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Dualities and dilemmas: Contending with uncertainty in large-scale safety-critical projects

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Abstract

Uncertainty is a fact of project life. Most decisions that are made on a safety-critical project involve uncertainty, the consequences of which may be highly significant to the safe and timely delivery of the project. Based on interviews with project management practitioners on 9 large-scale civil nuclear and aerospace projects, we explore how uncertainty emerges, and how project management practitioners identify, analyse and act on it. We make three important contributions. First, we present three approaches - structural, behavioural and relational - that individuals and organisations can adopt when contending with project uncertainty. Secondly, we characterise nine dualities at play in the management of project uncertainty and thirdly we identify key differences between how civil nuclear and aerospace project managers confront project uncertainty, which have important implications for how projects might be organised in both these industry sectors. Drawing attention to the structural, behavioural and relational approaches to project uncertainty and the tensions that manifest themselves in each approach should enable the project management community to make progress in environments of high uncertainty where situations are often complex, rapidly changing and confusing, and yet where, for reasons of safety, failure is not an option.

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Keywords

Project management; Safety; Uncertainty; Aerospace; Nuclear

1. Introduction

Project management as a field of study has moved from a deterministic view of projects as concrete entities delivering well-defined objectives on time and to budget (Meredith & Mantel, 2010) to a more expansive understanding of projects as complex emergent problems that often proceed under high levels of uncertainty (Havermans, Keegan, & Den Hartog, 2015; Morris, 2013; Winter, Smith, Morris, & Cicmil, 2006). In this new world, the individuals tasked with delivering projects must navigate their way through myriad uncertainties – in scope, stakeholder demands, organisational and technological complexities – acknowledging that uncertainty is a fact of project life (Böhle, Heidling, & Schoper, 2015; Cleden, 2009; O'Connor & Rice, 2013).

The challenges presented by uncertainty are magnified in large-scale safety-critical projects where project failure may result in reputational damage, loss of public confidence and long term physical damage; witness the severity of the environmental and reputational damage to BP caused by the Macondo Well blow-out in the Gulf of Mexico in April 2010 (US Chemical Safety Board, 2015). Safety-critical projects are defined as those where safety is of paramount importance, and where the hazards to be controlled can harm the environment, personnel or the public (Wears, 2012). Reiman, Rollenhagen, Pietikäinen, & Heikkilä (2015) argue that safety-critical projects constitute a distinct context of projects as, for example, the hazards of nuclear power generation (which involves the heating up of water, either directly or indirectly by nuclear reaction in order to generate electricity by passing steam through a turbine) differ greatly in magnitude from the hazards of a typical construction site. In safety-critical projects, such as those to decommission former civil nuclear assets or develop aircraft made of exotic composite materials, project managers have to deliver ultra-safe project outcomes. They must achieve this despite operating in a complex socio-technological environment replete with many layers of regulation; and within constrained budgets and finite numbers of skilled human resources. Uncertainty in these large-scale projects is an ever present, if often unwelcome, companion. It arises from the earliest stages of project inception, when uncertainty about scope and delivery mechanisms may be overwhelming, to the project end-game when new facilities must be commissioned in a timely manner. Amidst these uncertainties, project managers must remain calm and in control; demonstrating confidence and competence, whilst wrestling with an ever changing landscape of unknowns and risks to successful project delivery.

There is a growing body of literature on the management of project uncertainty (cf. Martinsuo, Korhonen, & Laine, 2014; O'Connor & Rice, 2013; Perminova, Gustafsson, & Wikström, 2008; Saunders, Gale, & Sherry, 2015). However there are only two prior studies of uncertainty in the specific context of safety-critical projects: a historical review of the 1940's Manhattan Project to develop the atomic bomb (Lenfle, 2011) and an exploratory study of project uncertainty in civil nuclear and aerospace sectors by Saunders et al.(2015). Given the importance of safety-critical industries to modern life, and recent calls in the project management literature to replicate rather than reinvent project management research (Reich et al., 2013), our contribution here is to validate Saunders et al., (2015) exploratory study on a larger and more purposefully selected data set. Based on semi-structured interviews with 30 project management practitioners on 9 large-scale safety-critical projects, ranging in value from £25Million to upwards of £10Billion, it addresses two key research questions:

RQ1: What are the different approaches adopted by project management practitioners[2] when faced with project uncertainty in safety-critical projects?

RQ2: Are there cross-sector differences in how uncertainty emerges, is analysed and acted on between civil nuclear and civil aerospace projects?

The next section of the paper introduces the theoretical context of the study. Subsequent sections describe the study design, its findings and their implications for how projects can better deal with uncertainty.

2. Theoretical context

Uncertainty is an interdisciplinary field, distributed across a range of disciplines from mathematics to economics, psychology and philosophy. Taxonomies of uncertainty have been formulated (Kerwin, 1993; Smithson, 1989) and scholars have compared and contrasted different scholarly perspectives on uncertainty in pursuit of a richer understanding of it, how it arises and how it may be effectively controlled (Osman, 2010; Perminova et al., 2008; Smithson & Bammer, 2009).

Grote states that "*uncertainty is understood in its most basic form as not knowing for sure due to lack of information or ambiguous information*" (Grote, 2015,p.272). Uncertainty will always be present in projects (Atkinson, Crawford, & Ward, 2006; Winch & Maytorena, 2011). However, what exercises scholars is how project managers understand it, how they represent it (either quantitatively or qualitatively) and whether it can be eliminated, must be tolerated or can actively be harnessed to the project's advantage (Smithson & Bammer, 2009).

[2] Project management practitioner is defined as a lead person in the project function; "a term which may be interpreted as including project team members, project team leaders, project managers and project directors" (Crawford, Morris, Thomas, & Winter, 2006, p. 723)

Addressing these questions, researchers have provided definitions of project uncertainty (cf., (Hillson, 2002; Perminova et al., 2008; Ward & Chapman, 2003), identified the different sources of uncertainty (Atkinson et al., 2006; Martinsuo et al., 2014; Saunders, Gale, & Sherry, 2016; Ward & Chapman, 2003) and discussed a variety of approaches to tame it (Browning, 2014; Chapman & Ward, 2011; Pich, Loch, & De Meyer, 2002).

Ward & Chapman (2003) argue that the project risk management process should be extended to incorporate uncertainty. They have also developed a first pass approach to improving estimation in projects (Chapman & Ward, 2000), a framework for managing stakeholder uncertainty (Ward & Chapman, 2008) and the PUMP process for managing project uncertainty throughout the project lifecycle (Chapman & Ward, 2011). Atkinson et al. (2006) support this approach, arguing that uncertainty needs to be addressed at each stage of the project with particular emphasis on the setting of objectives, clarifying the priorities of different performance objectives and making the ownership of uncertainty explicit.

More widespread and profound changes to the methods of the project manager in managing uncertainty are discussed by (Pich et al., 2002; Vidal, 2015; Weick & Sutcliffe, 2007). Cleden (2009) advocates identifying early warning signs of uncertainty through a combination of forecasting, scenario planning, anticipation strategies and fast-learning loops. He argues that uncertainty can be tamed provided project managers remain mindful at all times of the presence of uncertainty – a view echoed by Weick and Sutcliffe (2007). Pich et al., (2002) propose 'learning' and 'selectionism' as two alternative approaches to managing highly uncertain projects. Learning implies a continual monitoring of the project environment in search of unknown-unknowns accompanied by rapid problem solving and changes in direction to the project as new information emerges. Selectionism involves carrying out multiple parallel explorations and experiments into specific areas of uncertainty on the project and making a final decision on which is best during or after the process. More recently, Vidal (2015) elucidated three different stances –that of the engineer, the craftsman and the gardener- that project managers might adopt when confronted with messy, uncertain and ambiguous situations. The choice of stance adopted is contingent on the nature of the uncertainty being faced, the context in which the project is being undertaken and the world view of the individual confronting the uncertainty. So, in the stance of the engineer, uncertainty is caused by a lack of information and consequently acquiring more information or data, performing more calculations or testing can resolve the uncertainty. In contrast, the craftsman stance views uncertainty as ambiguity (where information can have multiple plausible interpretations) best managed using sense-making processes that seek to reduce this ambiguity. The third stance is that of the gardener. Here the world is too complex to understand and fully control so the only solution is to act consistently on the small issues which in turn should mitigate any larger uncertainties.

Other recent work on approaches to managing uncertainty (Martinsuo et al., 2014) identified three means of managing project uncertainty at the portfolio level; via rational, structural and power/culture based methods. Examples of rational approaches include planning, controlling, budgeting and measuring performance on projects. Structural approaches incorporate the governance of projects and the use of effective policies and power/cultural aspects address project values such as embracing failure and rewarding perseverance. Moving closer to the focus of this paper, Saunders et al. (2015) posited four approaches to uncertainty that are adopted by project managers in *safety-critical contexts* – structural, behavioural, relational and orientating. The structural approach encompasses project processes and routines whilst the behavioural approach is centred on attitudes such as flexibility, optimism and being constantly mindful of the presence of uncertainty. The relational approach stresses the collective nature of responding to uncertainty and the importance of communicating with key stakeholders including sponsors, clients and industry regulators. The fourth and final approach – an orientating one – concerns the use of navigational metaphors and aids to help project managers conceptualise and confront uncertainty. However, this earlier study was based on a small set (n=8) of interviews. Addressing this limitation, our aim in this present study is to explore how 30 individuals involved in 9 large-scale safety-critical projects in civil aerospace and nuclear sectors, identify, analyse and act in the presence of uncertainty.

3. Methods

Our research design is a qualitative one, based on semi-structured interviews with 30 project management practitioners involved in 9 safety-critical projects in the UK. Civil nuclear and aerospace sectors were chosen ahead of other safety-critical sectors such as oil and gas, as these two sectors although both highly regulated and manifestly safety-critical in nature, are subject to different commercial and regulatory pressures. Additionally, the timescales at which projects proceed are often considerably shorter in civil aerospace than in civil nuclear. The 9 UK based projects were purposefully selected to include projects from both sectors, drawn from six different organisations and to reflect two types of project –"new build/new product introduction projects" and "maintenance projects". Due to the commercially sensitive nature of the two sectors, extensive and time consuming negotiations were required to gain access to all of the projects. As a consequence, project selection was based on the authors' extensive industrial contacts. Despite this, collectively the nine projects do form a representative and balanced portfolio of projects across both sectors. The projects are coded CN1 to CN5 for the civil nuclear and CA1 to CA4 for the civil aerospace projects. Table 1 provides a description of each project: its type, lifecycle stage, approximate budget and respondent roles. Further details of the projects cannot be provided due to confidentiality restrictions. Respondents were chosen by intensity sampling; a form of purposeful sampling where individuals are selected who are experts about a particular experience (Morse, 1994).

On each project, respondents encompassed a variety of project roles (from technical to commercial) and operated at differing levels of seniority.

Project Title	**Code**	**Project Description**	**Industry Sector**	**Project Type**	**Respondent Roles**
Intermediate level waste (ILW) storage facility	CN1	Complete and commission a new storage facility capable of storing ILW nuclear material for 100yrs Budget £100's Million. Lifecycle stage: Design	Civil Nuclear	maintenance	Project Engineering Manager Project Director Project Controller Commercial Manager
Reactor life-extension project	CN2	Develop safety cases to extend the life of existing nuclear reactors. Budget: £10's Million/yr Lifecycle stage: Delivery	Civil Nuclear	maintenance	Group Head of Project Technical Lead Sub-project Manager Sub-project Manager
Development of new civil nuclear test facilities	CN3	Commission and make operational two new nuclear test facilities for nuclear materials from both ends of fuel cycle. Budget £10's Million Lifecycle stage: Commissioning	Civil Nuclear	new build/new product introduction	Senior Project Manager Project Manager Risk Analyst
Nuclear new build project	CN4	Construction of new nuclear power plant Budget: £Billions Lifecycle stage: Feasibility	Civil Nuclear	new build/new product introduction	Programme Manager Programme Manager Programme Manager Programme Manager
Decommissioning of specific elements of nuclear power station	CN5	Safe removal and clean-up of material from former nuclear power station Budget: £10's Million Lifecycle stage: Delivery	Civil Nuclear	maintenance	Project Manager Commercial Manager Client account director
Development of new gas turbine engine	CA1	Design and delivery of new gas turbine engine for wide bodied airliner. Budget: £100's Million Lifecycle stage: Design	Civil Aerospace	new build/new product introduction	Subsystem Programme Manager Subsystem Programme Manager Deputy Programme Executive
Retrofit of safety-critical assemblies to in-service aircraft	CA2	Design and retrofit of safety critical assemblies to in-service civil airliner. Budget: £10's Million Lifecycle stage: Delivery	Civil Aerospace	maintenance	In service Programme manager Operations Shift Manager Project Team Leader
Phased upgrades to in-service aircraft	CA3	Implement a number of change packages on two variants of in-service large civil airliner. Budget: £100's Million Lifecycle stage: Delivery	Civil Aerospace	maintenance	Deputy Programme Executive Chief of Subsystem Integrated Project team Leader Integrated Project team Leader
Development of new test facility	CA4	Design, construction and commissioning of aircraft assembly test bed. Budget:£10's Million Stage: Commissioning	Civil Aerospace	new build/new product introduction	Programme Executive Project Manager

Table 1: Description of the nine case study projects, together with respondent roles

The interviews were undertaken at the project sites between March and Sept 2014. Each interview lasted approximately 1 hour. Two to four respondents per project were interviewed to minimise individual respondent bias. During the second part of the interview respondents were asked to describe specific instances of uncertainty that had arisen during the course of their project (In part one of the interviews respondents had provided background information on the project, and discussed the sources of uncertainty in the project, as reported in Saunders et al., 2016). The interview prompts (Figure 1) were based on Daft & Weick's (1984) theory of the organisation as an interpretive system and included questions about how the instances of uncertainty had emerged, how they were analysed and acted upon and what the impact on the project was.

Part Two

I'd like you to recall 2 instances of project uncertainty that have occurred on this project. Please would you talk me through these incidents.

- How did the uncertainty emerge?
- How was the uncertainty identified?
- Who were the main actors and what did they do?
- How was the uncertainty analysed and interpreted?
- What action was taken?
- What was the outcome of this incident of uncertainty on the project?

Figure 1: A copy of the interview prompts

Asking respondents to provide detailed accounts of specific uncertainties enabled the building of a closer rapport with the respondents, which in turn generated richer accounts of these complex and uncertain situations. In total, 47 vignettes of project uncertainty were recounted, with two typical vignettes shown in Table 2.

Vignette of Project Uncertainty	How uncertainty emerged	How it was analysed	How it was acted on	Impact on project
Migration of project scope from in-house design to externally designed single stage contract (CN1)	The original project scope included a large in-house design activity. This design work was well underway, when suddenly the project team were told by the project sponsor to stop work and start the project again at the concept stage with a revised scope and different delivery mechanism.	Engineering Project Manager described it as "like the fog coming down" with no clear way forward apparent. Once emotional denial of change was overcome, a structured process was employed, using requirements capture, value engineering and optioneering.	A new concept for the project was worked out which was less costly, lower impact and more optimised. Then a new project was launched.	Delayed programme by a number of months.
Uncertainty over choice of technology to use for a nuclear material transfer flask (CN3)	Senior Project Manager had an intuitive sense, based on past project experience that the current flask design might not be fit for purpose. He initiated in-house calculations to verify transfer flask capability.	Results were analysed by the Senior Project Manager and engineers. Results confirmed that transfer flask is not currently fit for purpose.	Information passed up to the Board to make a decision on whether the flask must be redesigned with additional lining. The flask is not required until 2017, so there is time to make this decision.	No immediate impact on the project. There may be a redesign requirement which would lead to additional project costs.

Table 2: Two example vignettes recounted on CN1 and CN3

These vignettes were transcribed, anonymised and uploaded into QSR NVivo 10. The vignettes were then analysed using template analysis; an iterative technique which involves the use of a coding template which is generated either *a priori* or from a preliminary analysis of a subset of the data (King, 2004). The analysis process comprised three steps:

1) Preliminary data coding of a random subset of the vignettes was undertaken using the 4 conceptual approaches (structural, behavioural, relational and orientating) from Saunders et al. (2015) as the *a priori* high-level themes.

2) New second order themes that emerged from the subset of vignettes, such as whether uncertainty emerged during an incident or through the outworking of a project process, and the tensions between, for example, a data and judgement driven analysis of uncertainty and a proactive versus reactive response to uncertainty were then

organised into clusters. This enabled an initial coding template to be drawn up, incorporating both the approaches to managing uncertainty and a number of tensions or dualities that were observed in how uncertainty emerged, was analysed and acted upon.

3) This coding template was applied to the remaining vignettes, and was modified and refined as new clusters emerged in an iterative process. For example, during this process the relational and orientating approaches were combined, thereby reducing the conceptual approaches from four to three. This process culminated in the final coding template (captured in Figure 2 below), comprising three approaches and nine dualities. All 47 vignettes were then coded against this final template, generating a more comprehensive model for how project uncertainty is managed by practitioners and the tensions that accompany them.

Nodes

Name	Sources	References
Conceptual Approaches	0	0
Behavioural	17	55
Relational	16	38
Structural	17	35
Tensions and dualities	0	0
Analysis accepts uncertainty	14	17
Analysis denies uncertainty	4	4
Analysis is collective	15	25
Analysis is individual	1	1
Analysis_data driven	13	16
Analysis_judgement driven	5	7
Emerges by chance	0	0
Emerges by planning	8	11
Emerges via an incident	8	9
Emerges via project processes	11	14
Emerges_Project leaders are actors	13	23
Emerges_Project leaders are observers	1	1
Response is proactive	15	22
Response is reactive	3	3
Response privileges absolute location	4	5
Response privileges direction of travel	7	7
Responses are local	9	9
Responses are system-wide	5	8

Figure 2: Final NVivo 10 coding template

4. Findings

In total, 47 instances of project uncertainty were described in the 30 interviews; 23 from civil aerospace projects and 24 from civil nuclear projects. In the civil aerospace projects these incidents ranged from uncertainties in the choice of technical solution for an engine wiring harness, to unexpected failures on the engine test bed, to inabilities to communicate changed customer requirements to the project team. In the civil nuclear projects, uncertainties included difficulties in gaining clarity over the project scope, uncertainties in information on reactor designs, and a lack of understanding of the interconnectedness of key elements of operating nuclear power stations.

4.1 Conceptual approaches to project uncertainty

Perhaps to be expected in the highly technical, highly consequential environment of large-scale civil nuclear and civil aerospace projects, there was widespread adoption of ***structural*** approaches to the management of project uncertainty. Respondents in both sectors invoked key project processes, such as the project change board and gated reviews as triggers by which uncertainties emerged, were analysed and decisions made. Project uncertainty was quantified wherever possible, particularly in civil nuclear projects, using organisational norms, probabilistic scheduling (using P50 and P80 values) and Monte Carlo simulations, even though there was a tacit acknowledgement that the assumptions and figures underpinning these probabilistic techniques included elements of uncertainty in themselves. Contingency funds played an important role here in resolving this conundrum. Also captured was the structural importance of the test programme in the lifecycle of civil aerospace projects. In the test environment new components are introduced, theoretical analyses are scrutinised, minor adjustments made to optimise performance and engines (occasionally intentionally and expensively) damaged in pursuit of maximum learning about the system.

Here the entire project team responds to the drum beat of the test programme, which is paradoxically both reducing uncertainties as system maturity increases and simultaneously throwing up new ones in the form of unexpected test results or unanticipated component failures. In the civil nuclear sector the requirement to produce numerous safety-cases, allowing the current project status to be 'banked' at regular intervals provided a similar, if slower, rhythm for the projects.

In both civil aerospace and nuclear projects the dominant approach to project uncertainty was a ***behavioural*** one. Wrestling with uncertainty required flexibility, tenacity, resilience, decision-making skills and positivity, tempered with an appropriate level of caution. In the words of a Deputy Programme Executive (CA3), project managers should "*never underestimate the ability of the engine to tell us something which we didn't expect*." Many of these skills had been honed on previous projects and several respondents admitted that they were motivated by a fear of failure, which drove them to find, confront and resolve uncertainty. Managing uncertainty was also a collective, rather than individual endeavour with respondents acknowledging that no one person could resolve complex and unfolding uncertainties. Instead project managers drew repeatedly on teams of highly skilled and technically diverse specialists to minimise the risk of inadequately characterising an emerging uncertainty. There was also a requirement for high levels of trust and co-operation within these multi-functional, multi-organisational project teams, with consensual and collaborative problem solving required, even when this put the project team at odds with the host organisational culture; a challenge often exacerbated by sub-optimal contractual and incentive structures. This finding supports Saunders et al. (2015) argument that the capability of the project team and the wider project organisation are important determinants of uncertainty in the safety-critical context.

The third approach to managing uncertainty is a ***relational*** one. A collective response to uncertainties was observed using workshops and problem solving teams which typically involved external experts. These 'independents' were often technical experts whose skills and objectivity were required to reduce technical uncertainties. The engagement of the project supply chain was actively sought by respondents in this study, even if, as on the new nuclear build project (CN4) and the new aerospace test facility (CA4), key suppliers were reluctant to expose their detailed time-plans to scrutiny. In urgent situations, emerging uncertainties were quickly escalated to project director level where decisions could be made. In particular, the civil aerospace projects often thrived on the energy of firefighting emerging uncertainties, instead of proactively identifying uncertainties and putting in place sufficient resources to address them, before crisis point was reached and project delivery dates were at risk.

Stakeholder management was also central to the management of project uncertainty. In the civil aerospace sector, project sponsors were more sympathetic to the presence of uncertainty in projects, if they were made aware of it (i.e. there were no surprises). However communicating uncertainty to end customers (aircraft manufacturers or airline operators) was an often underestimated part of the management of uncertainty. In the civil nuclear sector respondents experienced greater challenges in gaining buy-in to realistically defined levels of uncertainty in the higher echelons of host organisations; evidence of this was observed at both ends of the nuclear lifecycle from new nuclear build (CN4) to the Intermediate Level Waste (ILW) storage facility (CN1). The relationship with external stakeholders such as the Nuclear Decommissioning Authority and the Office of Nuclear Regulation also had to be carefully managed. Failure to provide them with information in a timely manner could lead to a loss of confidence in the project, with potentially huge consequences for its future sanction and (or) licencing.

Within civil aerospace projects, there was only limited evidence of an ***orientating*** approach to the management of uncertainty. Respondents described "*shuffling the chairs*", "*travelling in hope*" and "*fumbling around in the dark*" but more as turns of phrase, rather than as a distinct approach to dealing with project uncertainty. In civil nuclear projects respondents also used a succession of travel metaphors but these metaphors also revealed important insights into the way in which the project uncertainties were managed, for example:

"*Projects start down multiple explorations – lots of pathways for the project and then at periodic intervals the emerging information and analysis is banked through the mechanism of a written safety case. Actually the safety cases are the project*" Group Head of Projects (CN2).

Within civil nuclear projects the orientating approach should not be discounted. However, given that there were only 9 references to this in civil nuclear project interviews in contrast to upwards of 30 instances of structural and relational and over 50 instances of behavioural approaches, it has been subsumed into the relational approach. The four conceptual approaches posited in Saunders et al., (2015) have therefore been rationalised into three – ***structural, behavioural and relational*** – with the relational approach expanded to incorporate not just people but also position, to take account of the orientating approach.

4.2 Dualities and dilemmas in contending with project uncertainty

Within the three approaches, nine dualities were identified based on observed tensions in how uncertainty emerged, was analysed and acted on by the respondents. Three of these nine dualities related to how uncertainty emerges, three to how uncertainty is analysed and three to how uncertainty is acted upon. The nine dualities are grouped around each of the three conceptual approaches to managing project uncertainty –structural, behavioural and relational generating a more comprehensive model (Figure 3) of how uncertainty unfolds and is responded to within these safety-critical projects. For example, in ‘how uncertainty emerges’ there is a structural duality in whether uncertainty emerges through an incident or through a process, a behavioural duality in whether it emerges by chance or through planning, and a relational duality around whether project leaders are observers or actors.

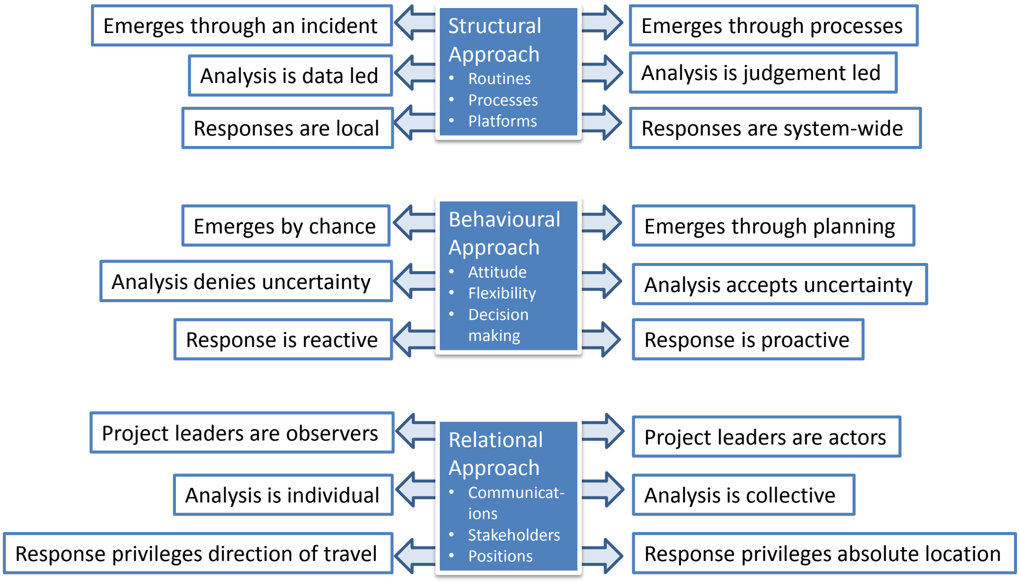

Figure 3: Dualities in how uncertainty emerges, is analysed and responded to in the three approaches to project uncertainty

Table 3 provides a brief definition of each of these nine dualities, showing that the dualities are, in most cases, not binary constructs, but are characterised by a spectrum of practices and behaviours.

Duality	**Brief Definition**
Emerges via incident vs Emerges via process	Does the project uncertainty emerge via an incident on the project (for example, the finding of unexpected asbestos in a nuclear decommissioning project) or does it emerge as a result of carrying out the regular and routine project processes?
Analysis is data vs judgement led	Is hard data or professional judgement privileged in the analysis of the project uncertainty?
Response is local vs system wide	Is the eventual solution to the uncertainty one which is local, pragmatic, incremental or in some sense suboptimal or is it one that is system (programme or organisation) wide and longer term?
Emerges through chance vs planning	Does the project uncertainty emerge through chance and good fortune or through good planning and the preparedness of the project team?
Analysis denies uncertainty vs accepts uncertainty	Is the presence of the uncertainty denied (for example, assuming that a technical fault is a one off rather than a precursor to a series of component failures) or does a mind-set of acknowledging uncertainty prevail?
Response is reactive vs proactive	Is the response to project uncertainty reactive in nature, or is the uncertainty proactively monitored so that contingency plans are ready to put in place should the need arise?
Project leaders are actors vs observers	Is the primary role of senior management that of an impartial observer, evaluating project decisions, or is their role that of an involved actor on the project whose actions and decisions

	may shape the emergence of uncertainty?
Analysis is individual vs collective	Is the process of investigating and analysing uncertainty an individual endeavour or is it more collective and collaborative in nature?
Response privileges the direction of travel vs absolute location	Do project management practitioners privilege responses to uncertainty that enable them to move forward in the right direction, rather than those that value absolute location and-exact status of the project at a particular point in time?

Table 3: Brief description of each of the nine dualities

4.2.1 Structural dualities in how project uncertainty emerged, was analysed and acted upon

Table 4 provides illustrative quotes of the three structural dualities – uncertainty emerges via incident vs process, its analysis is data led vs judgement led and the response is local vs system wide.

Structural Dualities	Illustrative Quotations Civil Aerospace	Illustrative Quotations Civil Nuclear
Emerges via an incident	"But almost immediately the product went into service [component x] began to fail, and we were all rather bemused as to why that was the case. "Deputy Programme Executive, CA3	"Asbestos was discovered when drilling through the structure. Staff immediately downed tools and stopped work." Account Director, CN5
Emerges via a process	"Each design gate asks a number of questions - tick box – so the team could eventually no longer prove the novel [subsystem] – they could not show the figures – suddenly became very uncertain and a very top issue. "Subsystem Programme Manager, CA1	"Having been asked to get a single stage contract for this project, we didn't have norms that we could use. Lack of norms became an uncertainty to us. So instead of running the risk model as we normally do ….. we ran the risk model with a much higher level of estimating uncertainty than usual." Project Director, CN1
Analysis is data led	"I try and be more structured and data driven in terms of making decisions." Deputy Programme Executive, CA3	"one of the things we have tried to do differently is to build a single integrated cost schedule risk programme, and we built it originally on a base schedule which says that if everything goes well, we can do it in these durations at this cost and the network is appropriate– challenging but sufficient. That gives us a deterministic completion date and also commensurate cost. We then apply our uncertainty. In addition to the uncertainty we then have the risks that are appropriate for our scope. So we apply the uncertainty to the base estimate, we then allocated the risks to the individual activities (with impact and probability) and then do bit of Monte Carlo to come up with impact of those risks on completion date and cost. This is a standard process. " Project Controller, CN1
Analysis is judgement led	"I went to talk to [x] who is a design person of long experience and seniority, and had an independent informal chat with him about it. After that I concluded that we would have to re-plan the project. "Team Leader project, CA3	"We got new data and there was higher weight loss than expected. In-fact it suggested that we could have exceeded the weight loss limit. We had to put an emergency safety case in place and it was on a judgement because in reality we did not believe the data. " Group Head of Projects, CN2
Response is local one	"I put a proposal on the table at this meeting, asking 'what is the minimum that we need to test?' And we decided that we could get the parts made quickly for development use only and test and this was the workaround. We also	"So I treated this [redesign] as a singular objective, and I didn't have the confidence that [company N] had the ability to design a solution, given their track record. So I formed a task force within my team to redesign the concept

	had to discuss how we could get the test done and on which engines as some of the engines are already on test. So again I asked 'what is the minimum we could live with in terms of numbers of engines to test?' This is how we put the plans together. " Cost Team leader, CA3	mechanical and electrical which was done within two weeks. It was redesigned, approved, procured, ordered and built and approved to operate in two months. So it took [Company N] two years to make it and we redesigned it and made it in two months. " Project Manager, CN5
Response is system wide	"Long-term this isn't feasible [to rig up the instrumentation at the new test facility]. It adds a lot of time and ties up expertise and knowledge and cost. And you lose your flexibility. ….. And this was all part of the business case, to say are we going to spend £x on the trailer and how many times would you have to ship an engine backwards and forwards to make it worthwhile. Four or five engines per year and it soon starts to pay back quite quickly." Programme Executive, CA4	"Should we carry on with what we've got and acknowledge that there would be a big commercial bun-fight at the end of it? And being the first contract is this giving us the behaviours that we want to see on the project? Should we terminate the contract -with potential big cost implications? Should we amend the contract? We did a series of pros and cons type analysis, with the project director and key stakeholders, construction director and the engineering director. We talked about removing elements of scope. But what we ended up with was to convert the contract from FIDIC to NEC target cost to try and get alignment with the other contracts." Programme Manager, CN4

Table 4: Illustrative quotations of the three structural dualities

The launching of a competitor product, in-service faults such as gearbox leaks, or broken sensors, and customer requests for change were all examples of uncertainty in civil aerospace projects that arose from a critical incident on a project. Unsurprisingly these incident driven uncertainties were more prevalent on maintenance projects, where the equipment is already in service but not yet optimised for routine aircraft operations. In contrast, on new product introduction/new test facility projects the uncertainty was more likely to emerge as a consequence of the execution of a specific project process, such as the gated review process or most commonly during the engine or aircraft test programme.

What is striking about the civil nuclear projects is that the great majority of the uncertainties described emerged via the outworking of specific project processes – for example the scheduling process on CN4 exposing uncertainties in the area of building inter-containment, or the building of the project risk model in the ILW storage facility project (CN1) which revealed an absence of organisational norms for the type of contract being adopted. There were examples of uncertainty in civil nuclear projects that emerged via an incident but these were much fewer in number (for example, higher than expected weight loss in the core of in-service nuclear reactors on CN2, and asbestos found in the building structure being decommissioned on CN5).

Possible explanations for this discrepancy between the two sectors could be the more tightly process bound environment of the nuclear industry compared with the more flexible approach in the aerospace sector. Nuclear industry project managers must always be seen to be following mandated processes and to be 'doing the right thing', whereas there seems to be more leeway for individual judgement and learning by trial and error in the civil aerospace project environment, with the engine/aircraft test programme providing a final safety check on all new technology and product development work-streams.

There was considerably less divergence between civil nuclear and aerospace projects in terms of the second duality – that of whether data or judgement driven processes were privileged in the analysis of a particular project uncertainty. In both sectors there was a preference for the use of data to underpin analyses of uncertainty and the use of logical processes to reach a decision on both its root cause and how to respond to it. Nevertheless, Table 4 demonstrates that data and judgement are not binary constructs, and several respondents described instances of uncertainty in which both data and judgement were applied in tandem in an attempt to address complex problems which often had several plausible root causes.

The privileging of data over judgement was in part influenced by the dominant engineering culture in the studied project teams, but was also a means of being able to justify the analysis to senior management and the customer/regulator alike. When analysing incidents of project uncertainty, practitioners face a dilemma between the need to produce hard confirmatory data to sponsors, customers and regulators and the oft-experienced difficulty of obtaining such data and the subsequent reliance on professional judgement and experience.

The third duality was that between arriving at a solution that was local versus one that was system wide. In both sectors there were a range of responses. At times an interim solution was adopted, enabling the project to maintain momentum whilst more robust longer term solutions were developed. This often necessitated a constrained or sub-optimal solution, that could be tested before decisions could be made on what longer-term, more resource-intensive solution was required. At other times, often after much wasted time and effort on finding a solution, a more comprehensive system-wide approach was taken. Project managers were also observed to implement solutions that gave the greatest benefit to the wider organisation, but not necessarily to the local project team. Such decisions were however only reached after much discussion and debate. The dilemma facing project management practitioners on safety-critical projects lies in knowing whether an incremental or longer-term, a local or system wide solution is more appropriate in acting on a specific project uncertainty. This is at best a difficult judgement call, and at worst a matter of trial and error learning from time consuming, expensive and failed solutions.

4.2.2 Behavioural dualities in how project uncertainty emerged, was analysed and acted upon

Table 5 provides illustrative quotes of the three observed behavioural dualities – chance vs planning, denial vs acceptance and reactive vs proactive.

Behavioural Dualities	Illustrative Quotations Civil Aerospace	Illustrative Quotations Civil Nuclear
Emerges via chance	"So next time I would make sure that we did this the same way. Last time I did it by luck but next time I will do it much more deliberately" Project Team Leader, CA2	NONE
Emerges via planning	"We've had this issue before on other test facilities …… It's something we are aware of, so we check for it from day one." Project Manager, CA4	"So as part of the project we have to deliver a transfer capability between two buildings. We have procured currently a flask based on a specification. It wasn't until last Friday when we did some advanced calculations on the capability of that flask, that the capability of that flask was brought into question. ………. I initiated these calculations." Senior Project Manager, CN3
Analysis denies uncertainty	"We spent the first few months in denial thinking that this was just a one-off and then it became a two off and it went on	"One contractor said 'we didn't actually read the tender as we were too busy'. But nobody here wanted to admit that there were problems

	and on." Deputy Programme Executive, CA3	in capacity in the supply chain. So the approach is that we will just muddle through the project and project timescale will just start to slip to the right. " Commercial Manager, CN1
Analysis accepts uncertainty	"One of the key characteristics of the role is the ability to deal with ambiguity and uncertainty. The reality is that week in week out there will be uncertainty arising. My engineering background means I like to know everything that there is to know about something. Over time I've got more comfortable with dealing with uncertainty. Sometimes it is gut feel and instinct; you just get a feel for the 3, 4 or 5 things I need to make sure are supported, coaxed along. The rest of the stuff will just happen." Deputy Programme Executive, CA3	"Based on a routine inspection – we got an outcome that didn't agree with the model. We have got a problem – panic. So we wrote an emergency safety case based on a judgement and that bought us 6months. I tasked someone in the team with this job. In that 6 months we set out 3 work streams to address the issue and basically one was to raise the limit a bit, second bit to look at data and reconfirm it was true, thirdly perform extrapolation to confirm – as everybody adds conservatisms. "Group Head of Projects, CN2
Response is reactive	"From a project management perspective your success indicators of costs, weight were brilliant. Then in a moment this was turned on its head and you suddenly had to find this resource when we thought we were finished and the whole regulatory impact of not achieving it was huge." Subsystem programme manager CA1	"If it's an uncertainty and we don't know what's going to happen we will just have to deal with it when the problem occurs." Sub-project Manager, CN2
Response is proactive	"At present it is a judgement call, but I cannot take my eye off it completely, so I keep giving it a knock every now and again, so that when it's needed I can resurrect the priority." Subsystem Programme Manager, CA1	"So a lot of the schedule uncertainty goes away when you are building confidence. The fact that there is uncertainty means that there are no absolutes at that point. So you have to start with establishing some assumptions. So we started to build the schedule and put assumptions around it. We validated these assumptions with other disciplines in terms of the interfaces. We had a lot of data coming out of [Project B], but the integrity of that data wasn't fully assured. We took the decision to take the data on face value, and put an assumption around it that it was based on [Project B] data. We then validated it in the supply chain. We gave it to one of the bidders and they worked with us to validate sections of the schedule so that we can extrapolate that to the rest of the schedule. It gave us a degree of underpinning." Programme Manager, CN4

Table 5: Illustrative quotations of the three behavioural dualities

There was more open acknowledgment from civil aerospace respondents that uncertainty often emerged in an unplanned and fortuitous manner. For example, on CA2, designers had prepared additional drawings of a key part, with a nominal hole that could be increased in size as required. So when an uncertainty in testing emerged and the holes were found to be too large, the project team could revert to the additional design drawings and only two days' time was lost on the project. Through good fortune, the supplier had not yet drilled the larger holes in the parts- otherwise the lost time would have been in the order of weeks not days. In contrast, strenuous efforts were made in the civil nuclear projects to plan for uncertainty; and to use the planning, contract management and other processes to drive out latent uncertainties in these large-scale safety-critical projects. On four of the five nuclear case study projects respondents described instances of uncertainty that had emerged in this way. And strikingly, none of the civil nuclear respondents reported instances of uncertainty that emerged by chance or good fortune – evidence of a concrete difference between the two sectors.

In civil aerospace projects there were several instances where uncertainty was denied, at least in the early stages of its emergence and analysis. There were also civil aerospace accounts that stressed the pervasive nature of project uncertainty within projects and the need for project managers to acknowledge it – however these were less common. More often it was assumed that a technical fault was a one off rather than a precursor to a series of component failures. The pressure of the project schedule also hindered the prompt identification of project uncertainties, with respondents hoping that a problem could be resolved before it needed to be escalated. These behaviours can slow reaction time on projects and cause issues to lie hidden, gradually growing in magnitude and consequence, until their presence can no longer be denied. Then individuals switch rapidly into a responsive, fire-fighting mode with resources mobilised, key stakeholders informed and myriad urgent actions taken to finally address the uncertainty. The difficulty with this approach is that it can be exciting and energising to work on an urgent problem, and more worryingly organisations often reward project managers who can heroically resolve problematic and pressing issues, without appreciating that it may be that same individual's initial denial of the issue that has led to the requirement for such a dramatic response. Such behaviour can be understood in terms of normalisation of deviance (Pinto, 2014) and can become an ingrained and culturally acceptable way of behaving.

Within the civil nuclear projects there was typically more acceptance of uncertainty within the project environments from the outset. There were only very few instances of uncertainty where the problem was denied or ignored by the project teams, with most respondents readily accepting project uncertainty and putting their efforts into resolving it as soon as possible. For example, the Group Head of Projects on CN2, when confronted with an unexpected situation in an operating nuclear reactor core, did not prevaricate, even though he did not fully understand the cause of the uncertainty. Instead, acknowledging the very high stakes involved, he immediately initiated a series of actions to characterise and quantify the uncertainty.

The dilemma facing organisations involved in safety-critical projects is to find a way of encouraging and rewarding these uncertainty accepting behaviours whilst also trying to reduce incidents of uncertainty denial. Modelling appropriate behaviour and rewarding the raising of uncertainty, as well as its heroic resolution might be steps in the right direction. Karl Weick (Coutu, 2003) recounts a powerful episode in military history when a Redstone missile lost control during testing. When one of the engineers admitted that he had caused the error, the lead scientist Werner von Braun sent him a bottle of champagne, rather than issuing a reprimand. Such stories stay long in the consciousness of organisations and their members.

The final behavioural duality concerns whether the response to uncertainty is reactive or proactive. In civil nuclear projects there was more extensive evidence of uncertainty being managed proactively, whether the nature of the response was to collect quantitative data or simply to ask questions. In civil aerospace, dealing with an uncertainty could be very reactive in nature, as articulated by one of the Civil Aerospace Sub System Programme Managers on project CA1 in Table 5. Here the project team quickly found themselves on the back foot, having to secure additional resources and even redesign whole elements of the project around one problematic subsystem. However there were also occasions where civil aerospace respondents kept a close eye on latent uncertainties in the project, which could not be resolved immediately but had the potential to derail future progress on the project. Here respondents were unable to resolve the uncertainty due to a lack of information; nor were they willing to ignore it and wait for it to result in a more complex and challenging situation. This tension between waiting and acting, between proactive and reactive behaviour is fundamental to the role of the project manager in dealing with uncertainty; yet is one where there is no single right answer, and it ultimately comes down to a complex judgement call underpinned by data, experience and intuition. These differing responses to uncertainty could also flow from how the uncertainties emerge and are analysed. An uncertainty that comes to light somewhat fortuitously, or whose presence is initially denied, is highly likely to lead to a response strategy that is reactive; one that is driven by events, rather than by anticipating them. In civil aerospace projects ‘the die is often already cast’ by the time the uncertainty is addressed, leading to fire-fighting and urgent, expensive reallocation of resources. In civil nuclear projects there is earlier acknowledgement and analysis of project uncertainties, engendering a more proactive organisational response.

4.2.3 Relational dualities in how project uncertainty emerged, was analysed and acted upon

Table 6 shows illustrative quotes of the three relational dualities – project leaders as observers vs actors, individual vs collective analysis and a response that privileges the direction of travel vs absolute location.

Relational Dualities	Illustrative Quotations Civil Aerospace	Illustrative Quotations Civil Nuclear
Project leader as observer	"Two [assemblies] had to be taken out of the development programme. The seniors knew all about it but weren't very good at flowing that information downwards. So, for the people involved in the supply chain, getting the parts in etc. it was all rumour and hearsay. You ended up taking a lot of flak from people underneath for not telling people what was going on." Subsystem Programme Manager, CA1	"There is a risk that we may need to tunnel in from outside, seal the joint and then backfill with concrete – so what's the probability of that and its impact on project. We are less good at paying attention to these risks, and it's not done by people sufficiently high up the food chain. We don't have buy-in at high enough level." Project Controller, CN1
Project leader as actor	"I was talking to the [supplier] CEO - so very senior level. I was asking him, looking for his commitment, has he got enough resource, his confidence levels…..So I was gaining my own confidence through the supplier, and I was able to communicate that to my seniors. We also did daily calls with the team on the ground, making sure we understood the exact status on the ground. ……. So I think it was about communication, about discussion, and about understanding." Programme Executive, CA4	"I know the technical people in the project – they are either glass half full or empty people. If you responded to every little minor perturbation the business would be getting a different answer every five minutes. So I provide a damper to it all. I try to realise which are important ones. I try to manage expectations. Everyone knows it is uncertain and there are challenges so what I try to do is to see what the important ones are and decide – do we stick with the same course or do we shift slightly. Rarely do we stop completely and change." Group Head of Projects, CN2
Analysis is individual	NONE	NONE
Analysis is collective	"So there was quite a significant team of people who were investigating it, the whole system." Operations Manager, CA2	"We do have to be careful to rank the consequences of uncertainty; we need to prioritise. Prioritisation is done with the safety-case officer but it's not an authoritarian approach, not prescriptive – more about openness with partners. We work better when we are more open. Whenever a question is raised I try to make sure that whoever has asked the question is satisfied with the answer. Typically these meetings have a dozen or so people round the table; none of whom are shy, all of whom are smart and only too quick to leap in if share concerns. We deal with it in an informal committee type way –consultative." Technical Lead, CN2
Response privileges the direction of travel	"When we test these parts in the engine – we think that will lower the risk but it won't – you'll get an understanding as you go down that journey - but you are travelling in hope" Subsystem Programme Manager, CA1	"While you've got uncertainty, what I'm always inclined to do is to show people all the little steps of success that we have achieved. There is no doubt that being able to pull the curtains off and go wow is a mass uplifter, but sometimes this means that you are inclined to ignore all the little successes. " Programme Manager, CN4
Response privileges absolute location	"I am by nature a planner. I like to see everything mapped out. I like to have a plan for short-term weekly, medium-term monthly and a long-term plan." Project team leader, CA2	"[The documents] are not fit for purpose. We had assumed those documents didn't need rework, so didn't build it into the program. Therefore we then had a long discussion with [the client] about who was right and who is wrong but we ultimately had to go back and redo this work. What we've learnt is, that, you know, all of our documentation has gone through a thorough rigorous check to make sure that we are up to date with modern standards, we are not going to trip ourselves up again" Project Manager, CN3

Table 6: Illustrative quotations of the three relational dualities

The role of senior management in identifying and acting on project uncertainty is the source of the next duality. Is the primary role of senior management that of an impartial observer, merely confirming project decisions, or are they an involved actor - a project insider - whose actions and decisions may shape the emergence of uncertainty? (Reiman et al., 2015) Or do they switch between these roles as the need arises? In the overwhelming majority of incidents described in this study senior managers (project sponsors, project directors etc.) were active participants as uncertainties emerged. On only one occasion did the senior management team remain detached from an issue; failing to communicate important changes to the project schedule to the Programme Managers. In most other incidences of uncertainty senior managers were at the heart of the action to recover the situation. Project directors generally saw themselves as very hands on, unafraid to make priority calls, set demanding objectives and defend the project team. The active role played by senior management in these high-consequence, complex safety-critical projects supports the accepted wisdom in the practice of project management that governance structures, effective communication and the modelling of “right” behaviours from the top down remain a key ingredient for effective project delivery (Pinto, 2014).

The notion of project actors influencing the emergence and analysis of project uncertainty continues with the next duality; between the individual and collective analysis of uncertainty. Within these safety-critical projects, the process of investigating and analysing uncertainty was always a collective and generally a collaborative one. Lone individual analyses were not observed in either sector. Instead the quotations in Table 6 demonstrate that the analysis of uncertainty was multi-disciplinary in nature, and reached beyond the host project organisation outwards into the supply chain, even when the supplier may also be a competitor. One explanation for this is that the sheer complexity of the technology coupled with its safety-critical nature overrides otherwise reasonable commercial sensitivities about proprietary information and processes in pursuit of a robust analysis of uncertainty. Additionally, in the nuclear projects, independent technical experts from outside the project team were regularly drafted in to peer review the analysis of uncertainty providing an additional level of scrutiny of uncertainties that could be highly-consequential in nature. This need to continually consult independent experts is driven in part by the safety-imperative that pervades the nuclear industry, but is exacerbated by the fractured and piecemeal manner in which nuclear assets have been constructed and maintained over the last 50 years in the UK. Instead of a fleet of similar reactors, all following a standard design the UK has three very distinct technologies developed in three successive waves of civil nuclear power expansion, and even within the same power station the design of the two reactors can vary considerably (Wearne, 2015). Technical uncertainties around the through-life maintenance and decommissioning of these nuclear assets are often context specific, necessitating the engagement of the few individuals who are familiar with that particular technology.

The final relational duality concerns the position of the project, in relation to its finished status. Here the dilemma facing project managers is whether to prioritise responses to uncertainty that enable them to proceed in the right direction, rather than those that value knowing the exact status of the project at a particular time. In both sectors a similar spread of responses to uncertainty was observed, from those which intentionally focused on a step by step process of reducing uncertainty, to those which set their sights on building a complete picture of the landscape of uncertainty with which they were confronted. These responses were independent of project type; instead they were context specific, influenced in no small measure by the amount of resources at hand to resolve the uncertainty faced by the team. Coutu (2003) argues that acting on and interpreting what is happening, even in the absence of a complete picture of events, helps individuals move towards a solution. Perhaps pragmatism was also at work here, given that the exact status of the project can change very quickly as a result of emerging uncertainties. It is also possible that individuals with varied psychological profiles interpret and respond to uncertainty differently as argued by (Madsen & Pries-Heje, 2009).

5. Discussion

This study has drawn attention to how project uncertainty emerges, is made sense of and responded to in the context of large-scale safety-critical projects. Our first contribution is to extend earlier work (by Chapman & Ward, 2011; Martinsuo et al., 2014; Olsson, 2006; Pich et al., 2002; Vidal, 2015) to proffer three approaches that project managers adopt when confronting project uncertainty – structural, behavioural and relational. These three approaches are complementary rather than competing; with a combination of all three required to deal with emerging uncertainties before they negatively impact on project delivery. In both civil aerospace and nuclear projects the behavioural approach was dominant with individual personalities, attitudes, skill-sets and actions central to confronting uncertainty. However these behaviours were augmented by effective relationships with stakeholders, sponsors and project team members, and underpinned with sound project processes and structures (as argued by Martinsuo et al., 2014). Being seen to be following the correct processes enabled respondents to demonstrate 'control' of some very complex and ambiguous project situations - important both for their psychological well-being, and in building stakeholder confidence in the project. Importantly, we have also demonstrated that contending with project uncertainty involves much more than implementing a new project process, or broadening the scope of the risk management process to incorporate uncertainty (Hillson, 2002; Ward & Chapman, 2003). Rather, managing uncertainty is a mind-set (Cleden, 2009; Weick & Sutcliffe, 2007): about accepting uncertainty as an unavoidable fact of projects (Chapman & Ward, 2011), about rigorous use of all available project processes to drive out uncertainties as early as possible and about leveraging relationships with project stakeholders, sponsors and team members to maintain focus on the project outcomes even in messy and ambiguous situations (Atkinson et al., 2006). These findings may also have wider implications for safety management practices within these two industry sectors. For example, adopting the three approaches to managing project uncertainty – structural, behavioural and relational - in the context of safety management and treating safety as a mind-set rather than as processes and procedures might also improve practices and facilitate a more safety-aware culture within high hazard organisations.

Our second contribution is to characterise nine dualities in how uncertainty emerges and how project managers analyse and act on it, building on earlier work (Reiman & Rollenhagen, 2012) on the broader tensions and trade-offs in nuclear power projects. These nine dualities reflect the challenges and dilemmas involved in identifying and confronting project uncertainty. Although the same dualities are observed in civil aerospace and nuclear projects, there are both similarities and some interesting differences between the two sectors in terms of how the dualities shape the emergence, analysis and responses to uncertainty.

Both sectors exhibit a strong preference for data-based analyses of uncertainty, reflecting the techno-professional culture in these technically-complex and highly-consequential environments. The analysis of uncertainty is always collective and collaborative. Senior managers are generally active in the decision making process – which is typically open, structured and rich in robust debate and technical expertise. The engineer stance (Vidal, 2015) is very much in evidence here, with individuals modelling data, calculating or testing to help resolve uncertainties. Our findings support work by Fischoff, Lichtenstein, Slovic, Derby, & Keeney (1981) that the combination of hard data and collective decision making is viewed as more objective than individual professional judgement, and a defence against blame in the remote possibility of a serious accident to an aircraft or a nuclear reactor. Both sectors also exhibited a range of responses to uncertainty, some of which involved local solution, others which were system wide; some of which privileged the direction of travel and others which valued absolute location and a complete picture of the impact of the uncertainty on project timescales, budgets and client expectations.

In the civil nuclear sector, uncertainty was more likely to emerge through the outworking of a project process and the response to it more likely to be proactive. Respondents expected and accepted that their project environment was a highly uncertain one. They sought out uncertainty using the extant processes and structures to achieve this (Kettunen, Reiman, & Wahlström, 2007). If a process wasn't available, then one would be developed. This highly process orientated approach to uncertainty, whilst proactive and comprehensive also had an undesired consequence – that of slowing progress on projects, and leading to an inexorable shift of deadlines into the future.

In civil aerospace projects uncertainty was more likely to emerge as a result of an unexpected incident, its presence was often initially denied and the eventual response was consequently more reactive. This is a revealing and important finding, given the highly consequential safety-critical nature of civil aerospace projects. There are three possible explanations for this. First, there are greater and more immediate competitive pressures in civil aerospace than in the civil nuclear sector (Lofquist, 2010), which leads to increased schedule and cost pressure on the project team, which in turn can tempt practitioners to supress emerging uncertainties in pursuit of rapid aircraft or assembly development. If progress on a nuclear decommissioning project slows in the UK, there are few alternative suppliers waiting to pounce and so fewer levers which clients can pull to drive progress. Also, in decommissioning projects a loss of time does not often lead to a detrimental impact on safety; often the safest course of action is to wait, allowing radioactivity to decay and new technologies for decommissioning to emerge.

Secondly, learning happens in profoundly different ways in the two sectors. In civil aerospace the development programme and test environment is used to drive out uncertainties, with constant iterations of technology being tested (Hollnagel, Woods, & Leveson, 2006), sometimes to destruction, and learning happening through experimentation and multiple explorations (akin to Pich et al., 2002). There are few equivalents to the test environment in civil nuclear; instead learning occurs through theoretical analyses and modelling, and through a slow and steady process of characterisation. This involves robust debate through a multi stage peer review process, followed by cautious and conservative sign-off of any new designs or procedures (Kettunen et al., 2007). No inter-containment buildings or nuclear materials, at least on a very large scale, are tested to destruction in the construction of a new nuclear power plant.

Thirdly, the nature of the regulatory framework in the two sectors is different with civil aerospace governed by international criteria based regulations that govern when an aircraft is safe to fly. In civil nuclear, the regulatory framework is country specific and evidence based. Operators have to demonstrate that a given technology or plant modification is safe before regulatory approval is given for its implementation. An important practical implication of our work is that in spite of the different competitive and regulatory pressures in the two sectors, there is still scope for each to learn usefully from one another. The civil nuclear project management community can harness its strength in processes and strong safety culture by learning from civil aerospace to be more flexible, fleet of foot contractually and to encourage learning through experimentation. Whilst the civil aerospace project community could work smarter not harder through its frenetic development programmes attending to, resourcing adequately and resolving project uncertainties earlier in the lifecycle before major issues blow up at huge financial and psychological cost.

6. Conclusions

6.1 Implications for practice

Based on vignettes of 47 instances of project uncertainty on 9 large-scale safety-critical projects, we argue that project managers adopt a combination of behavioural, structural and relational modes when confronting project uncertainty. This finding has a number of implications for the project management community. First, it contributes important insights into how uncertainty emerges, is analysed and acted upon and the tensions that accompany this process in the highly-consequential and complex environment of the safety-critical project. Secondly, acknowledging the presence of these tensions, and the dilemmas that ensue, should engender a more reflective approach to confronting uncertainty amongst project management practitioners, and a more deliberate process of uncertainty identification, analysis and action. Thirdly, it shows that managing uncertainty requires a mind-set, which accepts uncertainty as an unavoidable fact of projects and uses all available people, practices and processes to drive out uncertainties as early as possible in the project lifecycle. This may also include leveraging key relationships with project stakeholders, sponsors and team members, or utilising and adapting the extant project processes and structures to drive out uncertainty. These are difficult skills to deploy, particularly in high hazard environments which are often inherently conservative. Both civil nuclear and aerospace sectors need to consider how such skills and capabilities are encouraged, nurtured and retained amongst civil nuclear and aerospace project management communities. Lastly, our findings should be transferable (Denscombe, 2010) to other safety-critical projects in civil nuclear and aerospace sectors, given that the sample is sufficiently large and varied to be representative of current UK based safety-critical projects in both sectors.

6.2 Limitations and areas for future research

One question that arises from this research is to what extent safety-critical projects are "special" and whether the findings can be transferred to a broader spectrum of less "extreme" project organisations. Replicating this study in large-scale projects in a number of other important industry sectors, notably oil and gas, construction, healthcare and financial services would begin to answer this question. The findings may also have wider implications for safety management practices. Prior studies on building safe organisations have identified a number of factors that influence safety - notably structural factors, organisational leadership, effective decision making and communications (see for instance Kettunen et al., 2007; Øien, Utne, Tinmannsvik, & Massaiu, 2011). Extending our work to incorporate 'vignettes" of safety issues; how they emerged, were analysed and acted upon – might illuminate similar or different approaches and dualities in the management of safety in high hazard organisations to those observed in contending with project uncertainty.

There are number of limitations in the study which lead to further opportunities for research. First, although several respondents per project were interviewed, it was not possible to further triangulate the findings by accessing project documentation or undertaking participant observation. Also, interview based accounts are one step removed from project management actuality (Cicmil, Williams, Thomas, & Hodgson, 2006). They tell us only how project managers account for how they identify and act on project uncertainty rather than how they might be observed to actually approach project uncertainty in a natural setting (Czarniawska, 1998). Future studies of an ethnographic nature undertaken by researchers who are embedded within project teams would therefore lead to further insights into the day-to-day project actuality of confronting project uncertainty.

Secondly, data collection was a "snap-shot" based on one-off interviews. A longitudinal study into whether approaches to managing uncertainty change over the project-lifecycle would be a fruitful avenue for future research. Thirdly, the study was UK centric, although all the projects were highly dependent on international supply chains. Replicating the study across other geographical cultures, for example the US and Asia Pacific, which operate under different regulatory regimes, at least in the nuclear industry, might generate insights into the impact of national culture on how project managers deal with project uncertainty.

Uncertainty is a fact of project life. Most decisions that are made on a safety-critical project involve uncertainty, the consequences of which may be highly significant to the safe and timely delivery of the project. Drawing attention to the structural, behavioural and relational approaches to project uncertainty and the tensions that manifest themselves in each approach, should enable the project management community to make progress in these “swampy lowlands” (Winter et al., 2006) of uncertainty where situations are often complex, rapidly changing and confusing, and yet where for reasons of safety failure is not an option.

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