



MAPPING THE MULTI-FACETED: IDENTIFYING THE DETERMINANTS OF UNCERTAINTY IN SAFETY-CRITICAL PROJECTS

Fiona C Saunders - fiona.saunders@manchester.ac.uk
THE UNIVERSITY OF MANCHESTER
Andrew W Gale - andrew.gale@manchester.ac.uk
THE UNIVERSITY OF MANCHESTER
Andrew H Sherry - andrew.h.sherry@npl.co.uk
NATIONAL NUCLEAR LABORATORY

Category: 10 PROJECT ORGANIZING >> 10_00 PROJECT ORGANIZING GENERAL TRACK

Access to this paper is restricted to registered delegates of the EURAM 2015 (European Academy of Management) Conference.



ISBN 978-8386437-60-0.

Mapping the multi-faceted: Identifying the determinants of uncertainty in safety-critical projects

ABSTRACT

Project managers tasked with delivering safety-critical projects must demonstrate care, competence and confidence from the earliest stages of project inception, when levels of uncertainty about the scope, delivery mechanisms and required project outcomes may be ill-defined and even bewildering. This paper builds on work by Saunders et al. (2015), which posited the Uncertainty Kaleidoscope as a framework for conceptualising uncertainty in safety-critical projects. Our contribution here is to 1) refine and validate the Uncertainty Kaleidoscope and 2) explore the commonalities and differences between sources of project uncertainty across two safety-critical industries: nuclear and aerospace. The findings are that the six key determinants of project uncertainty (Complexity, Environment, Capability, Time, Information and Individual Perception) are broadly similar across both civil nuclear and aerospace projects. There are however sharper differences between the nature of projects with new build/new product introduction projects having lower information uncertainty and suffering less from uncertainties in capability, whether internally or across the wider supply chain.

Keywords: Project uncertainty; safety-critical

Mapping the multi-faceted: Exploring the determinants of uncertainty in safety-critical projects

Abstract

Project managers tasked with delivering safety-critical projects must demonstrate care, competence and confidence from the earliest stages of project inception, when levels of uncertainty about the scope, delivery mechanisms and required project outcomes may be ill-defined and even bewildering. This paper builds on work by Saunders et al. (2015), which posited the Uncertainty Kaleidoscope as a framework for conceptualising uncertainty in safety-critical projects. Our contribution here is to 1) refine and validate the Uncertainty Kaleidoscope and 2) explore the commonalities and differences between sources of project uncertainty across two safety-critical industries: nuclear and aerospace.

The findings are that the six key determinants of project uncertainty (*Complexity, Environment, Capability, Time, Information and Individual Perception*) are broadly similar across both civil nuclear and aerospace projects. There are however sharper differences between the nature of projects with new build/new product introduction projects having lower information uncertainty and suffering less from uncertainties in capability, whether internally or across the wider supply chain.

Keywords

Project uncertainty; safety-critical; large-scale projects

Introduction

Large scale and complex engineering projects are central to modern society. Without them there would be no reliable infrastructure, iconic buildings or inspiring Olympic Stadia. However, one of the myriad challenges facing these projects is how to adequately identify and manage their risks, uncertainties and complexities in order to minimise the potential for failure (PMI, 2013). In the specific domain of the safety-critical project¹, safe and reliable delivery is an imperative and project managers must bear the burden for projects, whose timescales are often long, budgets vast and technical complexity high. Irrespective of whether the project aims to deliver new nuclear power generation capacity, safely decommission an already shutdown nuclear reactor or design the most efficient gas turbine engine for the next generation civil airliners, the project landscape will be dominated by regulatory requirements and the need to be “in control” at all times. Given this challenging backdrop, this research aims to determine the sources of, and influences on uncertainty in safety-critical projects, and articulate them in a manner which will aid the project management practitioner throughout the lifecycle of their project assignment.

The study reported here is based on semi-structured interviews with 30 project management professionals on nine large-scale projects in civil nuclear and aerospace industries in the United Kingdom. It addresses two key research questions as follows:

RQ1: Can the previously posited framework for conceptualising the determinants of project uncertainty (Saunders et al., 2015) be refined, validated and generalised on a larger scale study of safety-critical projects?

¹ Safety-critical projects are defined as those projects where safety is of paramount importance and where the consequences of failure or malfunction may be loss of life or serious injury, serious environmental damage, or harm to plant or property (Falla, 1997 and Wears, 2012)

RQ2: What are the commonalities and differences in the determinants of uncertainty between civil nuclear and civil aerospace sectors and across different project types (new build/new product introduction (NPI) versus maintenance projects)?

The paper reviews the extant literature on project uncertainty and then describes the design of the empirical study. Findings are then presented, discussed and implications for practice and future research highlighted.

Uncertainty is a multi-faceted concept

Uncertainty: A concept that is rich, evocative and loaded with meaning. Uncertainty can conjure up fear and trepidation, or alert one to future opportunities that can be explored, depending on the perspective taken. An entrepreneur may look favourably on uncertainties within a particular market from which he can exploit and profit. In contrast, a project manager may fear the consequences of an uncertain future generated by an organisational restructure. What is clear from these two examples is that “uncertainty” is neither a simple nor a neutral term. Instead it is a multi-faceted concept; one that has been studied across a broad range of intellectual disciplines from economics to engineering to psychology (cf. Osman, 2010; Smithson, 1989; Smithson, 2009). To the mathematical mind, uncertainty may conjure up probabilities of outcomes (Attewell, 2009); to the psychologist the debate centres on the extent to which uncertainty is an objective or subjective phenomenon (Simon, 1956; Head, 1967; Kahnemann and Tversky, 1982), and to the business executive the presence of future uncertainties underlies most strategic decisions (cf. Porter, 1980; Sutcliffe and Zaheer, 1998; Harrison, 1992).

Within the domain of project management there has also been broad coverage of uncertainty (see for instance Loch et al., 2006; Perminova et al., 2008; Cleden, 2009; Hillson,

2002; Atkinson et al., 2006; Saunders et al., 2015). This scholarship has articulated the possible sources of uncertainties in projects (Ward and Chapman, 2003; Atkinson et al., 2006; Cleden, 2009; Winch, 2010; Saunders et al., 2015) and the various approaches to dealing with it (c.f. DeMeyer et al., 2002; Chapman and Ward, 2002; Olsson, 2006; Harris and Woolley, 2009). The scholarly discourse around the management of uncertainty in projects is closely related to the management of risk and there has been much discussion as to the difference between risk and uncertainty (c.f. Hillson, 2004; Loosemore et al., 2006; Perminova et al., 2008 and Sanderson, 2012).

The Oxford Dictionary of Current Usage defines uncertainty as “*the state of being uncertain; something you cannot be sure about*”. In simple terms, uncertainty is a state of unknowing - where the individual lacks full and complete knowledge of a situation. The world of safety-critical projects is however anything but simple, and in the complex organisational setting of a project to deliver a new gas turbine engine for the next generation wide bodied aircraft the consequences of underestimating uncertainty can be very serious indeed. Here the individuals tasked with delivering such projects must be comfortable operating in an environment of high uncertainty. Daily they must wrestle with technical dilemmas such as how to improve engine efficiency, reduce weight *and* maintain exceptional safety performance, whilst keeping development costs under control and timescales for delivery to the customer realistic. Or how to minimise the impact of the unexpected when relocating intermediate level radioactive waste from a storage facility which was sealed shut half a century ago.

Introducing the Uncertainty Kaleidoscope

The sources of uncertainty in safety-critical projects have been extensively described in Saunders et al. (2015) and include the *complexity* of the project, the *environment* in which it is being delivered, the *capability* of both the project team and the wider supply chain, *temporal* issues such as the timescales and speed of the project, the availability of *information* and *individual* team member perceptions of uncertainty. Each of these six determinants of project uncertainty can be further broken down into a number of different components. For example, environmental uncertainty may emerge through external factors such as political, market or competitor activity or may arise as a result of organisational culture, behavioural norms or decision making processes. Information uncertainty is similarly subdivided into an absence of information, lack of knowledge, inadequate understanding of cause and effect relationships, poor estimating ability and lack of clarity of project objectives. Many of the components of the Uncertainty Kaleidoscope are also interrelated, for instance the number and diversity of actors on a project impacts both its inherent complexity and also the potential breadth and alignment of stakeholder demands that the project may face. Both these components will shape the overall level of uncertainty on the project. Saunders et al., (2015) synthesised these various sources of uncertainty into the “Uncertainty Kaleidoscope” – see Figure 1 below.

INSERT FIGURE 1 HERE

This Uncertainty Kaleidoscope evolved from a systematic review of the literature on project uncertainty and in-depth interviews (n=8) with project management professionals in both civil nuclear and civil aerospace industries. Topics in normal text in Figure 1 were reported in the literature and topics in italics emerged during the interviews. 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 ‘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 even lead to new project objectives being necessary. Finally, it is important to note that the usefulness of the kaleidoscope does not lie in its predictive power, but as a framework to enable project professionals in safety-critical environments better anticipate where uncertainty may reside in projects, before it causes unwelcome surprises within the project team.

The major limitation of the Uncertainty Kaleidoscope, as presented in Figure 1 is that it had only been tested on a small sample of project management professionals. In order to refine and validate the kaleidoscope, it was necessary to extend the earlier exploratory study to a much larger number of project management professionals employed on a wider range of safety-critical projects in both civil nuclear and civil aerospace sectors. This was the primary purpose of the study reported on here.

Methodology

Given that the aim of this new study is to refine and validate the Uncertainty Kaleidoscope against a larger dataset, the methodology employed is consistent with that described in the earlier exploratory study reported in Saunders et al. (2015). It is based on a qualitative approach, comprising semi-structured interviews with 30 project management professionals involved in 9 large safety-critical projects in the UK. The projects were chosen to represent both civil nuclear and civil aerospace sectors (there were 5 nuclear and 4 aerospace projects drawn from 5 different organisations) and to reflect two major types of safety-critical projects –“*new facility/new product introduction projects*” and “*maintenance projects*”. The projects were selected based on their fit with the two project types above and their accessibility to the authors. The 30 interviews were undertaken face-to-face at the project sites between March and September 2014. Between three and four respondents per project were interviewed, in order to mitigate against any individual respondent bias and to allow more valid cross-project comparisons to be undertaken. A complete list of the projects and the respondents are provided in Table 1 below. All specific project data have been anonymised due to confidentiality restrictions.

INSERT TABLE 1 HERE

In the interviews respondents were asked to provide an overview of the project and their role in it. Then they were asked to discuss the sources of, and influences on, project uncertainty in the specific project on which they were employed. This part of the interviews lasted between 25 and 35 minutes. Later in the interviews respondents were questioned about how they manage project uncertainty but this analysis is outside the scope of this article. All interviews bar one were audio-recorded and later transcribed (one respondent did not allow the use of the voice recorder and written notes from the interview, approved by the respondent were used). The interview responses were analysed using content analysis, which is a technique “where the researcher interrogates the data for constructs and ideas that have

been decided in advance” (Easterby-Smith et al., 2008, p173). In content analysis, a set of categories are established from the data – in this case based on the earlier Uncertainty Kaleidoscope (Saunders et al., 2015) and the number of instances of each category counted. In this study, one count was noted if a respondent mentioned a particular category of project uncertainty: irrespective of the number of times that the category was mentioned within the *same* interview. The *a priori* identification and systematic counting of these specific categories in the interview transcripts allows inferences to be made from this set of data (Stone et al., 1966). Validity and reliability in content analysis is directly impacted by the level of inter-coder reliability – the consistency of agreement between two or more coders. Consistent with Evans (1996) and Neuendorf (2002) this study used one main coder, with a second coder undertaking a reliability check on the coding counts and categories. During the analysis process a small number of new categories of uncertainty emerged that had not previously been identified during the earlier exploratory study. These were added to the analytical categories, and the Uncertainty Kaleidoscope revised to take account of them. In this sense the study, whilst deductive in its main approach, in practice, retained an element of induction that was consistent with the earlier exploratory study. The findings of this study should be generalisable to other safety-critical projects in the civil nuclear and civil aerospace sectors, given that the sample (9 safety-critical projects) is sufficiently large and varied to be representative of current UK based safety-critical projects in these two sectors.

Findings and Discussion

The findings of this study are presented in two sections, consistent with the two research questions. First, the content analysis of the 30 interviews is presented and its implications for the validity and refinement of the Uncertainty Kaleidoscope discussed. Secondly, the commonalities and differences between the determinants of uncertainty across

civil nuclear and civil aerospace sectors and across the two selected project types are explored.

Refinement and validation of the Uncertainty Kaleidoscope

The interview data set which formed the basis for the content analysis comprised 18 interviews with civil nuclear project management professionals and 12 interviews with civil aerospace project management professionals. This imbalance between civil nuclear and aerospace data was not intentional but rather a manifestation of the extreme difficulty in gaining access to these commercially sensitive project environments. The categories and counts for the content analysis are provided in Table 2. All categories are drawn from the Uncertainty Kaleidoscope shown in Figure 1, with the exception of integration issues, technical novelty of solution, clarity of roles and responsibilities, project funding, site security, project scope clarity and client capability which were raised by respondents during the interviews and were added to the list of categories. The emergence of these new categories did not materially impact the Uncertainty Kaleidoscope as they fitted into the existing six top level determinants of uncertainty – for example integration issues and technical novelty both contribute to complexity, whilst funding and site security were classified as environmental determinants of uncertainty. Data saturation (Guest et al., 2006) was observed in this study, with no new categories being raised after Interview 22.

INSERT TABLE 2 HERE

The results of the content analysis of the 30 respondent interviews were compared with the earlier version of the Uncertainty Kaleidoscope (depicted in Figure 1), enabling it to be refined and validated. The refined model is shown in Figure 2 below.

INSERT FIGURE 2 HERE

The refined Uncertainty Kaleidoscope illustrates the 6 determinants of project uncertainty (previously these were referred to as perspectives). Each determinant comprises a number of more specific and detailed components. There are a number of minor differences between the earlier and current version of the model. First, the position of the determinants around the kaleidoscope has been reordered so that they appear in more logical sequence. Temporal has been renamed Time, and Environmental renamed Environment. The components of Individual and Information remain unchanged but additional components have been added to Capability (client capability), Complexity (technical novelty and integration issues), Time (changes in scope, information and priorities) and Environment (project funding and clarity of roles and responsibilities). As recognised previously, the utility of this framework lies not in its predictive power but as a model to help project professionals in safety-critical environments articulate better where uncertainty might reside in projects. Using the Uncertainty Kaleidoscope to explicitly frame, discuss and debate uncertainty in the early stages of project gestation may increase project managers' confidence in addressing the uncertainties with which they are confronted. As a minimum it will 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 (Olsson, 2007; Schlesinger et al., 2012).

Commonalities and differences in determinants of uncertainty between civil nuclear and aerospace sectors and between different project types

The content analysis in Table 2 was used to produce a number of polar diagrams to explore whether the determinants of uncertainty are similar or different across the two industry sectors (civil nuclear and civil aerospace) and across two types of projects (new build/NPI and maintenance).

Civil nuclear versus civil aerospace projects

Figure 3 depicts the number of respondent interviews in which each determinant of uncertainty was mentioned across both civil nuclear and aerospace projects.

INSERT FIGURE 3 HERE

In spite of the number of absolute counts being different across the two industry sectors (largely due to the variance in the number of respondents), Figure 3 demonstrates that the six key determinants of project uncertainty (Complexity, Time, Environment, Capability, Individual and Information) are broadly similar across both civil nuclear and civil aerospace sectors. The most commonly mentioned determinant of project uncertainty is the project Environment, followed by Complexity, Capability and Information. The impact of Temporal issues on project uncertainty and Individual perceptions of uncertainty were mentioned much less frequently by respondents. This similarity between civil nuclear and civil aerospace is not entirely surprising given the fact that both sectors must deliver complex, large-scale engineering projects to demanding safety and performance standards, under the spotlight of powerful and proactive regulatory authorities.

However, increasing the granularity of the content analysis to the specific components of uncertainty does yield more variations in the determinants of project uncertainty across civil nuclear and civil aerospace projects. Figures 4-8 show polar diagrams of the component sources of uncertainty that make up each determinant of uncertainty, subdivided into civil nuclear and civil aerospace projects.

IINSERT FIGURE 4 HERE

The Environment (Figure 4) was the most often mentioned source of uncertainty in projects in both sectors. In the civil nuclear industry, respondents described multi-

organisational project environments, replete with diverse organisational cultures, where the “ways of doing things round here” had yet to be established in the project. The primary challenge facing project managers was not the complexity or novelty of the technical solution, but rather satisfying the myriad internal and external stakeholders, many of whom held a metaphorical axe over the project and its continuing existence. In civil aerospace, environmental uncertainty emerged as a consequence of external market factors, such as the demand for global aviation, oil prices, industry responses to serious incidents such as the loss of Flights MH370 and MH17 in 2014 (The Guardian, 2014) and changes in requirements and cost pressures from the airline operators and aircraft manufacturers alike. In civil aerospace projects, environmental uncertainty also arose from a lack of clarity of roles and responsibilities within organisations that were frequently being restructured and re-engineered in the pursuit of cost savings and greater organisational efficiency. These organisational realignments were a major source of uncertainty for project management professionals, both in terms of their own careers and in terms of keeping the project on track. Securing project funding was an ever present source of uncertainty in both civil nuclear and aerospace industries, with project managers often unable to recruit staff due to ongoing funding uncertainties. In both sectors lack of funding was used as an excuse for inaction at the planning stages of projects, followed by an inevitable rush to deliver the project once funding sanction was given.

INSERT FIGURE 5 HERE

In civil nuclear, Complexity (see Figure 5) of the functional requirements of the product (for example, the range of nuclear materials that a test facility had to be able to characterise), was the most mentioned determinant of project uncertainty. In contrast, civil aerospace project managers were more concerned with technical novelty (when and how to implement new technologies within the product), and with the diversity of actors and

stakeholders from the project team, wider engineering community, customer and airline operator, all of whom were able to mandate changes in scope, or project requirements or delivery timescales for the project.

INSERT FIGURE 6 HERE

Figure 6 depicts the similarity between civil nuclear and aerospace sectors in terms of Information as a determinant of project uncertainty. Consistent with Harrison (1992) and Cleden (2009), the overwhelming majority of Information uncertainty arose from missing or incomplete information or a lack of knowledge of understanding. In the nuclear sector missing information comprised poor past record keeping over what materials were stored where, lack of ‘as built’ drawings of old facilities, and a failure of the relevant design authority to share critical drawings and design information. In addition, many nuclear subsystems, for example the performance of graphite bricks under seismic load, were perceived as being chaotic, scattered and extremely dynamic, making it hard to understand the causes of differences between modelled and experimental test results, and impacting on the preparation of essential safety cases. In civil aerospace projects, Information uncertainty often concerned an inability to frame the problem correctly, to understand the input parameters or to develop sufficient confidence in a new engine through analytical modelling before a very expensive first test engine was subjected to the rigours of the engine test bed.

INSERT FIGURE 7 HERE

Figure 7 shows marked differences between the sources of uncertainty around Capability across the two industry sectors. For example, in the civil nuclear sector the majority of the uncertainty emanates from a lack of capability within a long and often fragmented supply chain (Saunders et al, 2013). Lack of investment and attention to the nuclear skills base in the UK (Cogent, 2009) has caused the nuclear supply chain to wither,

leading to extreme resource challenges for nuclear projects that require nuclear-grade capability from external suppliers. Respondents described a dangerous assumption that was still prevalent within nuclear projects; that there was an unlimited pool of external skilled resources ready and willing to bid for any project work. This assumption was not held for internal resources, with project managers acknowledging that one of the major areas of uncertainty across both civil nuclear and aerospace projects was securing internal resources, particularly in specific technical disciplines such as design. Project managers often did not control their resources leaving them vulnerable to other project priorities, or even to other projects outbidding them for key staff.

INSERT FIGURE 8 HERE

The similarity in shape of both polar diagrams in Figure 8 indicates agreement across both sectors as to the role of Time as a determinant of project uncertainty. In both civil nuclear and aerospace projects the greatest contributor to temporal uncertainty is project turbulence (Weick, 1995), which manifests itself as changes in project scope, objectives and priority. Projects delivering safety-critical aircraft subsystems reported continual uncertainty over both scope and schedule. A nuclear decommissioning project faced repeated changes in project scope, requirements and permitted methods of working which delayed the project and damaged client-contractor relationships. Less frequently mentioned contributors to temporal uncertainty were the lifecycle stage of the project and the speed and timescale of the overall project although several respondents acknowledged that typically uncertainties are highest at the inception phase of projects and gradually reduce as the project evolves (Atkinson et al., 2006; Cleden, 2009).

Once surprising finding in this study was the lack of discussion of Individual perceptions of uncertainty; a strong theme in the literature (Kahnemann and Tversky, 1982;

Head, 1967, Madsen and Pries-Heje, 2009). Only 3 civil nuclear respondents and 1 civil aerospace respondent discussed uncertainty in terms of a state of mind that exists as a response to external triggers. Furthermore, there was one solitary mention of “uncertainty that exists in the mind of the one who doubts” (from the same civil aerospace respondent). Respondents in this study across both sectors seemed to view uncertainty as residing “out there” in the external world, rather than arising due to differences in the way different individuals perceive uncertainty. One possible explanation for this could be the pragmatism of the project management community, and a focus on delivering the project rather than agonising over whether uncertainties exist “out there” or “in the mind”. An alternative, although untested, hypothesis could be that large-scale safety-critical projects tend to attract individuals who are comfortable dealing with high levels of uncertainty.

New build/NPI projects versus maintenance projects

A comparable analysis of component uncertainties, broken down by project type and industry sector is not presented here as the numbers of projects in each category are too small and consequently less generalizable across other projects. Instead, the analysis focuses on the six main determinants of uncertainty (Complexity, Time, Environment, Capability, Individual and Information) and their comparison across different project types. Figure 9 shows the determinants of uncertainty across the two different types of project that were studied (new build/NPI vs maintenance).

INSERT FIGURE 9 HERE

It is more difficult to draw generalisable conclusions from the data in Figure 9, due to the diversity of projects studied. For example, new build/NPI projects in the study ranged

from the development of the next generation gas turbine engine to the building of new nuclear power plants and test facilities. Maintenance projects included the decommissioning and clean-up of the former sites of nuclear power stations, solving technical challenges in existing reactors to extend their safe operating life and retrofitting safety-critical aircraft assemblies to reduce their maintenance requirements or increase efficiency. All of the projects studied were also at very different stages in the lifecycle, from inception to final implementation. Nevertheless, pronounced differences were in evidence between new build/NPI projects and maintenance projects. For example, new build/NPI projects exhibited lower Information uncertainty and appeared to suffer less from uncertainties in Capability, whether internally or along the wider project supply chain. Possible explanations for this could be the lack of knowledge and understanding regarding the exact technical status of highly complex components of the civil nuclear reactor fleet and unknowns about the precise conditions and hazards of former nuclear sites. In contrast, a new nuclear plant is being built to an already approved and well-understood technical design. The requirements in retrofit and upgrade projects in the civil aerospace sector also changed more frequently than their NPI project equivalents, due to the rapid availability of real-time flight and maintenance data from airline operators. Capability and resource issues arose more frequently too, perhaps as a consequence of the less iconic nature of these maintenance projects and sometimes their challenging and remote locations.

INSERT FIGURE 10 HERE

Finally, Figure 10 highlights the contrast between the determinants of uncertainty across both different project types and different industry sectors. It illustrates that the differences between civil nuclear new build/NPI and maintenance projects are greater than the differences between those seen in civil aerospace new build/NPI and maintenance projects. Both civil nuclear new build/NPI and maintenance projects remain exposed to very

high levels of Environmental uncertainty, but new build/NPI projects have less uncertainty arising from project complexity, project and supply chain capability and information uncertainties. On the other hand, the differences between civil aerospace new build/NPI and maintenance projects are less pronounced – with the polar diagrams following a similar shape. The only exception to this is the difference in individual perception of uncertainty, but this difference is very small, and arises due to the mention of individual perception by one respondent on civil aerospace maintenance projects.

Conclusions and implications for practice

This study has addressed the determinants of uncertainty in safety-critical projects in two important industry sectors: civil nuclear and civil aerospace. We draw three main conclusions from this research, which provides new insights into project uncertainty in safety-critical project environments. First, the analysis of the 30 respondent interviews elicited a small number of new components of uncertainty, which were consistent with the existing framework of the Uncertainty Kaleidoscope. This study has therefore provided both validation of the Uncertainty Kaleidoscope as a model for mapping the determinants of project uncertainty in safety-critical projects and also adds to it richer contextual details.

Secondly, the study demonstrated that the six major determinants of project uncertainty (Complexity, Time, Environment, Capability, Individual and Information) are broadly similar across both civil nuclear and civil aerospace sectors. Content analysis of the 30 respondent interviews showed that the most commonly mentioned determinant of project uncertainty is the project Environment, followed by Complexity, Capability then Information. The impact

of Time on project uncertainty and Individual perceptions of uncertainty were highlighted much less frequently by respondents. There were also differences in the determinants of uncertainty depending on the type of project. For example, new build/NPI projects have lower Information uncertainty and appear to suffer less from uncertainties in Capability; whether internally, at the project client or or along the wider project supply chain.

Thirdly, there are more pronounced differences between civil nuclear and civil aerospace sectors at the finer granularity of the components of uncertainty that make up each determinant. In particular, the Environment, Complexity and Capability as sources of project uncertainty each manifest themselves in different ways in the two industry sectors studied. For example Complexity is more likely to arise due to the functional requirements of the product in nuclear but is caused more by technical novelty and the diversity of project actors in civil aerospace. And Capability uncertainty pervades the entire nuclear project supply chain – both internal and external whereas it is more focused on internal resource availability in civil aerospace.

Implications for practice

Research access to safety-critical projects has traditionally been very hard to achieve due to the high levels of commercial sensitivity that prevail in these industries. The ability to interview 30 respondents on 9 different large projects across two important safety-critical industries provided a valuable opportunity to explore these under researched project environments, which are vital to our modern infrastructure. What emerged from the study was that the project management professionals tasked with managing these complex, large-

scale safety-critical projects in civil nuclear and civil aerospace industries operate in an environment of high uncertainty. Using the Uncertainty Kaleidoscope to identify the sources of and influences on uncertainty in safety-critical projects may help individuals better structure their projects for success and render them less likely to be surprised by ‘unknowns’ that may delay project implementation, add additional costs and reduce stakeholder confidence in the project delivery team. In mapping the multi-faceted nature of project uncertainty and articulating it in the form of the Uncertainty Kaleidoscope, the authors have provided a starting point and a structure for workshops, debates and discussions to be held by project teams that explicitly address the issue of project uncertainty. By identifying areas of uncertainty early on in the project lifecycle, when the scope may be very fluid, costs and timescales little more than unsubstantiated estimates, and the required trade-offs between competing project objectives just beginning to emerge, it may be possible to reorient project managers’ perceptions of project uncertainty as unwanted and negative and bound up with risks to project delivery, into a more expansive, optimistic understanding of uncertainty as an opportunity to be exploited with positive approaches for changing how projects are delivered.

Limitations

The ontology underpinning this study is closest to the positivist research paradigm, viewing the determinants of project uncertainty as in some sense objective, real and external to the respondents, as opposed to being socially constructed by the actors engaged on the project. There are dangers in this positivist approach, as it can tempt researchers to believe that their conclusions are objective and imbued with predictive power. There is a risk therefore that the Uncertainty Kaleidoscope could be construed as “pseudo-scientific”, where as in reality it should serve only as a metaphor for the myriad landscapes of project uncertainty that may arise in safety-critical projects. Like many metaphors it is intended to be memorable and to act as a practical framework to enable productive discussion and debate

over where the sources of uncertainty are in a specific project context. Like all metaphors it has limitations and the authors acknowledge the weaknesses inherent in using a kaleidoscope as a metaphor for projects. 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.

Aside from the philosophical limitations of this study there are a number of practical caveats that must be placed on the data collected and conclusions drawn. First, the access to projects was to some extent opportunistic. Although strenuous attempts were made to identify a well-balanced portfolio of projects to investigate, access was not always granted, resulting in an imbalance in interviews between civil nuclear and aerospace projects. Somewhat surprisingly, it was often civil aerospace organisations who displayed a greater concern for commercial secrecy and less willingness to open up their project management practices to the researchers. Secondly, although the authors interviewed several respondents per project to mitigate against individual respondent bias and to allow more valid cross-project comparisons, it was not possible to further triangulate the findings by accessing other sources of data, for example project documentation or participant observation. Extending the study in this manner would make a fruitful line of further enquiry and importantly would enable a deeper exploration of the project actuality of safety-critical projects.

Future work

In spite of these limitations, this study, involving 30 project management professionals across 9 large scale safety-critical projects is large enough and sufficiently representative

(given the limitations of accessing such sensitive projects) to enable the findings to be generalisable across safety-critical projects, certainly in UK based civil nuclear and aerospace sectors. Further work is now required to test the validity of the Uncertainty Kaleidoscope across other safety-critical sectors, such as oil and gas. We would also encourage other researchers to repeat our study across other geographic regions. Another productive avenue for future investigation would be to better understand the practices and routines that project management professionals enact in order to respond to these uncertainties in their day-to-day project life and to link the use of the Uncertainty Kaleidoscope to enhanced systems of project governance in these safety-critical environments.

References

- Atkinson, R., Crawford, L., Ward, S. (2006). Fundamental uncertainties in projects and the scope of project management. *International Journal of Project Management*, 24(2006), 687-698.
- Attewell, R.G. (2009). Statistics: An essential tool for model citizens, in Bammer, G., Smithson, M. (Eds.), *Uncertainty and Risk: Multidisciplinary Perspectives* (pp. 81-91). London, UK: Earthscan.
- Chapman, C.B., Ward, S. (2002). *Managing Project Risk and Uncertainty: A Constructively Simple Approach to Decision Making*. Chichester, UK: John Wiley and Sons.
- Cleden, D. (2009). *Managing Project Uncertainty.*, Farnham, UK: Gower Publishing Limited.
- Cogent (2009). Power people: The civil nuclear workforce 2009–2025 Renaissance Nuclear Skills Series 1, 2009, <http://www.cogent-ssc.com/research/Publications/NuclearReportPowerPeople.pdf>. Accessed on 16th December 2014.
- De Meyer, A., Loch, C.H., Pich, M.T. (2002). Managing project uncertainty: from variation to chaos. *MIT Sloan Management Review*, Winter 2002, 60-67.
- Easterby-Smith, M., Thorpe, R., Jackson, P.R. (2008). *Management Research*. (3rd ed.) London, UK: SAGE Publications Ltd.
- Evans, W. (1996). Computer supported content analysis: Trends, tools and techniques. *Social Science Computer Review*, 14(3), 269-279.
- Falla, M., (1997). Advances in Safety Critical Systems - Results and Achievements from the DTI/EPSRC R&D Programme, <http://www.comp.lancs.ac.uk/computing/resources/scs/>. Accessed on 16th December 2014.
- The Guardian (2014). Is there a future for Malaysia Airlines after flights MH370 and MH17? <http://www.theguardian.com/world/2014/jul/29/is-there-a-future-for-malaysia-airlines>. Accessed 16th Dec 2014

- Guest, G., Bunce, A., Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field Methods*, 18(1), 59-82.
- Harris, E., Woolley, E. (2009). Facilitating innovation through cognitive mapping of uncertainty. *International Studies of Management and Organisation*, 39(1), 70-100.
- Harrison, E.F. (1992). Perspectives on uncertainty in successful strategic choice at the CEO level. *OMEGA International Journal of Management Science*, 20(1), 105-116.
- Head, G.L. (1967). An alternative to defining risk as uncertainty. *The Journal of Risk and Insurance*, 2(34), 205-214.
- Hillson, D. (2002). Extending the risk process to manage opportunities. *International Journal of Project Management*, 20(2002), 235-240.
- Hillson, D. (2004). *Effective Opportunity Management for Projects- Exploiting Positive Risk*. New York: Marcel Dekker.
- Kahneman, D., Tversky, A. (1982). Variants of uncertainty, in Kahneman, D., Slovic, P., Tversky, A. (Eds.), *Judgement under uncertainty: Heuristics and Biases* (pp. 509-520). Cambridge: Cambridge University Press.
- Loch, C.H., DeMeyer, A., Pich, M.T. (2006). *Managing the unknown: A new approach to managing high uncertainty and risk in projects*. Hoboken, New Jersey: John Wiley and Sons.
- Loosemore, M., Raftery, J., Reilly, C., Higgon, D. (2006). *Risk Management in Projects*, (2nd ed.). Abingdon, UK: Taylor and Francis.
- Madsen, S., Pries-Heje, J. (2009). Taking a closer look at uncertainty in IS projects. AMCIS 2009 Proceedings. <http://aisel.aisnet.org/amcis2009/119> Accessed on 12th October 2012.
- March, J. G., Simon, H.A. (1958). *Organisations*. New York: John Wiley and Sons.
- Neuendorf, K.A. (2002). *The Content Analysis Guidebook*. Thousand Oaks, CA: SAGE Publications Inc.
- Olsson, N.O.E. (2006). Management of flexibility in projects. *International Journal of Project Management* 24(2006), 66-74.
- Olsson, R. (2007). In search of opportunity management: is the risk management process enough? *International Journal of Project Management*, 25(2007), 745-752.
- Osman, M. (2010). *Controlling Uncertainty: Decision Making and Learning in Complex Worlds*. Chichester, UK: Wiley Blackwell.
- Perminova, O., Gustafsson, M., Wikstrom, K. (2008). Defining uncertainty in projects: a new perspective. *International Journal of Project Management*, 26(2008), 73-79.
- PMI (2013). PMI's pulse of the profession: The high cost of low performance. <http://www.pmi.org/Learning/~media/pdf/business-solutions/pmi-pulse%20report-2013mar4.ashx>. Accessed 16th December 2014.
- Porter, M.E. (1980). *Competitive Strategy*. New York: Free Press.
- Sanderson, J. (2012). Risk, uncertainty and governance in mega projects. *International Journal of Project Management*, 30 (2012), 432-443.
- Saunders, F.C., Gale, A.W., Sherry, A.H. (2013). *Understanding Uncertainty in safety-critical industries* at PMI Global Congress EMEA, Istanbul, 22nd -25th April.

- 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(2015), 467-478.
- Schlesinger, L.A., Kiefer, C.F., Brown, P.B. (2012) New project: Don't Analyse-Act in *Harvard Business Review*, March 2012, 154 -158.
- Smithson, M. (2009). The many faces and masks of uncertainty, in Bammer, G., Smithson, M. (Eds.), *Uncertainty and Risk: Multidisciplinary Perspectives* (pp. 13-25). London, UK: Earthscan.
- Stone, P.J, Dunphy, D.C., Smith, M.S., Ogilvie, M.N. (1966). *The general inquirer: A computer approach to content analysis*. Cambridge: MIT Press.
- Sutcliffe,K.M., Zaheer,A. (1998). Uncertainty in the transaction environment: an empirical test. *Strategic Management Journal*, 19, 1-23.
- Ward, S., Chapman, C. (2003). Transforming project risk management into project uncertainty management. *International Journal of Project Management*, 21(2003), 97-105.
- Wears, R.L. (2012). Rethinking healthcare as a safety-critical industry. *Work* 41(2012), 4560-4563.
- Weick, K.E. (1995). *Sensemaking in Organizations*. Thousand Oaks, CA: Sage Publications Inc.
- Winch, G.M. (2010). *Managing Construction Projects: An information processing approach*, (2nd ed.). Chichester, UK: Wiley-Blackwell.



Figure 1: The Uncertainty Kaleidoscope (from Saunders et al., 2015)

Project Description	Industry Sector	Project Type	Respondent Roles
Provision of two new civil nuclear test facilities	Civil Nuclear	new build/new product introduction	Senior Project Manager Commissioning Manager Risk Analyst
Planning of new nuclear power plant	Civil Nuclear	new build/new product introduction	Programme Manager Programme Manager Programme Manager Programme Manager
Transfer of intermediate level waste to storage facility	Civil Nuclear	maintenance	Project Engineering Manager Project Director Project Controller Commercial Manager
Reactor life-extension project	Civil Nuclear	maintenance	Group Head of Project Technical Lead Sub-project Manager Sub-project Manager
Decommissioning of specific elements of nuclear power station	Civil Nuclear	maintenance	Project Manager Commercial Manager Client account director
Development of new gas turbine engine	Civil Aerospace	new build/new product introduction	Subsystem Programme Manager Subsystem Programme Manager Deputy Programme Executive
Development of new test facility	Civil Aerospace	new build/new product introduction	Programme Manager Project Controller
Retrofit of safety-critical assemblies to in-service aircraft fleet	Civil Aerospace	maintenance	In service Programme manager Operations Shift Manager Programme Manager
Phased upgrades to in-service gas-turbine engine	Civil Aerospace	maintenance	Deputy Programme Executive Chief of Subsystem Integrated Project team Leader Integrated Project team Leader

Table 1: Study projects, their classification and list of respondents

Determinant	Components of uncertainty	Civil Nuclear (Number of interviews in which component was mentioned)	Civil Aerospace (No of interviews in which component mentioned)	Total number of interviews in which component was mentioned
Complexity	Functional requirements of the product	9	5	14
	Technology choice	5	1	6
	Diversity of actors and stakeholders	5	4	9
	Inherent project complexity (including Feedback loops, instability and emergent system properties/ integration issues)	5	2	7
	Technical novelty	3	3	6
Information	Incomplete and imperfect information	9	6	15
	Lack of knowledge or understanding	9	6	15
	Incomplete understanding of cause and effect relationships	2	0	2
	Inability to estimate accurately	2	2	4
Environmental	Environmental turbulence (due to changes in market, political environment or competitor activity)	8	8	16
	Competing and conflicting stakeholder demands	7	4	11
	Culture (organizational tolerance of uncertainty, Institutional norms and decision making processes, clarity of roles and responsibilities)	7	7	14
	Regulatory constraints	3	0	3
	Site security	3	0	3
	Funding	6	2	8
Time	Stage of project lifecycle	4	3	7
	Project tempo and timescale	3	1	4
	Project turbulence (rate of change of project facts, randomness of timing of changes and direction of change, clarity of scope)	8	4	12
Individual	Uncertain state of mind in response to triggers in the external environment	3	1	4
	Uncertainty exists "in the mind of the person who doubts"	0	1	1
	Bounded rationality and Fallacy of rational decision making	0	0	0
	Different psychological profiles perceive uncertainty in different ways	0	0	0
Capability	Skills and experience of project team members	4	1	5
	Project management maturity of organisation	5	2	7
	Internal resource availability	5	6	11
	Capability (skills, experience and resource availability across industry supply chain)	8	4	12
	Client capability	3	1	4

Table 2: Categories and interview counts for content analysis of respondent interviews
(In total there were 18 civil nuclear interviews and 12 civil aerospace)

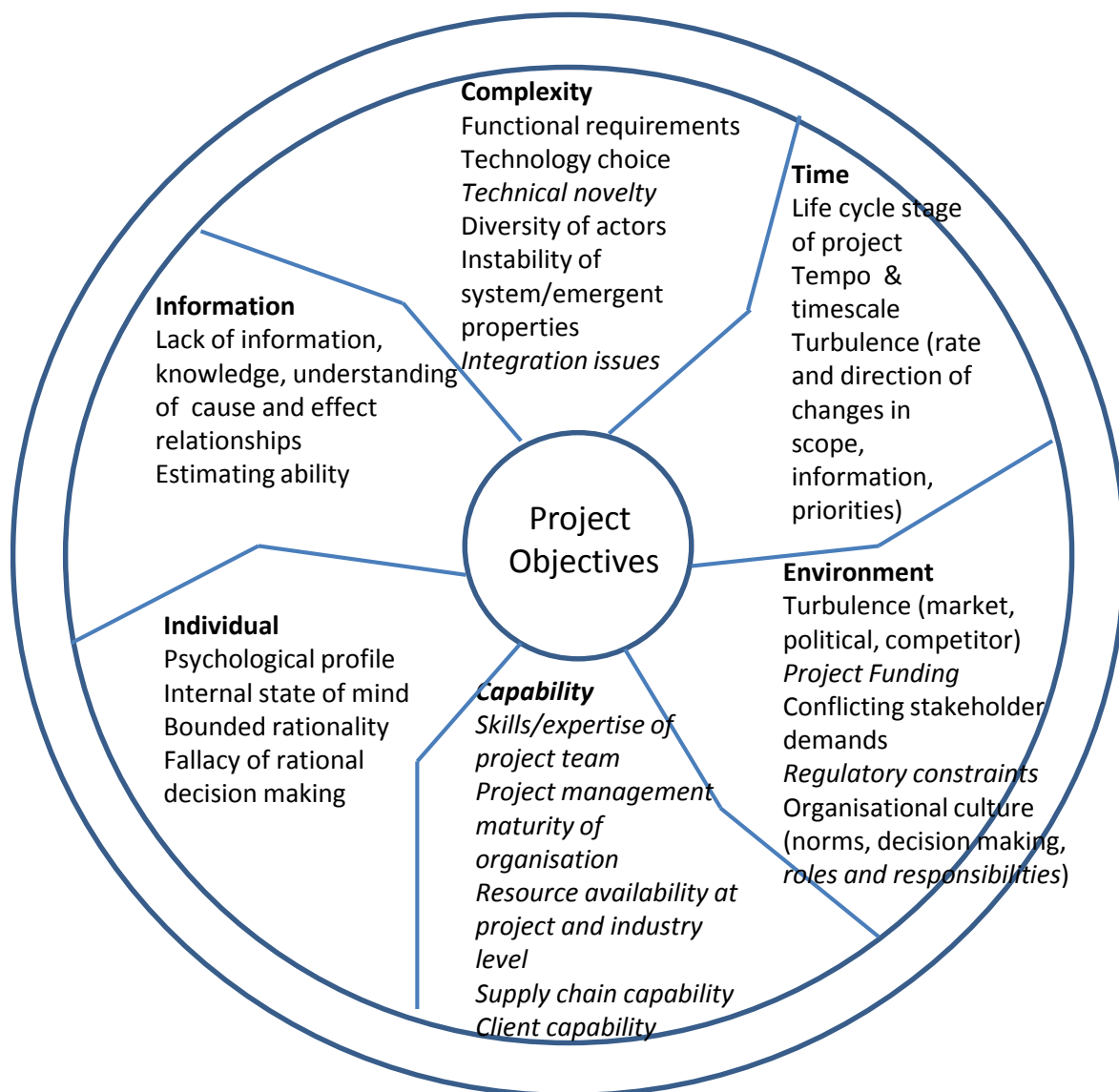


Figure 2: Refined and validated model of the “Uncertainty Kaleidoscope”. Components in italics arose from the empirical studies; those in normal from the literature.

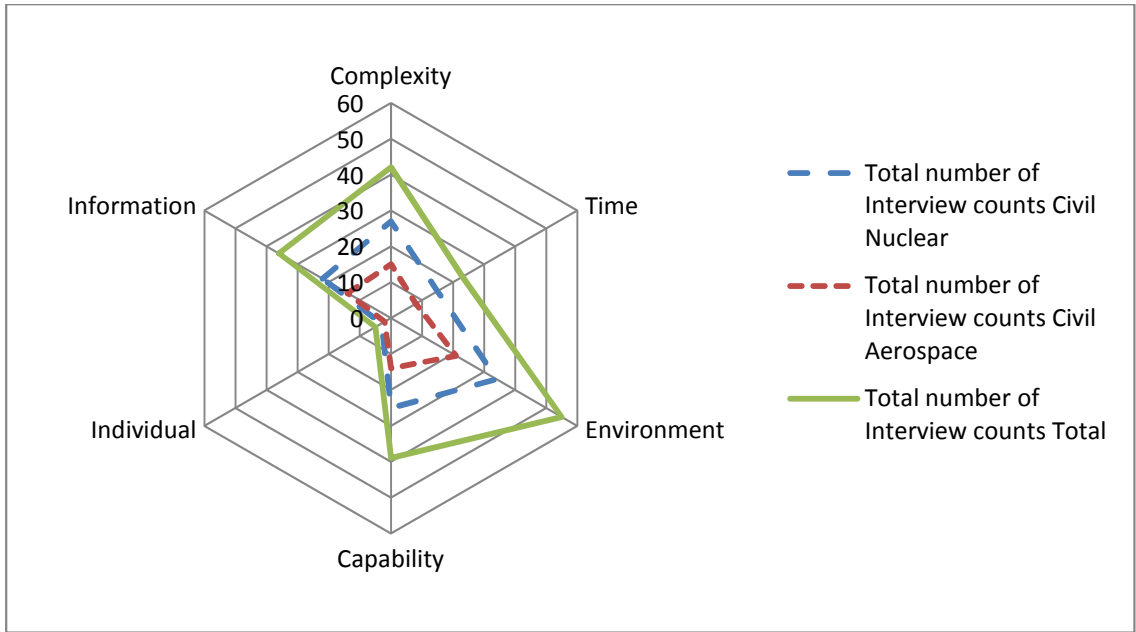


Figure 3: No of respondent interviews in which each determinant of uncertainty was mentioned

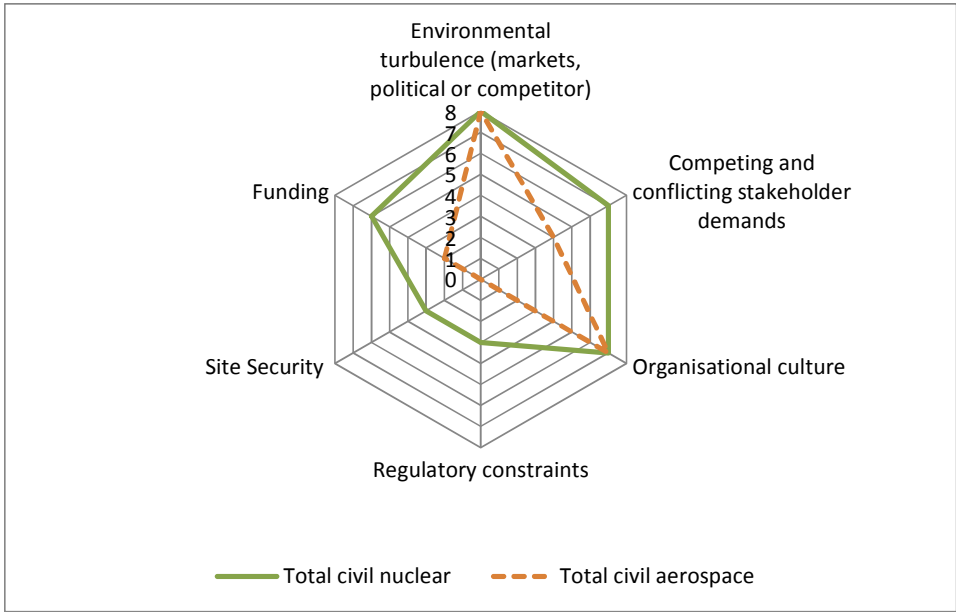


Figure 4: Components of the environment as a determinant of project uncertainty: Number of mentions across civil nuclear and civil aerospace respondent interviews

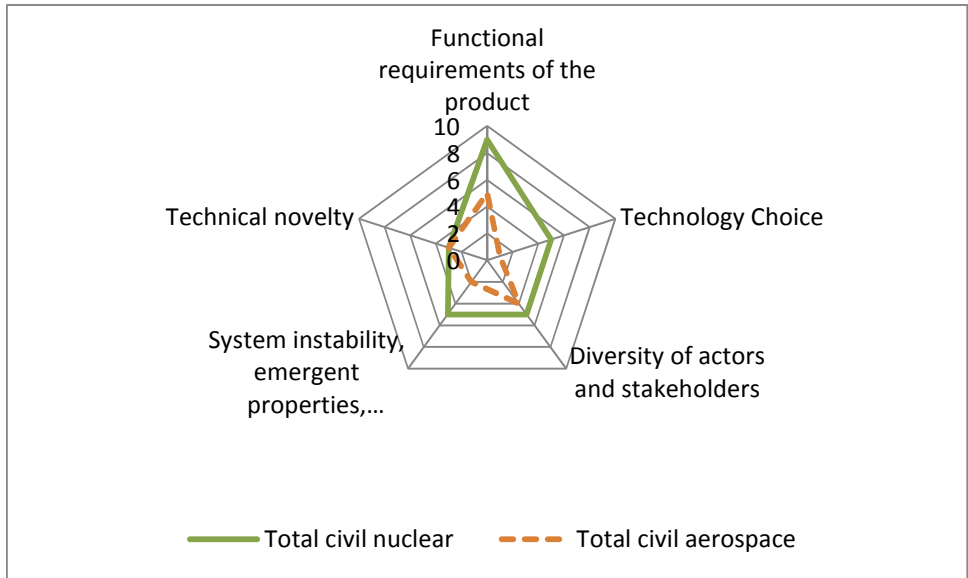


Figure 5: Components of complexity as a determinant of project uncertainty: Number of mentions across civil nuclear and civil aerospace respondent interviews

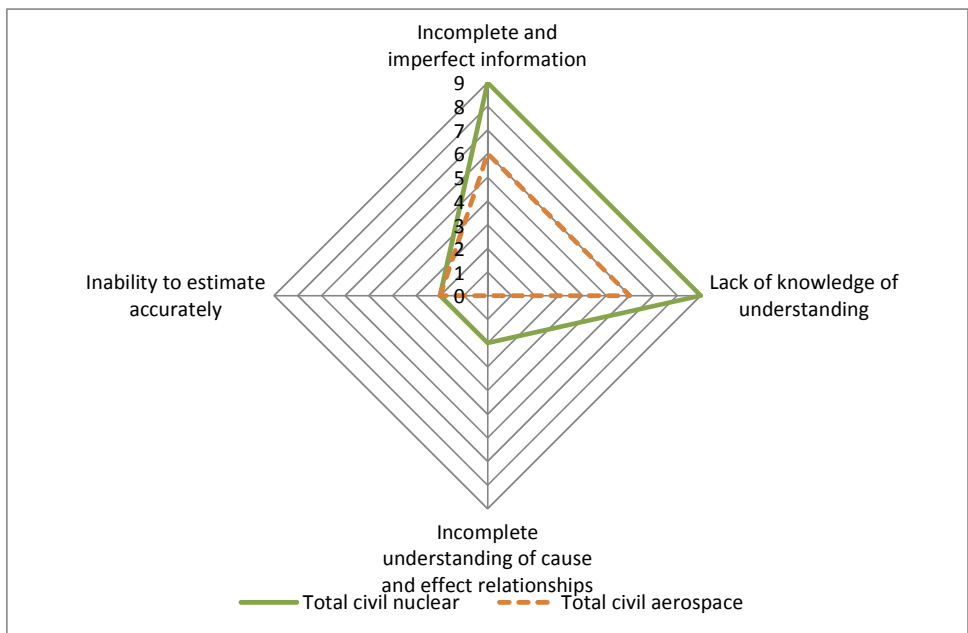


Figure 6: Components of information as a determinant of project uncertainty: Number of mentions across civil nuclear and civil aerospace respondent interviews

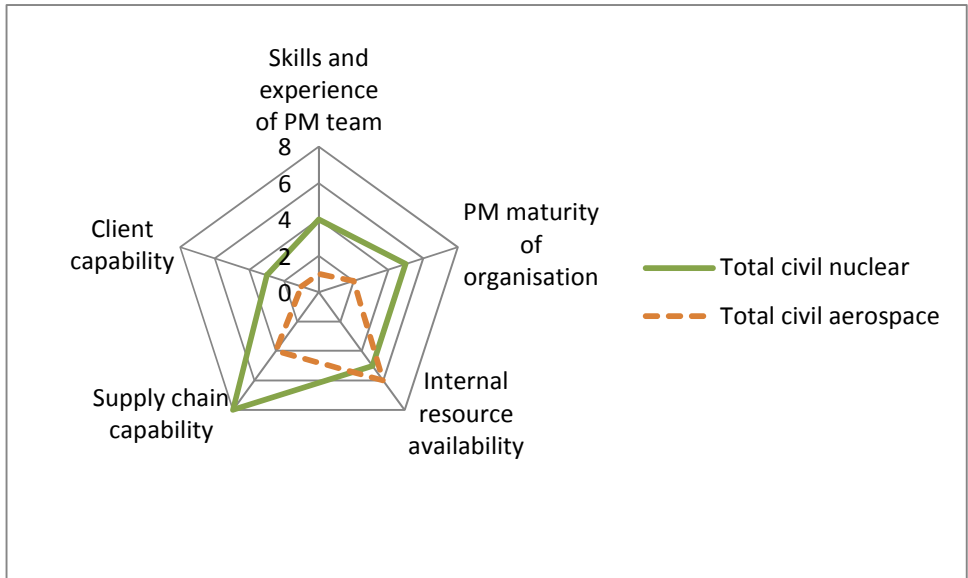


Figure 7: Components of capability as a determinant of project uncertainty: Number of mentions across civil nuclear and civil aerospace respondent interviews

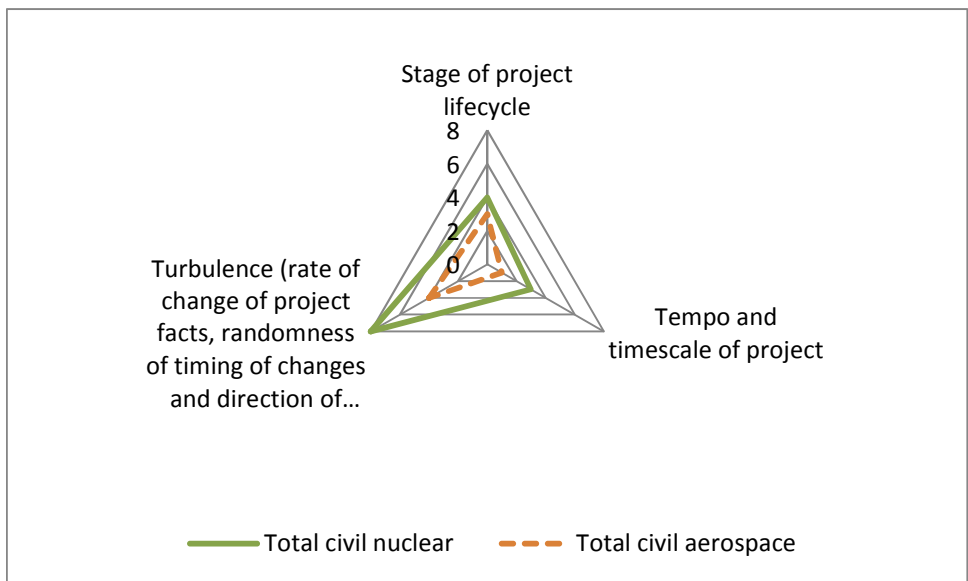


Figure 8: Components of time as a determinant of project uncertainty: Number of mentions across civil nuclear and civil aerospace respondent interviews

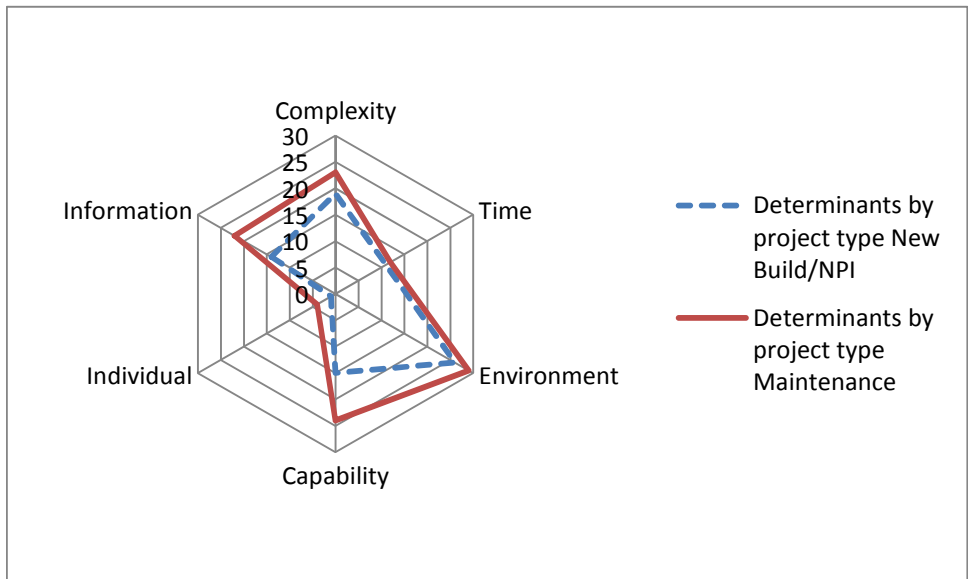


Figure 9: Polar diagram of the number of mentions of each determinant of uncertainty in the two different project types

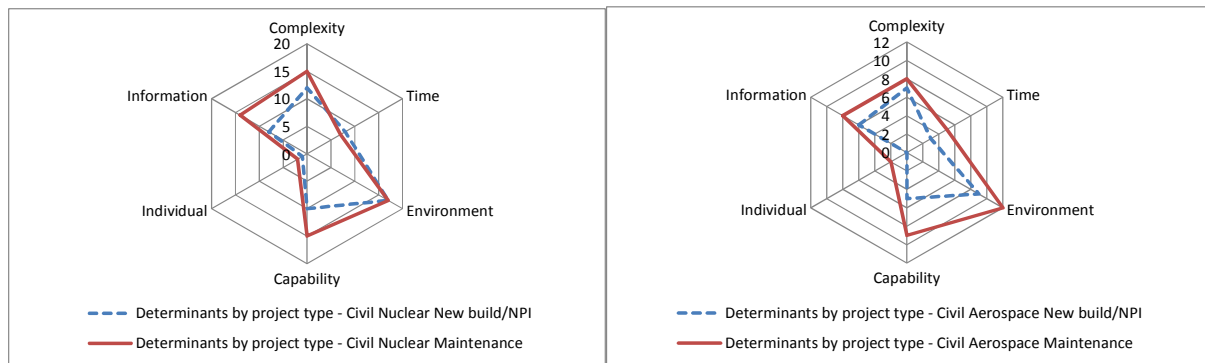


Figure 10: Polar diagrams of the determinants of uncertainty differentiated by project type and industry sector