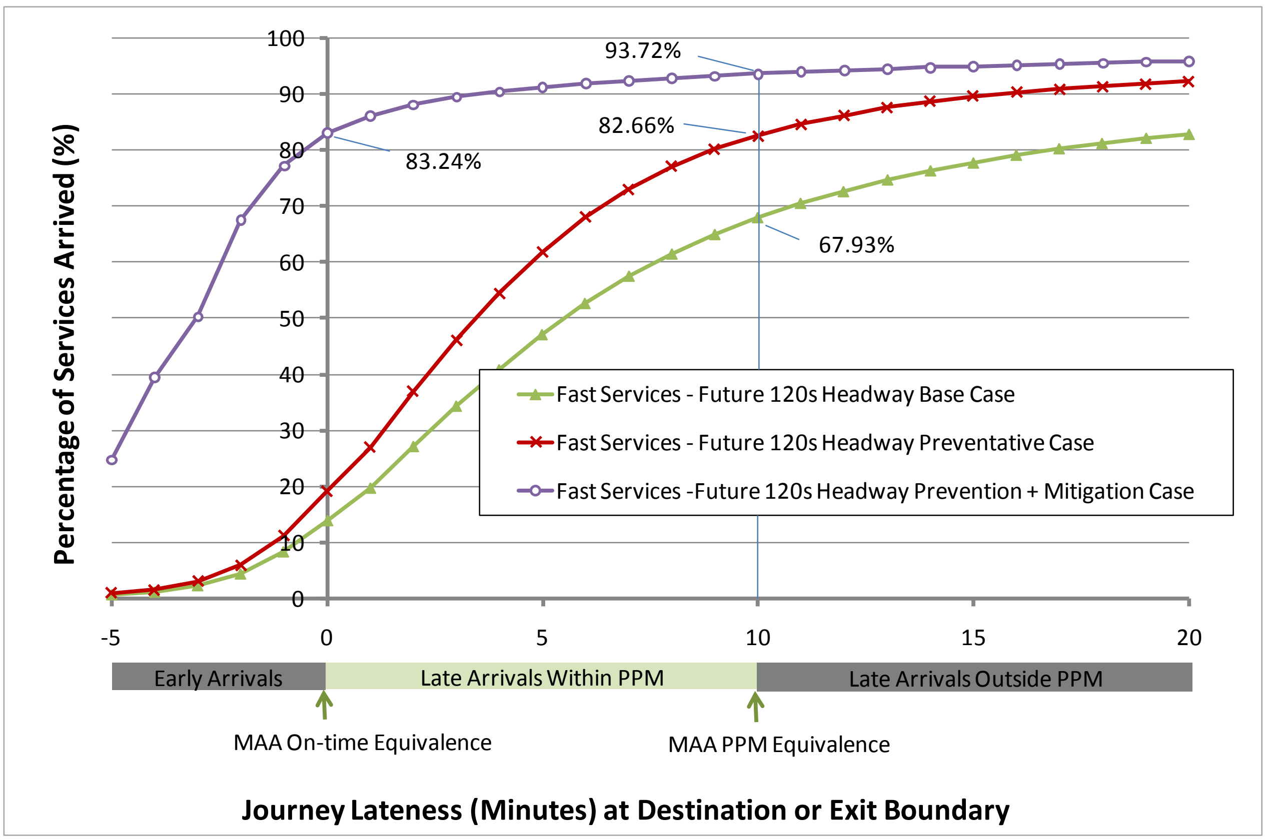

Figure 2: Forecasts for future reliability

Outcome

The two graphs together have acted as a catalyst for a transformation of thinking about railway reliability within UK railway companies. Figure 1 establishes the credentials of the model and underpins confidence in its forecasts while Figure 2 shows vividly that, by only motoring delays of three minutes of more, those running the UK's railways have been working to improve reliability without information on the causes of nearly half of all unreliability.

Following release of the results of the work described, there has been extensive interest from across the industry in translating these results into outcomes. Senior executives from across the industry have been directed to review the outputs at national industry task force levels and establish actions that can embed the findings into practice. As a consequence of this study, the UK railway industry is changing the way in which it collects data on delays and accelerating initiatives to help train drivers drive more closely to the timetable. There now a routine expectation that decisions between capital and operational expenditure and between alternative capital schemes will be tested using this model.

The model is now being adopted as the UK industry standard railway level analysis tool. This represents the transition of the industry to a systems-oriented approach with rational integration of analyses at the heart of decision making.

Conclusion

The case study has demonstrated that proven modeling tools which provide useful information in a comprehensible format can capture the attention of decision-makers and establish themselves as valuable decision-support tools. While the model has not been in use long enough to see the final benefits, there is every reason to expect that these will include delivery of increased performance and value for money.

Systems Engineering Case Study #12 The California High-Speed Rail Project

Acknowledgement

This case study draws heavily upon a paper entitled, "Entering a Brave New World: Applying Systems Engineering to American Infrastructure Projects", presented to the 2012 INCOSE International Symposium, held in Rome, Italy by Oliver M. Hoehne, Senior Engineering Manager at Parsons Brinckerhoff.

Keywords: Requirements management; Verification

Background to the Project

The California High-Speed Train Project will build an 800-mile (1,300-kilometer) high-speed railroad with operating speeds of up to 220-mph (350-kph). The new railway will connect the major cities of California, including San Francisco, Los Angeles, San Jose, San Diego, and Sacramento, with a trip time of approximately 2 hours and 40 minutes between San Francisco and Los Angeles. The first construction contract is expected to be awarded in 2013 and passenger service is expected to start on an initial section of the line in 2022.

Description of the Challenges Faced

The project must meet stringent requirements on journey time, capacity, reliability, safety and environmental impact, including requirements in federal and state regulations and California's proposition 1A: 'Safe, Reliable High-Speed Passenger Train Bond Act for the 21st Century'.

The project will build the first high-speed railroad in the US and the specific application of Systems Engineering concepts is also relatively new to the civil/structural aspect of railroad infrastructure projects.

Description of the SE Performed

Focus was placed on showing the benefits of Systems Engineering (SE) as early as possible and demonstrating that Verification and Validation (V&V) can help deliver a high quality product with fewer defects. The project V&V process will be performed throughout the project life-cycle, from preliminary engineering, through construction and final integration, testing, startup and commissioning.

The project V&V process follows the relevant provisions of ISO/IEC 26702 – "Systems engineering – Application and Management of the Systems Engineering Process" and ISO/IEC 15288 "Systems and Software Engineering - System Life Cycle Processes". The V&V process was tailored to the needs of the project and presented to the key stakeholders for buy-in and approval before being documented in a V&V management plan.

The V&V process was broken up into the following three phases:

1. Environmental review and preliminary engineering

2. Construction
3. Final integration, testing and certification

The final two phases had not started at the time of writing and this case study focuses on the V&V activities in the first phase.

V&V can only be successfully performed against a set of well-documented requirements. A significant amount of time was spent on ensuring the requirements were complete and correct.

The project started with **external requirements**. These are requirements that were either imposed on the project or which the project had chosen to follow. They typically represent federal or state law requirements, codes, standards and other authoritative guidelines.

From these, the project developed **internal requirements,** which describe the specific application of external requirements to the project and serve as a baseline for the design, construction and testing.

Internal requirements were captured in a professional requirements management tool. Traceability between external and internal requirements was achieved by embedding cross-references within the documents, supplemented by some additional traceability maintained by the requirements management tool.

Internal requirements were then analyzed, decomposed and apportioned to the contracts, to the engineering teams and to the subsystems. System requirements specifications for the project at the top level, for operations and maintenance, for infrastructure, for systems and rolling stock were created to document the decomposed and apportioned requirements. Relationships between contracts, engineering teams and subsystems were identified and documented in an interface register. The system requirements specifications and the interface register were managed using the requirements management tool.

The plans and preliminary design were verified against the identified requirements and interfaces. Validation will be performed later and is outside the scope of this case study.

Acceptance of this unfamiliar way of working by the project was facilitated by:

- the compelling need to demonstrate compliance of a complex system to federal, state and local regulations and to stringent safety and security requirements;
- strong support from senior management; and
- the adoption of a practical approach that factored verification comments into the existing review processes.

Outcome

The approach taken is allowing the project to progressively build confidence that all the external requirements will be met. The verification of early versions of the preliminary design revealed some areas where the design was not consistent with the requirements, allowing these to be put right in the final version before the costs of correction started to rise. The project has demonstrated that the preliminary design is consistent with the external requirements and has established a reliable baseline of apportioned requirements against which the detailed design and elements of the physical railway can be verified and validated.

Importantly, this has been done in a way that avoids premature design decisions and leaves the project with a wide range of options to choose from when seeking the greatest value for money. For example, as Hoehne explains in his paper, the steepest gradient on the railway has been limited in order to increase the project's choice of rolling stock.

The investment in establishing requirements and performing preliminary design at the level of the whole railway also allows the project to avoid duplicated work at the work package level.

Finally, the approach has assisted the different disciplines within the team to work together better and proved its value to engineers and managers who do not have systems background by helping them to get the job done.

Conclusion

The *potential* value of SE is greatest at the beginning of a project but the *actual* value is hardest to demonstrate at the beginning because the final outcome is so far away in time. This case study has demonstrated that it is practical to adopt an SE approach at the outset of a major rail project, before key design decisions are taken and construction contracts are let. This case study has also demonstrated that it is possible to integrate the SE activities efficiently with the engineering processes that are traditionally performed for such a project. It has also added to the evidence that adopting SE ideas at the start of a project can help the project avoid problems and exploit opportunities and thereby deliver significant benefits to stakeholders.

Systems Engineering Case Study #13 Denver RTD CAD/AVL and Radio Replacement

Keywords: Stakeholder Requirements Definition, Systems Analysis, Requirements Analysis, Configuration Management, Verification, Validation, Project Planning

Background to the Project

The project, led by Denver's Regional Transportation District (RTD), involved replacing entirely the existing Radio and Computer Aided Dispatch/Automatic Vehicle Location (CAD/AVL) systems used by Denver's fleet of buses. The project began in 2009 and at the time of writing this case study was near completion with equipment installed on 90% of the buses.

The need for the project arose because the existing CAD/AVL system, which was based on 1994 technology, was obsolescent and because the Federal Communications Commission (FCC) required Denver RTD to replace wideband (25 kHz) radio systems with narrowband (12.5 kHz) systems. The radio changes affected the AVL system directly and, as a consequence of the tight integration of CAD and radio systems, required changes to the CAD system.

This case study is drawn from an interview carried out in July 2013 with a senior member of the project team.

Description of the Challenges Faced

The key challenges faced by the project were typical of many projects and included obtaining funding, specifying accurate requirements and selecting technologies and products that met these requirements and delivered value for money. Clarifying user needs was a particular challenge, requiring significant effort.

Description of the SE performed

SE was applied to all phases of the project, beginning with the development of user needs and requirements at the start of the project. A concept of operations was prepared based on existing operational practices and an evaluation of new requirements.

The project team embarked on a review of related experience, talking to other agencies to garner lessons learned, and found this to be of significant benefit.

Approximately 1,200 requirements were developed over an eight-month period. A requirements review was undertaken to validate as early as possible that the requirements were correct.

The evaluation for the options for the radio system took one-half year, and eventually RTD decided to join a State-wide voice radio system involving the implementation of standard and upgradable technology as the best value based on total cost of ownership. A cellular radio system was selected for data transmission.

Technical specifications and contract documents were developed from the requirements so that the project could go to the market with a high level of confidence that RTD was asking for the right things. The process for selecting between offers was designed to obtain best overall value and considered not only price, but also technical compliance and the proposed solution. Before final selection, vendors were shortlisted, and the project team interviewed other agencies who had used these vendors' equipment.

Following final vendor selection and contract award, the project went through a design review process to establish that the vendor's design met the requirements before implementation started. Metrics were established to allow Denver RTD to monitor the degree of compliance with requirements. Factory acceptance testing and site acceptance testing were carried out to verify and validate the system prior to final acceptance.

A pilot implementation had also been planned to further validate the system in limited operation before complete system-wide implementation. As a result of the regulatory deadline for reducing the bandwidth of the radio channels, full system-wide implementation of the CAD/AVL system had to proceed without completing the pilot, but the processes followed thus far provided a sufficient level of confidence that the full implementation could proceed without undue risk.

Configuration management practices were used to manage project software, data and documentation. Requirements were tracked from development to implementation, test and acceptance.

A systematic process was employed for on-board installation and comprehensive Quality Control was used for these installations.

Outcome

The project was completed within budget. The FCC's timetable for reducing the bandwidth of the radio channels could not be met but the project was able to demonstrate enough progress as this deadline approached to convince the FCC to extend the deadline and then was able to meet the extended timescales. The project had to start system-wide implementation before pilot implementation had completed to make the necessary progress. There was risk inherent in doing this but the investment in SE processes mitigated this risk and the roll-out occurred without any significant disruption to operations. In fact RTD experienced significantly fewer problems on this project than it had on other projects of similar complexity and magnitude.

So a project which was exposed to the risk of both regulatory difficulties and operational disruption was steered on a course that avoided both mishaps and satisfied all stakeholders. The systematic process employed for the on-board installation assisted in making progress by ensuring that problems were promptly addressed as they arose.

The success of the project has led to a change in Denver RTD's philosophy for project management to include the system engineering process. Other project management changes have been progressing in parallel, including more rigorous configuration management, governance and technology management.

The SE approach used allowed the project team to meet reasonable schedules with minimal project changes and within budget. The requirements management approach resulted in demonstrably close adherence to requirements, so that it was clear that the project had delivered what it had set out to deliver. The overall procurement process allowed Denver RTD to obtain better value for money and reduced risk to both Denver RTD and the vendor.

Conclusion

The success of the project thus far has validated the approach and processes used, which are now being used by other projects. The project performance was found to be significantly better than that of similar projects, and this was attributed to the approach and processes used.

Systems Engineering Case Study #14 The Pasadena Adaptive Traffic Signal System

Keywords: Stakeholder Requirements Definition; Requirements Analysis; Verification; Transition; Validation; Risk and Opportunity Management

Background to the Project

Traditional traffic signal systems cycle the signals through one of a number of pre-programmed patterns, each suited to different traffic conditions and traditionally selected according to a time of day schedule. If traffic is disrupted, significant manual intervention is required from the operators in order to select a more appropriate pattern, or to modify a pattern 'on the fly'. Adaptive traffic signal systems have the ability to react to perturbations and perform this pattern generation.

This case study concerned a project initiated by the Department of Transportation for the City of Pasadena to install a pilot adaptive traffic signal system in a part of the city where traffic is regularly disrupted by several railroad crossings and to cope with traffic flows to and from events at the Rose Bowl stadium.

The project was started in 2011 and the system became fully operational in March 2013.

Description of the Challenges Faced

The introduction of new technology into an organization is always associated with risk. When procuring systems, the City of Pasadena must always obtain and be seen to obtain value for money on behalf of the taxpayer. The project had a diverse set of stakeholders to satisfy, including the police and fire departments and several transit agencies, in addition to the City's traffic signal operations and maintenance divisions, many of whom were unfamiliar with SE concepts.

Description of the SE performed

The project followed the sequence of activities in a typical 'V' diagram:

- A concept of operations was developed to clarify who would be involved with the system and what the project was trying to achieve.
- After consultation, functional requirements were established for the system and used to derive a technical requirements specification against which proposals were invited. When drawing up these documents, mandatory requirements were separated from desirable requirements. An effort was made to avoid 'overspecification', that is, to avoid including requirements that went beyond what was necessary to meet the users' needs.

- A request for proposals was issued and responses were evaluated initially to ensure all mandatory requirements were met. Required responses were not simply ‘comply’ or ‘not comply’; a written explanation was required of how each requirement would be satisfied, and the evaluation team confirmed whether or not the response complied with each requirement. An overall assessment of value for money was then made by the evaluation team, by considering both cost and the number of desirable requirements met. A supplier was then selected.
- The supplier was required to integrate their system with a traffic simulator before deployment in the field. This allowed the operators to test and fine tune the signal timing parameters prior to installation in the field. This integration unexpectedly revealed faults in the software used in the existing signal controllers (not the new controllers supplied with the adaptive system), which had gone unnoticed for some years. This showed the benefits of the more thorough testing that is possible with simulation compared to field testing, in revealing problems that are triggered by a low frequency combination of events.
- Verification testing was performed, first with the simulator and then on the deployed system, to confirm that every technical requirement was met.
- A validation exercise was carried out after system verification, to establish whether or not the user needs were met. This included comparing journey times and delays with the new system operating, and comparing the same metrics against measurements with the original signal timing operating.

The SE practices used in these activities were matched to the nature of the project.

A risk management plan was prepared at the outset. A register of risks was maintained and mitigations put in place to minimize those risks. For example, because accurate data with low latency is essential to the correct operation of the system, the communication system was configured to avoid potential problems in this area.

Outcome

The project was delivered on time and within budget. After site preparation and simulation testing, the deployment was completed without significant hitch within four days, an unusually short period for systems of this sort.

The system met its requirements and was found to deliver significant improvements in journey times and delays compared with the previous system. The system’s ability to cope with perturbations was put to the test when a traffic lane was unexpectedly closed for maintenance shortly after the system’s deployment and it responded as expected.

The stakeholders were not explicitly asked to confirm their satisfaction but, as they would not hesitate to register dissatisfaction and did not do this, their satisfaction may be inferred.

The avoidance of ‘overspecification’ maximized the number of suppliers who were able to bid, since the requirements were truly functional and did not assume specific design elements, providing confidence that value for money was being obtained.

However, the fact that the system can cope so well with variations in traffic conditions without manual intervention by the operators has resulted in some degradation of the ability of the operators to cope with emergencies. To overcome this, additional operator training is proposed in order to maintain competencies.

Conclusion

As in many other cases, the benefits of SE were enjoyed through the absence of unwanted surprises: a project associated with non-negligible risk was delivered smoothly, according to plan and successfully. The attention paid to requirements and risk meant that the system's specification and requirements matched the underlying needs and the systematic and progressive approach to verification, deployment and validation resulted in the orderly removal of the remaining faults.

Although this initial application of SE principles was undoubtedly a success, it was not beyond improvement. Taking a broader view of the system and paying more attention to the effects of the technical system on people and procedures could have foreseen the need for additional training at an earlier stage and would be recommended for future projects.

Non-Transportation Case Studies

Systems Engineering Case Study #X1 Construction of a Simulator for the Detroit Edison Fermi Nuclear Power Plant

Keywords: Requirements analysis; Systems Analysis; Architectural Design; Interface Management; Verification; Validation; Configuration Management; Project Control; Information Management

Background to the Project

This case study concerns the construction of a simulator for the Fermi nuclear power plant, which was owned and operated by the Detroit Edison company. The project started in 1988 and completed in 1993. This is self-evidently not a transportation case study but it provides useful context for the transportation case studies in this library.

The US Nuclear Regulatory Commission (NRC) required at the time that every operating nuclear power plant should have a working simulator. This simulator had to be of very high fidelity: it had to include a complete replica of the operational control room and it had to simulate the manner in which the plant performed and the timing of events two within a 3% margin of accuracy. Without such a simulator, a plant would have to cease operations, incurring costs of several million dollars per day for the operator.

The NRC had given notice that the simulator for the Fermi plant was inadequate and Detroit Edison therefore had to replace it in order to avoid closing the plant. The ABB Corporation was contracted to build a new simulator.

This case study is drawn from an interview carried out in May 2013 with a senior member of the project team.

Description of the Challenges Faced

The fidelity requirement was extremely challenging. From this flowed many hundreds of detailed requirements to match individual parameters of the operational plant.

Where possible, simulation was based upon the underlying physical behavior of the elements of a plant. The motion of the moving parts of a valve would be simulated on the basis of the forces acting on those parts and their masses, for instance. That required the involvement of specialists in many engineering and scientific disciplines and so a large multidisciplinary team had to be formed and coordinated.

The technology available at the time provided limited processing power and communications bandwidth and considerable ingenuity was required in order to deliver the required functionality within these constraints. As an example, there was insufficient bandwidth to drive control room dials by having the simulation computer continually calculate and retransmit the required reading. To overcome this, when a dial had to be moved, the simulation computer would calculate a final reading and the profile by which the dial's reading would be adjusted over time in order to reach that final reading and then transmit both to the controller driving the dial.

The simulator had to simulate accurately thousands of control loops, valves and other equipment and integrate many different computers using different operating systems and often incompatible interfaces.

The Engineering team had to define and simulate failure modes that had not been experienced and, it was hoped, would not be experienced in the operational plant.

The plant itself was undergoing changes during the duration of the project and the simulator had to accurately track all these changes.

Description of the SE Performed

Requirements were defined by the customer, negotiated and refined during the tender process and then embedded within the contract. All subsequent changes were subject to contractual agreement.

The parameters of the operational plant which underpinned the detailed requirements were compiled into a structured database, using a commercial database tool.

A domain-specific modeling language was created[9] and a single, integrated model of the simulator was constructed.

Regular inter-disciplinary meetings were held to ensure that all team members were following consistent approaches and working towards the same objectives. These meetings were also used to ensure that no team member made a change that would affect other team members, without working the implications through with the affected party first.

The hardware and software of the simulator was placed under configuration management as well as the data and model described above. The software build tools had the ability to regenerate any previously-built version of the software.

The system was designed for changeability, to accommodate and reflect changes in the operational plant.

The simulator was subjected to a rigorous series of factory tests and was required to operate without failure for six months before acceptance.

Outcome

The project took longer than planned, partly as a result of the need to incorporate changes. However, it was delivered in time to allow the Fermi plant to continue operating without interruption.

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[9] This project started before SysML had been created and during the period when UML was emerging.

Some detailed functional requirements were found to be infeasible with the technology available and alternative ways of meeting the underlying need were negotiated. The simulator as delivered provided the functionality and fidelity required for certification by the NRC.

The simulator was operated until 2006 and then retired only because the hardware components were obsolete and could not be replaced.

Conclusion

The project was at the very boundary of what was possible with the technology at the time. The complexity of the system and the number of disciplines involved made it impossible to deliver without adopting SE principles and it would have been unthinkable to try to do so. The long service life of the system demonstrated that it was fit for its purpose and maintainable and meant that the customer maximized the return on the considerable investment that it made in the system.

Although the project started 25 years before this case study was compiled, in some ways it still provides a pointer to the future for transportation projects. The nuclear sector was driven to adopt SE approaches from its birth by the complexity of the systems that it was building, the huge costs of failures – even of failures with no safety implications – and a stringent regulatory regime. As these same pressures build for transportation projects, we can see that SE will become, indeed is becoming, a normal part of business for these projects also.

The case study is also a useful reminder of the depth of experience which has been gained in other sectors and which is available for the transportation systems engineer to draw upon.