Managing Risk in Complex Systems

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Abstract
Experimental Flight Test routinely manages risk within complex socio-technical systems. Uniquely, the Flight Test system encompasses the crew and consequently, the potential for catastrophic outcomes precludes typical mitigations of robustness and resilience. This leaves Flight Test professionals to manage risk using a framework of tools that is implemented to preclude risk realisation events, guided by cultural lore. Ethnographic research to identify the Flight Test risk management framework identified a combination of statistical and non-statistical tools in use in parallel. While presenting an opportunity to streamline tool selection, this had the effect of matching the risk tool against the attributes of the underlying system. Complicated systems respond to statistical approaches, though complexity denies these same tools. Complex systems require risk management approaches that accommodate emergence, dynamic configurations and non-deterministic system performance. An understanding of why the Flight Test risk management framework is effective provides a case study for wider-industry to emulate, an opportunity to learn of the test pilots' risk management framework for dealing with complex, socio-technical systems.

Keywords: complex, system, risk, management, Cynefin

1. Introduction

The evolution to complexity in systems is challenging management frameworks implemented by organisations using contemporary, complex systems. Complexity brings attributes of dynamism and emergence[1] to the system and these impact traditional approaches to management of the broader socio-technical system that includes the technology and the humans. Given an opportunity to observe that Flight Test risk management practices are uniquely capable in the presence of complexity, a research project to learn of those practices was instigated. (The primary researcher is a member of the flight test community.) The objective of the research was to identify the risk management framework of the Flight Test community, and then to abstract that for use beyond Flight Test. This paper reports the identified risk management framework and observations of the unique Flight Test risk management culture. The theoretical basis of the Flight Test approach was examined to understand why the approach is effective and identify the limitations of existing risk theory. Examination of the theoretical basis to risk management identified alternatives and abstracting the Flight Test approach provides the sought after application to wider industry. The research has provided an empirically grounded analysis of why Flight Test risk management is effective in the presence of complexity, and for the wider field of management, the research is a case study offering insights to a professional group who successfully manage risk in complex systems.

The 2022 ASSC conference paper *Concepts in Assuring Artificial Intelligence* (Luther 2022) made use of the initial research outcomes, identifying that the attributes of complexity preclude contemporary risk management approaches by rendering them ineffective. With artificial intelligence making use of the emergence and non-deterministic attributes of complexity, statistical approaches to risk management are not available as there is no statistically valid data set from which to model future system performance (Luther, Gunawan & Nguyen 2023) The 2023 ASSC conference presentation *Risk Management Strategies for Testing Complex Systems* recognised that the non-deterministic nature of complex systems precludes

[1] Emergence in a complex system refers to the phenomenon where new system properties arise from interactions between components of a system, rather than being caused by the components themselves. (Yuan et.al 2024)

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knowledge of expected, baseline system performance. Consequently, with *a priori* system performance knowledge unavailable, risk management of complex systems must focus on the controls on system performance (boundary conditions), rather than the system performance itself. The approach to risk management in the presence of complexity was seen to be analogous to the approach to assuring of AI – focusing on the boundary controls rather than the unknowable system performance.

This paper elaborates on the approach to risk management undertaken by Flight Test professionals, informing the reader of why research into that community is of value. The research that was undertaken is then detailed, before a brief recounting of academic risk theory is provided as background. The body of the paper presents the research findings, specifically detailing the Flight Test Risk Management Framework, before the attributes of that are abstracted for a generalisable framework. Academic risk theory is reflected upon, to learn of why the Flight Test approach to risk management is effective. Finally, the implementation of an abstracted framework for risk management in complex systems outside of Flight Test is discussed, providing guidance for risk managers of tomorrow's complex systems.

2. Flight Test Risk Management

For the profession that develops new aircraft technologies, risk management has evolved to be endemic since unlike many human enterprises, aviation sits among those without a safe, stable resting state when in operation. Flight test crews know that an incident during flight testing will result in their death, so hazard realisation is not an option at any level of probability. Since Flight Test develop (and operate) complex socio-technical systems where hazard realisation is not an option, Flight Test crews have a cultural lore around this unique approach to risk management. Flight Test crews do not accept risk by considering the probability to be *rare*, or below a numeric threshold. Within the Flight Test community, there are formal classes on the principles of contemporary risk management and there is a strong culture of risk management that is bestowed on junior crews.

The capability of the Flight Test community's risk management framework was illustrated in events preceding the pair of Boeing 737Max aircraft accidents in 2018 and 2019 that were attributed to the Manoeuvring Characteristics Augmentation System (MCAS) (HCoT&I 2020). Utilising Leveson's (2012) insight to complex systems and terminology, at the time of the accident, the MCAS function was operating *as designed, though not as intended*. During development testing, a company test pilot identified the hazard of uncommanded MCAS activation (HCoT&I 2020), though the overarching organisational risk management framework wasn't capable of inducting that hazard into its risk framework for ongoing management. Consequently, the hazard was lost to administrative process. Noting some tragic exceptions, risk management in the development and operation of complex systems is an activity that the Flight Test community has evolved to over time. Consequently, their regular conduct of risk management in the presence of complexity provided a unique research opportunity to identify and understand why their approach is effective.

Somewhat uniquely to Flight Test, Flight Test crews are confronted with risks that pose catastrophic consequences. Using the conventional two-dimensional model of risk (consequence and likelihood), within Flight Test, death would be an infinitely negative consequence, with a non-zero, though unknowable probability of occurrence. This research considers risk from that perspective, considering the crew to be an irreplaceable part of the system, but also impacted by risk realisation. While robustness addresses the ability of a system to tolerate a level of risk realisation, this is not an approach adopted by Flight Test. A person cannot be robust to a consequence of death. Similarly, resilience speaks to an ability to adapt to realised risk consequences while maintaining operations. But with no possibility of maintaining operations or tolerating degraded operations after death, the notions of resilience and robustness are not considered as risk mitigations toward the catastrophic consequences of Flight Test risk. The unique feature of the Flight Test community as a subject of research is that they do not consider themselves fungible because they are inside the system. Consequently, they manage risk differently and that is the subject of this research.

Flight Test crews were observed to utilise nuanced, qualitative approaches to risk management, in parallel with the more conventional, and organisationally mandated, systems safety and 2D approaches that employ quantitative approaches. Observation of this duality lies at the genesis of this research.

3. Research

With an eye to the success of the Flight Test community in managing complex risk, a mixed methods qualitative study was conducted with ethnographic[2] approaches that included survey and interview. The research project was undertaken to learn the management practices and communal lore of the Flight Test community as they relate to risk. The unique circumstances and approach of Flight Test toward risk management enabled research where the risk manager is internal to the system, so that system operation would be terminated at the point of risk realisation. The unique feature of test pilots as a subject of risk management research is that they do not consider themselves fungible AND they are inside the system. So, they manage risk differently and that is the subject of the research. In academic terms, the catastrophic nature of the consequences to Flight Test risk precluded research consideration of complicating partial cases, and precluded consideration of post facto mitigations, specifically robustness and resilience. Removing consideration of partial cases and post facto mitigations bounded the research.

This ethnographic research project collected data through survey and interview of Flight Test professionals in 2022, filtered to be those with experience managing risk in a Flight Test project that encompassed catastrophic consequences within the preceding five years. Participants were required to be managing risk within an organisation operating with an engineering management system and to be engaged with a professional Flight Test society. This ensured participants were schooled, mentored and managed in their on-going conduct of risk management, within an organisational context, rather than operating as an individual. The subject of the research was the practices of the community, rather than individuals. Forty-nine valid responses were received from which 9 interviews were conducted.

Validation of the research was conducted in 2024 using the same criteria for all of the participants. Validation activity presented the data and the findings to potential research participants at a professional industry conference (Society of Flight Test Engineers, 2024 European Symposium), before using the survey data and interviews to gauge the validity of the underlying data set and the findings.

The Cynefin (Snowden & Boone 2007) ontological (categorisation) framework was used for analysis. Cynefin aided identification of different domains of systems, enabling identification of reasons for effectiveness of risk tools against systems with different attributes. Though the categorisation of domains within Cynefin is described by Snowden and others in various ways (including discriminating attributes relating to cause-and-effect relationships, coupling, and the level of knowledge about the underlying system), in this research, categorisation of systems was tightly implemented based on determinism, latency and stability in the system definition. Determinism is the presence of cause-effect relationships that are knowable a priori. Latency reflects the quantity of time between cause and effect, relative to stakeholders' ability to respond. Stability is a measure of the dynamism in a system, its preponderance to alter its form over time. Consideration of the system domain as a function of determinism, latency and stability was referred to as its intricacy domain. Complex systems were noted as being uniquely non-deterministic, and capable of changing form without deliberate human intervention.

Correlation with the work of Rasmussen (1997) provided further clarity in considering rates of occurrence of adverse events, particularly for the opportunity to build valid models of system performance based upon observation of prior occurrence.

References to safety were recognised as the sub-set of hazards with consequences adverse to human health. Thus, research participant references to safety were included in the data set, abstracted to be considered as risks though with special consequences. References to safety remained within the scope of the research. Financial risks were excluded from the definition of catastrophic as the potential for monetary compensation would serve as a remedy for continuation of the system, rather than terminating operation.

4. Background

Unlike the complicated systems of the early 2000's that were characterised by an enormous number of interfaces that were ultimately knowable, contemporaneously defined complex systems are non-deterministic, dynamic and feature emergence. While

[2] "Ethnographic research methods involve the examination of cultural phenomena from the perspective of the subjects under investigation." https://researcher.life/blog/article/what-is-ethnographic-research-methods-and-examples/

the enormous number of system interfaces can remain, it is dynamism that now characterises the system attribute of complexity (Sterman 2000), introducing a time dependency. For a complicated system (those that are deterministic and static), an optimal process can be designed and statistical information to support organisational decision-making is static, so it remains valid into the future. Knowledge of complicated systems is not perishable. While some academics recognised that statistical approaches to risk management are not appropriate with epistemic uncertainty (Paté-Cornell 2012; Xu, Yu & Li 2014), they attributed small samples (associated with low rates of occurrence) as causal. But a contemporary systems thinking approach identifies that it is the dynamic nature of complex systems (changing system environment, boundary and performance) that precludes use of frequency of occurrence as a proxy for probability.

Earlier papers and presentations for aSCSa and Engineers Australia (Luther 2022; Luther, Gunawan & Nguyen 2022) utilised the initial stages of the research to elaborate on the defining attributes of complexity and consider the impact of those attributes on the effectivity of risk management frameworks when the underlying system features complexity (Luther, Gunawan & Nguyen 2023).

5. Research Findings

Using the researched data, a system dynamics model of the flow of uncertainty through Flight Test risk management processes was constructed to understand the Flight Test Risk Management framework. This is presented at Figure 1. Systems thinking (Wright & Meadows 2009), and specifically Sterman's (2000) System Dynamics was used to generate this model of the flow of uncertainty through the Flight Test risk management framework. The Flight Test community were found to employ three controls on the flow of uncertainty through the organisation. These are controls are upon the Configuration, the Operating Environment, and the system Operator.

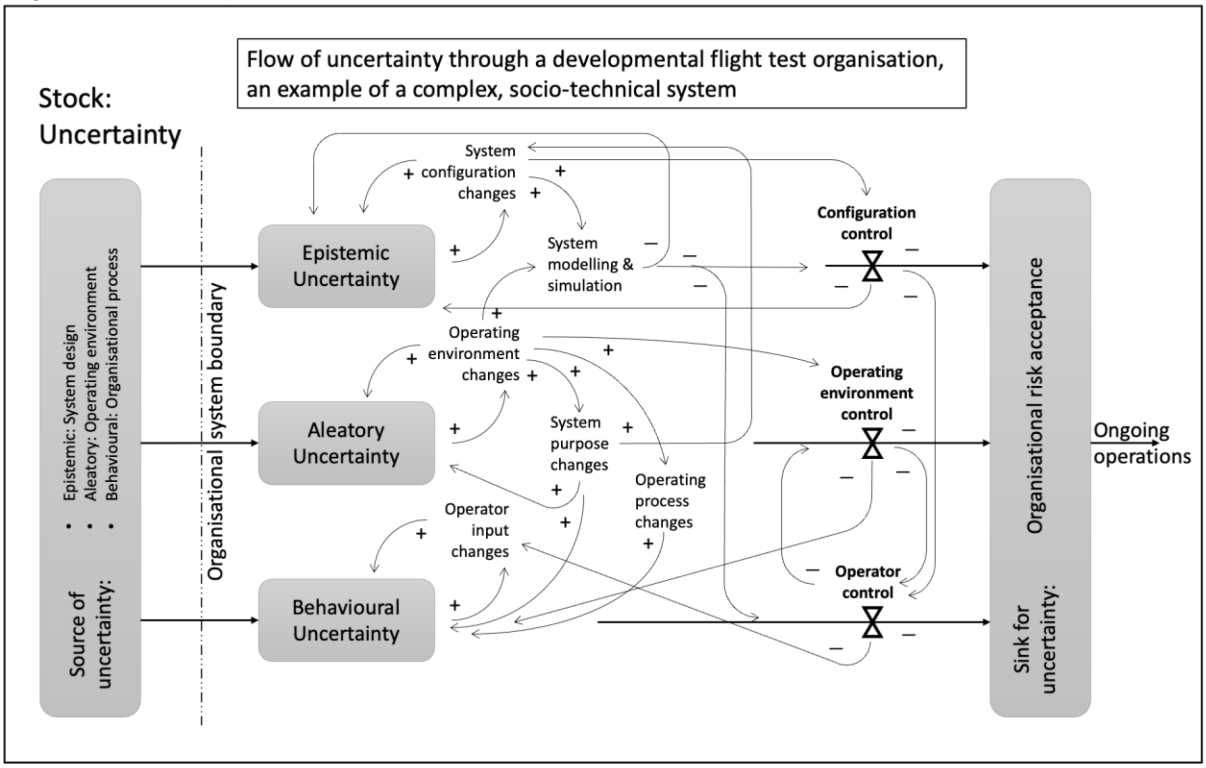

Figure 1. Systems Dynamics model of Flight Test uncertainty in Flight Test operations.

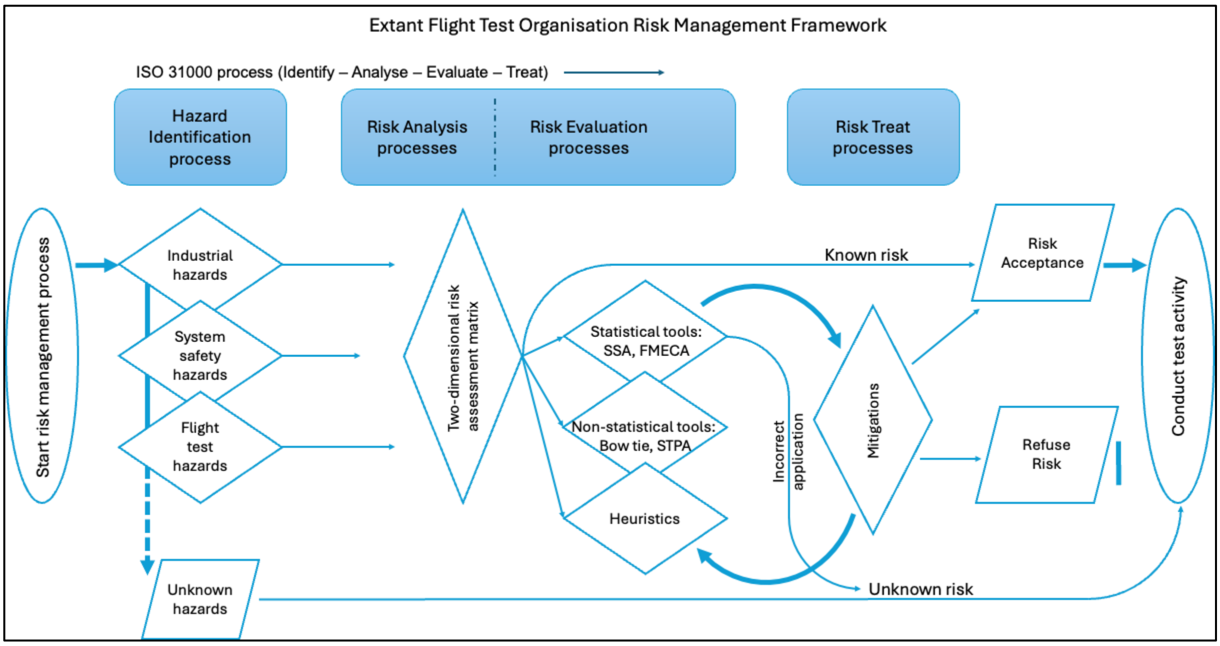

Figure 2. Extant Flight Test Risk Management Framework.

Note that an alternate reading of an operator exercising control on a system is not what is being reported here. This is an examination of the flow of uncertainty through the organisation and the organisation can control the flow of uncertainty through the organisation by utilising an operator with skill, experience and training. The operator is one of three organisational controls upon uncertainty in the generalised Flight Test organisation.

A unique attribute of the Flight Test Risk Management framework is its dual approach to risk management, employing both statistical and non-statistical approaches in parallel. That approach is implemented with different tools that would be effective against different levels of system intricacy, but the community did not apply the respective tool sets in a considered manner. The Flight Test community does not recognise the impact of system intricacy (level of determinism and latency) upon the effectivity of risk management tools. Rather, effectivity is assured by applying all the tools, to all the risks. The inefficiency of this is recognised within the community, however, the catastrophic nature of the risks compels the sustainment of parallel approaches to ensure availability of approaches that are felt to be more effective with complex systems. The Flight Test Risk Management Framework is depicted in Figure 2.

The Flight Test community's use of Bayesian (recurrent, statistical) risk management tools is effective in complicated parts of the system because recurrent system performance builds a statistically valid, empirical frequency model of occurrences. This serves as a proxy measure of probability. The empirical data set builds over time because the underlying system under test maintains a consistent system definition – complicated systems are static. Using the Cynefin ontological framework (Snowden & Boone 2007) to categorise systems, Complicated systems exhibit regression to the mean with repeated operation, and a consistent system boundary enables a system performance model that retains validity into the future. Consequently, statistical risk management tools are effective against risk elements in complicated systems. The Flight Test approach of revisiting (repeating) risk management activity makes their use of statistical tools Bayesian.

Conversely, the Flight Test community use non-statistical tools to manage risk in Cynefin – Complex parts of the system; being those that exhibit a dynamic system definition and emergent functions. These risk management tools are effective with complex systems because they are independent of measures of probability. Prevalent among Flight Test's non-statistical tools is the Precautionary approach (Cox 2009) which ensures consequences are tolerable, independently of any organisationally mandated assessment of hazard probability. Mosey (2014) identifies other tools that are independent of knowledge of the probability, including assuring integrity in information flow using review (examples of this would be the systems engineering review gates, and, experienced practitioner review), checklists, and hazard identification tools.

The Flight Test community self-identified the duplication of risk management tools and practices. This was expressed as frustration with duplicative overhead and tools felt to be ineffective against classes of risk. Despite a specious pursuit of singular process for perceived efficiency, the Flight Test community persisted with the parallel application of tools because of the value attributed to the ability of some tools to mitigate risk in complex systems, without knowing why. When Flight Test professionals were forced to use statistical approaches by organisational policy, they did not use the outcomes on complex elements of the system. Rather, they did enough to satisfy organisational policy requiring statistical-tools, before resorting to non-statistical tools to address complex risks with catastrophic consequences.

Parsing the research data identified the Flight Test community's risk management practices, specifically the employment of different risk management tools within a framework that was capable of addressing risk in different system intricacy domains. Parallel application of various risk management tools assured effectivity of risk management in Clear, Complicated and Complex sub-systems, without a requirement to filter risk or understand why it worked. Colloquially, all the risk tools were applied to all the risks.

6. An Evolved Theory of Risk

Humanity first grappled with concepts of risk in the context of games of chance (Bernstein 1998) but there is no grand theory of risk. Consequently, contemporary risk management pulls from adjacent fields, finding its foundation in the field of economics, with its academic theories of probability and utility. Von Neumann and Morgenstern's Utility Theory first introduced a two-dimensional model of risk using economic Utility Theory (Hartono et al. 2014), and that model using consequence and likelihood has become ubiquitous. That original two-dimensional model was published in 1944 (von Neumann & Morgenstern 2007) and Hastie & Dawes (2001) now describe the two-dimensional model as the most widespread risk model in use. Unsurprisingly given its genesis in economics, the model is best illustrated in the clean example provided in the financial sector. Here, consequences are measurable in currency units (quantitative, continuous data) and historical records of events serve to provide a frequency distribution (statistical model) that can be expressed as a mathematical probability (unit-less, quantitative, continuous data) that models the likelihood of occurrence. The quantitative, continuous nature of the data (not being nominal, ordinal or discrete) in both dimensions supports the model's mathematical process (multiplication) to assess a single, quantitative measure of risk. Relative risk levels can then be assessed against a quantitative scale on a single axis, baselined in currency units, allowing organisations to prioritise resources and attention toward the most significant threats to desired outcomes. But projects outside of the finance sector are not so clean.

However, Von Neumann and Morgenstern's Utility Theory is not useable when there is no valid measure of consequence or likelihood. Valid measures of consequences like the loss of life, or social outrage at environmental damage, are not easily determined. The threat of fatality to the system operator (an infinitely negative outcome) is rarely accommodated in the quantitative scale of the two-dimensional risk model, particularly without resorting to logarithmic scales. But it is in the consideration of likelihood where Flight Test discriminates strongly. Empirical frequency distributions provide measures of probability for recurrent events that are repeated in the same manner and Flight Test risk managers do use frequency distributions when they are available. They also report being increasingly uncomfortable assigning subjective probability to adverse occurrences when a quantitative value is not available. This is done when forced to apply two-dimensional risk management tools. Within the Flight Test context of operating novel aircraft, while adverse occurrences may be similar, they will not be occurring in exactly the same system. Since the definition of probability is the ratio of a sub-set to the whole set, in the real world, knowledge of the probability of a future outcome demands knowledge of the universe of potential outcomes. Clearly this is an unknowable and unrealistic state in Flight Test. In practice, such knowledge is constrained to games of chance. In Flight Test there is a statistical n=1 problem, representing no prior operating experience with the system in the presented configuration or operating condition. Theirs' will be the first use of the system in the configuration being considered.

The use of a two-dimensional model of risk from the field of economics does enable effective risk management in an efficient manner when a consequence and likelihood can be ascertained. Since systems are not homogenous, this remains a useful approach. For the parts of the system that aren't complex, existing approaches that use empirical frequency distributions, or the calculation of reliability using system safety data (FMECA and similar), present proven approaches to managing risk. But with elements that are complex, a different approach is required.

Early 20th century Nobel Laureates debated whether likelihood could be quantified as a probability, and how uncertain future losses could be compared to assess economic utility. On one side of the argument, Milton Friedman's Utility Theory, and his Probability Theory (Friedman 1976) underpins contemporary risk management, building on de Finetti's argument that a probability could be assigned to any future event. Assumptions of independence and a known, discrete set of possible outcomes underpin the concept of a sample of individual perceptions of future economic utility constituting a subjective probability (Galavotti 2015). But on the other side of the argument, Frank Knight (Faulkner et al. 2021; Knight 1921) and John Keynes (Keynes 1921) both independently distinguish between a knowable probability and an uncertainty, providing an alternative to the idea of subjective probabilities. Knight (1921) differentiates uncertainty from knowable probability. For Knight, a probability is either calculable because all potential outcomes are known (the surrounding circumstances are identical between repeated instantiations of the same event and the universe of potential outcomes are known – games of chance), or, it is an empirical observation of a frequency distribution. Keynes (1921) explicitly states that probability is not subjective, *nor subject to human caprice*. For Knight and Keynes, probability can only be calculated or counted. In the context of business decisions, Knight uses the term *uncertainty* to refer to the unknowable nature of future events, events that are always unique (having differences) in the real world.

Conversely, Friedman's Price Theory from the 1940's specifically refutes Knight's distinction between a knowable probability distribution and uncertainty (Friedman 1976, p84). Though Friedman, Knight and Keynes were not afraid to dispute each other's work, ultimately it was Friedman that was adopted in the field of economics. For Friedman it is a question of the accuracy of the measure of probability, where observations of empirical frequency offer the greatest potential for accuracy. But he acknowledges personal assessment of future economic utility as a valid, subjective probability – just without as much credence. For Friedman, subjective probabilities need increased sampling (multiple subjective probabilities) to provide a central tendency. Then it is the central tendency of the subjective probabilities that has credence. Friedman's Price Theory permits allocation of a subjective probability to enable pricing of future utility for economic analysis.

Reflecting economic theory to risk management requires careful consideration of the underlying assumptions. Recalling that there is no grand theory of risk management, the use of academic theory from adjacent disciplines is enabling but must be undertaken with understanding of the context and assumptions.

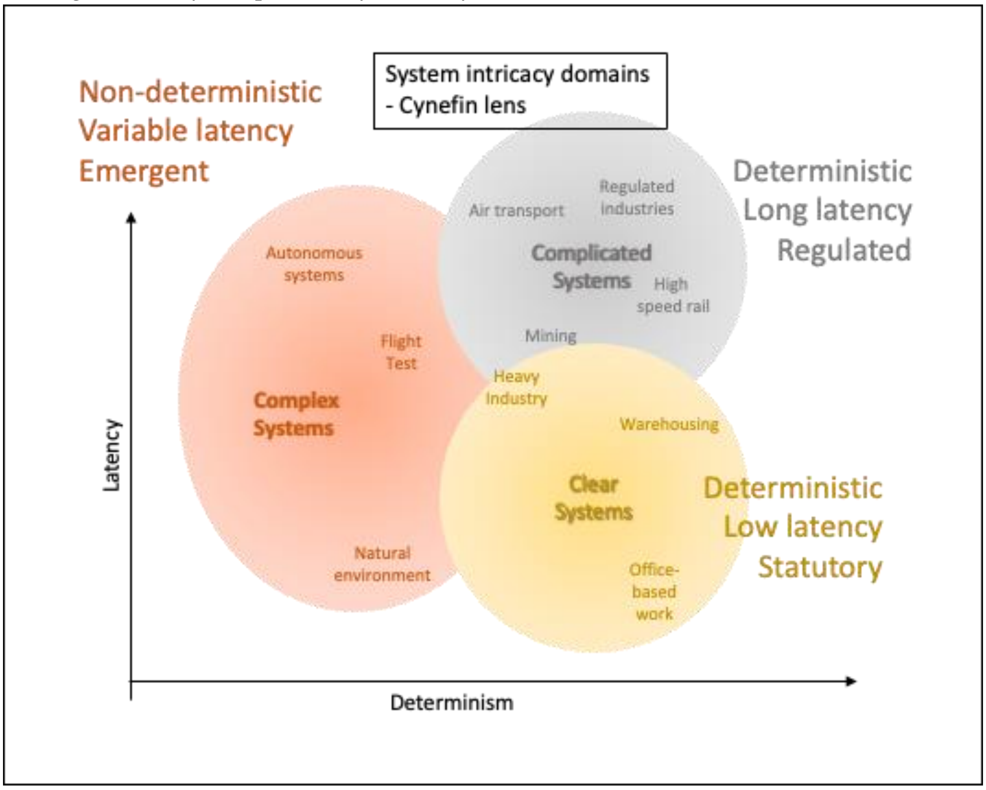

Figure 3. System intricacy domains differentiated by level of determinism and latency.

Within economics, Friedman's subjective probabilities are used with large samples and the Central Limit Theorem to provide a subjective probability. An individual assignment of a value as a probability is not a count or a calculation per Knight, nor a subjective probability per Friedman.

Snowden's ontological framework (Snowden & Boone 2007), along with Systems Theory provides a tool to parse systems for the discriminating application of risk management tools. When our systems are Clear or Complicated, both being deterministic, the parallels between economics and risk science are axiomatic – the application of economic Utility Theory remains effective and thus useful. But when our systems evolve to be Complex, the read across breaks down. Instead of Friedman's Probability Theory, Knight's Probability Theory becomes more useful. This is because when a system element is Clear (deterministic, static, low latency), each observation of an event is made on the same system and builds to be a valid empirical frequency distribution. For this, economic utility theory reads across to risk, supporting a useful two-dimensional risk management tool. When a system element is Complicated (deterministic, static, high latency), there is a long duration between events, so an empirical frequency distribution isn't practical. The static nature of the system means that system knowledge is not perishable so an investment (time and financial) in building an *a priori* calculation of probability is warranted. This is the Systems Safety approach. The Systems Safety approach does conflate component failure with safety (Leveson 2012), but when system reliability equates with safety incidents as occurs in the Complicated domain, differentiating these is not useful to users. System safety provides a useful tool for managing risk in the Complicated domain. But when a system element is Complex (non-deterministic, dynamic, high latency), a probability is not available and system safety approaches are not sensitive to emergent functions. As Knight's Utility Theory doesn't need probability – the likelihood is uncertain and the probability unknowable – it remains available for use with complexity.

Since Clear and Complicated systems are both deterministic and differ only in latency, observation of these two reveals only an axis. With the evolution to Complex systems, the introduction of non-deterministic behaviours reveals the plane. Figure 3 considers the plane of domains of systems delineated by attributes of latency and determinism, correlated with Cynefin categories. These system attributes impact the effectiveness of risk management tools (Luther, Gunawan & Nguyen 2023) and demand different risk management approaches. The attributes of systems categorised by their intricacy domain are impactful upon risk management and indicative systems have been labelled in Figure 3.

7. Discussion

The cultural lore of the Flight Test community is communicated and perpetuated with stories; stories that often have their genesis in developmental aircraft accidents that resulted in loss of life. Catastrophic outcomes serve to make lessons poignant, a manifestation of survivor bias distinguishing practitioners who heed and perpetuate the learning from those who do not. Flight test professionals closely align their risk management practices with the ISO framework (ISO 2018), focusing on system controls while emphasizing communication, coordination, and integration within the Flight Test team. This validates the best-practice principles of Complex Systems Governance (CSG) (Ireland 2016).

The delineation between complicated and complex isn't absolute and is relative to the observer. A Flight Test risk manager with a well-resourced Systems Engineering department at their disposal could afford to invest in learning the relationships within the system, driving the perceived level of intricacy to be complicated. (It could be amazingly complicated, but ultimately knowable.) Alternatively, a Flight Test risk manager without resources to learn the relationships within a system would perceive that system to be complex, featuring relationships that are unknowable to them, appearing indeterminate.

The idea of relativity in the categorisation of system intricacy domains provides organisations an opportunity when managing systems that inhabit the transition between complicated and complex. For organisations that are invested in systems engineering, there is an opportunity to drive systems toward the complicated domain with system knowledge. Acquiring sufficient system knowledge will necessitate bounding the context (the operating conditions and environment) and will be a significant undertaking. The alternative is to accept that complexity will render sufficient system knowledge unattainable. This leads to implementing a Precautionary approach. Precautionary risk management tools (Cox 2009) are independent of statistical models that would require a sufficiently complete systems knowledge. While assuming system complexity and adopting a Precautionary approach is optional for organisations with resources, it presents a viable option for those managing small organisations without resources to pursue sufficient system knowledge. The width of the boundary between the complicated and complex intricacy domains is relative, with larger systems engineering organisations having greater capacity to drive their system into the complicated domain. This relativity presents potential for successful risk management using either approach. Upfront investment could be weighed against the alternative of resource-intensive, non-statistical risk tools in the complex domain.

8. Implementing a New Risk Management Framework

While broader academic research into systems and management might consider robustness and resilience as risk mitigations, these are not appropriate when the risk manager also bears the consequence because they are internal to the system. A more appropriate correlation to academic theory would be the small slice of risk science that addresses a two armed-bandit problem with the twist of terminating play at a loss event.[3] But with a consequence of death (termination of the game) at the first unsuccessful outcome, … "there is no opportunity to alter behavior after an unsuccessful outcome. Introducing the risk of death into a sequential decision problem alters the structure of the problem." (Viscusi & DeAngelis 2018).

Facing risk with catastrophic consequences in complex systems, Flight Test crew have cultural lore toward controlling risk events prior to occurrence. By examining the test pilots' methodology as a case study, the essential characteristics of a risk management framework appropriate for complex socio-technical systems were identified. These characteristics must address the following aspects:

1. Heterogeneous system intricacy
2. The Hierarchy of Controls from occupational health and safety
3. The Systems Safety approach in Systems Engineering
4. Risk controls that effective with complexity

8.1. Heterogeneous Levels of Intricacy

A risk management framework needs to address industrial safety (Clear), system safety (Complicated), and complex system (Complex) risk. The attributes of risk management in the different domains demands unique, parallel approaches.

8.2. Hierarchy of Controls

To efficiently control hazards in the Clear domain, operating procedures, training, and Personal Protective Equipment (PPE) all present effective risk mitigations in this domain. With systems, or elements of a system of systems, in the Clear domain, there is one best way of operating (best = effective and most efficient) and that method of operation is knowable and stable. Knowledge of that method is not perishable and the key to profitable operations is maintaining the discipline to always operate that way. The rate of occurrence of deviations from that defined method of operations can be empirically counted and mitigating the likelihood of occurrence is efficient risk management.

8.3. Systems Safety

To control hazards in socio-technical systems operating in the Complicated domain, operations require control of the technical processes and machines. That control is predicated upon reliable function of the machines and processes in the system and failure to function precipitates hazards. Consequently, reliability is required to achieve safe operations in the Complicated domain. Operation of the machines in accordance with the procedures and within the design environment ensures the as-designed system safety regime remains valid. Bottom-up system safety assessments are effective in assuring engineering system safety in systems designed using a decomposition. The high cost of incidents and low rates of occurrence warrant investment in system knowledge. A safety management system provides assurance of on-going application of risk mitigations, to span the potential for extended latency between cause and effect.

[3] Multi-armed bandit decision problems

"… a problem in which a decision maker iteratively selects one of multiple fixed choices (i.e., arms or actions) when the properties of each choice are only partially known at the time of allocation"

"The multi-armed bandit problem is a classic reinforcement learning problem that exemplifies the exploration–exploitation trade-off dilemma."

(https://en.wikipedia.org/wiki/Multi-armed_bandit#:~:text=In%20probability%20theory%20and%20machine,known%20at%20the%20time%20of)

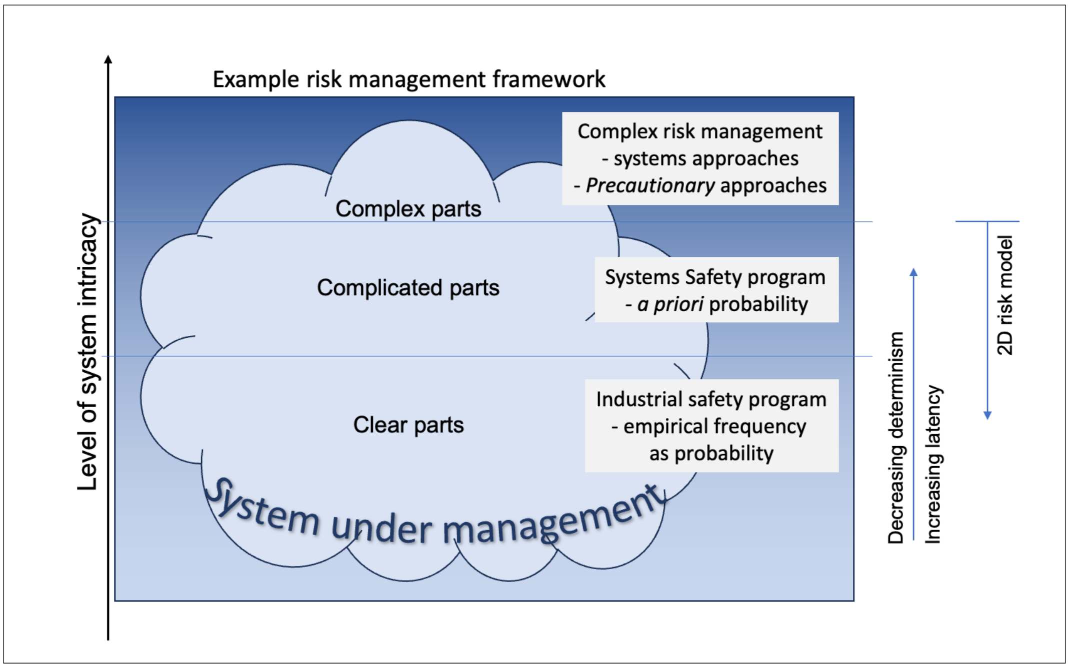

Figure 4. Sub-systems each demand a unique set of risk management tools.

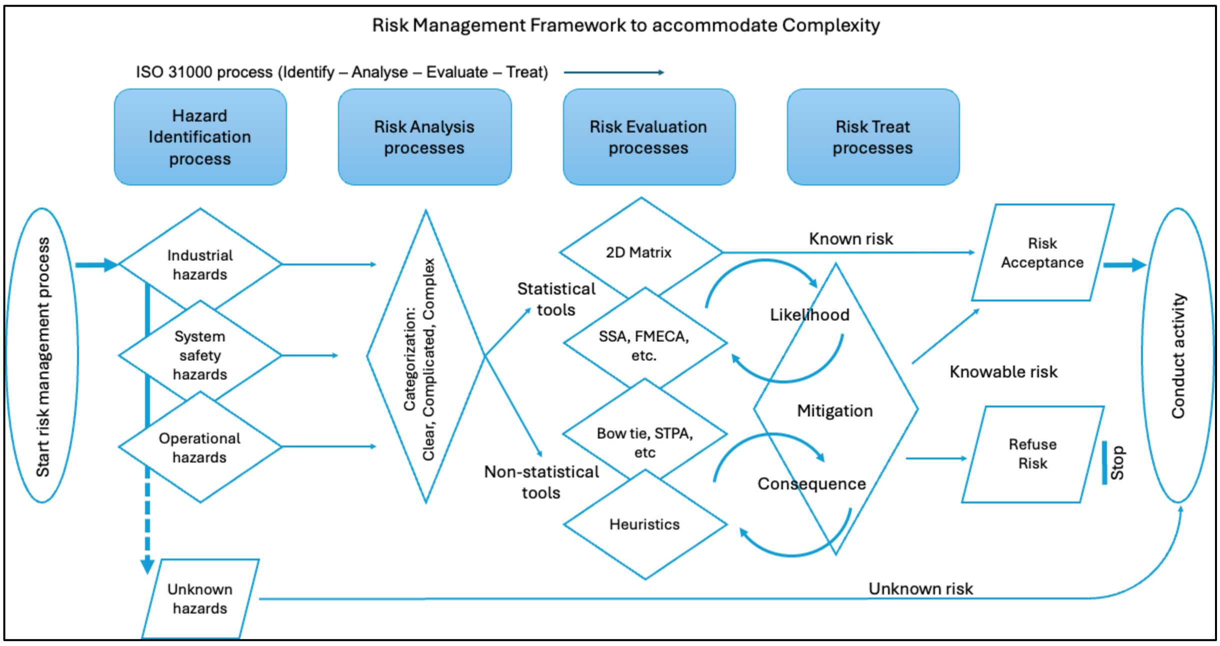

Figure 5. A Risk Management Framework encompassing three levels of system intricacy.

8.4. Complex Risk Controls

Efforts to quantify the probability of complex hazards are fictitious since variability in the configuration of complex systems (non-deterministic and emergence) precludes that knowledge. Since the probability of a complex hazard is unknowable, with the two-dimensional risk model, that leaves the consequences of complex hazards as the avenue for control. Utilise top-down assessments to capture emergent functions. Control the consequence of a complex hazard using Precautionary approaches that only present acceptable consequences at each increment. This avoids statistical approaches that would be invalid. Communicate nuance and adopt recursive approaches to accommodate the dynamic nature of complex hazards.

8.5. Illustrating the New Framework

Figure 4 illustrates the concept of an integrated system comprised of Clear, Complicated and Complex parts, each of which demands a unique approach to risk management on account of the attributes of the intricacy domain of the sub-system. Risk management tools that use statistical, quantitative approaches can only be utilised when a statistical model is available. Figure 5 presents a Risk Management Framework suitable for use with systems that contain complex elements. It is abstracted from the Flight Test framework for generalised, cross-industry application. Featuring both quantitative and qualitative approaches, hazards are filtered according to the level of intricacy in the underlying system. This filtering ensures that the risk management tool to be applied is effective in the presence of the system attributes. The filtering also improves efficiency by precluding ineffective tools.

9. Conclusion

In the manner of Aven (Abrahamsen & Aven 2012; Aven 2016), Flight Test risk management and assessment implements a dual approach of Bayesian and non-statistical tool sets to avoid assignment of subjective probabilities to complex system hazards. The array of tools in use address Clear, Complicated and Complex sub-systems effectively, though the Flight Test risk management framework is not efficient as all the tools are applied to all the risks.

The empirical collection of frequency distribution data to use as a probability is not available to complex systems. Statistical risk management tools are ineffective against complex systems because measures of probability are not available – the system is not static so system knowledge is perishable and emergence further precludes building knowledge of a probability of occurrence. Being indeterminate, it is a different system every time it is observed. (Organisations may choose to overlook the differences, though caution is warranted since complex systems also feature discontinuities.)

Complex systems demand risk management approaches that remain effective with the attributes of complexity. Knowledge of why different approaches work will provide Flight Test and other industries with the arguments to sustain risk management practices that are otherwise only empirically known to work. This paper provides an opportunity for risk managers of complex systems outside of the Flight Test domain to adopt the proven practices of test pilots. Doing so will expand their tool set to address complexity and streamline practices by targeting their risk management tools.

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