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Engineering maintenance decision-making with unsupported judgement under operational constraints

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ABSTRACT

In operational engineering maintenance situations, limitations on time, resource or the information available often inhibit rigorous analysis on complex decision problems. Decision-makers who are compelled to act in such circumstances, may be informed by some level of analysis if available, or else may have to rely on their unsupported judgement. This paper presents three engineering risk decision-making case studies across a 20 year span from the rail, aerospace, and military aviation contexts, highlighting the fallibilities of using unsupported judgements in an unstructured manner. To help situate this type of decision situation, we provide a descriptive model of the decision space which extends an existing description from the discipline of decision analysis. Furthermore, to help make and describe the distinction between unsupported and supported thinking, we provide another descriptive model, this time drawing parallels with the distinction made between Type 1 and Type 2 reasoning. This model is an extension of the default-interventionist model from cognitive psychology.

The paper concludes that there is a pressing need to provide some form of support to engineering decision-makers facing operational decisions under severe time pressure. While the ultimate aim must be to improve the quality of decision-making, improved transparency is an important additional benefit. Increased emphasis on decision justification and self-awareness are suggested as potential ways of improving this situation. A further contribution of this paper is to identify and strengthen linkages between safety science and two other relevant disciplines, decision analysis and psychology. Such linkages make it easier to communicate across traditional disciplinary boundaries and may provide opportunities for interdisciplinary learning or suggest future directions for collaborative research.

1. Introduction

This paper is concerned with a particular type of decision faced by engineering maintenance managers in operational environments. That is the decision to continue, limit or cease operations of some kind when an unforeseen structural integrity fault arises. Such decisions demand quick critical thinking given typically limited information, time and resources. Domains where this type of decision is common include aviation, rail, maritime, oil and gas. Despite the practical usefulness of risk analysis in such domains (Chen et al., 2018; Animah and Shafiee, 2018; Vagnoli et al., 2018; Rafiq et al., 2015; Gobbato et al., 2012; Khan et al., 2015) these environments are challenging for its application. In particular, structural integrity faults are often associated with low probability, high consequence events (Luxhøj and Morton, 2011; Uyar, 2019) and are further complicated by the individualistic nature of structural deterioration (even within a similar aircraft fleet) owing to unique usage profiles, environmental exposure and microscopic material imperfections. The proximity of this type of decision to the operational frontline often severely constrains the time available to the decision-maker to a matter of hours or less. In Fig. 1, we contrast this situation with less critical ones that are amenable to traditional decision analytic approaches as outlined, for example, by Howard and Abbas (2016).

Fig. 1 categorises situations in terms of the time required to reach a requisite decision (which can also be associated with decision complexity) and the time available to reach the decision (likely to be associated with its setting or environment). It extends the decision hierarchy presented by Howard and Abbas (2016, p28) which only considers the time required and therefore corresponds to Region 2 in Fig. 1. Within Region 2, points A, B and C represent the three layers in the existing hierarchy and correspond to different levels of

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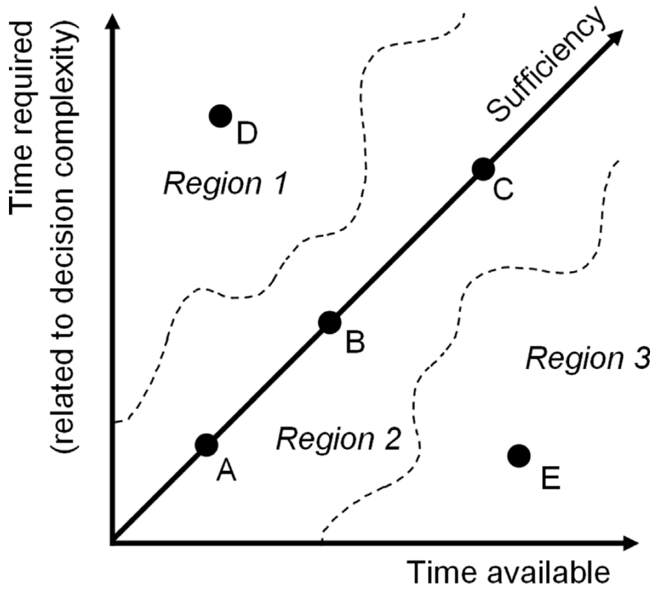

Fig. 1. An extended decision-making hierarchy, adapted from Howard and Abbas (2016). The line of sufficiency in Region 2 corresponds to decision situations where the time required to make a requisite decision is equal to the time available.

decision complexity. In Region 1, however, the time required for a requisite decision is greater than the time available — this is where the decisions of interest in this paper are situated. Point D, for example, might represent an urgent operational decision regarding whether an aircraft tasked to a mission with strategic importance should fly its next scheduled sortie when damage to critical structure has been identified during preparation of the aircraft. In Region 3, the time available to reach a decision is greater than the time required at that level of complexity. While an efficient decision-maker will not actually use this excess time, an inefficient decision-maker might. This could manifest itself as a decision situation being over-analysed — typically, low complexity decisions being afforded more time than is necessary. We believe the diagram is helpful a priori as a guide to stakeholders to provide consistency of expectation, e.g. in the methods used by decision-makers. At Point C, for example, we might expect quantitative methods to be used for assessing structural integrity risk. These are largely simulation-based, dynamic in nature (reflecting the temporal aspects of structural integrity), built on statistical theory, and require detailed knowledge of material degradation relationships and key structural system variables (see for example Theofanous (2003), Hurtado and Hoffman (2006), Cope and Moffett (2012), Rusk et al. (2001), Torregosa and Hu (2013), Yang and Manning (1994), Straub (2009), Straub and Der Kiureghian (2010), Straub and Papaioannou (2015)). However, such methods are information hungry, require expertise to build the model and appropriate software and time to conduct simulations, rendering them unsuitable at Point D. It has also been noted that even when the situation does allow quantitative methods to be used, the subjectivity applied in building a risk model (Aven, 2018, p239) can lead to problems in validation and accuracy in the quantitative risk assessment (Goerlandt et al., 2017).

The kind of operational decision-making considered in this paper is typically further constrained by additional resource limitations such as the expertise and analytical capability available over short timescales. Furthermore, decision-makers are often engineering managers who are better described as generalists than specialists or experts, having to deal with a wide range of potential faults and issues. In the military aviation domain, for example, these might include avionics, mechanical systems, weapons systems, structural items and electrical components, over multiple aircraft. The result is that such decision-makers need to rely heavily on their own broad experience and intuition rather than on more specialist advice from a specific engineering expert and/or computer model.

Engineering and other domain experts are not immune from bias and heuristic influences when assessing risks, even in analytical assessments (Rae and Alexander, 2017; Baybutt, 2018; Brown and Utley, 2019). Furthermore, in an operational situation where the decision basis will not have the support of rigorous analysis, the use of purely subjective judgement can be explicitly permitted. For example, UK military aviation regulations permit the use of such judgement:

"On occasions when a Maintenance activity cannot comply with relevant TI[1], or there is insufficient resource, the Maintenance must remain incomplete. However, an operational requirement may necessitate a Maintenance activity being completed prior to resources becoming available or prior to an approved and promulgated TI amendment being issued by the TAA[2]......Deferring Maintenance and deviating from TI carries risk. When considering deferment or deviation, the authorised individual must assess the associated risks and consider all factors that will mitigate the risk and ensure the Air System is airworthy. The mitigating factors must be adequately documented in the appropriate Maintenance work order."(Military Aviation Authority, 2018a, p10).

Quantitative or qualitative considerations of risk may be appropriate, which the above regulation leaves open to the decision-maker. Alternatively, adopting a conservative stance (such as using the accident avoidance approach (Yang and Haugen, 2015, p119)) by avoiding precise risk statements may be preferred. In whatever way a decision is formed, a decision-maker's judgement could be misguided by cognitive or behavioural influences. Ultimately, errors of judgement could expose many people to unintentionally high levels of risk. Risk assessment is intended to help prevent such problems by logically structuring available information about uncertain future outcomes to enable a rational decision basis. For equipment already in-service, failures can expose wrong assumptions made during design and necessitate redesign, particularly for domains that are heavily regulated to assure safety standards. But under operational constraints, judgements about risk that lack analytical support could be challenged on the grounds of credibility, irrespective of the decision taken. The need to maintain equipment often conflicts with demands for their use. For instance, a maintenance manager's decision to ground an aircraft, halt train services, or suspend oil production based on unsupported subjective judgement may invite dissent and criticism from operators, availability managers, or other stakeholders where the manager would be expected to justify their argument.

The decisions considered here are examples of this safety/production trade-off (Cowing et al., 2004; Wilson et al., 2009). A particular example from the aviation domain might be whether immediate maintenance is necessary to rectify a newly identified crack or damage from a bird strike. What makes these particular decisions special is the necessity to resolve that trade-off quickly, relying largely on the subjective judgement of the decision-maker. Here, we refer to such a situation as one which involves 'unsupported' judgement. This is in contrast to a situation where there is sufficient time for the decision-maker to obtain external advice, such as from a specialist engineering expert, a computer model or some other kind of formal analysis. We refer to that kind of situation as one involving 'supported' judgement. Such situations only arise in regions 2 and 3 of Fig. 1. We believe that this distinction is important and deserves to be highlighted much more

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[1] Technical Information, such as maintenance procedures or special instructions.

[2] Type Airworthiness Authority, a UK Ministry of Defence organisation with responsibility for the overall airworthiness and resourcing of a fleet of aircraft. They often act as the intermediary between the operators of the aircraft (the UK Ministry of Defence) and the manufacturers (defence industry), but provide immediate fleet and individual aircraft airworthiness advice to operators.

Table 1
Variations in the lexicon used in literature to describe Type 1 and Type 2 reasoning (Slovic et al., 2004; Aven, 2018).

Type 1	Type 2
Experiential	Analytic
System 1	System 2
Subjective	Objective
Hot emotional	Cold rational
Intuition	Analytical
Automatic	Deliberative
Non-verbal	Verbal
Animalistic	
Narrative	
Fast	
Natural	

in this context. It is particularly relevant to any discussion about how such operational decision-makers can be better supported. In our view, this is an under-researched topic which merits much greater attention in the risk and safety literature.

Attention has previously been drawn to the time and resource pressures that practitioners typically operate under. Surveys (Farooqi et al., 2022; Underwood and Waterson, 2013) have demonstrated how little time they might have to learn or apply even moderately complicated methods such as FRAM (Functional Resonance Analysis Method) or STAMP (Systems Theoretical Accident Modelling and Processes). This mismatch between the supply of formal tools and methods to support the decisions of practitioners and their uptake by the practitioners themselves is usually referred to as the 'research-practice gap' (e.g. Underwood and Waterson (2013)). This has to be borne in mind when considering any suggestions to improve the support available to decision-makers in the kind of situation we are focusing on here. In particular, this is especially relevant for contexts that demand accountability and transparency, such as in public organisations (Anon, 1958). However, if a decision-maker's assessment of risk is "normally invisible during the decision-making process and an informal assessment process is concealed in the mental models and the experience of professionals" (Yang and Haugen, 2015, p117), the route to the outcome becomes opaque. Decision-maker cognition should be accounted for when creating a risk management strategy. Bridging between risk assessment methods and human processing of risk decisions necessitates a resilience-focused approached in order to account for complex sociotechnical safety interactions that are impossible to predict (Swuste et al., 2020).

In this paper, three engineering-based case studies are used to highlight the need for improved risk decision support in real-world, time-critical operational situations that compel the use of unsupported, subjective judgement. The constraints that operational settings can impose upon the decision-maker mean that the resulting discussion of each case study incorporates threads of work from the fields of risk analysis, decision science, rationality, risk perception and applied psychology. We specifically make use of works by Aven (2018) and Evans (2019). Furthermore, we support the recent call for more empirically-grounded research in the safety domain Rae et al. (2020). We also note the prediction that the safe operation of future systems characterised by high complexity and diverse risk sources will require flexible, dynamic interventions with a capacity to handle unforeseen events (Swuste et al., 2020).

2. Theory and method

In this section, we begin by presenting some background theory concerning modes of thinking that are relevant to the type of decision-making scenario being considered. In particular, we make use of the default-interventionist model of Evans (2019) to highlight the situation where a decision-maker is constrained to rely on their unsupported subjective judgement. This background theory helps to inform our method by providing code words that are used as part of a thematic analysis of the three cases presented in Section 3. The nature of this thematic analysis is outlined, along with the rationale for case selection.

2.1. *Type 1 and type 2 thinking*

Although lacking any clear neurological explanation to date, psychologists have nonetheless long found it useful to distinguish between two types of reasoning, referred to as Type 1 and Type 2 by some, including Evans (2019). Others, notably Kahneman (2011) who has popularised the theory in recent years, use the terminology System 1 and System 2 instead. According to this distinction, humans have two ways of thinking - a fast, intuitive, subconscious and automatic mode (Type 1); and a slower, analytical, conscious and deliberative mode (Type 2). Regardless of which terminology is used, many psychologists make sense of this phenomenon in terms of so-called dual process theories (Wason and Evans, 1974). The characteristics usually associated with these two modes are reproduced in Table 1 based on Aven (2018, p238) who in turn obtained these from Epstein (1994) and Slovic et al. (2004). Although dual process theories offer an appealing description of a familiar phenomenon, there is disagreement over the underlying mechanisms responsible, as well as the ways in which these different modes interact (Evans, 2019).

Evans (2019) provides good reasons for using the Type 1/2 terminology rather than System 1/2 and also identifies the use of working memory as the key discriminating feature of Type 2 reasoning. However, there are competing views about the role played by Type 2 thinking and the nature of the interaction between the two modes. Some authors (Sperber and Mercier, 2017) still hold the original view that the function of Type 2 thinking is to justify and rationalise Type 1 intuitions. More recently, however, there is a consensus that the function of Type 2 thinking is to reason to a logical conclusion or decision (Evans and Stanovich, 2013). While the former view suggests a serial relationship, with Type 1 thinking preceding Type 2, the latter permits either a serial or parallel relationship. Evans (2019) offers what he describes as a default-interventionist model of the relationship. In this model, Type 1 thinking provides a potential response, e.g. an instinctive solution to a problem, while Type 2 thinking takes over if this initial response is somehow deemed inadequate. In other words, the initial Type 1 response is the default solution to be adopted unless Type 2 thinking intervenes. This raises a further question about the nature of the intervention mechanism — is this a part of the Type 2 response or is there a third mode of reasoning involved as a kind of adjudicator, only calling on Type 2 thinking when it is deemed to be required? Again, there are competing opinions on this point.

2.2. *Supported vs unsupported type 2 thinking*

In this paper, we focus attention on situations where a decision-maker is unsupported and solely reliant on their experience and subjective judgement. This is in sharp contrast to situations more commonly assumed in the literature where different kinds of analytical support, including modelling, simulation, and the use of external experts are considered possible. While any decision arrived at by an operational decision-maker in the engineering maintenance function will entail Type 2 thinking, we believe that it is useful to highlight the distinction between unsupported and supported Type 2 thinking, as outlined above. Furthermore, we argue that the default-interventionist model presented by Evans (2019) lends itself to an extension that incorporates this distinction and which makes the model more relevant to safety science. The extended model is presented in Fig. 2, within

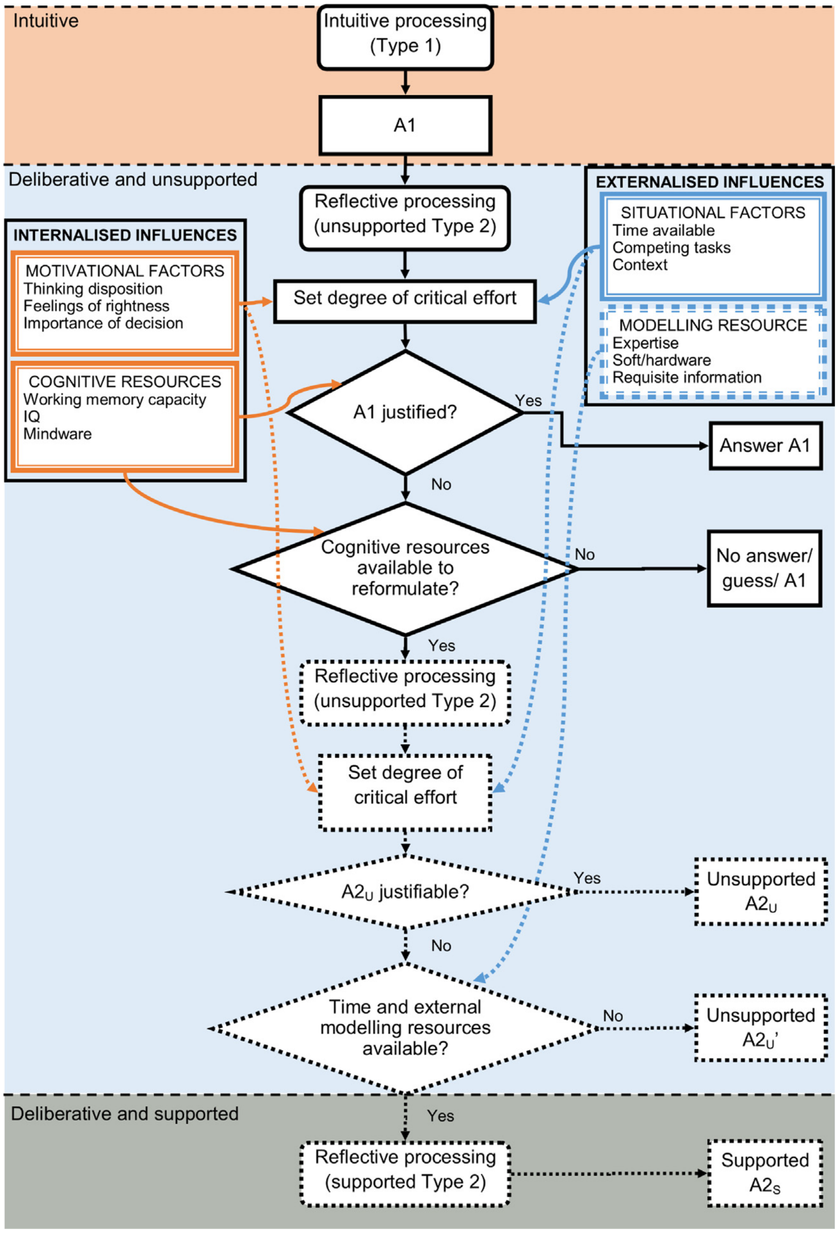

Fig. 2. The Default-Interventionist model (solid lines) including extension by the authors (dashed lines), describing how individuals form decisions from the position of a Dual Process Theory perspective (Evans, 2019, p395).

which the dashed lines indicate our proposed extension. The labels '$A2_S$' and '$A2_U$' refer to the answers produced following a supported or unsupported Type 2 reasoning process, respectively. Although the original part of the diagram is concerned with the Type 1/2 dichotomy, the proposed new part is concerned with the unsupported /supported dichotomy within Type 2 thinking.

From a safety science perspective, the answer $A1$ might arise from situations that involve sudden emergency decision-making (Yang and Haugen, 2015, p117) and so time may be too short for any Type 2 thinking. Alternatively, it could also arise in situations where more time is available but is unnecessary because the Type 1 answer is obvious or already sufficient. In such situations, there is time for the intuitive Type 1 response to be verified by Type 2 thinking.

The answer $A2_U$ will arise in situations where there is no definitive Type 1 answer and there is time for Type 2 thinking, but there are insufficient resources to allow any external support to be provided. Here, decision-makers must rely on their experience and subjective judgement alone.[3] The additional possibility, $A2_U$' shown in the figure corresponds to a situation where there is insufficient confidence to settle on the response $A2_U$, time to revise it to $A2_U$', but insufficient time or resources to establish a supported response.

Finally, the answer $A2_S$ might arise in situations where resources are plentiful and there is no clear answer, or at least little confidence in the $A2_U$ response. In non-emergency situations, it is often possible to move the decision horizon, thus making the $A2_S$ response feasible. Extending the decision time, however, will almost certainly incur some cost, possibly in terms of equipment availability. This is the heart of the production/safety trade-off, where a decision to seek external support is itself likely to be based on unsupported Type 2 thinking. Factors influencing this decision will include the importance of the situation,

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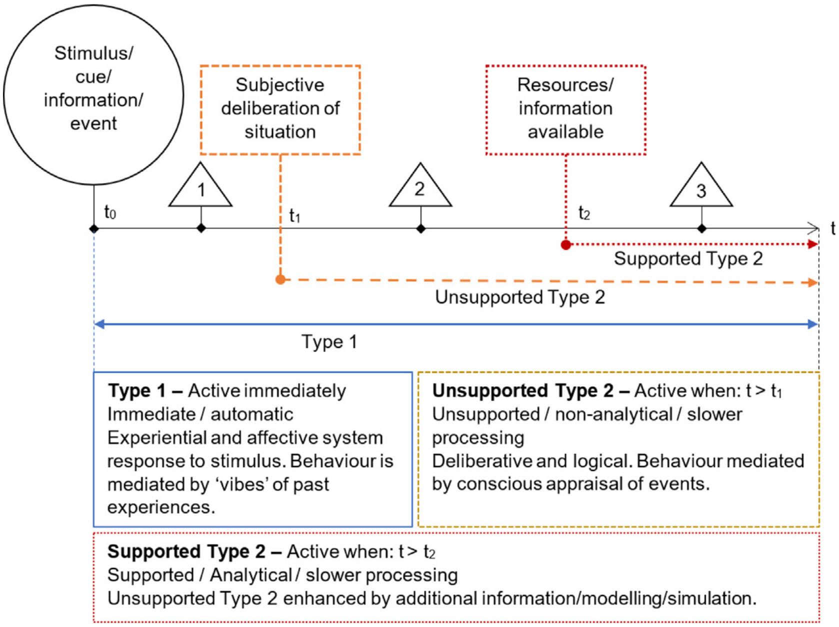
[3] Within the decision categorisations defined by Yang and Haugen (2015, p117), these may either be considered 'instantaneous' or 'operational' decision forms, depending on the time scale associated.



Type 1 – Active immediately
Immediate / automatic
Experiential and affective system response to stimulus. Behaviour is mediated by 'vibes' of past experiences.

Unsupported Type 2 – Active when: $t > t_1$
Unsupported / non-analytical / slower processing
Deliberative and logical. Behaviour mediated by conscious appraisal of events.

Supported Type 2 – Active when: $t > t_2$
Supported / Analytical / slower processing
Unsupported Type 2 enhanced by additional information/modelling/simulation.

Fig. 3. Decision horizon influences which decision modes are accessible.

the associated risks, the costs of lost availability and the confidence held in the unsupported Type 2 response, $A2_U$.

2.3. Shaping risk assessment around the decision-maker

Extending the default-interventionist model to operational engineering risk decision contexts accounts for the practical resource and information limitations enforced upon the decision-maker. For example, given aircraft structural damage in a maintenance environment, these additions account for whether the decision-maker can be supported by trustworthy structural analysis/expert information or not. The situation and possible responses in Fig. 2 may also be depicted along a temporal axis, as in Fig. 3. The variable t corresponds to the decision horizon. The numbered triangles indicate three distinct zones which the decision horizon can fall in. In zone 1, $t < t_1$, and a response in this zone will be of Type 1, corresponding to emergency decision-making. In zone 2, $t_1 \leq t < t_2$. A response in this zone will be unsupported Type 2. There is time for subjective deliberation of the situation but there is insufficient time or resources available for a supported assessment. In zone 3, $t \geq t_2$, and a supported Type 2 response is possible.

Refocussing risk assessments to be cognisant of the situationally-specific capabilities of the decision-maker moves away from traditional objective engineering approaches that focus on hazardous events, reliability and material performance. Human reactions to risk create automatic and uncontrollable perceptions of whether to consider the situation threatening: "what can happen, the potential consequences, judgements of likelihood and the knowledge base on which these judgements are based" (Aven, 2018, p239). Such judgements are deliberative, Type 2 in nature but unsupported. Accounting for such holistic subtleties, that defy reducibility to traditional risk parameters, will improve sensitivity to failure signals (Aven, 2018, p243) and provide more consistent and coherent scenarios for decision-makers (van Asselt and Renn, 2011, p442).

The consensus definition of risk given by Society for Risk Analysis (2018) identifies that consequences impact something that humans *value*, a quality that is a source of friction in discussions about risk. Hansson and Aven (2014) suggest that the information flow in a decision-making scenario for risk includes the values of the decision-maker. van Asselt and Renn (2011, p442) champion an holistic approach to "framing, appraising, characterising, evaluating, and managing risk" and argue for more coherence between risk assessment and risk management in their discussion on risk governance. When including scientific and value statements to describe the risk 'tolerability', Pidgeon (1998) advocates optimising the circumstances under which judgements are obtained, taking care to achieve diversity and detect prejudiced perceptions.

2.4. Case study method

By analysing narratives of engineering incidents, evidence of unsupported risk judgements can be extracted or inferred from the activity. A case study analysis using secondary data sources enabled post hoc evaluation of source credibility alongside the case narrative. While additional primary data were collected by the first author during his PhD studies (Green, 2021), these were limited to the aviation domain. Due to this lack of generality we have not included them here. The cases provided evidence of practical operational situations that required severely time-constrained engineering management decisions using an unsupported judgement.

2.4.1. Case study selection

Candidate cases were selected, which met the following situational criteria:

- A risk emerging within an established risk management system.
- The risk concerns a decision requiring an engineering or maintenance intervention.
- A human component that selects whether intervention is necessary.
- Operational environmental constraints.

The cases selected necessarily had to enable insight into the judgement applied by a human decision-maker. Numerous cases were found that illustrate where hazards have emerged and created risk to operating equipment. However, there were far fewer cases that detailed where and how the decision-maker interacted with the risk management system through the use of judgement. There were also many cases that describe the technical situation and available information, but few that explore the intervention choices and justification made by the decision-maker. Discussion regarding the suitability of the sources used is provided with each case study.

Table 2
Comparison of the case studies selected to highlight judgement-based decision-making situations.

	Year	Industrial field	Major asset	System keywords	Organisa-tional levels (Rasmussen, 1997)	Decision category (Yang and Haugen, 2015)	Region (Fig. 1)	Asset life cycle	Outcome
Case study 1: Challenger	1986	Astronautics	Shuttle launch vehicle	Propulsion system, case structural integrity	Company, Management and Staff	Instantaneous	1	Maintenance /operations	Loss of life, mission failure
Case study 2: Lamington Viaduct	2015	Rail	Bridge	Masonry, environmental erosion, structural integrity	Staff	Instantaneous	1	Maintenance /operations	Line closure, loss of earnings
Case study 3: UK military aviation maintenance	2017	Military aviation	Transport aircraft	Metal, accidental damage, structural integrity	Staff	Instantaneous	1	Maintenance /operations	Continuing aircraft availability

Table 3
Expressions used to codify the case studies in identifying unsupported decision judgements to risky situations, extracted from Aven (2018).

Code	Description	Reference
[LA]	Learned associations between ideas	Aven (2018, p238)
[PERC]	Perception of risk as high, fearful and unacceptable	Aven (2018, p238)
[RHI]	Judgements of the risk as high	Aven (2018, p238)
[RTHI]	Judgements of the risk as too high	Aven (2018, p238)
[UNHI]	Judgements of the uncertainties as high	Aven (2018, p238)
[UNTHI]	Judgements of the uncertainties as too high	Aven (2018, p238)
[NBPA]	When judgements of how large the risk is are not based on a professional assessment of how large the risk based on either: historical data, probabilistic analysis, or by comparing with other activities	Aven (2018, p238)
[BGKN]	Use of unsupported thinking in professional judgements, such as risk aspects that may be hidden in K (background knowledge) like assumptions.	Aven (2018, p239)

The cases selected demonstrate judgement-based risk decision-making across dissimilar domains, but which are similar in the technical complexity of their engineering systems: military aviation, rail, and astronautics. They are specifically related by the use of unsupported judgements, and are similar in their decision categorisation (as defined by Yang and Haugen (2015)) and system affected. Table 2 summarises the key differences and similarities, but highlights the use of unsupported judgement for decision-making on modern engineered systems.

2.4.2. Case study review methodology

A qualitative review based on textual accounts of historical events has been conducted using a template analysis approach (Saunders et al., 2016). This approach extracts a thematic structure from Aven (2018), shown in Table 3. The codewords defined do not differentiate between Type 1 and Type 2 thinking because this does not contribute to the focus of the study. The main intent is to illustrate the use of unsupported risk decision-making by using Aven (2018) as a descriptive framework for testing the selected cases against. [NBPA] modifies the source text to highlight the distinction between unsupported judgements and those based on professional analysis[4]. Where these codewords seem applicable, the relevant section of text is annotated with the codeword. If a code is applied to a section of text and there is no evidence or inference to a supported assessment, this is considered as unsupported thinking.

3. Case studies and analysis

3.1. Case 1 - Lamington railway viaduct structural failure

Lamington railway viaduct partially collapsed following erosion of the river bed beneath the structural supports of the viaduct. Related risk information is traced back nearly 30 years to when another railway structure in the UK collapsed due to erosion of the riverbed beneath supporting structure, highlighting organisational failings to appropriately handle a known risk. The Lamington viaduct incident report was published on 14 Nov 2016, taking approximately 11 months to investigate, conclude and release the findings.

3.1.1. Limitations of the sources used

The incident report seeks to improve railway safety without establishing blame or liability (Rail Accident Investigation Branch, 2016, p3). Accordingly, the textual summaries and inferences of the actions can be considered factual as far as was investigated at the time. However, as a single source from one organisation's perspective, investigators may have not had access to particular evidence, the report may suffer individual bias (on the part of the investigators), or they may have been subject to legal constraints at the time.

3.1.2. Narrative of events

On 31 December 2015, prolonged heavy rainfall and subsequent high flow in the River Clyde, Scotland, UK, created the conditions necessary for the erosion and removal of river bed material under the base of the Lamington viaduct. The erosion phenomenon known as 'scour' caused subsidence of the viaduct support structure, which became noticeable by train drivers passing over the viaduct that morning as a 'dip' in the track. Attending track maintenance engineers initially diagnosed minor track deformation as the cause for the reporting 'dip',

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[4] Original source reads "Professional judgements of how large the risk is, based on historical data and probabilistic analysis" and "Professional judgements of how large the risk is, by comparing with other activities" (Aven, 2018, p238).

but closed the line when a passing train created surprisingly large track movements. By this point, several trains had been permitted to travel over the viaduct. Subsequently, the maintenance team found damage to the central pier of the viaduct, which was the root cause of the track deformation. The trains that had passed over the damaged viaduct had been fortunate to escape derailment or to cause a more dramatic collapse of the viaduct. The incident was declared a "dangerous occurrence" (Rail Accident Investigation Branch, 2016, p26).

The viaduct had been subject to multiple formal assessments since 2005, consistently scoring as a 'high risk' structure by a contracted surveyor using a network-wide scour priority rating system. Annual underwater inspections provided routine mitigation activity and extreme weather precautionary measures that provided reactive procedural mitigation (such as monitoring river levels and closing the line if a threshold waterline was reached), but these had fallen out of use owing to organisational changes. Planned scour reinforcement works to the viaduct were deferred from 2015 until mid-2016 owing to essential environmental approvals not being secured.

3.1.3. *The on-call track maintenance engineers close railway*

On arrival at Lamington to assess the reported track fault, the maintenance team's combined experience initially misdiagnosed minor 'dips' in the line. This deliberative conclusion led to the exposure of three trains to a structurally-defective viaduct. The decision may have been reached because the maintenance team believed (or assumed) the track dips were isolated and the most likely root cause from previous experience or historical evidence: "the vast majority of track faults are directly related to track condition" (Rail Accident Investigation Branch, 2016, p35) ([LA], [NBPA] or [BGKN]). The maintenance team's lack of knowledge regarding scour risk and the specific threat posed to Lamington (Rail Accident Investigation Branch, 2016, p20) was also a missing cue. The decision was unsupported, made on the basis of underlying assumptions being true [BGKN] such as the fault being track related only, the supporting structure being unquestionably sound and with no other external influencing factors. The grounds for these assumptions were then found to be false once the maintenance team identified the structural damage to the viaduct and reacted by closing the line immediately. The team were not bridge specialists (having requested the attendance of a bridge examiner and being unaware of scour risk) but perceived the risk to be high, fearful or unacceptable [PERC].[5]

The non-structural-specialist track maintenance engineers were required to make a timely decision on an unfamiliar risky prospect, which was actually known about within the organisation's risk management framework. Their decision was unsupported by existing formal RA and required the use of their judgement to escalate the situation for wider organisational consideration.

3.2. *Case 2 - The Challenger Space Shuttle Accident*

The second case concerns the well documented Space Shuttle Challenger accident in January 1986 (mission number STS (Shuttle Transport System) 51-L), which experienced a mid-launch complete vehicle destruction. The mechanical cause was found to be the failure of O-ring seals to contain hot propellant gasses in the solid rocket booster (SRB), a major component that was designed to be recoverable following a launch, refurbished and reused in subsequent launches. The accident was preventable, and the post-incident investigations found that a series of conflicts between engineering and management decision-making led to a collective decision to launch, despite initial recommendations of 'no launch' and sustained dissent from specialist engineering personnel. In the wake of the accident, a Presidential Commission was convened (Rogers, 1986) to investigate the accident and all staff involved were subject to scrutiny by both the commission (under oath) and the public owing to media coverage (Vaughan, 1996, p388).

The case illustrates a major technical project that operated a risk management system and was subjected to operational stress factors for the Challenger launch scheduled for 28 January 1986. Although there is substantial discussion on this case that identifies organisational safety failures back to the design choice of the Shuttle vehicle, unsupported thinking is widespread in the hours prior to the launch of STS 51-L. For brevity, only one circumstance is explored to demonstrate where the shuttle programme risk management system might have included unsupported Type 2 thinking in the assessment of true risk.

3.2.1. *Limitations of the sources used*

The secondary sources used are contrasting narrative accounts of the decision to launch the Challenger shuttle. The Presidential Commission Rogers Report is criticised for being too focused, misunderstanding NASA procedures in decision-making, and not including some personnel's testimony in their consideration (Vaughan, 1996, p59), suggesting it is narrow in its conclusions. But it provides timely and personal testimony from the protagonists involved in the flight safety decision process on 27 and 28 January 1986, which is the prime consideration in studying how far unsupported thinking contributed to the Challenger accident. To balance the use of the commission report, Vaughan (1996) provides an alternate perspective and source of wider testimony not included in Rogers (1986).

3.2.2. *Narrative of events*

Following Challenger's planned launch on 27 January 1986 being deferred owing to strong winds at the launch site, the launch was re-planned for 09:38 on 28 January. The forecast temperatures were colder than any previous launch. SRB manufacturing engineers at Morton Thiokol (MTI) and Marshall (responsible for maintaining oversight of the SRB contract among others) raised their initial concerns of the temperature effects on the O-ring seals between the joints of the rocket segments shortly after the decision to defer the mission 24 h (Rogers (1986, p87) and Vaughan (1996, p286))[6]. These initial concerns triggered activity by both MTI and Marshall to collate the available data regarding temperature effects on SRB joint sealing, which was then discussed during two teleconferences between MTI, Marshall and NASA the night before the launch. During the second and more widely attended of these teleconferences, MTI initially presented a formal 'no launch' recommendation. Marshall rebutted the rationale on the grounds of inconsistencies between the data they presented and a history of behaviour by MTI who had not rejected launches given similar forecast temperatures[7] to those predicted on 28 January 1986 (Vaughan, 1996, p155, p308-310). Consequently, Thiokol reviewed their rationale and returned to the conference half an hour later with the conclusion that despite concerns over the cold effects on

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[5] It is noteworthy that railway signalling and control room staff would not have been permitted to allow trains to be exposed to *suspected* structurally damaged equipment (Rail Accident Investigation Branch, 2016, p35), however control room staff were also unaware that Lamington viaduct had been assessed as being at high risk of scour and therefore susceptible to structural damage. Although this suggests an information and communication breakdown, it also demonstrates the conservative intervention required in the face of insufficient structural risk information (Aven, 2016)

[6] MTI's design of the SRB required the rocket to be manufactured as several discrete sections at their plant in Utah, USA in order to enable transport by rail to the launch site in Florida, USA. This logistical constraint meant that the SRB could not be manufactured as a solid single (monolithic) section. A monolithic design was simpler by comparison, which had been offered as a solution by competing contractors when the contract was awarded (Vaughan, 1996, p425)

[7] Mission STS 51-C was scheduled for launch on 23 January 1985, but was delayed by the Mission Management Team owing to the below freezing temperatures. No concerns had been raised by MTI or Marshall regarding the effect of cold temperatures on propellant seal integrity.

the O-ring seals, the data was inconclusive. MTI subsequently signed their telefax recommendation for the launch of STS 51-L on 28 January 1986. Challenger launched at 11:38 on 28 January 1986 at an ambient launch pad temperature of 36° F (Vaughan, 1996, p7), exploding 73 s later in a fireball and with total break-up of the vehicle. The seals were found to have failed to perform their role during the first seconds of launch.

3.2.3. The initial ‘no launch’ rationale

The initial concerns raised about the cold by MTI and Marshall personnel infer an holistic, deliberative consideration regarding the primary cue (the forecast ambient temperature at the launch site) and the existing O-ring sealing risk. The O-ring seals had been subject to launch constraints and individual component testing after erosion and blow-by of the O-ring seals had been spotted following previous missions[8]. However, a normalisation of deviance within the team meant they had learned to accept some erosion of the O-ring seal during launch. The fact that forecast temperatures prompted individuals to behave differently and with urgency for STS 51-L indicates that background assumptions (that were perhaps based upon on the *normal* conditions expected for a launch) had become challenged. The uncertainty regarding how the Shuttle’s SRB seals would perform as a system, given the unprecedented cold, influenced multiple personnel to consider that the risk was high given their knowledge of previous instances of erosion and blow-by ([PERC], [UNHI] and [RHI]):

- Marshall’s Larry Wear, who was the initial trigger for consideration of the risk from cold temperatures, recalled the effect of low temperature on STS 51-C in January 1985 and asked Boyd Brinton (MTI), to call Thiokol’s Utah plant and find out if there were any concerns (Vaughan, 1996, p286).
- Team manager for the Solid Rocket Motor (SRM) project, Robert Ebeling (MTI), responded to the request from Brinton by calling a meeting of subject matter experts to review his initial temperature concerns: “The meeting lasted one hour, but the conclusion of that meeting was Engineering...were very adamant about their concerns on this lower temperature, because we were way below our data base and we were way below what we were qualified for.” (Rogers, 1986, p87)
- Allen McDonald (MTI) was at the Kennedy Space Centre: “I took that data [the forecast temperature data] and called back to the plant and sent it to Bob Ebeling and relayed that to him, and told him he ought to use this temperature data for his predictions, but I thought this was very serious and to make sure that he had the vice president, engineering, involved in this and all of his people; that I wanted them to put together some calculations and a presentation of material.” (Rogers, 1986, p87)
- Other Marshall employees also formed subjective qualitative-based concerns about the anticipated temperatures on the performance of the O-ring seal:
  “Schell and Riehl concluded that the O-ring would be all right at 25 ° F because when the ignition pressure hit it and jammed it into the gap, it would seal. Schell said: “It would have been a little harder, there is no question about that. I mean, there is data all over the world to show that it would have been a little less resilient and a little harder, but at those pressures, it would have sealed.” ”(Vaughan, 1996, p290)

In summary, uncertainty regarding the consequences of the weather compounded existing primary and secondary O-ring resilience concerns given the launch dynamics of the SRB joints, the ignition pressure and the time taken for the O-ring to form an adequate gas seal. Vaughan (1996, p290). There was uncertainty owing to the lack of scientific data regarding cold effects on SRB joint sealing capability in full scale equipment configuration, and a conflict in the conclusions drawn from component test results[9] and historical launch data[10]. Despite Thiokol’s worries about the cold, no ‘Launch Commit Criteria’[11] had been established for the O-ring temperatures after STS 51-C in January 1985 because “it was nobody’s expectation we would ever experience any cold weather to that degree before we had a chance to fix it again” (Roger Boisjoly, MTI) (Vaughan, 1996, p308). Consequently, the only full scale vehicle temperature-related data of the SRB performance was perceived to show no correlation between temperature and the O-ring erosion and blow-by (see Footnote 10).

MTI were unable to support their ‘no launch’ argument with any analytical evidence because there was not any for the whole SRB system at the forecast temperatures. MTI used unsupported judgement to argue that cold temperatures had resulted in O-ring erosion on previous flights. However, because available O-ring performance data was uncorrelated (Footnote 10) Marshall and NASA were able to construct a convincing counter-argument. Notably, the influence of group dynamics on the decision made, is discounted by Vaughan (1996, p404). Regardless of the counter-argument, MTI engineers still expressed their fearful perception of launching outside of their experience base [PERC]:

- MTI’s Roger Boisjoly stressed that “in launching below the data base they were moving away from goodness” (Vaughan, 1996, p317).
- MTI’s Jack Kapp: “Most of the concerns that we had presented were qualitative in nature. At that particular time we had a very difficult time having enough engineering data to quantify the effects that we had been talking about. A lot of it was based on “engineering feel” (Vaughan, 1996, p308).

Collective testimony coupled with post-event review of the information available to decision-makers shows the use of unsupported judgement regarding risk of cold temperatures to the Challenger vehicle. Without sufficient coherent analysis to substantiate the claim of safety, unsupported judgements were formed about the adequacy of the available technical data and the behaviour of MTI. These were consequentially found to be fallacious, with disastrous consequences.

3.3. Case 3 - UK military aircraft routine structural damage

The UK military aviation regulations require risks to life to be managed within a risk management system, with nominated duty holder personnel being accountable (Military Aviation Authority, 2014). Authorised engineering management personnel are also permitted to defer maintenance provided it is “considered justifiable and safe” to do so (Military Aviation Authority, 2018b, p8). Deferring maintenance is considered routine since spares, operational considerations, specialist

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[8] STS-2 was the first indicator of erosion, heat effects were found on two rings on STS 6 (Vaughan, 1996, p149), and then in 1985 seven out of nine shuttles launched experienced erosion and/or blow-by, with the worst arising yet seen when STS 51-C’s blow-by reached the secondary O-ring (Vaughan, 1996, p153)

[9] The team had data on subscale component tests of resiliency (prevention of blow-by) to temperatures down to 30 ° F, had conducted sufficient erosion resistance tests to conclude that the seal would still perform beyond the worst case seen from a live launch, and had data on how the O-ring seal material hardened with reducing temperature.

[10] STS 61-A launched in October 1985 and experienced blow-by and erosion at a calculated O-ring temperature of 75 ° F. STS 51-C launched in January 1985 with a calculated O-ring temperature of 53 ° F and exhibited the most severe O-ring erosion and blow-by from live mission launches (Vaughan, 1996, p153).

[11] Launch Commit Criteria were metrics that provided pre-determined thresholds and limitations beyond which a launch could not proceed.

equipment, or expertise are not always available at the point of need for a given maintenance task. This case reviews one such routine request sent to an aircraft airworthiness management team from front-line engineers operating the aircraft. Although it does not end in an accident, it highlights the routine use of unsupported judgement in operational situations.

3.3.1. *Limitations of the source*

The information was received directly from the engineering staff responsible for the structural airworthiness considerations of the particular military aircraft. Much of the detail is anonymised to protect individuals and teams from scrutiny and to prevent any breach of confidential information regarding the sustainment of military equipment. Although this restricts the level of clarity experienced by the reader, there is sufficient information to identify the use of unsupported thinking in daily aircraft engineering risk decision-making.

3.3.2. *Narrative of events*

On 3 May 2017, a request was submitted by the operating Squadron to the aircraft airworthiness authority and manufacturer[12] to defer carrying-out a full repair as required by the aircraft maintenance manual. A structural repair was necessary after accidental tooling damage was found on a shaped component that provides the structural connection support between the wing box and the outer wings of the aircraft. The component is known by the manufacturers to be susceptible to fatigue and the damage was spotted during a periodic non-destructive testing (NDT) inspection that preventatively searched for fatigue damage. The operating Squadron were only able to carry-out a partial repair as they were deficient in the necessary tooling to complete the repair at their location. However, as no damage limits for the component were provided in maintenance manuals, a request for airworthiness advice and legal maintenance data was dispatched. The Squadron had no legally approved maintenance data that a partial repair would be sufficient not to cause a structural integrity hazard to the safe operation of the aircraft. A NDT inspection of the repaired area was carried-out as mitigation for the absence of a full repair. The Squadron requested:

"Airworthiness Advice on continued unrestricted Operations... Tooling impact damage to R/H upper [component name ommitted for confidentiality]. Pre-blended damage[13] dimensions as follows [dimensions ommitted for brevity]. Damaged areas blended iaw (in accordance with) [structural repair manual reference ommitted for confidentiality] to a ratio of 10-1. NDT [reference ommitted] carried out with no fault indications. Roto peening[14] not carried out due to lack of tooling in theatre[15] Post blend dimensions as follows [dimensions ommitted for brevity]."

While awaiting a response, the Squadron deferred a full repair and continued operating the aircraft unrestricted. A month later (5 June 2017), approval for the partial repair was received from the manufacturer, via the airworthiness management team. In the interim, the acceptability of the risk to the aircraft had been based on the judgement of the front-line maintenance decision-maker without analytical or deterministic confirmation. The judgement had been carried-out in an unsupported manner.

3.3.3. *Unsupported judgement to defer maintenance*

Deficiencies in equipment, spares or information to complete engineering activity are frequent in military aircraft maintenance. While designers foresee problems as far as possible and maintainers plan equipment usage and manpower schedules as thoroughly as possible, aircraft operations inevitably generate unexpected damage as a result of human and environmental influences. Deferring maintenance at the point of need allows maintenance managers to use their judgement to balance safety and equipment availability, catering for real-world variations in situation while awaiting manufacturer advice. However, without access to the tools or cognitive ability to generate analytical structural integrity risk assessments, maintainers must proceed non-analytically.

Aircraft maintenance is typically documented scrupulously, recording references to procedures, policies and information used, providing "an audit trail of the work to enable quality assurance, data exploitation and investigations" (Military Aviation Authority, 2018b). The omission of references to quantifiable data, relevant historical events, or analytical assessment supporting the deferment request in Section 3.3.2 is conspicuous in its absence. If analytical tools had been used, they would almost certainly have been referenced in this maintenance paperwork entry. This suggests that an unsupported judgement regarding the structural risk was made by the engineering manager, given their personal state of knowledge regarding factors such as: (1) the assumed expected use of the aircraft, (2) the available knowledge and experience of the damage characteristics, (3) that the NDT inspection was suitable and accurate, (5) no other assumed factors would interact with the damage, (6) the impact on remaining structure if the damaged component was to fail. The factors that influence damage propagation are numerous and situationally specific. Decision choices also vary between decision-makers — another engineer faced with the same situation but with a different knowledge base may elect to ground the aircraft while awaiting specialist advice. Descriptive decision analysis provides insight into the motivational and cognitive biases that may cause this (see for example Tversky and Kahneman (1974), Brown and Utley (2019), or Baybutt (2018)). Although perhaps counter-intuitively, grounding an aircraft requires just as strong an argument as a decision to accept a fault and continue flying. Grounding aircraft impacts operational availability, may cause reputational harm (depending on the service the aircraft is providing), and commits organisational resources to rectifying the fault. In this case, unsupported judgement of risk posed by the partial repair did not exceed any personal thresholds for intervention. However, if the risk had been deemed unacceptable, the considerations influencing the operational decision-maker may have been:

- Mitigation being considered inadequate, for example the NDT technique might provide insufficient assurance or be considered unreliable [UNTHI].
- Previous experience of this type of repair technique might bias the judgement toward the success or failure of the experience base. This might be considered as a learned association [LA] or an assumption that the repairs are sufficiently similar to draw an inference between the damage situations ([BGKN] and [NBPA]).
- Other personnel may offer up their own experiences, which the manager will weight given their knowledge of the advice-giver, relying on social factors such as reputation and trust [LA] .

Such influences are very personal and impact people to varying degrees. In the case above, the operational urgency and perception of the risk meant that the maintenance manager resorted to their judgement and perception about the risk [PERC], exercising their authority to continue operating while awaiting supportive information.

4. Discussion

Risk assessment provides decision-makers with information about uncertain outcomes in order to help them decide upon the most appropriate action. Supported analytical assessments are desirable from

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[12] See Footnote 2.

[13] Blending is a repair technique that involves the abrasive rubbing and polishing of metal damage in order to smooth out damage such as dents, gouges or scores. Sharp edges create 'stress raisers' in materials under load, and can be initiators of fatigue or overload damage mechanisms.

[14] Roto peening is a specialist maintenance activity that imparts a residual compressive load into the surface of metal structure in order to provide tensile stress relief. The process improves resilience to fatigue and some corrosion damage processes.

[15] 'Theatre' refers to a deployed military operational location overseas.

a managerial perspective because they enable normative decision support approaches to be used to justify resource allocation. However, operational conditions may restrict decision-makers to using holistic or unsupported deliberative thinking. Reliance by decision-makers on unsupported thinking is not regulated or operationalised, resulting in an opaque decision process, which reduces the level of transparency and accountability that are essential to safety culture-focused communities. Work by Aven (2018) makes progress in this regard by drawing attention to the influence of such thinking on risk scenarios. However, the approach suggested there is not practical for decision-makers in operational situations who are unlikely to have the time or means to access a council of experts and risk analysts (as required in Aven (2018)) to support the construction of an unsupported assessment. Better guidance is required for decision-makers in such situations. The following discussion points from the case studies justify this argument.

Type 1 or type 2 reasoning. The decisions made in the cases studied are a result of both Type 1 and Type 2 processes. The influence of Type 1 reasoning has bearing on the deliberative Type 2 judgement applied, potentially influenced by emotions such as dread, fear, or a gut feeling of ‘rightness’, and the time between consideration and action. It is not possible to indicate whether decisions originated from Type 1 intuition and were then justified by Type 2 reasoning, or if the decisions only emerged after Type 2 deliberation. This matters not since the main consideration is to be aware of the extent of unsupported influences on decisions (deliberative, intuitive or otherwise) not their cognitive classification. Had there been better awareness, then the presumptions about the track deformation (Case 1), or decision to launch despite conflicting analytical data and judgements (Case 2), may have been scrutinised more effectively at the time.

Risk management system compatibility. The risk decisions were made under situational constraints that were incompatible with the risk management processes relevant to each case, compelling decision-makers to use unaided judgement in their decision. The initial decision by the Lamington viaduct track maintenance team caused them to react with an assumption regarding track deformation without knowledge of the known scour risk; the MTI engineers could not adequately quantify their concerns regarding the forecast ambient conditions but intuitively felt the risk was too high; the aircraft Squadron engineering decision-maker made an unaided judgement that the partial repair would not lead to structural collapse.

In the case of Challenger, the decisions, justifications and testimonies indicate that the risk management process was unable to accommodate the holistic and unsupported judgement that prompted numerous key personnel to initially argue a ‘no launch’ rationale in spite of the technical data available. This observation is not just because the correct decision (in hindsight) had not been selected, but because the risk management system was not configured to give weight to unsupported assessments in operational circumstances (Hoffrage and Marewski, 2015, 148). Rather than requiring evidence of the system being safe to operate in the expected launch conditions, NASA’s existing technical culture and processes demanded evidence of a manifest risk to the integrity of the launch vehicle, which was unavailable. Risk assessments followed scientific and rule-bound engineering standards, but Thiokol’s argument conflicted these:

> “...observational data, backed by an intuitive argument, were behind all engineering analysis. But subjective, intuitive arguments required lab work and tests before they were considered admissible evidence in FRR (Flight Readiness Review).” (Vaughan, 1996, p353-354)

In all cases, the holistic representations of risk perceived by individual engineers provided an actionable view on the risk situation but in Cases 1 and 2, the qualitative assessments could not reduce the risk exposure sufficiently. Furthermore, in Cases 1 and 2 the hazards and risks were known to the organisations. They were not black swan events that surprised stakeholders once they emerged, but the uncertainty surrounding risk propagation created sufficient room for arguments both in favour and against intervention. Unable to argue convincingly with holistic risk representations to gain support for timely intervention, the risks were unable to be prevented from becoming manifest.

Triggering more detailed investigation. Unsupported judgement is used in Cases 1 and 3 to guide decision-makers toward escalating intervention and commitment of resources, though stopping short of a slower supported Type 2 assessment.

In Case 3’s context, new faults are only referred to the duty holder if the risk is considered (by the maintenance decision-maker) to be a *risk-to-life*. The decision to refer requires either a rule-based trigger or relies on intuition; referring every occurrence as a risky prospect is conservative and unacceptably resource consuming. Regulation (Military Aviation Authority, 2014) provides such a rule-based threshold to the UK military aviation community via the use of risk matrices, but this method is incompatible with structural risks that are difficult to quantify under operational constraints. However, Type 2 reasoning (supported or unsupported) contains elements of Type 1 reasoning (Aven, 2018) and is therefore not judgement-free. Risk matrix outputs are therefore subjective, difficult to validate and of an unknown accuracy owing to insufficient data (Cox, 2008).

In the case of Challenger, unsupported thinking was insufficient to initiate intervention. A number of qualitative cues consistent with Table 3 may have alerted a need for more robust action. Firstly, to request a launch delay was unprecedented for MTI (Vaughan, 1996, p305), a clear signal that there was an overwhelming feeling of dread about the hazard [PERC], what Payne and Bettman (2005, p123) term problem-focused coping — treating negative emotion as a signal of decision importance. Secondly, that the normalised ‘acceptable’ erosion to the O-ring seals was overcome by the single cue that, for the complete Shuttle vehicle system, the launch was outside of any data base for acceptable damage, indicating a conflict with established assumptions [BGKN]. Thirdly, the effect of the cold on the complete system at launch was uncertain and the subscale test data only provided a partially complete representation of the expected vehicle performance ([UNHI] and [BGKN]). The unsupported rationale from MTI’s (largely qualitative) assessment (Vaughan, 1996, p308), that was based on conflicting data, was a weak signal for NASA and Marshall engineers. The lack of coherent scientific data enabled differences of opinion on the true impact of the cold effects to be argued, framed by a risk management system that necessitated objective scientific evidence to support risk assessments.

Being unable to conduct a methodical, analytical modelling of the scenario leads to reliance on unsupported thinking for risk decision-making. All of the cases indicated that this was owing to operational constraints of the time, resource or cognition available within the decision horizon. Referring such risks for more detailed appraisal and consideration can result in behavioural inconsistencies between actors.

Justifying the use of judgement. In Case 2, the MTI team had incomplete data and were ineffective in justifying their claims. Their holistic argument that the ambient temperature conflicted with the database for the complete vehicle was weaker than the competing rationally-presented argument concerning other available data. Had the advocates of ‘no launch’ been able to present their argument more coherently, they may have gained more support. Justification is also lacking in Case 3, where the engineering manager had not explained the grounds for deferral. The Toulmin (1958) theoretical framework for presenting an argument provides a generalised logical structure for the information being used to make a claim. Briefly, it states that in order for a conclusion to be drawn from the foundation of an argument (the data), there must be a bridging inference-license, rule or principle that exists to justify the step from data to conclusion. In Case 3, such a logical bridge is not apparent between the available information (damage dimensions, the non-destructive test for subsurface damage indications and the use of a recognised repair technique) and the claim that deferral was appropriate. Although links can be inferred, the perception of acceptability depends on the knowledge base of the inferencer. For instance, where the deferral wording reads "NDT carried out with no fault indications", there is an assumption that the NDT was 100% accurate, which may not be true and can be open to challenge. Improvements in the ability to justify holistic, non-analytical arguments in a logical but situationally-specific rational manner, particularly in the face of hard data, will be crucial to incorporating such thinking into risk assessment.

4.1. Supporting analyses may be a paradox

Case 1's data also highlighted a situation where decision makers relied upon unsupported judgement despite having access to supporting risk analyses. Despite three separate contracted scour risk assessments (in 2005, 2010 and 2013) evaluating Lamington as at high risk from scour, mitigation reinforcing works were not permanent and inspections were found to be inadequate. Lamington's listing on a schedule for scour protection works in 2012 indicates that risk influencing factors were known about:

"Lamington was prioritised due to its location on the West Coast Main Line and known shallow foundations. (Rail Accident Investigation Branch, 2016, p33)"

Management decision-makers had understood the business and reputational consequences given the route that the Lamington viaduct was situated on ("its location on the West Coast Main Line") and had knowledge of the formal risk assessment findings ("known shallow foundations"). The decision-makers appear to have interpreted the supporting risk analyses within a wider value-focused decision (Hansson and Aven, 2014), since rail authority personnel "requested authority to defer the scheme until the next financial year due to environmental permissions not being sought in time for the work to be completed during the low flow summer period" (Rail Accident Investigation Branch, 2016, p33) [NBPA]. The scour risk (or uncertainty in the formal assessment) was not sufficiently high to exceed the management personnel's threshold for intervention ([RHI] and [UNHI]).

Despite analysis being available, the supportive material was not trusted sufficiently to prevent a safety occurrence in this case. As a component of the decision-making apparatus, having support may not be a panacea and may not wholly override existing (or default) thinking. In this particular case, the risk assessment may not have provided sufficient precision and meaningful intervention was only initiated once a clear unsafe condition was recognised — when damage was visible to the on-track engineers.

4.2. Future development opportunities

Drawing attention to the use of unsupported judgement is useful, but converting this attention into a practical tool requires further work. Let us consider a decision-maker's rationality as being situationally-specific. This bounded view of the context in which a decision is being made could help decision-makers form an "ecologically rational"[16] decision basis (Mousavi and Gigerenzer, 2014). This may be done by applying defined, situationally validated heuristic processes, such as Fast and Frugal Trees. In some situations, these methods have provided comparable performance to more complicated methods requiring greater understanding such as linear and logistic regression (Gigerenzer and Gaissmaier, 2011; Hafenbrädl et al., 2016; Gibbons and Stoddart, 2018). However, handling engineering decision situations by fast and frugal means steps boldly away from the formalised mechanisms, models and analytical devices that provide more traditional forms of decision support. While not denigrating or diminishing the role that such methods play in supporting decision-makers, there is a need to explore simpler, faster methods which can still provide some level of support in highly constrained, operational situations.

Another consideration for tool development is the influence of wider system elements on risk, such as management policies and human factors. "In complex systems, major failures seldom result from a single problem, but are typically caused by multiple problems that coincide to allow catastrophic failure" (Murphy and Pate-Cornell, 1996). The System-Action-Management (SAM) framework has been used to model how management decisions influence engineering risk (Pate-Cornell, 2007). Although, modelling behaviour is not immediately useful for operational maintenance decision-makers, the concept demonstrates how risk can be linked to behaviour and organisational policies through an influence diagram.

In the related space of engineering design, logic frameworks (Toulmin, 1958) have been found to be useful for structuring justifications for parameter selections (Polacsek et al., 2018). Applying this approach to documenting unsupported decision justifications would enable post hoc reflection of decisions taken, and benefit risk communication. The importance of reflection and communication is apparent from their inclusion as crucial tenets within the emerging risk governance framework, which proposes new principles for supporting complex, uncertain and ambiguous decisions (van Asselt and Renn, 2011). Externalising one's own argument may also help individual decision-makers in situations with no access to a committee (as required by Aven (2018)), and provide a much needed audit trail for regulated industries that necessitate this.

5. Conclusion

This paper has argued that greater attention should be paid to how risk decision-makers are constrained by operational conditions that restrict resources, information and time. There is no shortage of literature discussing structured methods and modelling approaches aimed at supporting decision-makers with the luxury of time and resources at their disposal. There is rather less, however, aimed at supporting frontline operational decision-makers in constrained settings, forced to rely on their own subjective judgement. Our extension, shown in Fig. 1, of the decision space model of Howard and Abbas (Howard and Abbas, 2016) highlights this distinction and provides a useful way of characterising decisions in terms of the time available and the time required for decision-making. In this paper, we have been mainly concerned with decision-makers operating in Region 1 of Fig. 1. Most of the published literature is aimed at Region 2.

We have taken this characterisation of the decision space further to highlight the dichotomy between unsupported and supported Type 2 reasoning. We have drawn a parallel between this dichotomy and the much more widely discussed one of Type 1 and Type 2 thinking. Emanating from the cognitive psychology discipline, this latter theory now aids communication and informs research in a host of other disciplines, including risk analysis, behavioural economics and marketing.

We have also shown how Evans' default-interventionist model from cognitive psychology can be extended to describe the progression from Type 1 thinking to unsupported Type 2 thinking and finally to supported Type 2 thinking (see Fig. 2). We believe that this distinction between unsupported and supported Type 2 thinking is an important one and deserves much greater attention in the safety and risk literature. This dichotomy is also represented as a function of the decision horizon in Fig. 3. By highlighting the prevalence of unsupported subjective decision-making, it is hoped to stimulate suggestions for improvement.

Cases from three different engineering domains were analysed using template analysis. These helped to demonstrate the role and frequency of unsupported Type 2 thinking in safety-related operational decision-making. Within organisational risk management constructs, this invites criticism of why judgement and holistic perspectives have not been

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[16] The term ecological rationality refers to functional matches between cognition and environment (Mousavi and Gigerenzer, 2014, p1671).

more openly accounted for in risk processes. Addressing naturalistic risk decision-making and judgement use contributes to the safety domain's growing momentum toward improving system safety resilience, handling unforeseen events (Swuste et al., 2020) and reality-based safety science (Rae et al., 2020).

A case comparison was conducted to highlight their similarities and differences. We believe that close similarities between the chosen case study domains and most other engineering domains make the findings here more generally applicable. Similarly, any improvements to unsupported decision-making which can be demonstrated for any one of these domains is likely to be useful across many others.

Basing decisions on unsupported thinking is hazardous because it is even more susceptible to cognitive and motivational biases than supported thinking. Without a committee to debias judgements or provide consensus, as suggested by Aven (Aven, 2018), alternative approaches are necessary to support operational maintenance decision-makers. Some promising avenues of work have been highlighted, including the use of Toulmin-style argument justification and situationally-specific heuristics. To establish the utility of such approaches requires real-world decision-makers to test their credibility and suitability for use in pressurised, operational situations.

There will always be occasions when unsupported, subjective judgement in risky, operational situations is required. Identifying ways of improving that judgement, including its transparency and justification, has obvious benefits for safety-related decision-making. Strengthening linkages and relationships with other relevant disciplines such as decision analysis and psychology is one way of helping to bring about such potential improvements. This may offer a rich seam of possibilities for future safety science researchers.

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