The Management of Uncertainty in Large-Scale Safety-Critical Projects

Practitioner Summary

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Executive Summary

Projects to develop new civil aircraft or construct the next generation nuclear power plants are long-term, large-scale and complex endeavours that must be delivered in a safe yet timely manner. The uncertainties at play in these complex socio-technological environments are many and non-trivial in nature, and have the potential to derail or delay the project. A key challenge facing project managers tasked with delivering these safety-critical projects is to identify the sources of project uncertainty and navigate a path through these uncertainties in pursuit of successful project outcomes.

This research draws on 38 semi-structured interviews and 86 questionnaire responses from project management practitioners in two sectors – civil nuclear and civil aerospace – to establish the sources of uncertainty in large-scale safety-critical projects and assess how uncertainty emerges, is analysed and acted upon. The findings of the research are fourfold: First, that the sources of uncertainty can be understood as a kaleidoscope of influences on the project, such as environmental factors and the capability of the project delivery team. Secondly, that project management practitioners adopt a combination of structural, behavioural and relational approaches to confronting uncertainty, within which there are a number of dualities in how uncertainty emerges, is analysed and acted upon. Thirdly, there is evidence for high reliability project organising as a response to project uncertainty, although these practices are often fragile, emergent and contingent. Finally, there are both commonalities and differences between the two industry sectors, in terms of the sources of uncertainty and how it emerges, is analysed and attended to; an awareness of which could improve practices in both sectors.

This research enriches our understanding of projects as complex emergent problems that often proceed under high levels of uncertainty. It proffers frameworks, approaches and practices that, when added to the armoury of the project manager, should enable uncertainty to be dealt with rather than dreaded. Its implications are profoundly important to the delivery of safety-critical projects in both civil nuclear and aerospace sectors, where a failure to fully appreciate uncertainties, complexities and risks is a major cause of poor delivery in contemporary projects.

1. Introduction

In safety-critical industries, such as civil nuclear or civil aerospace, the need to contend with uncertainty is particularly important as any miscalculations or misjudgements may have catastrophic consequences, leading to loss of life and serious environmental damage. To study projects in these demanding environments is to enter a world dominated by "*massive machines, extraordinary engineering and procedural complexities*"(La Porte, 2006, p.156). Here, project managers must deliver the next generation nuclear power plants; decommission former nuclear assets and safely store their waste products; or design ever lighter and more fuel-efficient civil airliners. These are long-term, large-scale projects that must satisfy myriad stakeholders and where the uncertainties at play are diverse and non-trivial in nature (Oedewald & Gotcheva, 2015). For example, archive 'as built' drawings of a nuclear reactor may be incomplete or inaccurate, creating additional challenges during site decommissioning work. Similarly, an aircraft engine testing programme might generate results that do not fit the theoretical models by which the engine has been designed. Effectively identifying the sources of project uncertainty and navigating a path through them is one of the main challenges facing project managers in these complex, socio-technical environments.

Addressing this challenge, the aim of this research was to establish the determinants[1] of project uncertainty in large-scale safety-critical projects, to examine different approaches that are adopted by project managers when faced with project uncertainties, and to explore whether there is evidence for high-reliability project organising as a means of managing project uncertainty.

The research consisted of a three-phase study of UK focused safety-critical projects across the civil nuclear and civil aerospace sectors, undertaken between 2012 and 2015. It included a total of 38 interviews (spanning 12 projects in 6 organisations) and 86 questionnaire responses. The research design was a mixed methods one, utilising both qualitative and quantitative data collection techniques. The data collected were in the form of semi-structured interviews and a quantitative questionnaire. The study did not intend to investigate any causal relationships between how project uncertainty is managed and eventual project outcomes.

2. Key findings and implications for practice

2.1 The determinants of uncertainty in safety-critical projects

This research argues that project uncertainty can be understood as a kaleidoscope of influences on safety-critical projects. It builds on previous research into the sources of uncertainty in projects (cf. Atkinson et al., 2006; Chapman & Ward, 2011; Cleden, 2009; Martinsuo et al., 2014; O'Connor & Rice, 2013) to present the Uncertainty Kaleidoscope as a visual framework for identifying the sources of uncertainty in safety-critical projects. The Uncertainty Kaleidoscope comprises six major determinants of project uncertainty (Complexity, Time, Environment, Capability, Individual and Information), each of which is further broken down into a set of sub-components (Figure 1).

[1] Determinant is defined as a factor, circumstance, etc., that influences or determines

Figure 1: The Uncertainty Kaleidoscope

The framework is in the form of a kaleidoscope as a metaphor for understanding project uncertainty. It reflects a key similarity between large scale projects and the eponymous children's toy; in that a kaleidoscope can generate a multiplicity, perhaps even an infinite number of distinct landscapes of project uncertainty from the same six determinants – *complexity*, *environment*, *capability*, *time*, *information* and *individual*. New uncertainties may also emerge as the project progresses. This is equivalent to the kaleidoscope being shaken, which may lead to the emergence of a very different project landscape. For example, the archive 'as built' drawings of a nuclear reactor may be insufficiently accurate to prevent major new uncertainties emerging during the project to decommission the site and return it to a clean state. Conversely a gas turbine engine on the engine test-bed may deliver test data that does not fit the theoretical models by which the engine has been designed. Many months of work and large additional expenditures may be necessary to correct the engine design and allow it to be certified to fly. These sudden changes in project landscape, often small but on occasion highly consequential, can affect the likelihood of the project objectives being achieved, or may result in the need to develop new project objectives.

Identifying which of the six determinants are most prevalent in safety-critical projects was an important finding of this research: Environment was the most often mentioned determinant of project uncertainty, followed by Complexity, Capability, and Information; the impact of Time and Individual perceptions of uncertainty were highlighted much less frequently. The Uncertainty Kaleidoscope is the first framework to be developed for the specific context of the safety-critical project and the first to rank the prevalence of the different sources of uncertainty.

The usefulness of the Uncertainty Kaleidoscope lies not in its predictive power, but as a visual framework to enable project practitioners in safety-critical environments to discuss and debate where uncertainty may reside in projects before it causes unwelcome surprises within the project team. Like many metaphor based models it is intended to be memorable and to act as a visual tool, enabling productive discussion and debate about the sources of uncertainty at each stage of a project's lifecycle. Like all metaphors it is an imperfect approximation for reality, but one that is intended to open up fresh ways of seeing project uncertainty. After all the very purpose of a kaleidoscope is to be shaken to make new patterns, in contrast to projects, which in an ideal world would remain stable and not subject to violent perturbation!

In spite of this limitation, using the Uncertainty Kaleidoscope to explicitly identify, characterise and debate uncertainty may increase project managers' confidence in addressing the uncertainties with which they are confronted. As a minimum it should enable areas of uncertainty to be identified and explored, rather than ignored or overlooked. As an added benefit it may also lead to a gradual change in perspective from uncertainty as risky, problematic and something to be feared, to uncertainties as potential opportunities, from which the project may exploit and profit.

These findings have been published as:

Saunders, F. C., Gale, A. W., & Sherry, A. H. (2015). Conceptualising uncertainty in safety-critical projects: a practitioner perspective. *International Journal of Project Management*, *33*,2, 467–478. ttp://doi.org/10.1016/j.ijproman.2014.09.002 and

Saunders, F. C., Gale, A. W., & Sherry, A. H. (2016). Mapping the multi-faceted: determinants of uncertainty in safety-critical projects. *International Journal of Project Management*, 34,6,1057-1070. http://doi.org/10.1016/j.ijproman.2016.02.003

Copies of both papers are available on request from the author.

2.2 What approaches are adopted by project managers when faced with project uncertainties

This research characterised three main approaches that project managers adopt when confronting project uncertainty – structural, behavioural and relational. 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. These three approaches are complementary rather than competing. This research showed that the behavioural approach dominated in safety-critical projects - with individual personalities, attitudes, skill-sets and actions central to confronting uncertainty. However these behaviours were underpinned by good relationships with stakeholders, sponsors and project team members, and enacted through sound project processes and structures. Being seen to be following the correct processes enabled project managers 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.

The research also identified nine dualities (or tensions) in how uncertainty emerges and how project managers analyse and act on it (Figure 2).

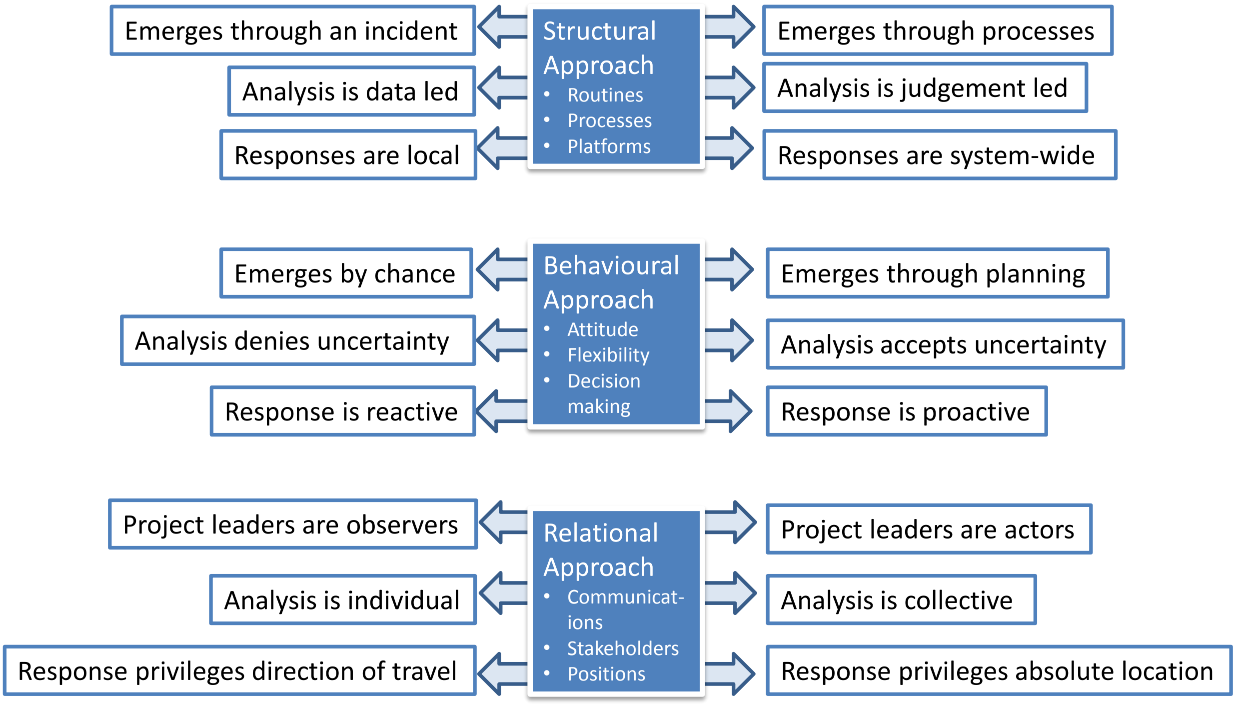

Figure 2: Dualities in how uncertainty emerges, is analysed and acted upon

These dualities reflect the challenges and dilemmas involved in identifying and confronting project uncertainty. 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 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. As background, Table 1 defines 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 prioritise 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 1: Description of each of the nine dualities

Cross Sectoral Differences

Although the same dualities were observed across both civil aerospace and nuclear projects, there were some interesting differences between the two sectors in terms of how uncertainties emerge and are responded to.

Both sectors valued data-based analyses of uncertainty, reflecting the strong techno-professional culture in these technically-complex and highly-consequential environments. The analysis of uncertainty was always collective and collaborative. Senior managers were generally active in the decision-making process – which was typically open, structured robustly debated. Perhaps the combination of hard data and collective decision making was 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.

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 acknowledged and accepted that their project environment is a highly uncertain one. They sought out uncertainty using the extant processes and structures to achieve this. If a process was not 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 often 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 was a revealing and important finding, given the highly consequential safety-critical nature of civil aerospace projects. There are three possible explanations for it.

First, there are greater and more immediate competitive pressures in civil aerospace than in the civil nuclear sector, which leads to increased schedule and cost pressure on the project team, which may 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 naturally 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, sometimes to destruction, and learning happening through experimentation and multiple explorations. 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. 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, thus UK operators have to demonstrate that a given technology or plant modification is safe before regulatory approval is given for its implementation.

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 and learn from civil aerospace to be more flexible, fleet of foot contractually and to encourage an element of 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.

These findings have been published as

Saunders F.C., Sherry, A.H. and Gale, A.W. (2016) Dualities and dilemmas: contending with uncertainty in large-scale safety-critical projects. Construction Management and Economics, http://dx.-doi.org/10.1080/01446193.2016.1196824

Copies are available on request from the author.

What evidence is there for high-reliability project organising as a response to project uncertainty?

What is a high reliability organisation?

A number of authors have sought to characterise high reliability organisations (Boin & Schulman, 2008; La Porte, 1996; Roberts & Rousseau, 1989; Weick & Sutcliffe, 2007) as organisations that can maintain safe and reliable operations, while operating under considerable time pressure in high-risk environments. To date, however, most research into high reliability organisations has focused on high hazard and high tempo *operations* and there are few empirical studies of high reliability organising in the *project* context. Saunders (2015) argued that safety-critical projects were sufficiently similar to their operational counterparts to permit theories of high reliability organising to be translated into the project context. It also synthesised an "ideal-type high reliability project organisation" (Figure 3) which comprises five main features: clear organisational objectives, a strong organisational culture, the presence of redundancy and slack, mindful behaviour and the ability to prosper in the paradoxes.

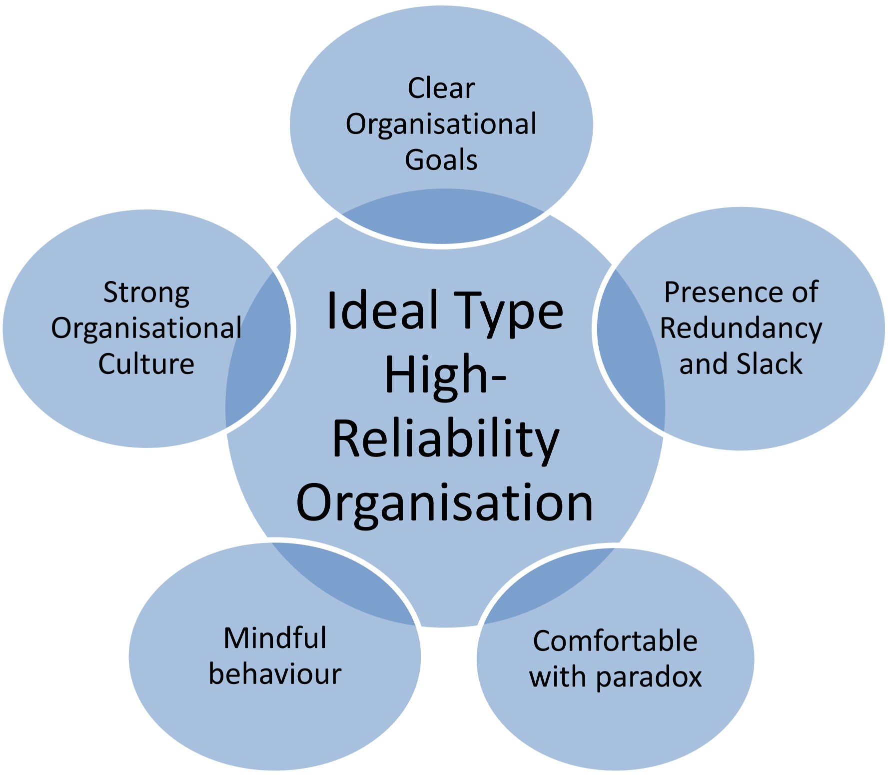

Figure 3: Characteristics of an 'ideal-type' high reliability organisation

This research empirically tested these ideas, based on interviews with 30 project management practitioners on nine large-scale safety-critical projects in the civil nuclear and civil aerospace industries. It found evidence of many practices in safety-critical projects that are consistent with high reliability project organising. Respondents expressed a sense of balancing and juggling in the paradox, for example, in knowing whether to test new engines for flight or run further experiments; and provided evidence of learning, acting mindfully, avoiding over-rigid processes, and of upholding constructive tensions, conceptual slack and close interdisciplinary working. However these practices were often fragile, with much depending on the tenacity and strength of will of individual project managers, rather than being embedded in the organisation's culture. The challenge facing safety-critical projects is how to identify, develop and nurture sufficient numbers of such individuals who can begin to change the organisation's long established ways of working.

High reliability practices in this study also often emerged in response to situation-specific difficulties as opposed to being planned for from the start, and occurred at the project operational level, rather than being mandated by senior management. One implication from this study is the need to increase senior management awareness of the principles of high reliability project organising without this becoming merely the latest management fad.

Lastly high reliability practices in dealing with uncertainty were contingent (localised) to particular sets of circumstances, organisational structures and individuals, and were difficult to influence beyond the core project team. Structural factors in both civil nuclear and aerospace often thwarted attempts by project managers to act in a manner more consistent with theories of high-reliability project organising. For example, complex ownership structures, the quasi public-sector nature, and short term incentive mechanisms in the civil nuclear industry can tempt organisations to adopt short-term financially expedient project solutions. Oedewald & Gotcheva (2015) argue that it is difficult to delegate decision making in large nuclear projects as they are typically structured around long and often fragmented networks of contractors and subcontractors, not all of whom have specific nuclear industry expertise. And in civil aerospace, the commercial imperative to deliver safe engines to tight customer deadlines can lead to suboptimal resource allocation, reactive responses to emerging problems and a pervasive organisational culture of firefighting. These are structural issues that reside beyond the sphere of influence of even the largest, most consequential safety-critical project.

This study also identified a number of sectoral differences between civil aerospace and nuclear projects. There was more evidence of practices associated with high reliability project organising in civil nuclear projects, particularly in terms of having a stronger sense of mission, clearer objectives and core events that had to be precluded, in reporting mistakes openly and affording areas of ignorance in the project the same importance as areas of certainty, in better separating technical and cost delivery, and of a lack of complacency and being attuned to small changes that could be the precursors to larger issues. In civil aerospace projects, there was considerably more emphasis on the tempo of projects, and on avoiding over-rigid processes. There was virtually no evidence of practices at odds with high reliability thinking in civil nuclear. This differed from civil aerospace, where there were several instances where objectives were not clearly communicated, of complacency and slow initial reactions to emerging uncertainties.

There are a number of wider implications of this study. Firstly there remains the risk that high reliability project organisations are viewed as somehow 'heroic'; embodying cultures and cognitive processes that enable high reliability projects to outperform non-high reliability projects. This study has provided no empirical evidence of this. A second issue raised by this study is the transferability of prior high reliability organising research from the operational context into projects. Safety-critical projects do share many similarities with ongoing operations, notably their complexity, consequential nature, the presence of uncertainty and the marshalling of many specialist resources to enact organisational processes to deliver a set of objectives. However there are a number of differences between operations and projects, including the more measured tempo at which projects proceed and the temporary and non-routine nature of the work. This research indicates that there are sufficient similarities between operations and projects to translate high reliability theory to the project context.

A final question raised by this study, and one that has not yet been adequately answered, is the extent to which the characteristics of high reliability project organising are unique to safety-critical projects as opposed to constituting good practice in any project context. For example, learning from past projects, clarity of objectives and close interdisciplinary working are all aligned with good project management practice across all sectors. In this regard, the findings that many practices in safety-critical projects are consistent with high reliability project organising are perhaps not so astounding. However, this research argues that the highly- consequential nature of large scale safety-critical projects and the imperative attached to their safe execution, render the practices of high reliability project organising essential, even if that comes at the increased cost and effort of providing redundancy and conceptual slack and of maintaining a razor sharp clarity of focus on safety over other performance objectives.

Comprehensive reviews of high reliability organising and its application to safety-critical projects are available in

Saunders, F. C. (2015). Toward high reliability project organizing in safety-critical projects. Project Management Journal, 46(3), 25–35. http://doi.org/10.1002/pmj

Saunders F.C., Gale, A.W. and Sherry, A.H. (2016) Responding to project uncertainty: evidence for high reliability practices in large-scale safety-critical projects**.** International Journal of Project Management, 34,7, p1252-1265.

Copies of these papers are available on request from the author.

3. Conclusions

In summary, this research has argued that uncertainty can be understood as a kaleidoscope of influences on a safety-critical project. It has empirically examined how uncertainty emerges, is analysed and acted upon in the under-researched context of large-scale safety critical projects and assessed the extent to which high reliability project organising is practised as a response to these uncertainties. It enriches our understanding of projects as complex emergent problems that often proceed under high levels of uncertainty, and importantly proffers frameworks, approaches and practices that, when added to the armoury of the project manager, should enable uncertainty to be dealt with rather than dreaded. Its implications are therefore profoundly important to the delivery of safety-critical projects in both civil nuclear and aerospace sectors, where a failure to fully appreciate the uncertainties, complexities and risks is a major cause of poor delivery in contemporary projects.

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