**DEVELOPING AN INTEGRATED SYSTEMS PERSPECTIVE OF ENGINEERING PROJECT MANAGEMENT**

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# Abstract

Engineering projects can be subject to significant complexity that often manifests on a systemic level. Therefore, following a literature review a conceptual view for managing engineering projects through an integrated systems perspective has been formulated. This framework is explored through a case study investigation of a complex infrastructure development project at a UK university involving equipment manufacture in USA. The case study is based on critical analysis of the project, which involved the refurbishment and upgrade of an existing large laboratory to allow installation of a new high-pressure experimental facility. The research advocates moving beyond the traditional iron triangle view of projects thereby allowing the project manager to leverage existing best practice including engineering methodologies and social-based levers. Managers can refer to the insights and activities described to provide options and strategies for reducing project risk and achieving wider benefits beyond the primary outputs of the project.

**Keywords**

Engineering projects, integrated systems, planning and control, project performance, social dimensions.

# Introduction

The subject of project management is increasingly informed by a multidisciplinary and systemic approach that seeks to provide new insights into this field (Chinowsky, 2011). Indeed projects need to be effectively and efficiently managed across many industries and in a diverse range of organisational circumstances (Burke, 2001). In the construction sector (Hendrickson, 1989), there are major building works projects that are predicated on structured project management, which is needed to ensure multiple areas of project activity, for example, from finance, resourcing, design, construction scheduling, service installation and commissioning, are coordinated to meet the client brief through provision of new or modified infrastructure. Project management itself has been researched widely and from multiple perspectives. There are theoretical studies that examine how different tools and techniques can be applied to support the project management process (Jacob and Kwak, 2003) and there are conceptual studies that evaluate the underpinnings of project management (Whitty, 2011). Conversely there are empirical studies that examine project strategies from project case study research (Akkermans and van Helden, 2002) and how such findings can then be applied to different project environments. Project management is also encapsulated within recognised management standards, such as PMI’s project management body of knowledge (PMBoKTM) in USA (PMI, 2008), and in the UK there is the PRINCE2TM approach (OGC, 2009). These methodologies provide overall frameworks to guide those involved with projects and ensure projects benefit from practitioner insights.

Project management can in some ways be considered a mature discipline that has been investigated widely from a theoretical perspective and used to support many successful projects. However, some projects continue to fail (Kappelman, 2006). The success of research and development projects has been found to be highly sensitive to technological uncertainty (Sadeh, 2000). Information systems projects can have a particularly high failure rate as reported by the Standish reports (1995 and 2009), for example, often through a combination of budgets being exceeded along with missed deadlines and schedule slippage or through a failure to meet user requirements. Information systems can fail on a technical basis, or the required technical outputs may be delivered but the systems still fail due to a lack of acceptance by the user community. Consequently, there are challenges that remain in the development of useable and adaptable approaches that can be efficiently deployed by practitioners to ensure effective project delivery.

The causes of project failure can be contingent on certain project characteristics related to internal and external variables and in engineering projects this has been connected to three contingency variables, which include the precise way in which failure was defined; the type of project; and the stage of the project in its life cycle (Pinto and Mantel, 2000). Indeed the so called ‘Big Dig’ (Ring, 2000), which involved provision of a much needed major underground arterial road system through central Boston in USA was delivered at a cost of approximately $15Bn, approximately seven times the original budget. Whilst the project has undoubtedly helped ease congestion in the city, the level of financial expenditure when compared to original estimates would nevertheless appear to indicate a significant failure within the project. Consequently, it can be observed that a project may exceed budgetary or schedule estimates, or it may not deliver exactly the required quality but over an extended timeframe the project may eventually be considered a success.

The construction of Heathrow’s Terminal 5 facility, which was a major airport development project in the United Kingdom, was completed both on schedule and within budget. However, the initial opening of the terminal building suffered from a number of problems, such as issues connected with the baggage handling system and this included inadequate provision of baggage handling staff to operate the system (Brady and Davies, 2010). Many of the identified problems, whilst not necessarily being major on their own, did nevertheless contribute to a disastrous initial period of operations for the terminal at the airport and there was a resulting perception that the construction project was a failure. Consequently, viewing these problems from a broader viewpoint and for example, designing the entire baggage handling system and operations systemically would have helped to mitigate such project risks.

Furthermore, construction of the Sydney Opera House is reputed to have cost around fifteen times the original cost estimate (Flyvbjerg et al., 2002) and yet many people would argue this building has been a fantastic success for Australia as an iconic structure and through helping to promote the country internationally and as a tourist destination. Although admittedly this success may not have been predicted immediately after the building was completed and this success has only been revealed over a long timeframe. Consequently, using a broader or systemic range of factors, such as using a longer timeframe, or wider set of business outcomes, to measure project success would appear to have merit. Furthermore, studies have indicated that project success may be aligned with many contributing factors, such as the organisational environment, the project manager’s characteristics (such as management style and qualifications), the flexibility of management approach employed, and the level of organisational learning (Dvir et al., 1998). These studies point to engineering projects being less like idealised and linear chains of activities and can instead be more accurately characterised as complex systems, where there are many factors that ultimately contribute to whether the project objectives are delivered.

Viewing projects systemically allows a broader consideration of underpinning factors that can ultimately contribute to project success, and such a holistic approach needs to link the project management processes with engineering systems and crucially also with the social (or networked) dimensions of projects. Consequently, this paper will explore the management of engineering projects through developing an integrated systems perspective and Exhibit 1 provides a summary of the research methodology employed.

**Exhibit 1**. Research methodology employed.



**Literature Review**

Projects need to be controlled according to schedule, cost and quality/performance criteria and any systems related viewpoint should include this fundamental feature of project management (Kerzner, 2003) as well as the need for robust risk management (Besner and Hobbs, 2012). Indeed within the construction industry there has historically been a time/cost trade-off to ensure that project quality can still be achieved and a three dimensional time/cost/quality trade-off has also been reported (El-Rayes and Kandil, 2005). This case highlights how such an approach can be used to help support decision-making in highway construction and rehabilitation projects. Moreover, Rodrigues and Bowers (1996) have previously advocated moving beyond traditional project management through developing system dynamics models to support decision-making in projects.

As part of a holistic view of project management there will need to be integration of managerial practice with the technical delivery function and this includes an appropriate consideration of the knowledge dimension of projects (Bourgeon and Devinney, 2010). This can have a significant bearing on delivery of project outcomes through ensuring technical activities are controlled according to a relevant and effective engineering methodology (Philbin, 2008). For example, the use of concurrent engineering approaches in the construction sector (Angelides, 1999), and latterly integrated project design or IPD for complex infrastructure projects (Kanagaraj and Mahalingam, 2011). Moreover, engineering project management needs to include appropriate risk management approaches that accommodate the technical complexities (Riggs and Brown, 1994), such as through the FMEA (failure modes and effects analysis) process (Carbone and Tippett, 2004).

The social dimensions within a project environment can have a significant bearing on project outcomes and an integrated systems view needs to accommodate organisational issues including cultural norms, levels of reciprocity and leadership qualities of the employees as well as the level of trust and social capital within the project (Cheung et al., 2012). Traditionally project management takes account of hard systems and the technical realities of projects but delivery of project change initiatives also requires adequate capture of the social dimensions in order to be effective (Metcalfe, 1997), such as the role of senior management and also the motivations of staff involved in the project. Indeed the level of collaboration within project teams can have a significant impact on project performance (Chiocchio et al., 2012). Consequently, undertaking practical steps, such as improved team meetings and a greater level of learning opportunities for project staff should help underpin project performance through creating an enhanced collaborative environment for the project.

Project-based organisations can be viewed as specific scenarios for organisational learning and Koskinen (2011) has systemically analysed learning as part of a feedback loop. In this view the process outputs are defined by the project contract that contributes to the user requirements, which the project manager is tasked to deliver and as part of associated problem solving within the project. The feedback loop itself could involve two-way discussions between the project staff and the client that leads to revision of the user requirements through more detailed consideration of the engineering implications of the project. The process inputs include project planning as well as existing levels of expertise and knowledge held by the project team and where appropriate, the client and suppliers/contractors. Finally within this framework, the process throughput involves interdependencies between the project manager, project team members and the various activities and processes required in order to facilitate delivery of the user requirements. This perspective provides a useful conceptual discussion of the merits of considering projects through a systems lens. The implication being that projects provide a range of opportunities for learning by those involved with project design and delivery, and therefore adequate planning and capture of this learning on an individual level can contribute to enhanced learning on an organisational level. For example, through systematically recording the outcomes of key decisions and technical discussions throughout the project and then subsequent analysis as part of the project lessons learnt stage upon completion of the project.

In terms of project success factors, Dvir and Shenhar (2007) advocate a holistic view of project management, where project performance can be incorporated within five dimensions:

1. Project efficiency: This relates to meeting project budgetary and schedule requirements.
2. Impact on the customer: This relates to achieving the stated requirements for the project, including customer benefits, satisfaction and arising loyalty.
3. Impact on the team: This relates to the impact the project has on the team members including the levels of satisfaction, retention and the resulting personal growth.
4. Business results: This relates to the outcome of the project in terms of any return on investment, market share or growth that is achieved.
5. Preparation for the future: This relates to how the project deliverables result in new technologies, new markets and new capabilities.

This assessment and measurement framework adopts a systemic view of projects. It seeks to move beyond the traditional iron triangle through capturing the wider benefits that may arise. Achieving project delivery according to time, cost and quality constraints is still important but inclusion of this holistic set of metrics allows both tactical and strategic implications to be considered across both short and longer timeframes.

Through building on the literature review it can be observed that project performance can be a function of three contributing systems, which are: process system; engineering system; and networked system. The process system (PS) includes standard project planning and controls, which ensure the required schedule, cost and quality parameters are delivered as well as project risk management undertaken. The engineering system (ES) includes artefacts related to the technical content of the project and is therefore focused on delivery of technical outputs arising from the engineering design methodology. Finally, the networked system (NS) is predicated on the project context including networks, connectedness as well as social, cultural and leadership factors. Therefore, the research hypothesis is based on the premise that pursuing a project strategy and supporting activities according to these three areas and throughout the project lifecycle will (systemically) underpin effective and efficient commissioning, design and delivery of engineering projects. In order to validate this hypothesis, a case study investigation has been undertaken and the findings from the study are provided according to the three project system areas.

**Case Study Investigation**

The case study investigation was based on critical analysis of a three-year infrastructure development project at a university. The project involved the refurbishment and upgrade of an existing large laboratory (having dimensions of 20 metres by 5 metres) along with installation of complex M&E (mechanical and electrical) services to house new high-pressure experimental research equipment. This equipment was required as part of the establishment of a new research institute at a UK university. The equipment was designed for plate impact experiments to be conducted as part of research on how different metallic materials behave under pressures in the gigapascal (GPa) range (Isbell, 2005).

The project was led by the university, which although had significant experience in facilities refurbishment and construction projects did not have a track record in commissioning and delivering new experimental facilities of this type. There was significant technical risk that the equipment would operate at the required pressure levels in order to support suitably demanding experimental conditions. Due to the need to operate at high pressures using a pressurised gas system there was also significant safety risk to be considered for the facility. Furthermore, although the university operated an established project management process this did not extend to supporting the development of the engineering requirements for the facilities provision. Additionally, at the beginning of the project there was a deficiency in organisational mechanisms to support the relational or social context of the project. For illustrative purposes, Exhibit 2 (adapted from Department of Defense, 2001) provides a summary of the system design process employed within the infrastructure development project, including details of requirements capture as well as the initial and detailed design stages.

## Exhibit 2. System design process for infrastructure development project.



The case study investigation involved reflective analysis by the author on the activities that were carried out during the infrastructure development project as well as discussion of the problems that arose and how they were alleviated. The project was initiated in 2008 and completed in 2011, which resulted in the provision of an advanced research facility suitable for high-pressure shock physics experiments. The project involved approximately 60 man-years of effort (roughly 20 man-years per annum). The following analysis is provided according to the three project system areas together with a brief consideration of the resulting project performance.

**Process System**

The process system (PS) can be related to the management standard used within the project. In the case study the three-year project was managed according to the recognised PRINCE2TM management standard that involved use of standardised project documentation, including, for example, a project brief and project initiation document (PID) as part of project initiation. These documents were approved by the university’s portfolio review board (PRB) and there was a supporting business case also developed. The business case linked the project to a wider initiative to establish the institute at the university, which was funded by an industrial organisation. This business case included calculation of the net present value (NPV) for the expected investment by the company using a discounted cash flow technique, where the industrial funding was contingent on the university undertaking the project in order for experiments to be carried out on the new high-pressure research facility. The infrastructure development part of the project was funded by the university, whereas the equipment procurement was funded by the main industrial partner.

Extensive planning was undertaken at the early stages of the project and this helped to reduce technical risks encountered later in the project. Planning included resource profiling and budget estimation, which was undertaken at two separate points at the beginning of the project. Initially there was a very approximate planning activity carried out to provide rough order of magnitude (ROM) costs and schedule requirements for the project. Then an engineering feasibility study was commissioned, which involved an independent structural engineer working with a quantity surveyor to assess the structural feasibility of the project as well as a more detailed view of the project cost and schedule envelope. Project delivery involved the use of traditional project tools, such as Gantt charts to plan and control the project schedule, a project risk register for capturing and monitoring project risks as well as project budget and cost reports to ensure project finances were kept under control.

Project governance was implemented through a project board that was chaired by a project director from the university. The project director provided overall leadership of the project but day-to-day activities were managed by two project managers. There were two project managers due to the project being a joint university/industry initiative, where the project manager from the university managed the renovation of the laboratory and upgrade of M&E (mechanical and electrical) services. Conversely the project manager from the industrial company managed the procurement and manufacture of the high-pressure equipment.

**Engineering System**

The engineering system (ES) can be related to the technical activities undertaken within the facilities development project, which included the requirements capture, design, installation and testing of the experimental facility and related equipment. In this regard the project involved a significant level of design work and safety case development as the experimental equipment was required to operate at high pressure, under safe conditions, and within a laboratory of specified dimensions (i.e. there were engineering constraints on the facility). Initial design activities were based on the aforementioned feasibility study, which had assessed the suitability of the laboratory to accommodate the high-pressure equipment as well as the initial interface requirements for the required M&E services.

An important part of the design work in the project included the use of the failure modes and effect analysis (FMEA) technique (Philbin, 2010) to ensure technical risks were captured from the early part of the project and then the necessary process controls were included in the final design. This was also a crucial part of developing the safety case for the new facility. During initial design meetings there were many viewpoints given from the technical staff involved in the project and there were sometimes difficulties encountered in reconciling the conflicting perspectives. However, the use of the FMEA process provided an overall structure to support such project discussions. From a practical perspective, FMEA worksheets were used to formally capture technical information related to the facility design, including infrastructure specifications and operating conditions for the high-pressure equipment.

The FMEA process identified that the failure mode with the highest risk priority number (RPN) was a potential breech of the high-pressure pipework (see Exhibit 3). Consequently, the design had to include a range of features to ensure such a breech would not occur. Such features included the incorporation of pressure release valves and emergency venting pipework (stainless steel pressure line) that was connected to the high-pressure breech unit of the equipment. The RPN metrics were derived from an assessment of the severity of the potential effect of the failure along with likely occurrence of the effect in combination with the level of difficulty in detecting the failure. The use of this systematic approach allowed all the potential failure modes to be captured, which provided confidence to the project team and wider stakeholders that the safety risks were being adequately controlled.

The project also included detailed systems integration for the facility. This was because the design and refurbishment of the large laboratory (in UK) was being carried out in parallel with the design and manufacture of the high pressure equipment (in USA). This parallel nature of the project added an additional layer of complexity, since the laboratory had to have a complex set of M&E services installed prior to the eventual installation of the equipment. Such services included extensive small power for diagnostic equipment (such as high-speed cameras, lasers and piezo-electric sensors), several three-phase power supplies for related equipment (such as a compressor, gas booster/intensifier and vacuum pump), fibre-optic cabling for data transmission, dedicated gas venting and extraction units and associated pipework as well as high-pressure gas delivery lines connected to a pressurised gas bottle storage facility. These services were specified as part of an overall systems level design process that detailed integration of the various services with the equipment, which included taking account of how the M&E services would physically connect to the equipment as well as the compatibility of the services. The design work was completed in accordance with the European Union’s Pressure Equipment Directive (PED) (EU, 2003), thereby ensuring the facility and equipment would be designed to meet recognised levels of safety and operational performance.

## Exhibit 3. Representative failure mode identified by FMEA process (Philbin, 2010).



**Networked System**

The networked system (NS) involves the social or soft dimensions of the project. The project had a project management team as well as project governance framework as specified by the project management approach employed (PRINCE2TM). However, at an early stage it was realised that a technical working group needed to be formed to take forward the project work. The technical working group was chaired by the project director and included both the university project manager and industrial project manager and various other staff. The working group represented a multidisciplinary team approach and consequently all the main functional areas related to the facilities project were represented in the working group. This included the consultant engineering team (namely mechanical engineer, electrical engineer, structural engineer and quantity surveyor), technical staff (industrial staff as well as technician and academic staff from the university), safety engineers as well as other management representatives.

The technical working group met throughout the project although significant work was needed in the design stage and equipment manufacture stages, which necessarily involved the most intensive phases of work. Initially when the working group met there was an apparent lack of agreement on the technical direction of the project. Some technical staff involved also felt that their perspectives were not being adequately accommodated and other team members were somewhat frustrated. At this stage it could be observed that the working group had yet to establish the social norms and patterns of working practice and there may have even been a lack of trust. However, further technical working group meetings were held. Although the meetings had clear direction, such as through careful consideration of meeting objectives and agenda items, there was nevertheless significant opportunity for the technical staff involved to voice their opinions and ensure their views were understood. This approach helped to build up levels of trust and an understanding that the university and industrial partner would have reciprocal benefits (and risks) arising from the project. Moreover, this enhanced social capital position helped the project to move forward when confronted with major technical challenges, such as the need to achieve PED certification of the US manufactured equipment. This certification had not previously been secured for equipment operating at such a high pressure and consequently an extended series of design cycles had to be carried out. This involved computational modelling of the gas pressure levels likely to be observed within the equipment along with finite element analysis (FEA) and assessment of the corresponding structural integrity of the pressure vessel.

The multidisciplinary team approach adopted by the technical working group was also a feature of the FMEA process, which is predicated on the need to consider potential failure modes from all relevant functional areas. Consequently, brainstorming sessions were held by the working group to develop FMEA worksheets for the design of the overall facility as well as for the installation and eventual operational stages of the project. It could be observed that the effective functioning of the multidisciplinary team was facilitated by the levels of trust that had been established between the project team members.

In addition to the technical working group, the two project managers also managed their own project teams. The university-based project manager was responsible for managing the suppliers and contractors required to upgrade the laboratory through installation of the new services. Conversely, the industrial-based project manager was responsible for overseeing the relationship with the equipment manufacturer in USA. Due to the geographic separation of the manufacturer there were initial challenges associated with managing this activity, however, through a combination of site visits to USA supplemented by regular teleconferences and videoconferences it was possible to build up social norms and effective working relations with the manufacturer. Such norms of practice included an understanding by both the manufacturer and industrial/university team of what was expected from each organisation as well as an appreciation by the manufacturer of the quality levels required to ensure the equipment could be certified to the PED standard in order to allow operation in the United Kingdom.

**Assessing Project Performance**

The project resulted in the establishment of an advanced facility for the university, which had involved a complex series of tasks with a significant level of project risk (including financial, organisational, technical, and major safety risks). Although the project was delivered within budget and the technical quality level of the facility was achieved, the project did not however meet the original schedule requirements. The project was completed after three years instead of the originally scheduled two years. Consequently, through considering the traditional iron triangle of project parameters, it could be observed the project may have failed. However, it is useful to consider the project outcomes against a broader (i.e. systemic) set of success factors, such as those developed by Dvir and Shenhar (2007), which are provided in Exhibit 4.

## Exhibit 4. Assessment of project outcomes from the case study according to the

## five project dimensions developed by Dvir and Shenhar (2007).



**Engineering Project Management Framework**

The proposed management framework is provided in Exhibit 5, which incorporates the influence of the three project system areas. The project system areas contribute throughout the project lifecycle in order to ensure stakeholder needs are met and sustainable project benefits delivered. The systemic basis of this approach is geared towards recognising the wider success factors and business implications for projects although the central need to deliver according to schedule, cost and specification requirements is not diminished.

**Exhibit 5**. Integrated system perspective of engineering project management.



The integrated system perspective links together the process system (efficiency driven) with the engineering system (content driven) and the networked system (context driven), which collectively support delivery according to the project lifecycle (including project inputs and outputs). The project inputs include capture of stakeholder needs, external factors and engineering requirements, and the outputs include delivery of the project requirements in addition to a holistic view of the wider benefits arising. Although the three system areas collectively contribute to project delivery they also result in corresponding benefits (efficiency, knowledge, or social) and this further emphasises the broader interpretation of project benefits (i.e. moving beyond simply measuring against the project iron triangle).

The framework leverages recognised best practice for project management (e.g. as part of PRINCE2TM, or the PMBoKTM) along with the need for a particular technical focus that will be driven by the features of a given engineering project along with the crucial need to consider the social elements of a project that is contingent on the context and organisational setting. These systems need to be effectively coupled and ultimately it is the responsibility of the project manager to ensure that project systems are operating effectively and efficiently through managing stakeholder needs, motivating project teams and delivering required performance levels. In much the same way that a conductor has to lead the different sections (namely string, brass, woodwind and percussion instruments) of an orchestra to achieve the overall level of music quality and not simply the sound of a particular instrument or section.

**Conclusions**

This paper has provided a discussion of project management in the context of the continuing need to address the question: Why do some projects fail? A comprehensive literature review has been used to focus on the systemic nature of projects and through building on this wider interpretation of engineering project management, whilst not diminishing the importance of the so called iron triangle, an integrated system perspective has been developed. This conceptual framework provides a logical and adaptable approach that can be used by engineering project practitioners. The framework has been examined through a case study investigation including assessment of project performance through a holistic set of success factors (Dvir and Shenhar, 2007), thereby providing a contextual background into the practical steps that can be undertaken during implementation of the framework in engineering projects.

Within the engineering and construction industry there are established processes in place to support the planning and delivery of projects for the built environment. There are recognised engineering techniques and processes used by construction and architectural companies. Whilst effective in regards to planning and managing design and construction, such approaches only partly meet the need of client organisations when faced with a physical infrastructure development that includes multiple layers of complexity. In regard to the case study investigation, this complexity was manifest in several areas. The design and installation of the upgraded laboratory and services in the UK had to occur in parallel with the design and manufacture of the high-pressure equipment that took place in USA. This led to significant risk that the engineering specifications for the laboratory services and equipment would be within tolerance to allow overall system integration to be effective. Other areas of complexity and risk included the need for ‘first-of-kind’ PED certification of such a piece of high-pressure equipment as well as the demanding safety case required for the facility.

The case study included evaluation of the project outcomes and although the schedule requirements were not met it can be observed that a holistic treatment of the project would indicate significant areas of success. However, a potential failing of a deviation beyond the iron triangle as the sole criteria for project success factors could lead to a greater level of subjectivity associated with assessment of the overall level of success (or failure) of a project. Moreover, over how long a timeframe is it reasonable to consider the overall success of project? Even if an extended timeframe is used to consider the eventual level of project success, the resulting assessment will still need to be of some use to the stakeholders involved so as to contribute to appropriate lessons learnt from the project or eventual best practice.

A limitation of the paper is with the qualitative approach employed and the nature of the reflective analysis by the author as part of the case study investigation. However, the conceptual framework developed builds on an extensive literature review that takes account of multiple perspectives of engineering project management and seeks to position the framework in connection with existing best practice. Furthermore, the case study allows a contextual exploration of the activities carried out according to the three project system areas of the framework in order to highlight the merits of the approach. This helps to underscore the practitioner relevance of the findings from this research paper.

Future work is suggested on application of the integrated system perspective to different engineering applications in order to highlight differences and potential improvements when compared to other project management approaches. It is also suggested that the systemic nature of projects is further explored through, for example, the use of systems dynamics to improve project planning and control processes.

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Simon P Philbin is Associate Director of Enterprise Projects at Imperial College London in the United Kingdom and Visiting Fellow at Imperial College Business School. In his current role he directs corporate development projects across the university and prior to this he was the founding Programme Director of the Institute of Shock Physics at Imperial. He holds a PhD (Brunel University) and BSc (University of Birmingham) both in Chemistry and an MBA with Distinction (Open University Business School). Dr Philbin has authored/co-authored over forty journal and conference papers across several areas including project management, systems engineering, university-industry research collaboration, and chemistry. Along with being a certified Project Manager (PRINCE2 Practitioner) and Programme Manager (MSP Practitioner) he is also a Fellow of the Royal Society of Chemistry and a Member of the American Society for Engineering Management.