UNIVERSITY of TASMANIA

FUZZY SYSTEM DYNAMICS RISK ANALYSIS (FuSDRA) OF AUTONOMOUS UNDERWATER VEHICLE (AUV) DEPLOYMENT IN THE ANTARCTIC

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) are self-powered robotic devices that operate underwater with a propulsion system. In recent years, the maturing of autonomous technology and commercialization of AUVs has led to the rapid expansion of AUV types and capabilities. As a result, they are now being used in many scientific, commercial and military applications, such as underwater mine-clearing operations, feature tracking, cable or pipeline inspection, deep ocean exploration and air crash investigations. In a relatively new development, there has been a growing interest in the use of AUVs for under-ice marine science research in the Antarctic. For many years, researchers have limited access to investigate these ice-covered waters, but the use of AUV aims to change that. Concealed under the Antarctic's sea ice lies a vast amount of intrinsic scientific information across a wide range of scientific disciplines, offering insights from Earth's climate system to human biology. In particular, understanding the impact of climate change on Antarctic's sea ice is critically important because of its contribution to global sea level rise and its role in regulating the world's climate system.

However, the deployment of AUVs in the Antarctic for under-ice marine science research is not an easy undertaking. It is a complex operation involving thorough and careful planning, collaboration with multiple stakeholders, working in adverse environmental conditions, and often fraught with logistical, financial and technical challenges. During the mission itself, additional considerations are needed to account for ice cover, accessibility and emergency abort procedures. Therefore, it comes as no surprise that there is an increased risk of losing an AUV during operations in the Antarctic when compared to open water missions in other relatively benign environments. The loss of an AUV is not only financially costly due to the resulting higher insurance premium for all (if it is insured, or loss/rebuild costs if it is not), it can also delay research projects, damage the reputation of the AUV community, cause the loss of valuable research data and a possibility of harming the delicate Antarctic environment. It is therefore imperative that the risk of loss be analysed and managed effectively for deployment of AUVs in the Antarctic.

Significant developments had been made over the years in risk analyses methodologies to better analyse and manage the risk of AUV loss during deployment. Early efforts focused on the prevention of technical failures to improve reliability and increase life span of AUVs. Later, proactive and systematic risk analysis approaches emerges, to predict the likelihood of loss by analysing historical performance data of the AUV. Gradually, the scope of risk analysis broadens from analysing historical performance of an AUV to other operating uncertainties and phases of deployment. In recent development, more attention has been devoted to the role of organisational and human factors in the overall risk of AUV loss during deployment. Despite improvement in risk analysis approaches to AUV deployments, predicting the risk of loss remains a highly uncertain exercise heavily dependent on historical performance data. Two main areas for improvement were identified to develop a more comprehensive and effective risk analysis methodological framework for Antarctic AUV deployment. First, the time-dependent nature of risks and the complex interrelationships between risk variables of an AUV program

needs to be examined collectively as a whole. Second, to reduce dependency on historical performance data by accounting for vagueness and ambiguity in elicitation of expert's opinion.

To address the first shortcoming, a dynamic systems-based risk analysis framework facilitated by system-dynamics methodology is proposed. The use of system dynamics enables modelling of the complex, interrelated and dynamic systems behind an AUV program which may influence the risk of AUV loss during an Antarctic deployment. For the second shortcoming, a fuzzy-based risk analysis framework based on expert's judgement is suggested. The use of a fuzzy logic overcomes limitations due to the lack of empirical data and accounts for the uncertainties about causal relationships between risk variables. Lastly, a hybrid Fuzzy System-Dynamics Risk Analysis (FuSDRA) framework is proposed. Leveraging strengths while overcoming limitations of both fuzzy logic and system dynamics, the novel approach provides a structured, robust and effective solution for risk analysis of Antarctic AUV deployment.

The usefulness of the FuSDRA framework was demonstrated in a case study based on the University of Tasmania's (UTAS) *nupiri muka* AUV program. Supported by the Australian government through the Antarctic Gateway Partnership initiative, the objective of the program is to develop a polar capable AUV for the acquisition of high-quality underwater data. The explorer-class AUV was delivered in May 2017 with its first Antarctic deployment in December 2018. Using information sought primarily from interviews of domain experts in UTAS and supported by other knowledge sources, FuSDRA models were developed and tested. Scenario analysis was performed on the models to understand the behaviour of the risk of loss under different circumstances. This included: 1) Knowledge loss due to departure of critical employee, 2) reducing government support and increasing alternatives to the AUV, and 3) increasingly dysfunctional interpersonal dynamics. Simulation results from model testing and scenario analysis were then used to derive a set of policy recommendations to better manage the risk of loss. The importance of implementing an effective budget management system, obtaining diversity in funding, reducing risk of obsolescence, optimizing recruitment strategy and improving interpersonal dynamics and stress awareness were highlighted.

This dissertation lays the foundation for structured risk analysis frameworks with the eventual goal of reducing risk of AUV loss during Antarctic deployment. The main contribution, the FuSDRA approach may also be applicable to other types of AUV operations or complex technological systems. To enhance the usability and ability to solve real-world problems, further work is proposed on the FuSDRA framework.

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As the common adage goes “The journey is more important than the destination”. I could not have chosen a more apt way to describe my PhD journey. It was a journey filled with emotional rollercoaster of hope, despair, fear, self-doubt and achievement. I mourned the passing of my beloved mother and the joyous welcome of my second boy. I left my job and moved my family four thousand miles from Singapore to Tasmania, all within the first year of my PhD. Without the support from some of the most amazing people in this journey, I would never be where I am today. They have shown me that with determination, willpower and more importantly, pure hard work, it is possible to achieve your goals and live your dreams.

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DEFINITIONS

The study of risk is a complex discipline with many unstandardized terminologies. Therefore, different terms and concepts used throughout this dissertation must be clarified to facilitate references to extratextual materials. This section presents basic definitions for common terms with more detailed descriptions for key concepts and terms provided in their respective sections.

Accident

Events or occurrences that result in unwanted and undesirable outcome (8). In the context of this dissertation, it refers to the loss of AUV during mission in the Antarctic.

Ambiguity

The condition of admitting more than one meaning or interpretation (9).

Autonomous Underwater Vehicle

A self-powered robotic device that travels underwater with a propulsion system, controlled and piloted by onboard computer systems.

Deployment

An AUV exists in two main states: in storage or deployed. A deployment to the Antarctic encompasses all activities from transportation of the AUV out of the facility to its return. Usually, a set of missions are executed during any deployment.

Failure

The inability of the item to perform its function within previously specified limits (10).

Hazard

A hazard is a state or set of conditions of a system (or an object) that, together with other conditions in the environment of the system (or object), will lead inevitably to an accident (loss event) (11).

Incident

Unwanted and undesirable outcome occurring or could have occurred. Encompasses accidents and near-misses (12).

Probability

A measure for representing or expressing uncertainty, variation or beliefs, following the rules of probability calculus. (9)

Reliability

The probability that an item will perform its intended function for a specified interval under stated conditions (10). Not to be confused with Safety.

Risk

The effect of uncertainty on objectives (13).

Risk Analysis

A systematic process to comprehend the nature of risk and to express the risk, with the available knowledge (9)

Risk Appetite

Amount and type of risk an organisation is willing to take on risky activities in pursuit of values or interests (9).

Risk Factor

Adapted from epidemiology, a risk factor is a variable (action, sub-activity, component, system, event, etc.) which alone or in combination with other risk factors is associated with an increased potential to give rise to some specified consequences (typically undesirable consequences). Used interchangeably with the term “Risk Variable” in this dissertation.

Risk Management

Activities to handle risk such as prevention, mitigation, adaptation or sharing It often includes trade-offs between costs and benefits of risk reduction and choice of a level of tolerable risk (9).

Risk of AUV Loss

The likelihood that, during a mission, an AUV will be rendered unusable for future missions, a definition adopted from NASA (14).

Safe

Without unacceptable risk [9].

Systemic Risk

Risk emerging from the intervening risk factors and feed-back loops which are not predictable based on behaviour of each risk factor.

Survivability

The ability of a system to minimize the impact of a finite disturbance on value delivery [15]*.* Sometimes used as an antonym to ‘Risk of loss’.

System

A purposeful collection of inter-related components working together to achieve some common objective [16].

The Antarctic

Defined either by the Antarctic Circle or the Antarctic Polar Frontal Zone. The Antarctic Circle is defined by places where the sun is above the horizon for 24 continuous hours and below the horizon for continuous 24 hours at least once a year. The Antarctic polar frontal zone or Antarctic Convergence, is a circular belt of water where cold, northward-flowing Antarctic waters meet the relatively warmer waters of the subantarctic.

Uncertainty

An imperfect state of knowledge or a physical variability resulting from a variety of factors including, but not limited to, lack of knowledge, applicability of information, physical variation, randomness or stochastic behaviour, indeterminacy, judgment, and approximation [17]

INTRODUCTION: ON THE RISK OF AUV DEPLOYMENT IN THE ANTARCTIC

The advancement of science and technology has resulted in an emerging trend in the use of autonomous equipment for research activities in the Antarctic. From the collection of weather data [18] to ozone monitoring [19] and to meteorite identification [20], it is now possible to perform a diverse range of research activities in the Antarctic without human interference. In particular, autonomous technology has proven to be an invaluable asset for Antarctic's under-ice research. Collection of under-ice data once depended mainly on drilling from above the ice and the use of ice-breaking vessels [21]. However, the emergence of AUVs now offered new possibilities. With advantages of versatility with customizable payloads, ability to access remote locations, efficiency, higher data quality and lower costs of operations [2], it comes as no surprise, that there is a growing presence of AUVs in the Antarctic.

Despite its advantages, the deployment of AUVs in the Antarctic presents its own unique set of challenges, be they logistical, financial or technical. The harsh Antarctic environment not only pushes the technological limits of an AUV, but also challenges the on-site support team both physiologically and psychologically [22]. In any event of incident during mission, recovery of the AUV may be virtually impossible or very costly. Although publicly available reports of AUV incidents are limited, there are several anecdotal accounts of AUVs being severely damaged or completely lost during deployment in the Antarctic. More than just tangible financial impact such as increase in insurance premium, any mishap to an AUV during a mission can also cause indefinite delay to research projects, loss of valuable research data, damage to the reputation of the AUV community and a possibility of contaminating the pristine Antarctic environment [2]. Therefore, preventing the loss of an AUV during deployment is one of the top priorities for AUV owners embarking on an Antarctic research program.

Early efforts to reduce the risk of loss focused mainly on technical aspects of AUVs. Often, a modular approach is adopted to improve robustness and reliabilities in specific areas such as; the mission management software, navigation system, collision avoidance system, emergency abort system, power system, homing system and communication system [23–31]. As AUV technologies continue to be refined, there is now compelling anecdotal evidence that technical risks arising from design, manufacturing and technological processes have decreased over the years. Consequently, a need arises to shift the focus of attention from technical aspects to broader issues for more effective analysis of risk. This includes the people associated with the AUV program, operational processes, operating environment, organisational policies and external constraints such as regulations and political climate. The synergistic combination of these factors associated with the AUV program consists of dynamic complex interrelationships between risk factors with multiple feedback loops. These interactions lead to a collective emergent behaviour which can be difficult to understand or predict purely based on the behaviour of individual risk factors. For example, it is intuitive that an AUV team with higher operating experience translates to a lower risk of loss, when considering only a single risk factor. However, with the inclusion of additional risk factors, such as reducing organisational commitment to the AUV program, poor interpersonal dynamics, high mental workload, etc, the analysis becomes more challenging. Complicated by the interrelationships and uncertainties about the degree of causality between these risk factors, this larger context of risk received considerably less attention as compared to the technical aspects of an AUV.

Throughout the literature, there are limited accounts of AUV lost in the Antarctic. One of the high-profile loss was that of *Autosub2*, an AUV developed and owned by the National Oceanography Centre, Southampton, United Kingdom. The AUV was lost in 2005 under the Fimbulisen ice-shelf most likely due to a fault introduced during the manufacturing/assembly phase [32]. Although the direct cause of loss was determined to be due to technical failure, organisational issues were also highlighted in the loss report. For example, there is little documented information on any prior risk assessment made for *Autosub2* and the setting of risk acceptance criteria as well as approach to management of risks in projects was found to be inadequate [32]. Risk arising from organisational factors does not apply only to the AUV domain but also to many other domains. Valuable insights can therefore be gained by examining the loss of other comparable autonomous equipment. The loss of NASA's Mars Polar Lander is one such example. On December 1999, The USD $110 Million unmanned spacecraft failed to establish communications after entering Mars atmosphere and has remained lost till this day. A subsequent investigation by a special review board concluded that the most likely cause of loss was the premature shutdown of lander engines due to spurious signals generated from the lander leg during descent onto Mars [33]. While the loss can be directly attributed to software error, a more thorough review of the context in which the incident occurs revealed inadequate management oversight and excessively optimistic project implementation [33]. Throughout the project, considerable funding and schedule pressure resulted in inadequate staffing, requirements creep and poor requirements management [33]. These organisational factors and more importantly, their interrelationships eventually resulted in insufficient time and workforce available to provide checks and balances necessary to detect the software error [33]. In almost an irony, NASA was one of the early organisations to recognize the importance of adopting a systems perspective in the analysis of risk. In 1968, the director of NASA Manned Flight Safety Program for Apollo, Jerome Lederer [34] wrote:

> *"System safety covers the total spectrum of risk management. It goes beyond the hardware and associated procedures of system safety engineering. It involves: attitudes and motivation of designers and production people, employee/management rapport, the relation of industrial associations among themselves and with government, human factors in supervision and quality control, documentation on the interfaces of industrial and public safety with design and operations, the interest and attitudes of top management, the effects of the legal system on accident investigations and exchange of information, the certification of critical workers, political considerations, resources, public sentiment, and many other nontechnical but vital influences on the attainment of an acceptable level of risk control. These nontechnical aspects of system safety cannot be ignored."*

The commonality between the causes of the two losses lies in systemic issues, particularly organisational factors. In recent years, there has been a growing recognition on the importance of adopting a systems perspective for risk analysis to address systemic issues. This is evident, especially in safety-critical industries such as aviation [(35)], petrochemical and nuclear energy [(36)]. The AUV domain, associated with relatively new technologies and an emerging industry, needs to keep pace with such developments to overcome shortfalls in existing approaches. Therefore, it is proposed that a new form of interdisciplinary risk analysis, which goes beyond the typical cause and effect analysis is required. Focusing on the complex interrelationships between various risk factors associated with an Antarctic AUV program, such an approach will enable broader issues to surface. This would facilitate determining of leverage points for risk controls and allow monitoring of both the level of risk and effectiveness of remedial actions. As AUVs evolve to take on more critical and diverse roles in Antarctic research, effective management of the risk of loss becomes an imperative goal for the AUV community. It is only by reducing the risk of AUV loss can the full potential of AUV technology be realised and benefits reaped.

The eventual goal of this dissertation is to lay the foundation for a structured, robust and effective solution for risk analysis of Antarctic AUV deployment. These approaches, presented as frameworks, will account for the complex interrelationships between identified risk factors, uncertainties about their causal relationships, as well as their dynamic behaviour. More importantly, they will support the AUV community with the identification, modelling and evaluation of risk factors associated with an Antarctic AUV program.

CHAPTER 1: BACKGROUND AND LITERATURE REVIEW

The main contribution of this dissertation is the presentation of a novel fuzzy system dynamics risk analysis (FuSDRA) framework. The framework facilitates the modelling and analysis of risks involved in AUV deployments, with a focus on the risk of loss in the Antarctic. This chapter provides a review of existing risk research on AUV deployments and highlights gaps to be addressed. A brief background on the Antarctic as well as broader concepts of AUV, risk and risk analysis are also presented. The aim of this chapter is to orient the reader to the foundation on which the rest of this research is based.

1.1 AUTONOMOUS UNDERWATER VEHICLE (AUV)

AUVs are best described as self-powered robotic devices that operate underwater with a propulsion system (Figure 1.1). They typically comprise a pressure hull, power supply, communication and navigation systems, propulsion system, sensors, control unit and actuators. AUVs can range in weight from tens of kilograms to thousands of kilograms and depth ratings of 100m to more than 5000m [(37)]. Sometimes referred to as unmanned underwater vehicles (UUVs) or by manufacturer's model names, they are untethered and are pre-programmed to perform a series of underwater data acquisition missions. Apart from the ability to operate autonomously, their versatility with customizable payloads allows AUVs to perform a wide range of tasks with many scientific, commercial and military applications.

The commercialization of AUVs in recent years has fostered a rapid expansion in AUV types and capabilities. Consequently, AUVs have been deployed for all manner of tasks in many scientific, commercial and military applications, such as underwater mine-clearing operations, feature tracking, cable or pipeline inspection, deep ocean exploration and air crash investigations. The following sections present a necessarily brief overview of AUVs, to provide relevant background information required for subsequent analysis of risk.

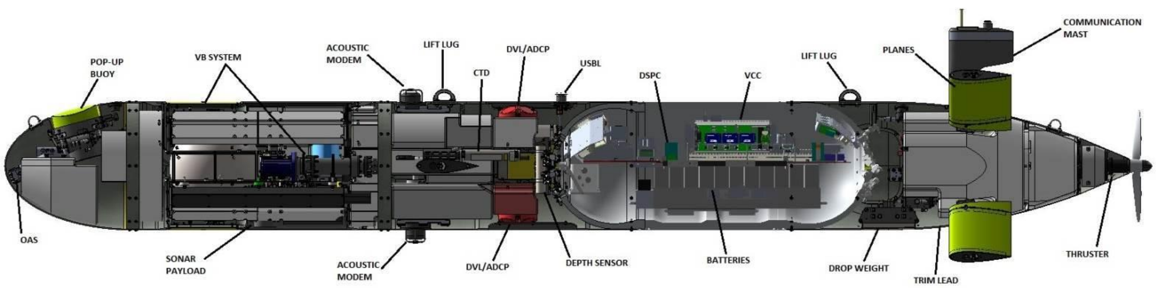


Figure 1.1: An Explorer-class AUV.

1.1.1 AUV Developmental History

The theoretical concept of AUV has been around for some time before the first AUV (Figure 1.2) was developed in 1957. The "Special Purpose Underwater Research Vehicle", or SPURV was built by Stan Murphy, Bob Francois, and later Terry Ewart of the University of Washington for specific purposes of studying submarine wakes, diffusion and acoustic transmission [(38)].

Figure 1.2: The first AUV, the Self-Propelled Underwater Research Vehicle (SPURV) developed by the University of Washington in the late 1950s.
Image downloaded from http://www.navaldrones.com/SPURV.html on June 2017.

In the 1970s, several academic institutions and military organisations started research and development in AUV technology. It was also during this period that the oil and gas industry started to show interest in deploying AUVs for development of offshore oil fields (39). Moving forward to the early 1980s, a global recession during this period slowed down AUV developmental efforts. When the economy gradually recovered, technological advances outside of the AUV domain such as miniaturization of computers and advances in software systems reinforced the developmental efforts of AUV technologies. By 1987, there were six operational AUVs and many others under construction (40), with AUVs moving closer to commercialisation. During the 1990s, many universities started to develop AUVs for academic research. By the turn of the millennium, technological maturity and market demands led to the emergence of AUV commercialisation, with the first AUV, a Hugin 3000 available for charter in the year 2000 (41). Since then, AUVs continued to evolve and are now capable of performing varied and diverse tasks, travelling longer duration and reaching deeper depths.

Today, there are more than 10 major companies that sell AUVs internationally, including Kongsberg Maritime, OceanServer Technology, Teledyne Gavia, Bluefin Robotics, Atlas Elektronik, ISE Ltd, JAMSTEC, ECA SA, SAAB Group, Falmouth Scientific, Tianjin Sublue and Tianjin Ostar. As AUV technologies continue to improve and capabilities expand, the AUV market is poised for almost certain future growth. The 2018 BCC Research market report highlighted the global market for AUVs reached USD $671.5 million in 2017 and forecast a compound annual growth rate of 4.5% to 2022 (42). This growth naturally translates to increase usage of AUVs and naturally, calls for more to be done in terms of risk control to promote safer AUV deployments.

1.1.2 AUV Types

AUVs constitute part of unmanned underwater vehicles (UUVs), a classification which also consists of remotely operated vehicles (ROVs) (Figure 1.3). While a ROV is controlled and powered through a series of cables from the surface, an AUV operates autonomously without human intervention, requiring minimal or no monitoring from a human operator.

Between the classifications of AUVs and ROVs lies Hybrid Remotely Operated Vehicles (HROVs), which are vehicles capable of operating in both untethered AUV and tether ROV mode. An example of HROV was *Nereus,* developed by Woods Hole Oceanographic Institution (WHOI) to explore depths of up to 11,000 metres (43). Examination of the AUV classification further reveals three sub-classes. The most common subclass, underwater gliders, are commonly used for oceanographic studies that require autonomous and long-term operations. Unlike the 'typical' AUV, underwater gliders have no thrusters or propellers, but rely entirely on buoyancy variation, internal mass distribution and ocean currents for motion. Its low speed translates to energy savings and ability to travel far distances over long periods, allowing oceanographic sampling in remote locations with reduced capital and labour costs. There is also other lesser known AUV sub-classes such as bottom crawlers, which are vehicles that crawl on the ocean floor for benthic sampling. The benthic rover, developed by Monterey Bay Aquarium Research Institute (MBARI) is an example of a bottom crawler which takes photographs and makes measurements on the community of organisms living in the seafloor sediment (44). In more recent development, there are biomimetic AUVs which mimics natural designs of underwater animals, such as the BOSS Manta Ray by EvoLogics (45) and AquaJelly by Festo (46). With the AUV market poised for almost certain future growth, more AUV types with specific capabilities are expected to be developed. Consequently, analysing risk of deployment becomes increasingly challenging, with the need of tailoring the analysis to both organisational requirements and specific AUV capabilities.

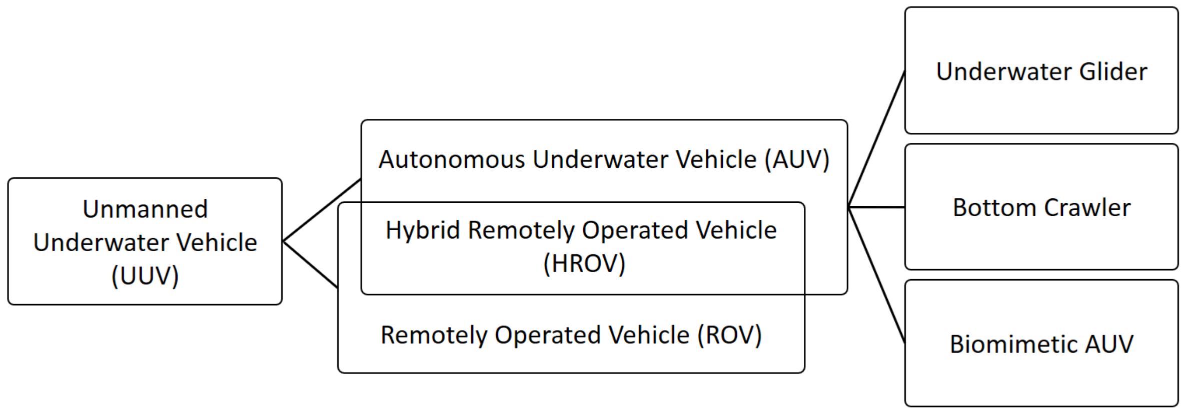


Figure 1.3: Some existing AUV types.

1.1.3 Applications

According to the latest 2018 market forecast by Westwood global energy group (47), the military sector is the greatest user of AUVs, accounting for 70% of the market. Research is the second largest sector, representing 25% while commercial sector accounts for 4%. AUVs perform myriad tasks in these sectors that to list them all would be nearly impossible and unnecessary. For a general overview of AUV's capabilities and to facilitate scoping of risk analysis, some of the common applications are listed in the following sections.

1.1.3.1 Military Applications

The military is one of the earliest adopters of AUV technology, leveraging on AUVs' ability to gather information or engage targets in areas inaccessible to traditional navy forces. Initially used for mine reconnaissance, they are now commonly used for intelligence, surveillance and reconnaissance (ISR), mine countermeasure missions, anti-submarine, clandestine payload delivery, inspection of ship hulls and ship husbandry [48].

1.1.3.2 Commercial Applications

The commercial usage of AUVs is currently predominated by the oil and gas industry, where they are widely used for surveying of drilling sites and pipe routes, as well as the inspection of pipelines and subsea infrastructure [49]. Increasingly, they are also applied in other areas such as the deployment and inspection of undersea cables, fisheries research, search and recovery, wreck and navigational hazard mapping, and water profile sampling [50].

1.1.3.3 Research Applications

The continuous drive for knowledge in the Earth's water bodies had resulted in a constant spur of new technologies and innovation for underwater data acquisition. AUVs especially, has become an attractive ocean research tool for bottom mapping, under-ice surveying, water column observations and more recently, physical sampling of water column, seabed [51] and even beneath ice-shelves [52]. Their versatility in payload allows a wide range of mapping sensors to be installed, such as side-scan sonar, mechanically scanned sonar, multibeam bathymetric sonar, laser-line scan imaging systems, still and video imaging, and sub-bottom profilers [37]. Water column measurements include dissolved oxygen, temperature, pH, turbidity, salinity, chlorophyll fluorescence, optical backscatter and water velocity [37] [53]. AUVs can also be used as mobile acoustic arrays or mobile sources for acoustic tomography [37]. Additionally, specialized instruments such as magnetometers, gravimeters, specific chemical sensors can be deployed on an AUV [54–56]. The data collected supports the furtherance of knowledge across a wide range of scientific disciplines, such as oceanography, limnology, hydrography, archaeology and marine ecology. Herein, the focus of this dissertation lies in the use of AUVs for research activities in the Antarctic.

1.1.4 A Typical AUV Program

An understanding of the AUV program is essential to account for time-dependent risk factors associated with an Antarctic AUV program. These factors that can cause or culminate in the loss of an AUV during deployment in the Antarctic reside in different phases of an AUV program. For example, poor scope definition, over-design, poor budgeting and scope creep during pre-operational phases can have a downstream impact on the risk of AUV loss during later Antarctic deployment. Subsequent sections present a brief overview of a general AUV program (Figure 1.4), although, it must be recognised that the actual program will vary according to context and circumstances.

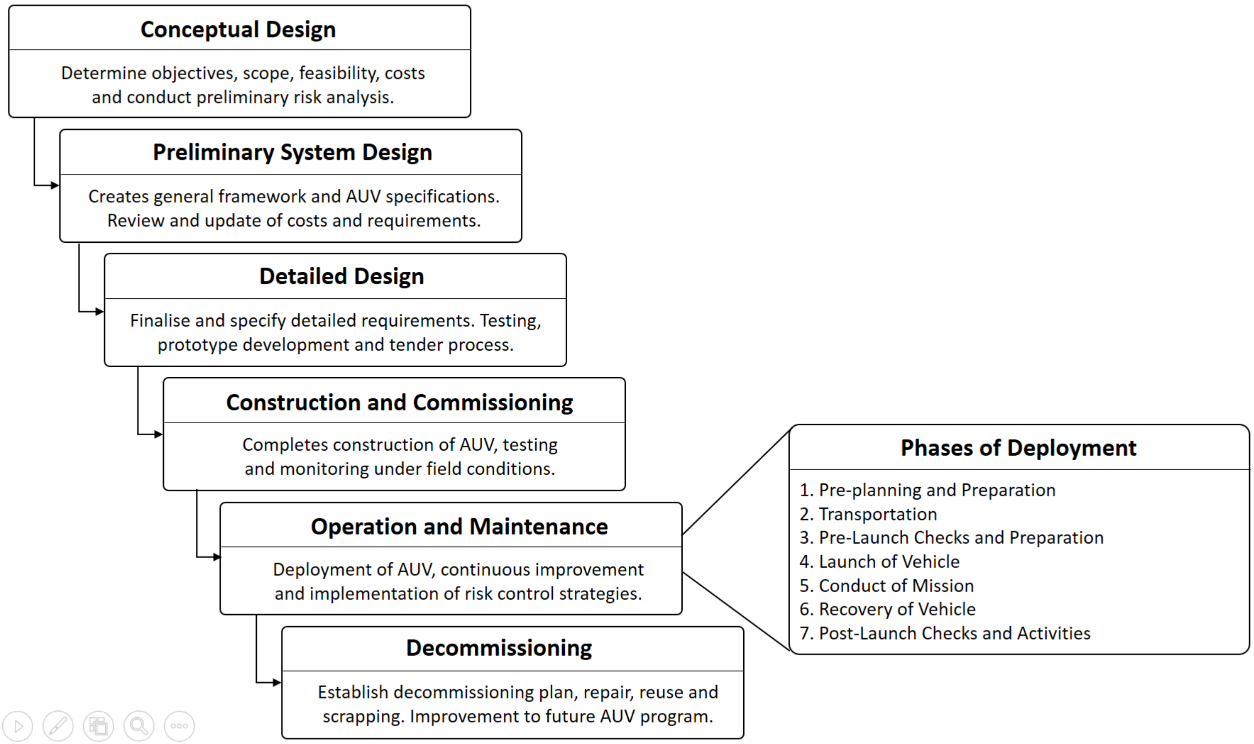


Figure 1.4: Overview of a general AUV program, adapted from [2][3].

1.1.4.1 Conceptual Design

During this initial phase, objectives, scope and feasibility of the program are determined. The overall program costs are usually estimated based on the planned operational requirements, evaluation of available technology and the availability of commercial solutions. Preliminary risk analysis will be usually carried out based on the knowledge and experiences of the AUV team, with an acceptable level of risk established by the AUV owner. Decisions made at this phase may have a significant impact on the risk of AUV loss later in the program. For example, poor scope definition, inaccurate estimates of program budget and poor analysis of risks can lead to excessively optimistic implementation resulting in a higher risk of loss.

1.1.4.2 Preliminary System Design

This phase focuses on creating the general framework of the AUV program, with the establishment of the AUV's specifications without excessive technical details. Some examples of specifications are; the required transit distance, submerged duration, dive depths, scientific payloads and optional payloads, timeline and post-purchase support requirements. After the confirmation of operations concept and technical specifications, a review and update of costs and resource requirements are carried out. A comprehensive risk analysis with an outline of risk control measures and procedures are further conducted to ensure that an acceptable level of risk can be achieved in the AUV program. Possible risk factors in this phase associated with loss of AUV include over-design, scope creep and poor constructability.

1.1.4.3 Detailed Design

This phase specifies and finalises the detailed requirements for implementation of the AUV program, and construction of the AUV. Additionally, design drawings are created to guide the construction of the AUV and the facilities required to support the AUV. This phase also includes the testing of components, development of prototype models, tender evaluation and refinement of tender specifications. Relevant regulatory and expediting requirements are also considered in preparation for the commissioning of the vehicle. One of the main risk factor in this phase which can have a significant impact on the risk of AUV loss lies in poor procurement practices, such as an ineffective evaluation process in the selection of AUV manufacturer.

1.1.4.4 Construction and Commissioning

AUV components are brought together during this phase for construction of the AUV, may it be in-house or external. Periodic inspection of the AUV during this phase is vital to ensure relevant standards and requirements are met and that the components are fit for purpose. The utilisation and allocation of resources are to be reviewed and updated at this stage to control construction time, cost and quality of the AUV. Prior to commissioning, various tests such as field tests, acceptance tests, operational system tests and system assessment are carried out. The construction and commissioning phase can be plagued with risks of delays and quality issues, influencing the risk of loss both indirectly and directly.

Shortly after commissioning, the AUV team continues to monitor the vehicle and systems under field conditions. Potential risk factors which are overlooked or undetected in the earlier phases are identified and analysed.

1.1.4.5 Operation and Maintenance

During this phase, the AUV is deployed into the field for its intended data acquisition. In a typical mission, an AUV is transported to the intended site after the initial pre-planning and preparation for deployment. This includes determining and specifying mission planning, risk controls, recovery strategies, resource requirements and mission logistics. Prior to conduct of the mission, pre-launch checks are performed, and mission parameters uploaded. The AUV is then launched from an appropriate support platform; vessel, shore or submarine before it follows a pre-programmed path to a designated location. Upon arrival at its target location, the intended underwater data acquisition is performed over a predetermined period before the AUV returns to a rendezvous position to be retrieved. After retrieval, a set of post-launch checks and activities will be performed, such as cleaning and data download. As a good practice, information on the AUV's performance and incidents are documented and used as feedback for continuous improvement of future deployments. Additionally, corrective, preventive and predictive maintenance are usually carried out with due diligence to ensure that the AUV maintains a certain level of availability and prolong service life.

Some risk control strategies commonly implemented in this phase involves the establishment of planned maintenance routines, operating instructions, safe work procedures, management of change and roles and responsibilities. Regular review on resource (human, material and equipment) requirements, availability of the AUV, and outputs from the program are pivotal for the long-term sustainability of the AUV program. A learning from incident process ensures continuous improvement with management made aware of significant incidents and risks. Periodic audits are carried out to determine whether the AUV program conforms to the pre-established requirements and identify gaps in the system for rectification.

1.1.4.6 Decommissioning

While not directly influencing the risk of AUV loss for the existing AUV, appropriate decommissioning is valuable for reducing risks of future AUV programs and maximise the return of investment. An AUV which cannot be utilised any more due to their obsolescence or being beyond economical repair will be decommissioned. A detailed decommissioning plan describes the schedule of decommissioning activities, regulatory considerations and the required resources to carry out the process. Useful parts of the AUV are salvaged and the others scrapped.

Observations and review during the decommissioning process are documented and used as feedback for improvement of future AUV programs. This may include areas of unexpected deterioration, over-design, integrity of upgrades and repairs, reliability of a specific component, hull material selection and effectiveness of corrosion monitoring.

1.2 DEPLOYMENT OF AUVS IN THE ANTARCTIC

The harsh Antarctic environment is irrefutably one of the main contributory factor in the higher risk of AUV loss as compared to other benign environment such as inland lakes and lagoons. To facilitate subsequent analysis of risks, it is useful to have an appreciation on the background and challenges involved in an Antarctic AUV deployment, as presented in the following sections.

1.2.1 The Antarctic – A Brief Background

The term "Antarctic" meant "Opposite of the Arctic" is defined by different boundaries but most commonly by the Antarctic Circle or the Antarctic Polar Frontal Zone (Figure 1.5). The Antarctic Circle, which separates the Antarctic and the Southern Temperate Zone currently runs at a latitude of 66.3^{o}. It is defined by places where the sun is above the horizon for 24 continuous hours and below the horizon for a continuous 24 hours at least once a year. The Antarctic Circle accounts for approximately 4% of Earth's surface with most of the area within covered by the continent of Antarctica.

The Antarctic polar frontal zone or Antarctic Convergence is a circular belt of water where cold, northward-flowing Antarctic waters meet the relatively warmer waters of the subantarctic. The Antarctic waters predominantly sink beneath subantarctic waters, while associated zones of mixing and upwelling create a zone high in marine productivity, especially for Antarctic krill. This zone encircles Antarctica, varies slightly seasonally and creates a natural boundary which defines the Antarctic region.

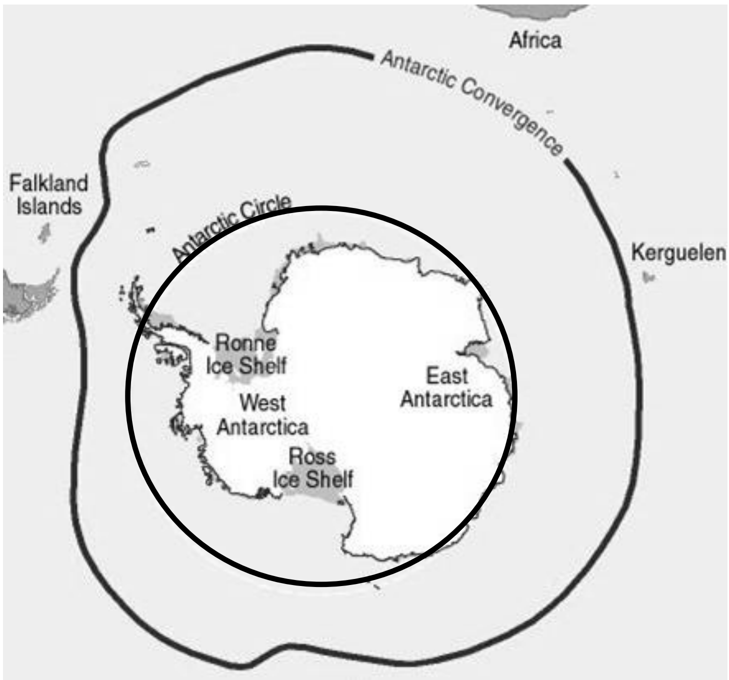


Figure 1.5: The Antarctic Circle and the Antarctic Polar Frontal Zone.

The first Antarctic island, South Georgia, was discovered in the year 1675 [57] with the continent of Antarctica eluding explorers and remained purely speculative for many more years. It was not until 1820, that Russian explorers Fabian Gottlieb von Bellingshausen and Mikhail Lazarev officially sighted and discovered Antarctica [58]. The early 1900s saw the mounting of several Antarctic expeditions which resulted in territorial claims in Antarctica, with the largest area claimed by Australia. With increasing interest in the Antarctic, the first permanent research station in Antarctica, Mawson station was established by Australia in 1954.

By the end of the 20th century, intensive scientific and geographic exploration began in the Antarctic region with various expeditions launched from different countries. Since then, the pristine environment of the Antarctic continues to interest researchers and captivate the world's imagination, drawing people from around the globe to the region. Today, seven countries; Argentina, Australia, Chile, France, New Zealand, Norway and the United Kingdom had made territorial claims to parts of Antarctica; some overlapping (Figure 1.6).

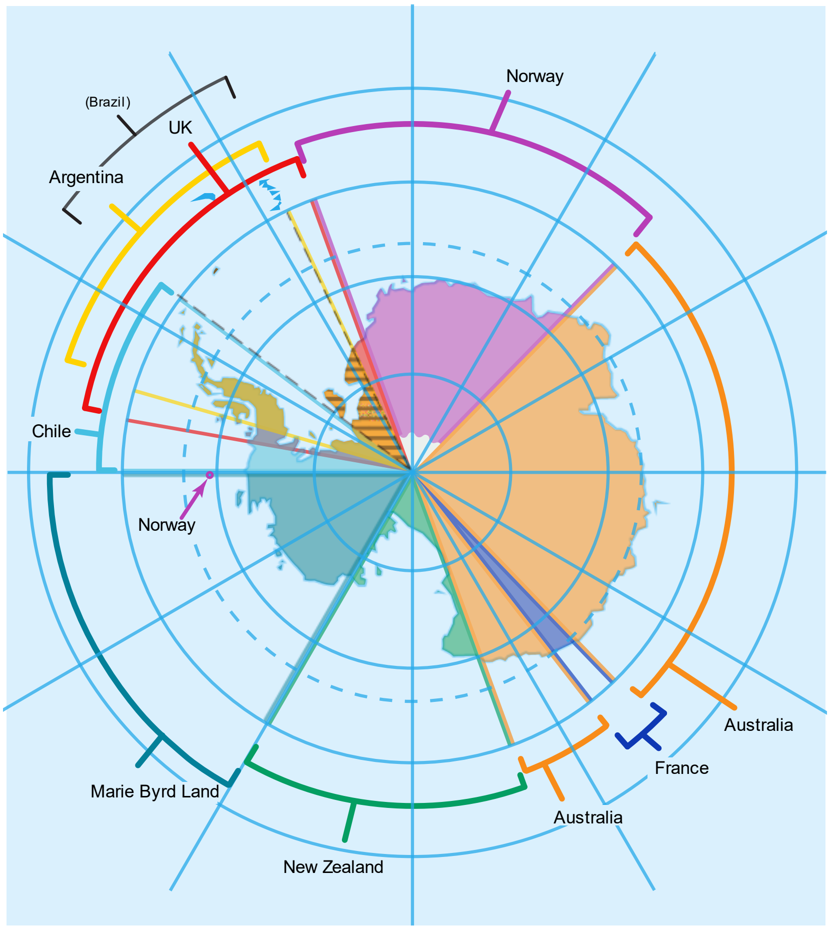


Figure 1.6: Territorial claims in Antarctica.

Image downloaded from https://en.wikipedia.org/wiki/Territorial_claims_in_Antarctica#/media/File:Antarctica,_territorial_claims_including_Brazil.svg on June 2018.

1.2.2 Governance

The Antarctic is an area unique not only in its geophysical qualities but also its governance. Early disputes over territorial claims eventually led to the signing of the Antarctic Treaty signed 1959 [(59)], and the other subsequent treaties. At present, the Antarctic Treaty System, which comprises four major international agreements, forms the basis for governance of the Antarctic. These agreements are; the 1959 Antarctic Treaty, the 1972 Convention for the Conservation of Antarctic Seals, the 1980

Convention on the Conservation of Antarctic Marine Living Resources and the 1991 Protocol on Environmental Protection to the Antarctic Treaty.

The main Antarctic Treaty, originally signed by 12 nations, applies to all area south of 60° latitudes to ensure the following:

> *"in the interest of all mankind that Antarctica shall continue forever to be used exclusively for peaceful purposes and shall not become the scene or object of international discord."*

To this end, the treaty moves beyond the doctrine of territorial states by prohibiting military activities and the rights of sovereignty in Antarctica. It promotes freedom of scientific research, exchange of information and holds all territorial claims in abeyance.

As for the maritime areas, jurisdiction is usually vested in the coastal state adjacent to those areas as prescribed by the United Nations Convention on the Law of the Sea (UNCLOS) (60). This definition, however, gave rise to several contentious issues for the Antarctic. First, UNCLOS only came into force in 1994 and any sea claims off the Antarctic territory contradicts the Antarctic Treaty 1959, which states that no new claims are permitted. Second, UNCLOS determines maritime zones based on the low-water line along the coast. For the Antarctic, the area where land meets the sea is frequently covered in thick ice so accurately establishing the low-water line is a challenge. Last, while territorial claims may be accepted by other countries, there is no requirement for them to recognise their validity. At present, all parties are restrained from having conflicts over these contentious issues while there is no imperative to change the legal status quo. However, governance of the Antarctic remains an area vulnerable to conflict and exploitation, comparable to the international space law for space exploration. Therefore, it plays a subtle yet pivotal role in influencing decision-making of AUV deployments, such as the choice of deployment location and potential liabilities in the event of loss. It is therefore, fair to say that governance of the Antarctic sets the context for the analysis of risk, directly and indirectly affecting the risk of AUV loss. Interested readers are therefore encouraged to refer to (61) for further details on the law governing AUV operations in the Antarctic.

1.2.3 Research Value

Trading off the risk of AUV loss are the values in Antarctic research. The uniqueness of the Antarctic offers a vast amount of intrinsic scientific information across a wide range of scientific disciplines, offering insights from Earth's climate system to human biology. This is evident from the quantity and diversity of new scientific discoveries emerged from the International Polar Year of 2007 to 2008. With the participation of more than 60 countries, the myriad new information ranges from climate system (62) to social processes (63) and human health (64).

In particular, it is critically important to understand the impact of climate change on the Antarctic because of its contribution to global sea-level rise and its role in regulating the world's climate system [65]. The warming of the Antarctic has caused changes to both its physical and living environment. Noticeably, many glaciers have retreated, and ice shelves broke off and collapsed in recent decades. Under Antarctic's ice, increasingly warm waters have caused underwater melt-off, which is a growing source of concern for the global sea-level rise [66]. This has also affected marine biodiversity, with changes to the seafloor ecosystem and the decline of Antarctic krill stocks [67]. To this end, further research of the Antarctic will enable better future climate predictions and allow policymakers to make informed decisions about climate change.

Beyond planet Earth, the Antarctic also offers a glimpse and often used as an analogue for other similar icy worlds such as that of Jupiter's moon Europa, Saturn's moons Enceladus and Titan, and even Neptune's moon Triton [68].

1.2.4 AUVs in the Antarctic, Advantages and Challenges

When the first AUV, the Unmanned Arctic Research Submersible (UARS) vehicle was deployed under Arctic's ice in 1972, it demonstrated not only the feasibility, but also future potentials of AUVs in the Antarctic. The use of AUVs has several advantages over traditional data collection means such as visual observations, drilling from above the ice, ROVs or the use of ice-breaking vessels [21]. It has the ability to access remote locations autonomously which was previously inaccessible, such as under ice shelves. Additionally, operating underwater also mean that AUVs are generally unconstrained by the vagaries of Antarctic's weather, although that can still impact the launch and recovery of the vehicle. Other advantages include AUV's versatility with customizable payloads, higher efficiency, improved quality of data collection and potentially lower costs of operations [2].

However, the deployment of AUV in the Antarctic is far from an easy undertaking. The remoteness, coupled with a limited summer field season meant that logistical, financial and operational challenges are ever-present. Additional considerations are also needed to account for ice cover, inaccessibility and emergency abort procedures during missions. Exacerbating the problem is the dynamic and harsh Antarctic environment: Temperature so cold that it freezes exposed skin, whiteout conditions which reduces visibility to inches, hurricane force katabatic winds and months of winter darkness, just to name but a few. Early Antarctic explorers offer a glimpsed of the hardships while working in the Antarctic through their written journals. One of those, written in 1912 by explorer Robert Falcon Scott [69] reads:

"It fell below -40° in the night, and this morning it took 1½ hours to get our foot gear on, but we got away before eight."

Today, technological and medicinal advancements together with permanent research stations have improved accessibility and safety for researchers in the Antarctic. However, the harsh environment continues to challenge on-site AUV personnel both physiologically and psychologically (22), increasing the likelihood of human error during deployment. The condition underwater is no better. Water turbidity, changes in water density and strong currents can affect sensors and navigation of an AUV. Underwater communication itself is subjected to propagation delays, limited ranges, relatively low bandwidth and limited data transfer rates (70)(37). Additionally, the southerly latitude affects navigation and ice-cover prevents surfacing of vehicle during an emergency.

Previous risk analysis of *Autosub 3* AUV showed the median probability of AUV loss for under sea-ice missions to be 4.9 times higher than that of open water missions (71). Risk of loss for under ice-shelf missions is even higher, with the median probability 9.4 times higher than open water missions (71). To this end, AUV owners also face another contentious issue pertaining to the uncertainty of the legal status of an AUV. The autonomous nature of AUVs resulted in ambiguity of whether an AUV should be classified as a 'ship', and this has legal implications in circumstances of loss, such as collision, salvage or incidents in foreign water (61). The uniqueness of governance in the Antarctic exacerbates the problem further with the lack of clarity. These challenges, together with the remoteness and adoption of the Antarctic treaty has so far suppressed commercial and economic motivation in the Antarctic, although the same cannot be said for the future. Thus far, only a few AUVs have been documented to have conducted research activities in the Antarctic, as presented in Table 1.1. As a result, there are very limited available risk studies of AUV deployment to the Antarctic.

Table 1.1: Documented AUVs deployed for research activities in the Antarctic (Excluding gliders).

AUV	***Built***
Odyssey I	*1992*
Tadpole	*1992*
Autosub 2	*2000*
Autosub 3	*2005*
Autosub 6000	*2006-7*
Seabed (Puma)	*2007*
Seabed (Jaguar)	*2007*
UBC Gavia	*2010*
Autosub Long Range	*2010-11*
Explorer (nupiri muka)	*2017*

1.2.5 Incidents of AUV Loss in the Antarctic

Despite the paucity of risk studies and historical data, some reports on the loss of AUV in the Antarctic are publicly available. In 1993, Tadpole, an AUV operated by the Institute of Antarctic and Southern Ocean Studies, Australia, was one of the first reported loss in the Antarctic (72). Modified from an actual torpedo, the AUV failed to return from its second mission after deviating from its intended course (72).

Another loss was that of *Autosub2*, an AUV developed and owned by the National Oceanography Centre, Southampton, United Kingdom. The AUV was lost in 2005 under the Fimbulisen ice-shelf with unknown exact cause of loss [(2)]. A subsequent board of inquiry established that the cause of *Autosub2* loss was most likely to be due to a fault introduced during the manufacturing/assembly phase [(32)]. Although the direct cause of loss was determined to be due to technical failure, organisational issues were also highlighted in the loss report. For example, there is little documented information on any prior risk assessment made for *Autosub2* and the setting of risk acceptance criteria as well as approach to management of risks in projects was found to be inadequate [(32)]. Seaglider SG522, owned by the University of East Anglia, United Kingdom, was lost at the Weddell Sea in the Antarctic in 2012. The subsequent inquiry panel concluded that an erroneous command script placed Seaglider SG522 in an unsafe state which eventually resulted in its loss [(73)]. While the loss can be attributed to human error, it reveals other systemic issues such as the lack of pilot training and software design [(73)]. Anecdotal evidence also exists for other near-miss incidents which could have potentially resulted in a loss in the Antarctic, such as the Seabed AUV [(74)] although these were never formally reported.

The loss of both *Autosub 2* and Seaglider SG522 provided an indication that systemic issues played a role and any analysis of risk should be sufficiently holistic to consider these issues. Otherwise, the lack of publicly available investigation reports on AUV loss makes it challenging to pinpoint the exact commonalities between these incidents. The difficulty in recovering loss AUVs in the Antarctic environment for direct examination only further exacerbates the problem. This lack of systematic and regular data for AUV deployment, especially for missions in the Antarctic requires a tailored approach for analysis of risk. One which can cope with the lack of or non-existent data and account for uncertainties in the Antarctic AUV program.

1.3 RISK OF AUV LOSS DURING ANTARCTIC DEPLOYMENT

The risk of AUV loss refers to the likelihood that, during a mission, an AUV will be rendered unusable for future missions. This can represent either a complete loss, or an AUV being destroyed or damaged beyond economic repair. The loss of an AUV during deployment in the Antarctic can have several adverse consequences. This includes higher insurance premiums for the AUV community, delay to research projects, damage to the reputation of the AUV community, loss of valuable research data and a possibility of harming the delicate Antarctic environment [(2)]. It is therefore imperative that risk of loss be analysed and managed effectively prior to deployment of AUV to the Antarctic. The next few sections present the relevant fundamental concepts necessary for analysing risk, with additional information provided in appropriate references.

1.3.1 Definition of Risk

Although risk pervades in all forms of human activities, it was only in the last few centuries that significant theoretical and empirical advances on the subject of risk have been made. Consequently, many different definitions for risk had been proposed. Most early definitions of risk simply refer it as the likelihood of an adverse event (consequence) occurring. However, contrary this common perception, risk does not always represent negative outcomes. It also encompasses positive risk, which are opportunities that have a positive impact on the objectives. For instance, a change of government policy leading to increase funding in Antarctic research programs or a change in legislation leading to fewer restrictions in Antarctic AUV deployments. This presents a positive risk for an AUV owner who may fail to leverage on the opportunity. In 1995, the Australian and New Zealand standard on risk management AS/NZS4360 extended the definition to include both positive and negative events (75). In the latest edition published in 2004, risk is defined as:

"*The chance of something happening that will have an impact on objectives.*"

This dual view of risk gradually gained wide acceptance and led to the development of ISO 31000 in 2009, the first global standard on risk management (13). In this commonly used standard, risk is defined as:

"The effect of uncertainty on objectives."

Here, effect refers to a deviation from the expected and uncertainty results from a deficiency of information, understanding or knowledge of an event, its consequences or likelihood (13). This definition will be adopted for the remainder of this thesis.

1.3.2 Origins of Risk

Risk arises from uncertainty about the future. An outcome which is certain to happen has no risk associated with it. If a specific component of an AUV will surely fail after exactly five years of service, then there is no risk because the exact moment of failure is known. Uncertainties are therefore future outcomes that are unknown or known only to a certain degree of precision. They are also dynamic in nature, evolving with time with the in-flow of information.

There are numerous causes of uncertainty and one of the most conventional and common distinctions categorises uncertainties into two different types, aleatory and epistemic. (Figure 1.7)

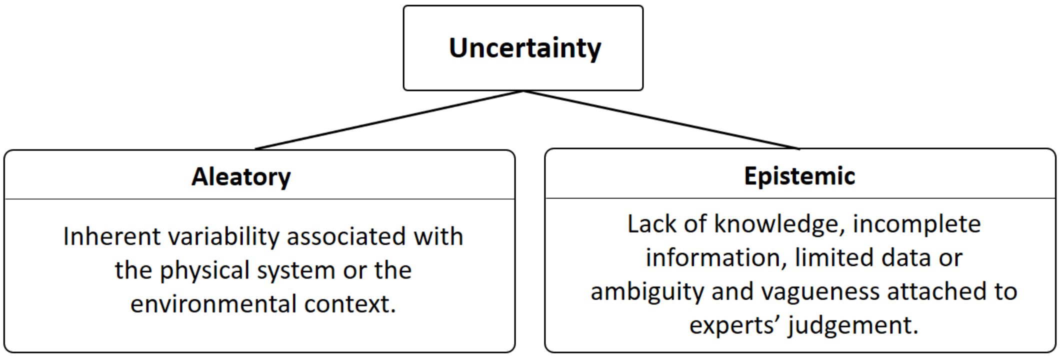


Figure 1.7: Two main types of uncertainties.

Aleatory uncertainty, also known as irreducible uncertainty, are variations associated with a physical system of environmental context [76]. AUV component failures and environmental variables such as weather condition falls within this category. For example, despite knowing the Mean Time Between Failure (MTBF) for a specific AUV component, the precise moment of component failure is still never certain.

Epistemic uncertainties, also known as reducible uncertainty, exists due to a lack of knowledge, incomplete information, limited data or ambiguity and vagueness attached to experts' judgement [76]. An AUV which has yet to be commissioned or relatively new in operation will have a higher level of risk arising from epistemic uncertainties. With the operation of the AUV over time, the inflow of information and gaining of experience will result in a gradual reduction of epistemic uncertainties (Figure 1.8). Although generic data from other AUVs can be used as a reference to reduce epistemic uncertainties, the difference in specifications, manufacturers, design and systems can result in inaccurate risk analysis outcomes. Organisational risk management systems are often designed in attempt to identify and reduce epistemic uncertainties because they may be characterised statistically [76] with time and effort.

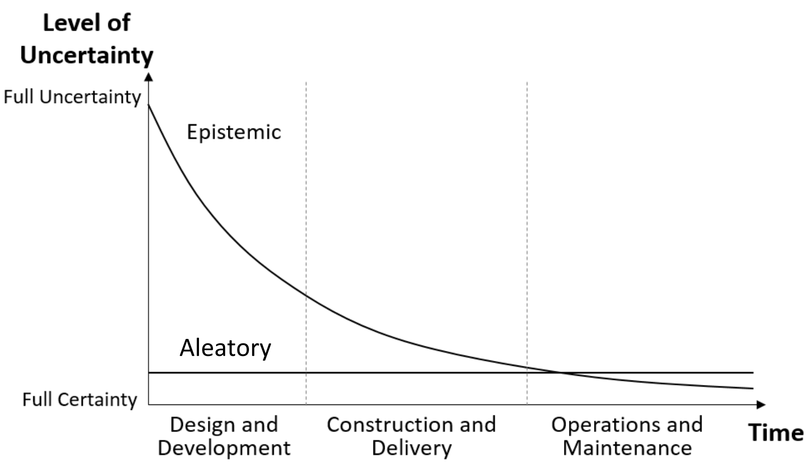


Figure 1.8: The level of epistemic and aleatory uncertainties throughout an AUV program lifecycle.

Probabilistic approaches are often applied to assess both aleatory and epistemic uncertainties, typically the relative-frequency approach for the former and the subjective probability approach for the latter (77). As a result, there are many established probabilistic methodologies such as Monte Carlo simulation or Bayesian Belief Networks used for the assessment of risk (77). For handling the vagueness and ambiguity of risk analysis, a fuzzy-based approach is still the method of choice (78)(79)(80), although the use of interval probabilities may also provide a solution (81).

1.3.3 Definition of Risk Analysis

It is irrefutable that the intent of performing a risk analysis is to enhance the ability of an organisation to achieve its objectives. However, debate exists over the precise definition for the term "Risk analysis", particularly in reference to the scope of activities it encompasses. The term "Risk analysis", often used synonymously or interchangeably with "Risk assessment", is also frequently confused with terms such as "Risk estimation", "Risk Characterization" or "Risk Evaluation". Despite the somewhat equivocal definition for risk analysis, most would agree that it generally refers to the process of examination, judgement and evaluation of risk, under given circumstances. For the purpose of this dissertation, a broad definition based on the Society of Risk Analysis (SRA) is adopted (9). The SRA defines risk analysis as a:

"Systematic process to comprehend the nature of risk and to express the risk, with the available knowledge"

This 'process' stated in the definition refers to risk assessment, risk characterization, risk communication, risk management, and policy relating to risk, under a range of different contexts (9).

1.3.4 Risk Analysis Methods

Over years of development, myriad risk analysis methodologies have been proposed in adaptation to different systems, industry, environments, components or stages of processes. There is no single method that suits all needs and most organisations adopt multiple methods for analysis of risk. The choice of method usually depends on a variety of factors, such as the purpose of analysis, nature of risk, and the availability and quality of data. Results from analysis of risk are used to inform decision-makers on the types of response required, which generally falls into five main actions; transfer, tolerate, treat, terminate or leverage on the opportunity. Additionally, leverage points and leading indicators can be identified for risk monitoring and risk control recommendations.

The most common analysis of risk uses either quantitative or qualitative means to measure the combination of magnitude of potential consequences and the likelihood of these consequences occurring:

Risk (Expected) = Likelihood (Consequence) x Magnitude (Consequence)

Stemming from this formulation was arguably the most widespread tool used for evaluating risk, the risk matrix. Despite its flexible and ease of use, the risk matrix is limited by a strict interpretation of risk level based on risk rating number. This sharply fixed boundaries between risk ratings is further discussed in Chapter 2.

Even with the use of a risk matrix, calculating an accurate risk level is usually far from straightforward. One of the difficulties lies in quantifying the magnitude of potential consequences. While the loss of an AUV can be measured financially in dollars, other impacts such as delays to research projects or damage to reputation can be difficult to quantify accurately. Estimating the likelihood of consequences occurring can be even more challenging due to uncertainties. For example, the potential consequence of an AUV losing communication far under an ice shelf is the complete loss of the vehicle. However, it is hard to estimate the exact probability of an AUV losing communication while under an ice-shelf, which can be due to a wide variety of reasons, from modem failure to noise disturbance. Therefore, it came as no surprise that simply using the risk matrix to characterise risk often produce unrealistic estimate of risk level, impacting the quality of decisions made based on the estimate [(82)]. As a result, myriad methods were developed over the years in attempt to improve the analysis of risk. These methods can be broadly grouped into three categories based on outputs of the analysis: qualitative, quantitative and semi-quantitative.

Qualitative risk analysis first requires risk factors to be identified before classifying them subjectively into descriptive categories of risk levels such as ‘minor’, ‘moderate’ or ‘major’. Results from the analysis are usually used to set priorities for the next course of actions, including further analysis, either semi-quantitatively or quantitatively. Qualitative risk analysis methods offer many advantages such as simplicity, ability to handle a greater range of uncertainty due to lack of information, and time-saving [(83)]. Not surprisingly, they received widespread adoption across industries and disciplinary boundaries. However, qualitative risk analysis methods also suffer from several limitations such as the lack of accuracy, high inherent subjectiveness and low discriminatory power.

Semi-quantitative risk analysis aims to establish ranking of risks against a quantification, to determine the order of priority for the next course of actions. It analyses risk using an indicator value rather than explicit probability or other measurable units. For instance, the risk matrix adopted by many organisations uses a score of 1 – 5 as a representation of likelihood and magnitude of consequences, where 1 may refer to rare likelihood or insignificant consequences and 5 refer to almost certain likelihood and catastrophic consequence. Although falling short of a comprehensive quantitative risk analysis, they are more rigorous than qualitative methods, providing more refined and precise estimates of risk level.

Quantitative risk analysis (QRA) aims to assign a set of measurable, objective data to determine the risk level, which is usually the probability of risk occurrence. Especially well-suited for situations where quality data is available, QRA methods are effective in handling typically random failures and/or unorganized complexity within a system [84]. With the ability to quantify risk instead of analysing risk in relative terms, it overcomes many limitations of qualitative and semi-quantitative methods. Although QRA methods are typically more time intensive and require additional effort to apply, there are many advantages to outweigh the associated effort and costs. First, QRA allows the complex interactions between risk factors within a system to be accounted for [85]. Second, QRA recognises the need for contributions from diverse disciplines in the analysis of risk [85]. Lastly, QRA enhance the completeness of the analysis by providing an in-depth understanding of potential failure modes, thus providing valuable inputs for decision making [85]. There are many examples of QRA approaches, such as:

- Bayesian Belief Network (*BBN*), which uses graphical statistical model used to describe probabilistic dependencies between random variables [86].
- Markov Analysis, which uses models to represents possible chains of events to forecast the activity of a random variable at a given point in time based on current circumstances.
- Monte Carlo Simulation (MCS), which generates random numbers for inherently uncertain factors, resulting in a probability distribution of all possible outcomes [87].
- Artificial Neural Networks (ANN), which acquires, represents and compute a mapping from one multivariate space of information to another through an adaptive multi-layered connected neural net [88].
- Genetic Algorithms (GA), which is adaptive in nature and inspired by the process of natural selection to derive solutions and solve optimization problems [89].
- Petri Nets, which is uses both graphical and mathematical approach to model logical interactions and the dynamics of complex systems [90].

An attempt to review all risk analysis methods within these three categories is beyond the scope of this dissertation and unnecessary as many of them are very similar. Interested readers are therefore referred to Appendix B for examples of risk analysis methods within each of these categories, many of which, have been previously applied in the AUV domain.

1.3.5 Risk Analysis of AUV Deployment

Being a relatively new domain, there is a paucity of literature on risk analysis of AUV operations. Herein, key relevant literature on risk analysis of AUV operations are reviewed and presented.

Most early AUV literature on risk had focus skewed towards improving technical reliability, with efforts centred around the prevention of technical failures. However, some risk studies provided an early indication that the broader aspect of risk may be an area that requires further attention. Griffiths et al. [91] initiated one of the earliest quantitative risk analysis of AUV deployment. Using statistical models on historical fault logs of Autosub AUV, the study estimated that the mean number of missions to failure under an ice shelf to be 53, or 0.27 *faults per mission*. Although this figure may not hold much relevance to other AUVs types or in today’s context, several pertinent issues were highlighted. First, a high incidence of human error was observed, possibly due to an overstretched team. Second, higher fault incidence was observed during overseas deployments, which may be a result of time pressure and a shift in risk tolerance. Last, the introduction of new software can lead to a temporary decrease in reliability. This reduction in reliability as an effect of upgrades was also noted in a separate study [(92)], indicating that effective management of change may be important in ensuring reliability of an AUV. Chance [(93)] analysed the trend of availability for a C–Surveyor AUV over two years and 24,000 km of use. An increase in availability was observed to correlate with the amount of operating experience possessed by the AUV team. Another observation of the study, was a temporary reduction in availability whenever modifications were made to the vehicle, similar to that previously described by Griffiths et al. [(91)(92)]. Manley [(94)] performed a qualitative risk analysis on the development and deployment of AUVs, which includes not only technical risks but also operational risks. Technical risk, which encompasses both software and hardware failure, arises from the complexity of AUV systems and challenges of undersea operations. Operational risk, arises from three main areas; First, physical deployment processes such as launch and recovery of the vehicle. Second, ambiguity in regulatory aspects of AUV operations. Last, legal risk and liability of AUV operators. Interestingly, the author noted that at the point of writing, underwriters considered operational risks to be a major concern as compared to technical risks. In conclusion, Manley emphasised the role of organisational factors in managing both technical and operational risks of AUV deployment. A thorough evaluation of the AUV program's goals, objectives, budget, anticipated needs and existing situation was therefore, recommended for the effective management of risks.

As AUV technology gradually makes the transition from research and development to operations, Griffiths and Trembanis [(2)] recognised the need for a more proactive and systematic risk management framework to better support AUV owners in decision making. The proposed framework begins with the establishment of a risk acceptance level by the AUV owner and setting of campaign requirements. In the next step, the technical team has to exercise judgement in assessing the vehicle's historical performance, to determine the impact level of each documented fault. A probability of loss is then derived quantitatively using Weibull distribution and Kaplan Meier estimator. Based on the calculated probability of loss, a decision can be made on whether to proceed with the campaign or implement additional measures to improve survivability. (Figure 1.9)

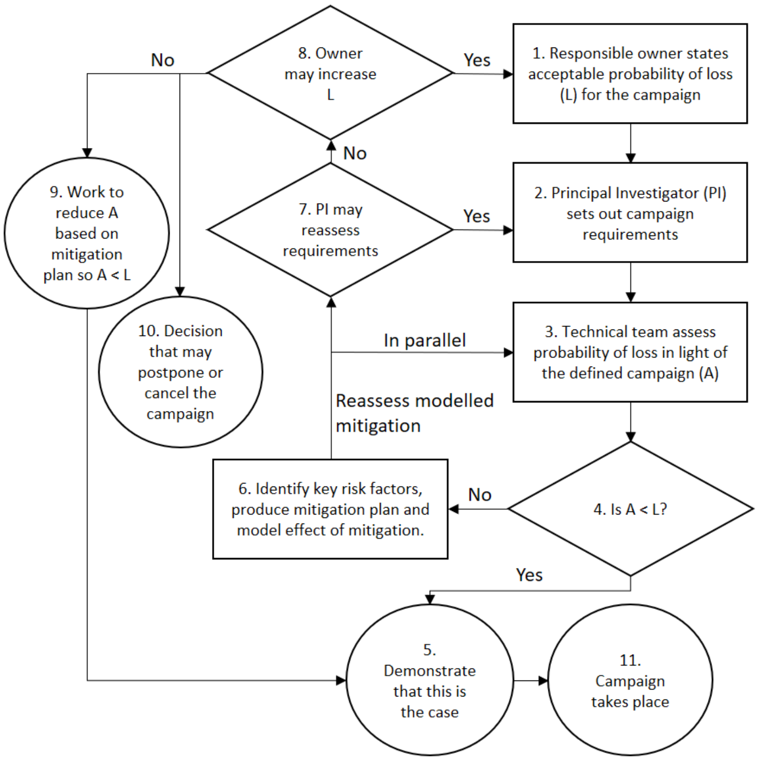


Figure 1.9: Risk management process for AUV operations, presented by Griffiths and Trembanis [2]. (Permission granted to reproduce)

The realisation that expert judgement plays a vital role in analysing risks of AUV deployments necessitates the need for a systematic and structured elicitation procedure. Brito et al. [71] performed a quantitative risk analysis to estimate the probability of loss under four operating environment; Open water, coastal, sea ice and ice shelf. Experts' assessment of historical faults were elicited, aggregated using linear opinion pool and clustered according to optimistic and pessimistic views. An extended Kaplan-Meier estimator was then applied on the experts' assessment and frequentist probability of fault occurrence to predict the probability of loss. Using a forthcoming Autosub 3 AUV campaign at the Antarctic as a case study, the probability of loss was found to be in the range of 0.26 to 0.96 for four under ice-shelf operating scenarios. As this exceeds the risk acceptance limits defined by the AUV owner, a series of risk mitigation measures were subsequently implemented. This included fault rectification, preventing entanglement of recovery lines with propeller, use of penetrators for critical connections and having a pre-defined distance for monitoring the AUV's performance prior to start of a mission. The similar elicitation procedure was applied in the reliability analysis of two Remus-100 AUVs [95]. In the Remus AUV study, a recommendation was made for the use of behavioural aggregation instead of mathematical aggregation to minimise the intrusion of bias during the elicitation process. This recommendation was subsequently adopted and demonstrated to improve the accuracy of a risk analysis [96].

As AUV technologies continue to refine with improving reliability, risk analysis gradually broadens from analysing historical performance of a vehicle to other operating uncertainties and phases of deployment. Griffiths and Brito [97] extended their earlier risk studies on the Autosub AUV program to account for sea-ice conditions and support vessels of differing ice capabilities. The use of Bayesian belief networks (BBN) was explored, and a risk model established based on expert judgement, past sea ice data, probability distributions of ice thickness and concentration, and ships of differing ice capabilities. BBN uses probabilistic dependencies between random variables, represented as a set of interconnected nodes representing variables and the causal relationships between them to solve complex problems [98]. From the model, a probability distribution for risk of AUV loss during under-ice missions was derived. Apart from demonstrating the use of BBN as a structured approach for risk analysis, this work also represented significant progress in accounting for uncertainties of an AUV deployment. In a later study, the similar approach was demonstrated on risk analysis of Autosub 3 AUV's deployment to the Antarctic [99]. The use of BBN also proved to be useful in accounting for the effectiveness of failure prevention and risk mitigation process, keeping the risk profile updated for better decision-making [100]. However, a limitation of BBNs is that it does not account for feedback effects, which is a chain of cause-and-effect between risk factors that form a loop. It also depended on quality historical fault data and is a time-intensive process due to iterative elicitation of experts. With the recognition that risk of AUV loss may also depend on decisions made within different phases of an AUV deployment, Brito & Griffiths [101] proposed the use of Markov chains to model the sequential steps of a deployment, from pre-launch to recovery. Based on the AUV's historical performance data and experts' judgement, the resultant model allowed the overall risk of loss for a deployment to be estimated. The methods described so far represented the forefront of risk analysis for AUV deployment. However, one major limitation still exists; the heavy reliance on the availability of the vehicle's historical performance data.

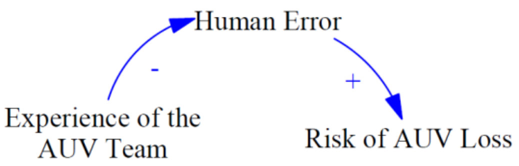
The broadening scope of risk analysis also meant that there is a need for reduced dependency on a vehicle's performance data, as relevant data may not always be available. For instance, during the early phases of an AUV program or for an AUV which is relatively new in operation [102]. Recognising such a need, Bian et al. [103] proposed the use of a fuzzy fault tree for technical reliability analysis of AUVs. The approach is an extension of traditional fault tree analysis to cope with the lack of data and accounts for uncertainties in AUV's subsystem failure. However, fault trees adopt a chain of events approach starting with the top failure event before branching downwards to basic events. Such direct and linear view ignores the complex interrelationships between risk factors and oversimplifies the problem. Despite the limitations of fault tree analysis, the study clearly demonstrated the potential of hybrid fuzzy logic approaches for analysis of risk. Chapter 2 presents a detailed discussion on risk analysis of AUV operations based solely on fuzzy logic, which to the best of our knowledge, has never been attempted before. In another example of handling the lack of data, Xu et al. [104] demonstrated the use of a qualitative fault tree analysis, together with Monte Carlo simulation. The reliability of a 45000m AUV, which was in its design phase, was examined with the proposed approach to derive several risk control recommendations. First, to emphasise on user-centred software and structure design to facilitate future maintenance and operation of the vehicle. Second, implement sufficient testing to ensure robustness of the AUV software. Third, to use commercially available components whenever possible to reduce the complexity of construction and ease of maintenance. Last, to design redundancy for critical components. In both examples, the fault tree analysis is applied on AUVs which are still in its design phase without historical performance data. Although the method facilitates prioritization of risks and creates the foundation for further analysis, it does not capture complex problems with multiple levels of causes and feedback loops.

In recent risk studies, there is more attention devoted to the role of organisational and human factors in the overall risk of AUV loss during deployment. Brito and Griffiths (105) applied system dynamics models to analyse the required risk mitigating efforts for AUV deployment. Based on a “rework cycle” system archetype, the risk model consists of several organisational factors such as workforce requirement, productivity, work scheduling and hiring rate. Although the study had focused more on human resource management, suggestions were made to investigate organisational, cultural and stress factors using the same approach. A detailed discussion on the application of system dynamics for risk analysis is presented in Chapter 3. Thieme et al. (106) presented the use of a qualitative BBN to assess the role of human factors in the monitoring of an AUV during missions. Trust, workload, fatigue and situation awareness were some of the factors mentioned to affect the performance of an AUV operator. Several other studies had also found human errors playing a significant role in contributing to the overall risk of AUV loss (107)(108). Notably, during a four years deployment of the Autosub AUV from 1996 to 2000, Griffiths et al. (6) identified human error as the most common ‘fault’ instead of technological failures. As the scope for risk analysis broadens, Utne et al. (109) recognised the need for a structured and holistic risk analysis framework that accounts for technical failures, natural events, human errors and organisational failures. The recommendation was to adapt existing internal standards, such as the ISO 31000 - Risk management, as basis for such a framework. A risk management framework which focused on both human and organisational factors was eventually proposed by the Thieme et al. in a separate literature (110). The framework, based on human reliability analysis (SPAR-H), fault tree and event tree analysis, was applied on a REMUS100 AUV as a case study. On top of revealing “internal faults of the AUV” as the most likely cause of AUV loss during mission, the case study also recommended risk reduction measures, in areas of maintenance, mission planning and fault recognition and solving. Although the focus on organisational and human factors represented significant progress in the scope of risk analysis for AUV deployments, further research is needed to account for the dynamic nature of risks and interactions between risk factors.

1.3.6 Limitations of Existing Risk Analysis Methods in AUV Deployment

Since the first autonomous underwater vehicle (AUV) was developed more than 60 years ago, there have been significant developments in risk analyses methods to better control the risk of AUV loss in the Antarctic. Many aspects of risk for an AUV deployment, both spatially and temporally, had been examined in parts, some in details and others superficially. For one, further study is needed in specific areas, such as the role of human, organisational, social, political, governance and environmental influences in risk of AUV loss. But more importantly, the synergistic combination of technical system(s), people associated with the AUV program, operating environment, work activities, organisational factors as well as external influences need to be analysed collectively as a whole. Consider an analysis focusing solely on a single risk factor such as operating experience of the AUV team. It would be fairly intuitive and statistically straightforward (With the availability of relevant data), to investigate the inverse relationship between operating experience of an AUV team and the risk of loss (Figure 1.10a). However, the inclusion of other risk factors complicates the analysis. For instance, reducing organisational commitment to the AUV program, poor interpersonal dynamics, high mental workload, etc (Figure 1.10b). The uncertain inter-relationships between these risk factors, unclear degree of causality and their dynamic behaviour resulted in an unknown combined effect on the risk of AUV loss. Consequently, these complex interrelationships between risk factors are often neglected during risk analysis as they can be highly uncertain and difficult to quantify.

A



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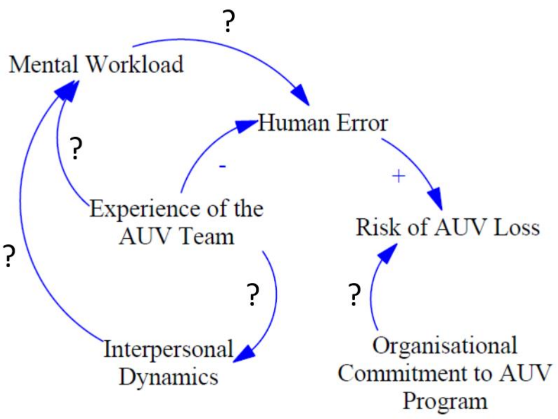


Figure 1.10: **A**: An analysis focusing on experience of the AUV team. **B**: A more complex analysis involving additional risk factors with uncertain inter-relationships and unclear degree of causality.

Such a situation is analogous to the folklore describing how a group of blind men drew different conclusions about the look of an elephant by touching different parts of it. While each of their perspective is correct to a certain extent, it does not sufficiently capture the entire picture. As Leveson [(11)] puts it,

> *"A systems approach to safety recognizes that safety is a property of the system as a whole, not a property of individual system components: The socio-technical system must be treated as an integrated whole using a top-down rather than a bottom-up perspective. This fact, in turn, implies that effectively tackling safety problems will*

require researchers and practitioners to step outside their traditional boundaries and take a broad view of the problems"

Contradictory as it may seem, the aim of a risk analysis is not to capture all possible risk factors and their interrelationships. Doing so is not only onerous and time-consuming, but it will also result in models which are too complex for any practical analysis. Instead, the risk analysis aims to tackle specific problems and include only relevant risk factors from different aspects, regardless of quantifiable or non-quantifiable.

Another limitation of existing risk analysis method is the adoption of chain-of-events perspective. Chain-of-events approach views the loss of an AUV as the final unintended outcome and the chain must be disrupted to prevent the loss from happening. Such views promotes a reductionist mentality, which often results in a simple linear narrative that displaces more complex, and potentially fruitful accounts of multiple and interacting contributions. For instance, the fault tree analysis which has been applied on reliability analysis of AUVs (103)(104) starts from the top at a single event before branching downwards till it reaches the basic events. Such direct and linear view ignores the complex interrelationships between risk factors and oversimplifies the problem. It misdirects the focus on identification of a possible 'root cause' where there may not be one (111). In an attempt to break the chain of events, redundancies and upgrades are often introduced with little considerations on how these changes may adversely impact the overall vehicle reliability. Additionally, the chain of events perspective is also static in nature, and does not sufficiently capture the dynamic nature of risk.

The lack of systematic and regular data for AUV deployment, especially for missions in the Antarctic, posed another challenge to risk analysis. As a result, most existing approaches depended on the elicitation of expert's opinions for subjective probability quantification. Although a formal experts elicitation process for risk analysis of AUV deployment had been proposed, experts may face difficulties to provide precise numerical figures due to the vagueness and ambiguity nature of risk (78)(79). Additionally, experts have varied level of experience working with different types of AUVs and organisations. As a result, assumptions, perceptions and expectations differ between experts, which can affect the overall accuracy of the risk analysis.

To overcome these limitations requires a new form of hybrid risk analysis approach, which is the core contribution of this dissertation.

1.4 THESIS OBJECTIVE AND SCOPE

The focus of this dissertation is on the risk analysis of AUV deployments in the Antarctic. The eventual goal is to lay the foundation for a risk analysis framework to support the AUV community in reducing the risk of AUV loss. Specifically, the objective is to support safer AUV deployments in the Antarctic with a risk analysis framework that facilitates the identification, modelling and evaluation of risk associated with an AUV program. This novel framework will account for the dynamic nature of risk, interrelationships between risk factors, as well as the uncertainties involved in the causality between risk factors. Insights gained through application of the framework can be used to improve mental models of decision makers for better decision making. Additionally, leverage points and leading indicators can be identified for risk monitoring and risk control recommendations.

The objective will be achieved through:

a) Addressing uncertainties in causality and overcoming lack of data with fuzzy logic.
b) Addressing the dynamic behaviour and complex interrelationships between risk factors with system dynamics.
c) Proposing a novel fuzzy system dynamics (FuSDRA) risk analysis framework by leveraging on the strengths while overcoming limitations of both fuzzy logic and system dynamics.
d) Demonstrating the application of the framework through an actual Antarctic AUV program.

The scope of this dissertation needs to be defined for clarity, in particular to three main areas: Risk of AUV loss, risk analysis and the focused level of abstraction within an AUV program. Here, the risk of AUV loss refers to the likelihood that during a mission, an AUV vehicle will be rendered unusable for future missions. While the term 'AUV loss' is commonly associated to the complete loss of an AUV, it can also represent an AUV being destroyed or damaged beyond economic repair. Not without precedent, there have been reported incidents of AUVs being destroyed by a ship propeller [(94)] or damaged by marine mammals such as killer whales and leopard seals [(2)].

Despite the broad definition for risk analysis adopted in this dissertation, the proposed framework limits the processes to identification of risk factors, risk modelling and risk evaluation. To simply state, the iterative framework encompasses familiarization to understand the problem, quantifying risk of loss, and develop recommendations for risk controls. Although the eventual control of risk is conditional upon successful implementation of risk control recommendations, details of the implementation process, which is highly dependent on the organisational context, is beyond the scope of this dissertation.

A functional AUV program comprises several levels of abstraction, from high level regulatory influences to detailed AUV technicalities. The focus of this dissertation is at the organisational level, where the overall management of an AUV program takes place. This includes the people working on the program and any external influences which may affect decision-making and contribute to the risk of loss. This is also the area which has received relatively lesser attention in the published risk studies of AUV deployments.

1.5 THESIS OUTLINE

This dissertation is organised into six chapters. Four of the chapters have been submitted for publication and details are provided in their respective chapters. The chapters are structured according to natural progression, from background and literature review to details of the proposed risk analysis framework and lastly, a detailed case study on its application. In summary, Chapter 1 provided the relevant background and literature review of which this dissertation is based on. Three main areas were highlighted, the AUV, the Antarctic and risk analysis of AUV deployments. Chapter 2 introduces fuzzy logic as a method to address the lack of data as well as the vagueness and ambiguity of many risk factors and their causal relationships. It also presents a fuzzy-based risk analysis framework for quantifying the risk of AUV loss for an Antarctic under-ice mission. Chapter 3 introduces system dynamics as a method to address the dynamic behaviour and complex interrelationships between risk factors. A risk analysis framework facilitated by system dynamics methodology is proposed and demonstrated in this chapter. Chapter 4 builds on the strengths of both methods in chapter 2 – Fuzzy logic and 3 – System Dynamics to present a hybrid fuzzy system dynamics risk analysis (FuSDRA). An eventual FuSDRA framework is proposed and demonstrated. Chapter 5 presents a case study on application of the FuSDRA framework in the University of Tasmania's *nupiri muka* AUV program. Chapter 6 concludes this dissertation with the contributions from this work and suggestions for future work.

CHAPTER 2: ADDRESSING UNCERTAINTIES AND THE LACK OF DATA WITH FUZZY LOGIC

The content of this chapter is drawn mainly from the paper “A fuzzy-based risk assessment framework for autonomous underwater vehicle under-ice missions” which was published on the *journal of risk analysis* on the 18 Jul 2019. The following authors have also contributed in the preparation of the paper; Mario P. Brito, Neil Bose, Jingjing Xu and Kiril Tenekedjiev.

The aim of this chapter is to introduce a fuzzy-based risk analysis framework for AUV deployments in the Antarctic, which to the best of our knowledge, has never been attempted before. The use of a fuzzy-based approach addresses uncertainties about causal relationships between risk factors and is well-suited for the lack of historical data for precise quantification of risks. Additionally, the proposed framework facilitates knowledge elicitation from domain experts to derive a quantifiable risk level output to aid decision making.

2.1 Introduction to Fuzzy Set Theory

The concept of multivalued logic was introduced by Lukasiewicz [(112)]. Later, this concept was generalised by Zadeh [(113)] with mathematical logic, establishing the fuzzy set theory. One key difference between fuzzy set theory and classical probability theory lies in its ability to account for vagueness and ambiguity by representing a proposition with a degree of ignorance.

Fundamental to the theory are the two main concepts of linguistic variables and fuzzy sets. Linguistic variables are used in day to day conversations to represent opinions, which are independent of the measuring system and are easily comprehensible by most listeners. For instance, ‘weather condition’ during AUV deployment is a linguistic variable if it is described in linguistic terms of ‘bad’, ‘average’ and ‘good’.

The second fundamental concept is fuzzy sets. In contrast with traditional set theory where an object either belongs to a set or not, every object (in the universe of discourse) belongs to a fuzzy set but with different membership function of 0 to 1 [(113)]. To illustrate this, consider the ‘five by five’ risk assessment matrix, which is a commonly used semi-quantitative tool for assessing risks. The matrix, with an example from the University of Tasmania shown in Figure 2.1 and in Appendix J, defines risk level by considering the likelihood of occurrence and severity of consequence. It is a practical and simple tool with widespread usage across industries to assess risk and assist management in decision making.

	Severity of Consequence				
Likelihood	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	Mod 11	High 13	Ext 20	Ext 23	Ext 25
Likely	Mod 7	High 12	High 17	Ext 21	Ext 24
Possible	Low 4	Mod 8	High 16	Ext 18	Ext 22
Unlikely	Low 2	Low 5	Mod 9	High 15	Ext 19
Rare	Low 1	Low 3	Mod 6	Mod 10	High 14

Figure 2.1: Five by five risk matrix with the risk level of low, moderate, high and extreme, represented by risk ratings of 1-25. (Source: University of Tasmania)

Based on traditional set theory, the risk assessment matrix presents crisp boundaries between risk level categories, with the term ‘crisp’ referring to quantitative or countable data [114]. In the matrix presented in Figure 2.1, each risk rating number from 1 to 25 belongs to a specific category of either ‘Low’, ‘Moderate’, ‘High’ or ‘Extreme’. Adopting this strict interpretation means that two risks with ratings of 11 and 12 will belong to two separate risk levels of ‘Moderate’ and ‘High’ despite being only one rating apart. On the contrary, two risks with ratings of 12 and 17 will belong to the same risk level of ‘High’ despite being five ratings apart. The graphical representation in Figure 2.2 shows an example of such crisp boundary. Such an approach cannot represent vague concepts and can be unnatural, as it does not match a human’s perception due to the sharply fixed boundaries [115].

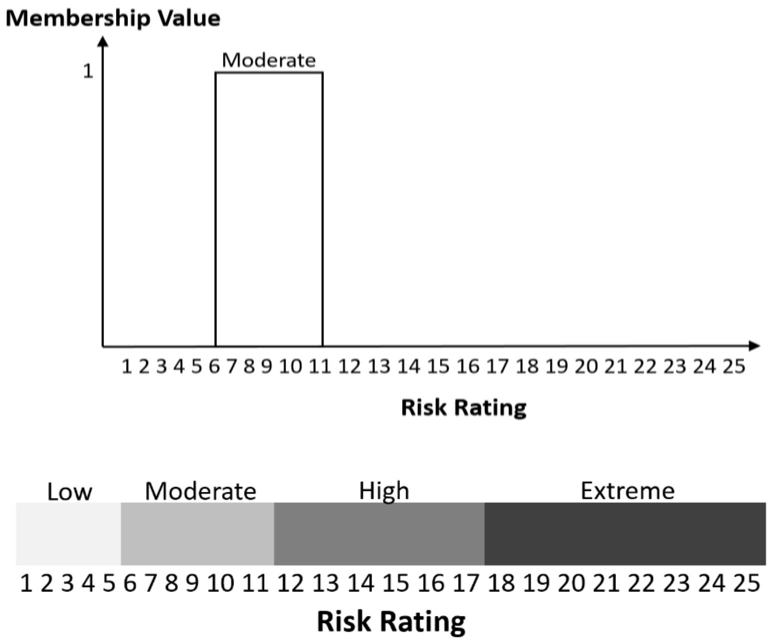


Figure 2.2: An example of membership value for ‘moderate’ risk (Top) and graphical representation of the risk assessment matrix shown in Figure 2.1, illustrating the crisp boundaries between risk level categories (Bottom).

In contrast, fuzzy set theory takes a less rigid view and reflects more naturally each element's association with a particular set. It does so by using membership function $\mu(x)$ which assigns membership values of between 0 and 1 to its elements x, defined as:

$$\mu(x): X \rightarrow [0,1] \quad \text{---- (2.1)}$$

Applying fuzzy set theory to the risk assessment matrix in Figure 2.1 resulted in a gradual and smooth transition between risk level categories as illustrated in Figure 2.3. A risk rating of 11 under the new fuzzy risk assessment matrix now belongs to both risk level categories of 'Moderate' and High' with membership function of 0.6 and 0.4 respectively.

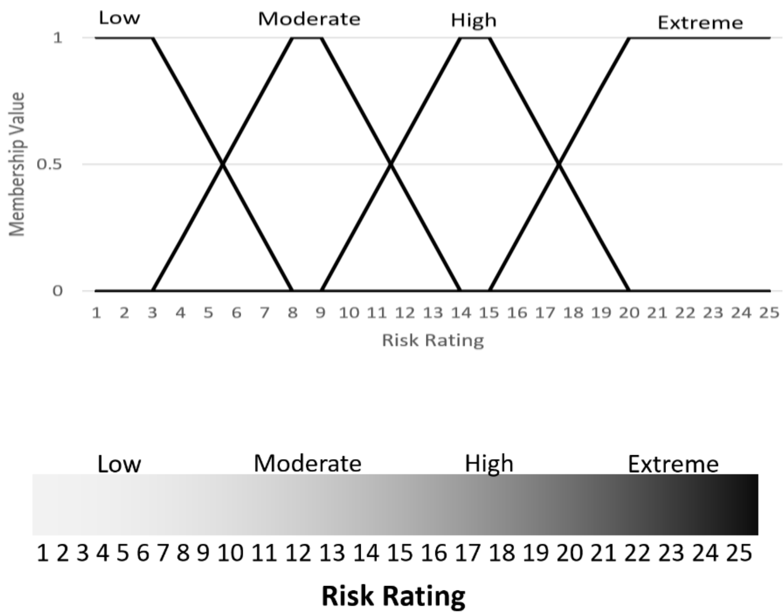


Figure 2.3: Graphical representations of the risk assessment matrix (Figure 2.1) after application of fuzzy set theory. Membership values (Top) and smooth transition between risk level categories (Bottom).

The application of fuzzy set theory for risk analysis has garnered attention over the years with application in various domains from nuclear power plants [116] through construction [117] to medical fields [118][119]. It is also often used in synthesis with other methodologies such as Bayesian network (BN) [120][117], system dynamics [121] or fault and event tree analyses [122] to improve assessment of risks. In the AUV domain, Bian et al. [103] proposed the extension of traditional fault tree analysis with fuzzy logic for technical reliability analysis of AUVs. Besides lacking an applicable framework, the study focuses solely on technical risks and is subjected to limitations of fault tree analysis (Refer to section 1.3.5).

This work aims to present and demonstrate the use of fuzzy set theory in a risk analysis framework for AUV under-ice deployment. To the best of our knowledge, the analysis of operational risks based solely on fuzzy logic has never been attempted before. In section 2.2, the details of the fuzzy-based risk analysis framework are presented. Section 2.3 demonstrates application of the framework, with a sensitivity analysis. Lastly, section 2.4 concludes the chapter with a discussion of the benefits, drawbacks, implications and potential areas of continuing research.

2.2 METHODOLOGY

2.2.1 Overview

The proposed fuzzy-based risk analysis framework incorporates the generic architecture of a fuzzy expert system [7] with the risk analysis process presented in widely used international standards such as ISO31000 (Risk Management) [13] and ISO45001 (Occupational Health and Safety) [123]. Based primarily on experts' judgement, the three steps iterative framework requires extensive discussion with domain experts. The overview of the framework is presented in Figure 2.4.

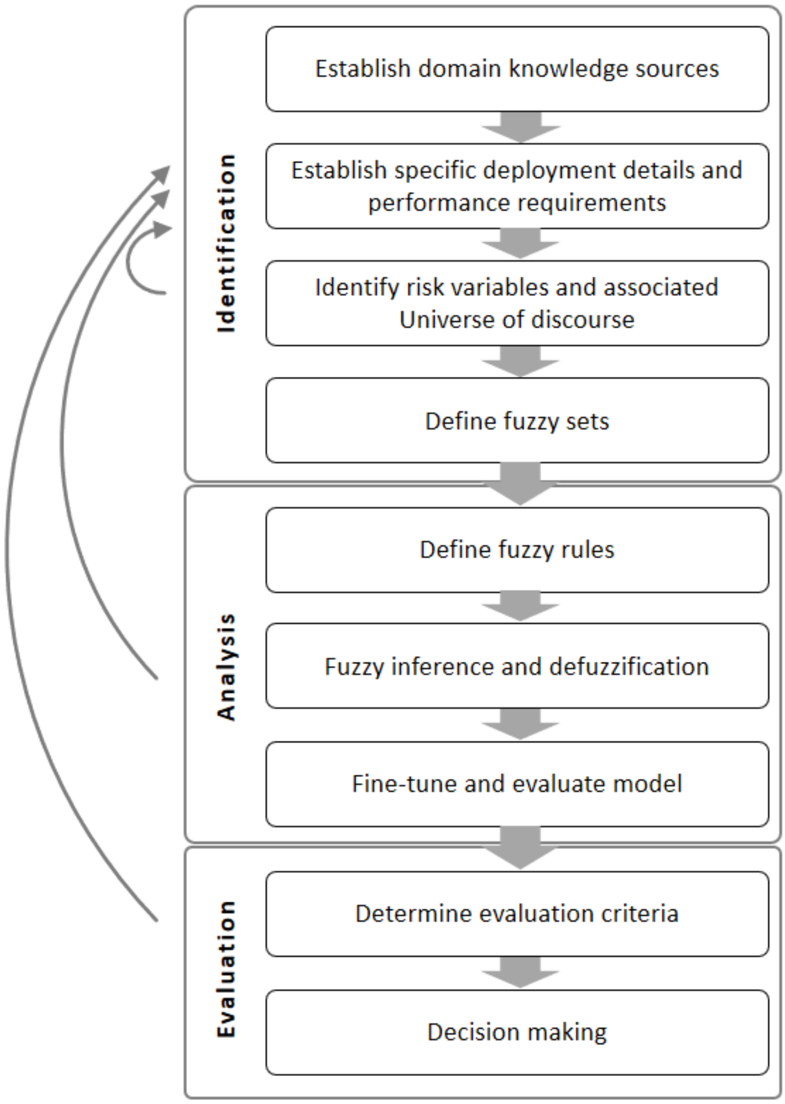


Figure 2.4: Overview of the steps involved in the fuzzy-based risk analysis framework. Curved arrows represent the iterative nature of the steps.

2.2.2 Scenario identification

Adopting and referencing international standards [13] [123], the scenario identification phase lays the foundation for risk analysis by finding, recognising and describing sources of risk. It consists of several tasks and should be executed iteratively to ensure that objectives of the risk analysis are met.

The first task aims to establish the available sources of knowledge. In the early stages of an AUV program, expert knowledge is often the only source of information, and this can come from AUV engineers, AUV program owners as well as manufacturer or contractors. Additional information can also be sought indirectly from experts in the form of documentation such as technical specifications of the AUV, safe work procedures, fault logs, risk assessment records, program schedules, budget plans, previous audit findings, online articles or publications, organisation charts or incident reports. For instance, examining a budget plan can reveal budget priorities and the AUV program's financial condition. This may be relevant to the risk analysis in terms of infrastructure investment, human resources and technical maintenance. In addition, specific deployment plans and expected performance requirements can also hold important information about possible risk factors influencing the risk of AUV loss.

The second task involves the identification of risk factors in the form of linguistic variables and the universe of discourse. The universe of discourse is the numerical range of possible values associated with the risk factor. There are two main ways to accomplish this task using available sources of knowledge:

1. Through semi-structured interviews and discussion with domain experts, and
2. Through the extraction of information from texts in documentation.

Important considerations for interviews are the choice and number of experts necessary to capture both spatial and temporal risk factors of interest and the fuzzy membership function. While there is no formal guidance tailored specifically to risk analysis of AUV operations, guidance can be taken from the recommended selection criteria published by Kotra et al. and Pulkkinen and Simola [124]. The number of experts to interview lies between 6 - 12 as recommended by Cooke and Probst [125]. These experts should be someone familiar with the AUV program, with responsibilities such as budget allocation for the AUV program, technical training on the AUV, determining operational strategies and objectives as well as implementation of risk controls based on any form of risk analysis conducted on the AUV. These usually comprises of the AUV engineers, AUV users, facility manager as well as the AUV owner. The eventual outcome of this task is a comprehensive list of risk factors relevant to the AUV under assessment. As an example using published risk studies, some risk factors influencing the risk of AUV loss during under-ice mission in the Antarctic and their possible associated universe of discourse are presented in Table 2.1.

The next task involves the definition of fuzzy sets and membership functions using same sources of knowledge as the previous task. Fuzzy sets allow the handling of linguistic uncertainties, such as the vagueness of good, average and bad weather. To ascertain fuzzy set, a list of typical adjectives associated with each risk factor is identified. Using some of the risk factors from Table 2.1 as an example, the fuzzy sets were determined through a best estimate consensus by the authors of Paper 1 (see page 4), resulting in an output similar to one shown in Table 2.2.

Table 2.1: An example of some risk factors and their associated universe of discourse.

Risk factor	Reference(s)	Possible Universe of Discourse (Units)
Situation Awareness	(132)(133)(134)	1-3 (Dimensionless, Level (135))
Annual Insurance Premium	(136)	0 – 12 (Dimensionless, % Capital Cost)
Trust on the AUV	(132)(133)(137)(138)	Arbitrary - 0 to 10 (Dimensionless)
Distance of Mission	(56)	0 to 400 (Kilometres)
Maximum Depth of Mission	(139)	0 to 5000 (Meters)
Weather Condition	(140)(76)	Arbitrary - 0 to 10 (Dimensionless)
Average Experience of AUV Team with Under-Ice Missions.	(141)	0 to 30 (Years)
Operator Stress and Fatigue Level	(140)(142)	Arbitrary - 0 to 10 (Dimensionless)
Level of Interactions within AUV Team	(140)	Arbitrary - 0 to 10 (Dimensionless)
Technical Reliability	(143)(139)(68)	0 – 20 (MTBF, Years)
Level of Automation	(143)	0 – 10 (Automation Level (144))
Mental Workload	(132)(133)(138)	Arbitrary - 0 to 10 (Dimensionless)
Operator Complacency Level	(145)	Arbitrary - 0 to 10 (Dimensionless)
Time Duration Under-Ice	(146)	0 to 48 (Hours)

Table 2.2: Example of risk factors and their associated fuzzy sets.

Risk factor	Fuzzy Sets
Situation Awareness	Poor, Normal, Good
Distance of Mission	Short, Average, Long
Maximum Depth of Mission	Shallow, Intermediate, Deep
Weather Condition	Good, Average, Bad, Severe
Average Experience of AUV Team with Under-Ice Missions.	Inexperience, Average, Experienced
Operator Stress and Fatigue Level	Low, Average, High, Extreme
Time Duration Under-Ice	Short, Medium, Long

To define the membership functions, experts' opinion can be elicited using matrices, which are dependent on the adopted distribution shapes. For instance, bell-shaped, Gaussian, triangular or trapezoidal [126]. The choice of distribution shape is problem dependent and reflects how experts relate the range of possible values to the fuzzy set. However, both triangular and trapezoidal shapes are most commonly used because of their effectiveness in capturing subjective and imprecise information, as well as being simple to compute [127][128][129]. A triangular membership function is defined by a lower limit a, an upper limit c, and a most likely value b, as shown in Figure 2.5a. A trapezoidal membership function is defined by a lower support margin a, a lower core margin b, an upper core margin c, and an upper support margin d, as shown in Figure 2.5b. Table 2.3 shows an example of a matrix to define membership function for the risk factor 'Maximum Depth of Mission', with the graphical representation shown in Figure 2.6.

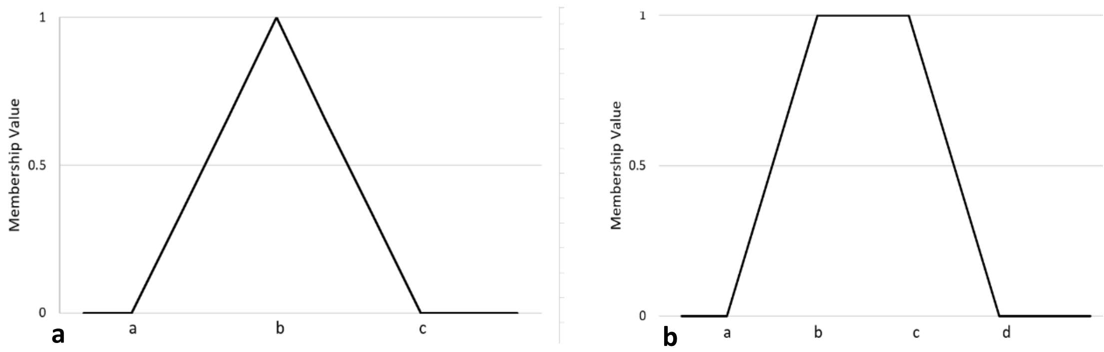


Figure 2.5: Types of membership functions. a. Triangular membership function. b. Trapezoidal membership function.

Table 2.3: Matrix to elicit experts' opinion for risk factor 'Maximum Depth of Mission '.

Maximum Depth of Mission (0 – 5000m)			
	Membership Functions		
Fuzzy Sets	Min (m)	Most Likely (m)	Max (m)
Shallow	0	500	750
Intermediate	250	750	1500
Deep	750	1500	5000

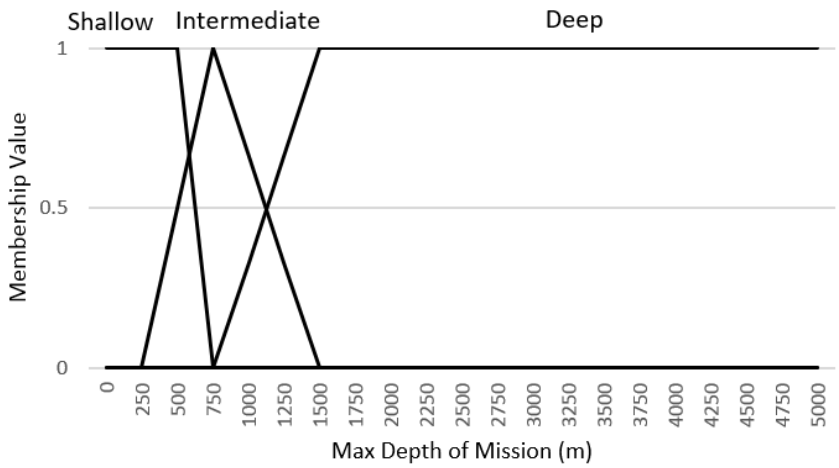


Figure 2.6: Membership function for the risk factor ‘Maximum Depth of Mission’.

Lastly, if more than one expert is elicited in the earlier described tasks, aggregation of different opinions will be required. Several aggregation methods have been proposed in the literature, a summary of which are described below:

1. Using the lowest and greatest value provided by experts as the lower bound and upper bound For each fuzzy set, use the lowest and greatest value provided by experts as the lower bound and upper bound. The average value is then used as the modal value (130).
2. The similarity aggregation method (SAM) (131) which utilises a similarity index to measure the consistency of each opinion from others. Other aggregation methods based on SAM can also be used, such as the consistency aggregation method (CAM) (132) and the optimal aggregation method (OAM) (133).
3. The Delphi method (134) where opinions of experts are made to converge through iteration until it meets predefined criteria. The Fuzzy Delphi Method (FDM) draws ideas from fuzzy theory in synthesis with the original Delphi method. It utilises a similarity function to assess the level of consistency between experts. The similarity coefficient is then used to derive the fuzzy evaluation value of all experts. (135).

2.2.3 Analysis

The analysis step aims to understand the nature, effects and relationships of risks variables by eliciting and constructing fuzzy rules. A fuzzy rule infers information using linguistic variables and fuzzy sets to derive an output. While there are several forms of fuzzy rules, one of the simplest representation uses If-Then rule statements in the form of:

$$\textbf{IF } Risk\ Variable \text{ is } x \textbf{ THEN } Risk\ of\ Loss \text{ is } y$$

where x and y are adjectives associated with the risk factor and risk of loss respectively. The fuzzy rule can also be in the form of *AND OR* statement, such as:

IF weather condition is bad, **AND** the AUV team is inexperienced,

THEN risk of AUV loss is high.

For intuitive elicitation of fuzzy rules based, a hypercube matrix can be used. A hypercube is a geometric shape of *n*-dimensions, determined by the number of input risk factors (136). For instance, a 4D hypercube can be used for a fuzzy system consisting of four input risk factors and a 3D hypercube for a three-input risk factor fuzzy system. While fuzzy rules can be established using the same sources of information as earlier steps in the risk analysis framework, the process can become increasingly complex with the number of identified risk factors. This phenomenon, where the number of fuzzy rules increases exponentially with the number of inputs, is known as the 'curse of dimensionality' (137). One common method to overcome the curse of dimensionality is to implement the use of a hierarchical fuzzy system (138). The idea is to decompose a large fuzzy logic unit (Figure 2.7a) into several smaller, related fuzzy logic units which are then interconnected according to a given topology (138) (Figure 2.7b and 2.7c). Each single fuzzy logic unit consists of a fuzzifier, membership functions, a fuzzy rule base, an inference engine and a defuzzifier (114). Adopting a hierarchical fuzzy system reduces the total number of fuzzy rules which consequently reduces computational time and increases the efficiency of the system (138). As an example, an aggregated hierarchical fuzzy system is presented in Figure 2.8 using some risk factors from Table 2.1.

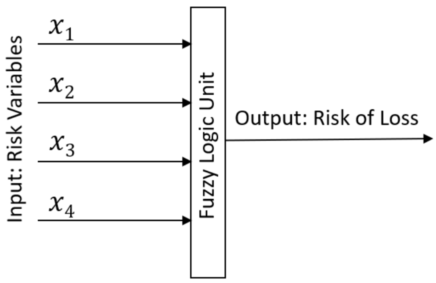


Figure 2.7a: A single layer fuzzy system consisting of four risk variables as input and risk of loss as output.

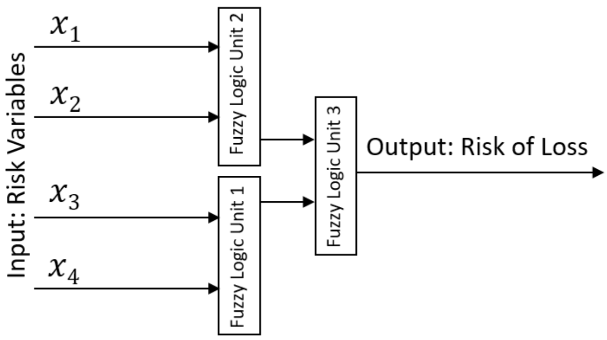


Figure 2.7b: An aggregated hierarchical fuzzy system based on Figure 2.7a

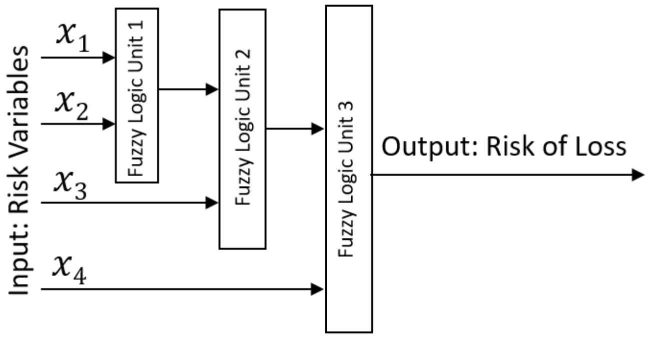


Figure 2.7c: An incremental hierarchical fuzzy system based on Figure 2.7a.

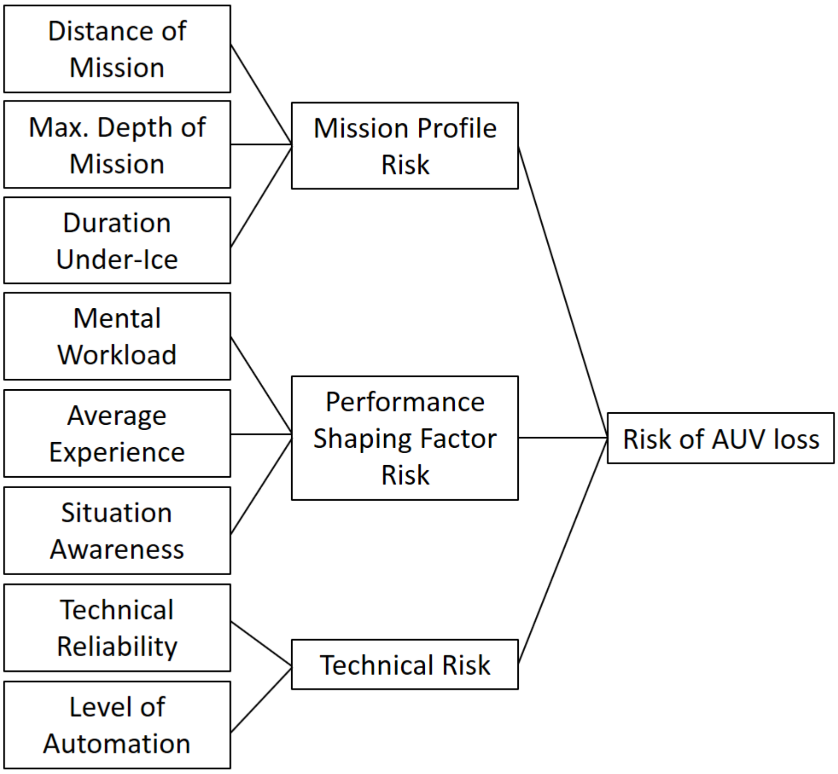


Figure 2.8: Example of an aggregated hierarchical fuzzy system.

In the process of establishing of fuzzy rules, experts may provide differing opinions resulting in redundant, inconsistent or conflicting rules. This can affect the risk analysis outcome and interpretability of the model [139]. Several methods had been proposed in the literature to overcome this, such as; complexity reduction with fuzzy clustering techniques, rule reduction by orthogonal transformation methods, algorithms based on similarity measures and genetic optimisation [140].

Upon establishment of fuzzy rules, the next task is to formulate the mapping from inputs to output in a process called fuzzy inference. Two most commonly used fuzzy inference methods are the Mamdani [141] and Sugeno [142] inference. The fundamental difference between these two methods lies in the way outputs are represented and determined [143][144]. Mamdani inference uses defuzzification of a fuzzy output to generate a crisp output while Sugeno inference uses a weighted average to compute the crisp output [141][142]. The Mamdani method is widely accepted for capturing expert knowledge and is more intuitive while the Sugeno method works well with optimization and adaptive techniques, particularly for dynamic non-linear systems [143][144]. An example of the fuzzy inference process is presented in section 3.3. Defuzzification is the process of deriving a quantifiable output from the fuzzy system. Consider the following rule:

IF weather condition is <u>bad</u>, **THEN** risk of AUV loss is <u>high</u>.

Defuzzification translates 'high' into a quantifiable risk level, such as a risk rating value based on the organisational risk matrix (Figure 2.1). There are several defuzzification methods such as the centroid method, weighted average method, centre of sums, centre of largest area, mean-max membership and max-membership principal [145][146]. Each method has its advantages and disadvantages, and the appropriate defuzzification method should be chosen based on nature of the problem, the number of input and output variables and sensitivity of the method [147].

The final task of the risk analysis step is to evaluate and fine-tune the system. Despite being a time-consuming process, proper execution of this task improves reliability of the risk analysis and ensures that original objectives are met. Carried out in close consultation with experts and decision-makers, this task involves one or more adjustments of fuzzy rules and fuzzy sets (Table 2.4).

Table 2.4: List of fine-tuning actions

Fuzzy Rules Adjustment a. Add, reduce or optimise fuzzy rules. b. Add hedge operators by using adverbs such as "Very", "Somewhat" or "Indeed". c. Adjust rule execution weights to increase or reduce the force of any fuzzy rules.
Fuzzy Sets Adjustment a. Add fuzzy sets. b. Widen or narrow existing sets by reviewing membership functions. c. Shift existing fuzzy sets to ensure sufficient overlaps. d. Review and adjust the shape of existing fuzzy sets.

2.2.4 Evaluation

The objective of the risk evaluation step is to support decision making through significance of the results derived from the risk analysis step. The significance of which is based on its acceptability in relation to pre-determined evaluation criteria set by the AUV owner, higher management of the organisation or external groups. External groups who may exhibit interest in the results of the risk analysis may include insurance companies and the regulators. An acceptable probability of AUV loss based on the capital and operating cost of the AUV [2] is an example of evaluation criteria. However, for an AUV program in its early phases, the evaluation criteria may be uncertain and yet to be established. In such circumstances, the organisational Safety and Health standard can be used as a good starting reference for criteria setting.

At the fundamental level, the risk of AUV loss will be either acceptable or unacceptable, as decided by the AUV owner. If deemed acceptable, the Antarctic under-ice mission can proceed under close monitoring and regular review to ensure that risk remains acceptable. if unacceptable, the AUV owner has to make decisions taking into consideration available resources and time constraints, which may include:

a) Whether the deployment should proceed by accepting a higher risk of loss.

b) Whether treatments are required, taking into consideration the adequacy of existing control measures.

c) The priorities for risk treatment.

Although risk evaluation is the last step of the proposed risk analysis framework (Figure 2.4), analysis of new information and filling of data gaps needs to be performed on a regular basis. This iterative process helps ensure relevancy and effectiveness of the risk analysis.

2.3 EXAMPLE OF APPLICATION

2.3.1 Description

To demonstrate application of the fuzzy-based risk analysis framework, an example based on the *nupiri muka* AUV program is presented. Readers are referred to section 5.1 on details of the *nupiri muka* AUV program. Delivered in May 2017, the AUV was relatively new at the time of writing and has very limited historical failure fault log data. Initial semi-quantitative risk analysis was performed in accordance to the Work Health and Safety Policy stipulated by the University of Tasmania [148] and leveraging on prior experience of the AUV team.

To apply the proposed fuzzy-based risk analysis framework, the risk assessment matrix recommended under the University of Tasmania's Work Health and Safety Policy (Figure 2.1) was converted to a fuzzy risk assessment matrix (Figure 2.3) as the output of the risk model. Assessment on risk of AUV loss was carried out on a planned deployment to the Sørsdal Glacier in Antarctica (Figure 2.9), which took place between December 2018 and March 2019. There are several missions comprising of both open water and under-ice operation. One of the proposed mission requires the *nupiri muka* to travel approximately 100 kilometres from launch to recovery, with 6 hours under ice-shelf at a maximum depth of around 800 meters. Being the longest mission for this deployment in terms of both distance and time duration, the fuzzy-based risk analysis framework was applied to determine the risk level of this mission.

Figure 2.9: Map showing location of the Sørsdal Glacier in the Antarctica (Photo: Australian Antarctic Data Centre).

2.3.2 Scenario Identification

In this initial step, five risk factors, their associated universe of discourse and fuzzy sets were identified (Table 2.5). These were based on best available deployment information at the time of writing, as well as through available sources of knowledge and information, which included in-house AUV engineers, technical specifications of the AUV, safe work procedures, risk analysis records and literature. The experts consist of three members of the University's AUV team and an AUV researcher who is a main user of the AUV. These domain experts had a combined experience of 24 years working with AUVs and are currently responsible for different aspects of the AUV program, such as implementation of risk control measures, resource allocation, operation strategies, maintenance, technical training and the analysis of risk and data.

Table 2.5: Identified risk factors, universe of discourse and fuzzy sets.

Risk factors	Universe of Discourse	Fuzzy Sets
Distance of Mission	0 to 140 (Kilometres)	Short, Average, Long
Maximum Depth of Mission	0 to 5000 (Meters)	Shallow, Intermediate, Deep
Time Duration Under-Ice	0 to 24 (Hours)	Short, Medium, Long
Weather Condition	0 to 10 (Dimensionless)	Good, Average, Bad, Severe
Average Experience of AUV Team with Under-Ice Missions.	0 to 10 (Years)	Short, Average, Long

To define membership functions, a mixture of triangular and trapezoidal membership functions was used for elicitation after considering their advantages (Section 2.2.2). The resultant membership functions are represented graphically and presented in Figure 2.10a – 2.10e. For the risk factor 'Weather Condition', there are existing weather classification systems being used, such as the classification by McMurdo Weather Office (Mac Weather) [149] for Antarctica. However, an arbitrary scale of 0-10 was in this case used for simplicity, where 0 represents excellent weather and 10 represents extreme weather.

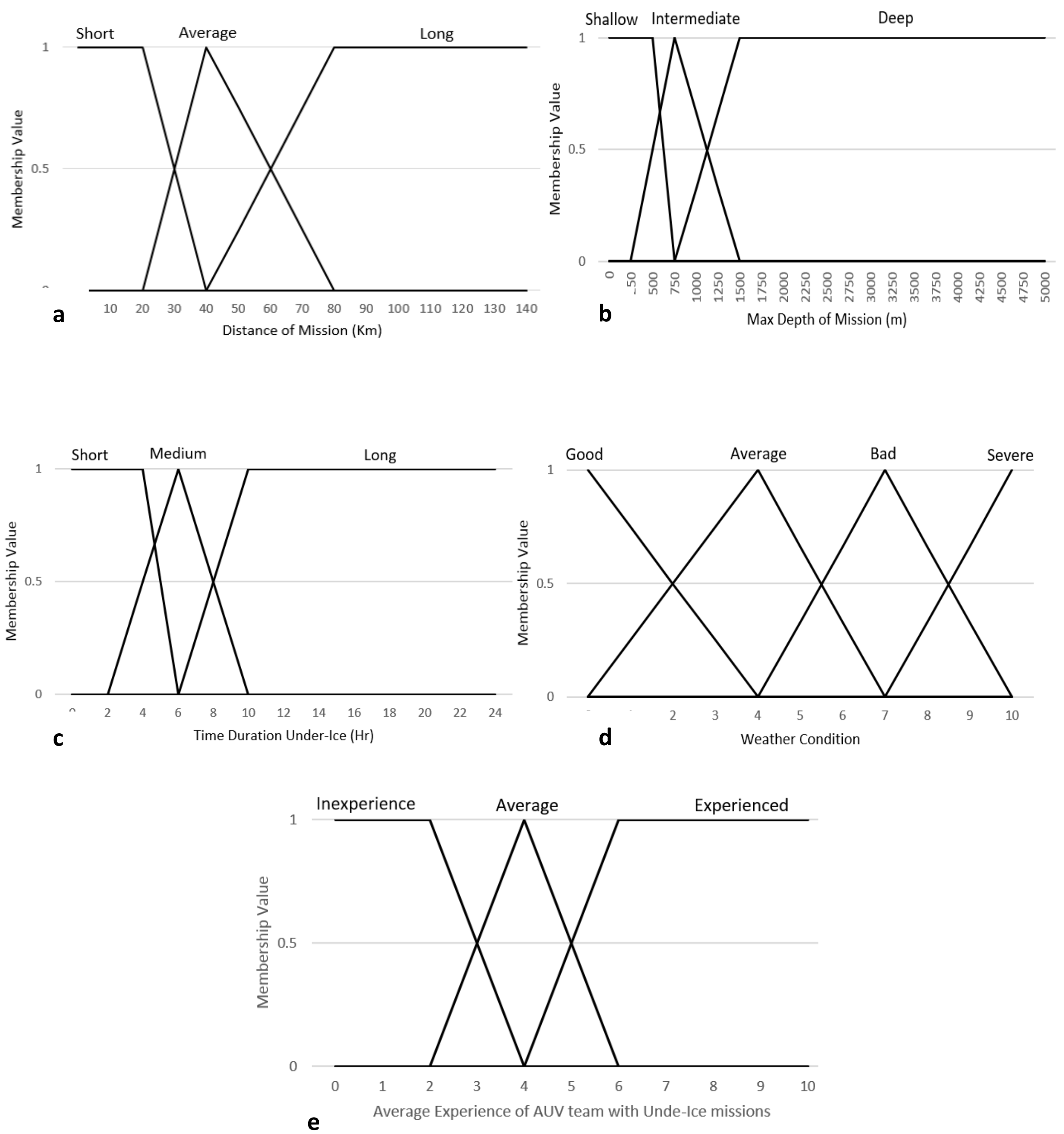


Figure 2.10: Membership function for the identified risk factors. a. 'Distance of Mission'. b. 'Maximum Depth of Mission'. c. 'Time Duration Under-Ice'. d. 'Weather Condition'. e. 'Average Experience of AUV team with Under-Ice missions'.

2.3.3 Analysis

To facilitate the construction of fuzzy rules and overcome the curse of dimensionality (Section 2.2.3), an incremental hierarchical fuzzy system as shown in Figure 2.11 was used. 'Distance of Mission', 'Maximum Depth of Mission' and 'Time Duration Under-Ice' were grouped under 'Mission Profile Risk' as an AUV mission profile is often presented in terms of mission length, mission depth and operating environment characteristics. Existing literature has also identified these three mission profile characteristics as significant factors for risk of AUV loss [(71)]. 'Weather Condition', which is highly uncertain and 'Average Experience of AUV Team with Under-ice Missions' which is influenced by organisational policies, were separate input to 'Risk of AUV Loss'.

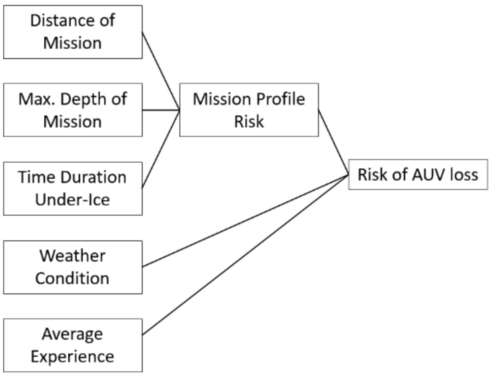


Figure 2.11: The risk factors in an incremental hierarchical fuzzy logic structure.

For intuitive elicitation of fuzzy rules based, a 3D hypercube matrix consisting of three input risk factors and one risk level output were used (Figure 2.12). The cube was further sliced into separate tables as shown in Table 2.6(a), where there are three slices and Table 2.6(b), where there are four slices. These tables represent a series of IF-THEN rules such as:

IF Distance of Mission is Short **AND** Time Duration Under-Ice is Short **AND** Max. Depth of Mission is Shallow **THEN** Mission Profile risk is Low.

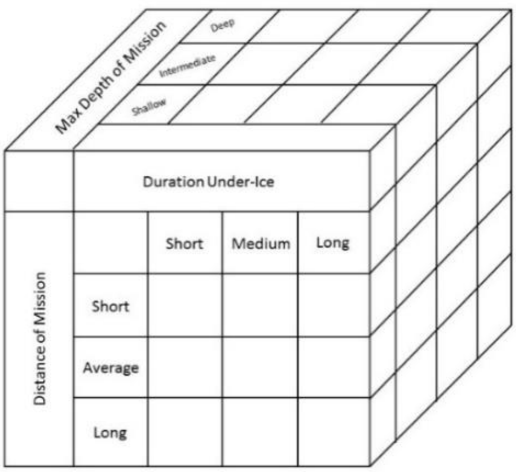


Figure 2.12: A 3D hypercube matrix to elicit experts' opinion on the construction of fuzzy rules for 'Mission Profile Risk'.

Table 2.6(a): Fuzzy rule table for 'Mission Profile Risk'.

		Time Duration Under-Ice		
		Short	Medium	Long
Maximum Depth of Mission – Shallow				
Distance of Mission	Short	Low	Low	Mod
	Average	Low	Mod	High
	Long	Mod	High	Ext
Maximum Depth of Mission - Intermediate				
Distance of Mission	Short	Low	Mod	High
	Average	Low	High	Ext
	Long	Mod	High	Ext
Maximum Depth of Mission – Deep				
Distance of Mission	Short	Mod	High	High
	Average	High	High	Ext
	Long	High	Ext	Ext

For the next task of fuzzy inference, the Mamdani method was adopted as it is widely accepted for capturing experts' knowledge (143). Many methods exist for the composition of fuzzy relations for use in Mamdani inference. Examples include *min-max, max-max, min-min, max-min and max-product*. Among these, the *max-min* and *max-product* inference are the most commonly used (150). In *max-min* inference, the inferred output of each rule is a fuzzy set chosen from the minimum firing strength, which is the degree to which the rule matches the input (141). The resultant output set has its membership function cut off at the top, resulting in some information loss. In the *max-product* inference, the inferred output of each rule is a fuzzy set scaled down by its firing strength via an algebraic product (141). This way, the original shape of the fuzzy set is preserved, resulting in less information loss as compared to *max-min* inference (151)(152). Therefore, the *max-product* inference was adopted for this example. To apply the *max-product* inference, consider two rules with three risk factors (RV) inputs and one risk level (RL) output of the following form:

IF $RV1$ *is* L_A *and* $RV2$ *is* L_B *and* $RV3$ *is* L_C **THEN** $RL = P_D$

IF $RV1$ *is* L_W *and* $RV2$ *is* L_X *and* $RV2$ *is* L_Y **THEN** $RL = P_Z$

L and P are adjectives of the fuzzy set associated with the risk factors and risk level respectively. The alphabetical subscripts differentiate different values of L and P. The aggregated output membership function $\mu_Q(RV,RL)$, which is a function of both the input risk factors and output risk levels can then be calculated as follow:

$$\text{Max}\begin{Bmatrix}\min(\mu_{L_A}(RV1), \mu_{L_B}(RV2), \mu_{L_C}(RV3))\mu_{P_D}(RL),\\ \min(\mu_{L_W}(RV1), \mu_{L_X}(RV2), \mu_{L_Y}(RV3))\mu_{P_Z}(RL)\end{Bmatrix}$$

Table 2.6(b): Fuzzy rule table for 'Risk of AUV Loss'.

		Average Experience of AUV Team		
		Experienced	Average	Inexperience
Weather Condition – Good				
Mission Profile Risk	Low	Low	Low	Mod
	Mod	Low	Low	Mod
	High	Mod	Mod	High
	Ext	High	High	Ext
Weather Condition – Average				
Mission Profile Risk	Low	Low	Low	Mod
	Mod	Mod	Mod	Mod
	High	Mod	High	High
	Ext	High	High	Ext
Weather Condition – Bad				
Mission Profile Risk	Low	Mod	Mod	High
	Mod	Mod	High	High
	High	High	High	Ext
	Ext	Ext	Ext	Ext
Weather Condition – Severe				
Mission Profile Risk	Low	High	High	Ext
	Mod	High	Ext	Ext
	High	Ext	Ext	Ext
	Ext	Ext	Ext	Ext

To demonstrate the Mamdani *max-product* inference, two fuzzy rules were extracted from Table 2.6(a), of the following form:

IF *Distance of Mission is Long and Maximum Depth of Mission is Intermediate and Time Duration Under-Ice is Medium,* **THEN** *Mission Profile Risk = High*

IF *Distance of Mission is Long and Maximum Depth of Mission is Deep and Time Duration Under-Ice is Medium,* **THEN** *Mission Profile Risk = Extreme*

Using the *max-product* inference, the aggregated output membership function μ_Q can be calculated as:

$$\text{Max}\begin{Bmatrix} \min(\mu_{Long}(Dist), \mu_{Int}(Depth), \mu_{Med}(Time))\ \mu_{High}(Risk), \\ \min(\mu_{Long}(Dist), \mu_{Deep}(Depth), \mu_{Med}(Time))\ \mu_{Ext}(Risk) \end{Bmatrix}$$

The graphical representation in Figure 2.13 shows the aggregation of output membership functions for each rule to result in μ_Q. Essentially, μ_Q comprises of the outer envelopes of the individuals truncated membership forms for each rule.

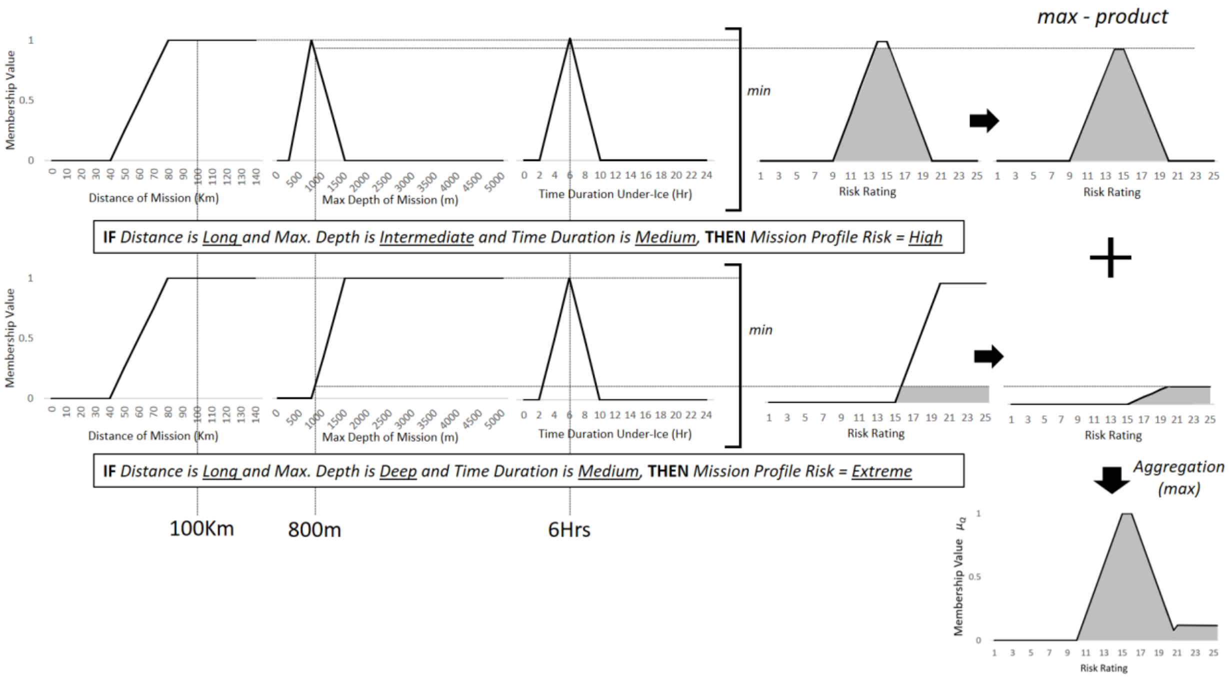


Figure 2.13: The graphical representation of Mamdani max-product inference.

For defuzzification, the commonly used centroid method was chosen for this example. It has the advantage of being well-balanced, sensitive to the height and width of the fuzzy output and providing consistent results [153]. The centroid method defuzzify by finding a point representing the centre of gravity of the aggregated fuzzy set. For a fuzzy set A, the centre of gravity χ^* can be expressed mathematically as (Figure 2.14):

$$\chi * = \frac{\int \mu_A(x)\, x\, dx}{\int \mu_A(x)\, dx}$$

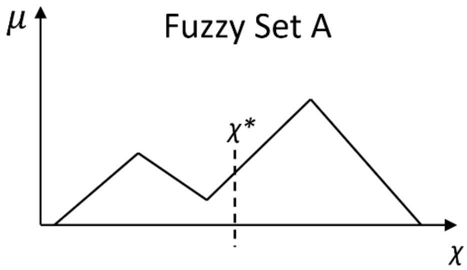


Figure 2.14: The centroid method of defuzzification.

The fuzzy inference and defuzzification process were implemented using MATLAB® fuzzy logic toolbox 2017 [154]. An example of the graphical interface is shown in Figure 2.15. In the interface, membership functions from Figure 2.10a-c and fuzzy rules from Table 2.6(a) were used as inputs to the model to assess 'Mission Profile Risk'. The fuzzy risk assessment matrix in Figure 2.3 was used as the output. Using the above information, the proposed mission with a distance of 100 Kilometres, Maximum Depth of 800 meters and 6 hours under-ice will have a mission profile risk rating of 14.97. Under the University of Tasmania's organisation's risk assessment matrix, a risk rating of 14.97 falls into the 'High risk' category.

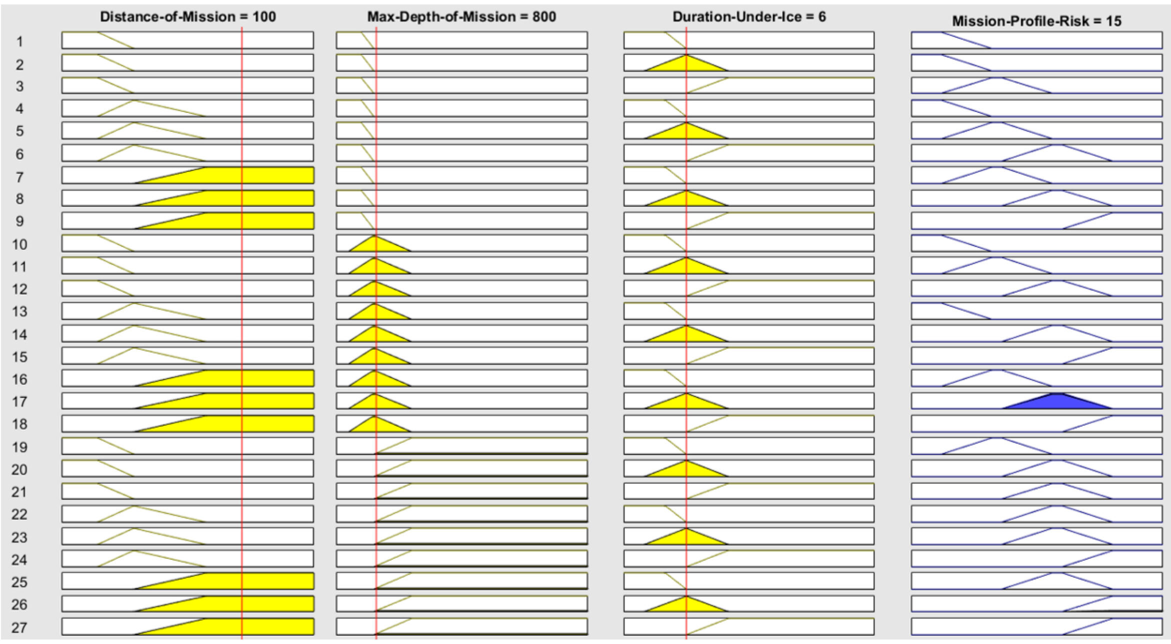


Figure 2.15: The graphical interface of MATLAB Fuzzy Logic Toolbox showing 'Mission Profile Risk'.

In the next level of the hierarchical fuzzy system (Figure 2.11), the risk of AUV loss was computed using 'Mission Profile Risk', 'Weather Condition' and 'Average Experience of AUV Team with Under-Ice Missions' as inputs. The average experience of the team is approximately three years, information attained by speaking with the team. December to February is the summer season in the Antarctic with generally lower precipitation and wind speeds as compared to the winter season. Sørsdal Glacier, which is near to Davis Station, has a relatively milder climate due to the surrounding Vestfold Hills (155). Despite this, the weather conditions in Antarctica can be highly dynamic and unpredictable (156). Therefore, it can be assumed at this stage that the weather is 'Good' with a rating of 2 out of 10, with 10 being the most extreme weather expected. Using Simulink® software to construct the hierarchical fuzzy system as presented in Figure 2.16, it was now possible to estimate the Risk of AUV loss.

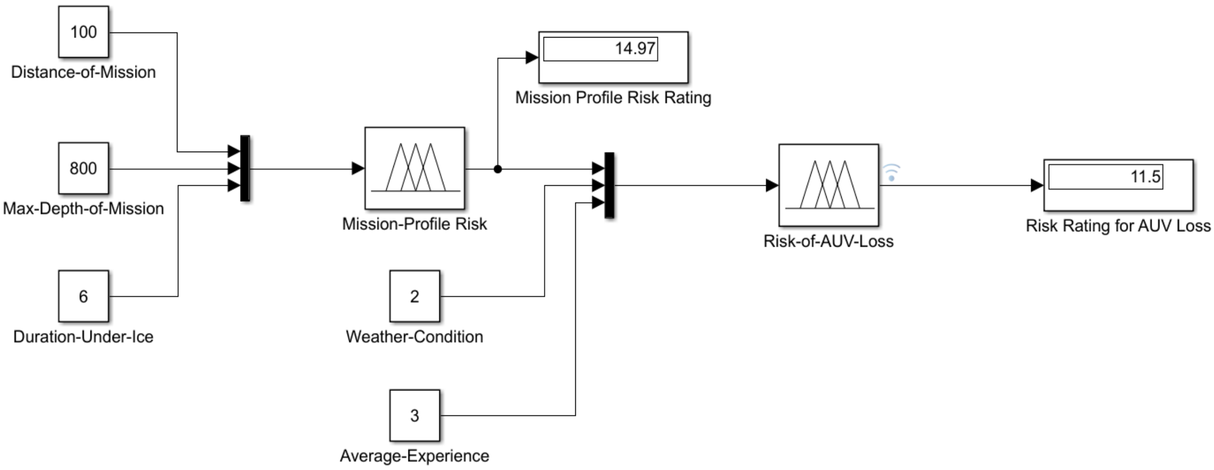


Figure 2.16: The hierarchical fuzzy logic structure constructed using Simulink® to assess 'Risk of AUV Loss'

The resultant risk level for the risk of AUV loss has a rating of **11.5**. Apart from achieving a numerical risk level, the behaviour of the risk factors and the risk of AUV loss can also be studied using 3-Dimensional plots. An example showing the influence of 'Mission Profile Risk' and 'Weather Condition' over 'Risk of AUV loss' is shown in Figure 2.17.

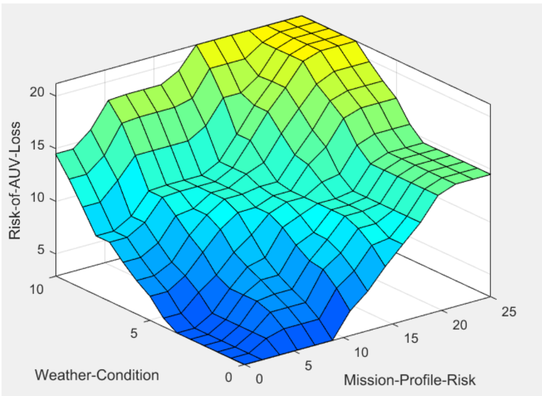


Figure 2.17: 3-Dimensional plot showing the behaviour of model output with changes to model inputs.

2.3.4 Evaluation

In the evaluation step, the significance of the result is used to support decision making. Referring to the University of Tasmania's 'five by five' risk assessment matrix (Figure 2.1), the risk rating of 11.5 falls between the 'moderate' and 'high' risk level category (Figure 2.18).

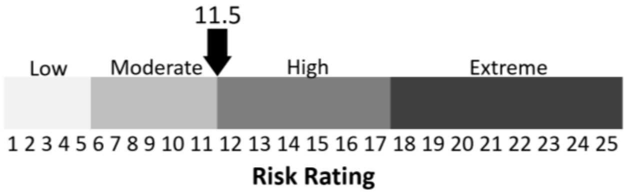


Figure 2.18: Risk Rating of 11.5 on The University of Tasmania's risk matrix.

Consequently, a set of actions can be determined using the Risk Management Standard from the University of Tasmania (Appendix J) [148] as the evaluation criteria. To err on the conservative side, the requirements for 'high' risk level should be considered. Under the standard, a mission with 'high' risk level requires approval from heads of school, budget centres or staff on authorised job risk analysis. The audit and risk committee of council and senior management team have to be kept informed of the mission and risk control measures reviewed annually. The risk of AUV loss is also to be included in strategic and capital planning and fiscal strategies.

2.3.5 Sensitivity Analysis

A sensitivity analysis was performed on the model to examine how changes to each risk factor input can affect the risk rating output. Using the established model in Figure 2.16 as the base model, each input risk factor was then changed sequentially while the values of other risk factors remained constant. The universe of discourse for each risk factor was divided into ten equal incremental parts for the analysis, starting with minimum value. Graphical representation of the results are shown in Figure 2.19.

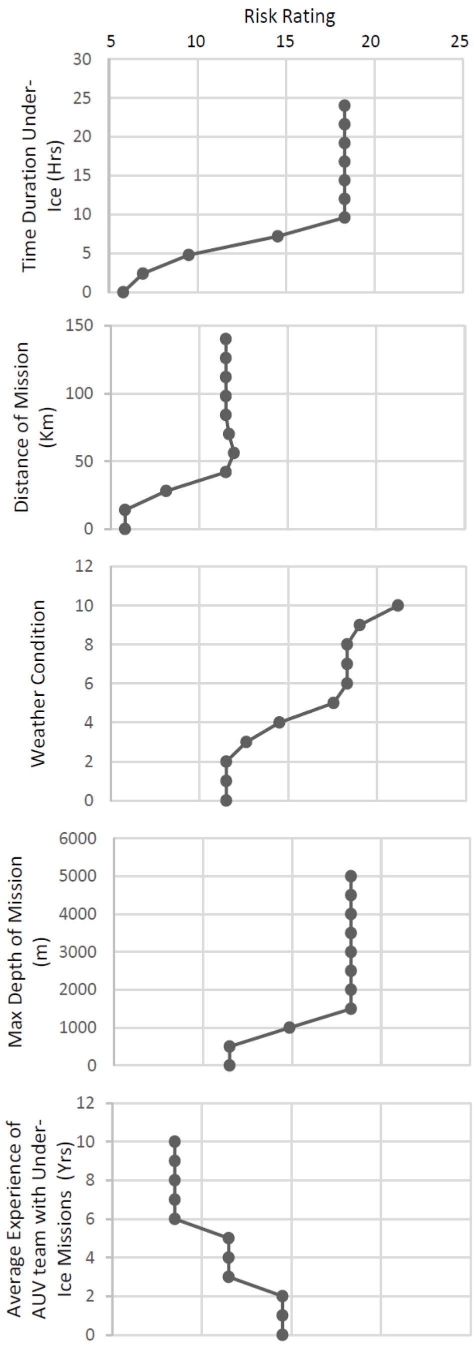


Figure 2.19: Sensitivity analysis of how changes to each risk factor input affect the risk rating output.

The result of the analysis shows that the risk rating output is most sensitive to 'Time Duration Under-Ice', with an increase of 215 percent from a risk rating of 5.81 to 18.31 when time duration under-ice increases from 0 to 9.6 hours. This is followed by risk factor 'Distance of Mission', 'Maximum depth of Mission', 'Average Experience of AUV team with Under-Ice Missions' and lastly, 'Weather Condition' which risk rating is least sensitive towards. The close similarity of sensitivity between 'Time Duration Under-Ice', 'Distance of Mission', 'Maximum depth of Mission' to risk rating is expected due to some degree of proportionality. The result of the sensitivity analysis can also be used for identification of leverage points setting priorities for risk control. For instance, a reduction of 'Time Duration Under-Ice' from 6 hours to 5 hours reduces the eventual risk rating for AUV loss from 11.5 to 9.9.

It is difficult to validate the model at this stage with a lack of historical data record for the *nupiri muka* AUV. However, when results of the sensitivity analysis were compared to the risk and reliability analysis of *Autosub 6000* AUV [(157)], the findings were found to be quite similar. In the report on *Autosub 6000* AUV, mission distance and depth were analysed against risk of AUV loss. For mission distance, the results show the probability of loss increasing at a near constant rate before plateauing off at about 90 kilometres. For depth of mission, the probability of loss remains nearly constant from 1000 meters to 2500 meters before a large increase in risk occurs at greater than 2500 meters' depth. In the sensitivity analysis for *nupiri muka* AUV, risk level plateaus off at 84 kilometres for distance of mission and remains constant after 1500 meters of mission depth (Figure 2.19).

2.4 DISCUSSION AND LIMITATIONS

The application of fuzzy-based risk assessment has its disadvantages. In this section, we will discuss the approach proposed focusing on its limitations. Subject matter experts can sometimes have incomplete and episodic knowledge, especially when there is a lack of data. This can result in incorrect or incomplete fuzzy rule bases for the inference system, which lowers the model performance. Therefore, it is imperative that a suitable judgment elicitation process is adopted to enable reproducibility of the results. During elicitation of fuzzy rules, circumstances where redundant, inconsistent or conflicting rules may arise. Consequently, a significant amount of time is required to overcome this and fine-tune the model. Therefore similar to formal judgment elicitation methods, the proposed method must be applied iteratively. The inability to self-learn means the model requires consistent regular review of rules and membership functions to ensure relevancy.

To overcome some of these drawbacks and present a better risk assessment approach for the AUV community, further research can follow four tracks: 1. Expand on the list of risk variables as input into the fuzzy-based risk model. This includes having a more robust method for identifying risk variables and the use of both crisp and fuzzy risk variables in the model. 2. Develop and explore risk aggregation methods for the fuzzy-based risk models to establish a risk level for an entire AUV deployment. This usually includes a number of open water missions and under-ice missions during the deployment. Other aspects of the deployment such as launch and recovery as well as transportation of the AUV should also be considered. 3. Identify and quantify potential causal relationships between risk variables to better understand systemic behaviour. This can be performed with fuzzy cognitive maps or synthesising fuzzy logic with system dynamics or structural equation models. 4. Adopt the use of more advanced fuzzy approaches such as belief rule-base inference methodology by Yang et al [(158)]. In this approach, a fuzzy rule base takes into consideration the belief degrees in all possible consequents of a rule, which increases its accuracy. Another example is the fuzzy rule-based evidential reasoning approach, which designs fuzzy rule-base using belief structure to capture uncertainty and non-linear relationships [(159)]. Fuzzy rule-based Bayesian reasoning (*FuRBaR*) [(160)], can also be adopted to model the incompleteness encountered in establishing the knowledge by assigning subjective belief degrees. A Bayesian approach is then used to aggregate all relevant rules to prioritise potential failure modes. These advanced methods can also be used to test the robustness of the fuzzy-based risk assessment as proposed in this chapter.

There are different types of AUV. Many faster vehicles (1m/s and more) have an endurance of days whilst slower buoyancy driven vehicles (such as underwater gliders) or propeller driven vehicles (speed less than 1m/s) tend to have an endurance of months. AUVs, also vary in terms of operating depth and the required human effort for operation. Different AUV characteristics imply different membership functions and different risk variables influencing its risk of loss. When using the proposed method one must be aware of this and update the membership functions and potentially the fuzzy rules according to the vehicle characteristics. As a result, the risk profile for different AUVs also differ.

2.5 CONCLUSION TO CHAPTER

In this chapter, a fuzzy-based risk analysis framework for under-ice AUV missions in the Antarctic is presented. The use of a fuzzy-based approach is especially well-suited for an AUV program in its early phases due to the lack of historical fault log data for precise quantification of risks. It takes into account the vagueness and ambiguity of many risk factors and their causal relationships which are difficult to quantify and are usually described in natural language. The framework facilitates the capturing of knowledge and experience from domain experts, to derive a quantifiable risk level output. This output can then be evaluated against a set of risk criteria to aid decision making or to be used relatively to compare risks of different missions. Additionally, the framework can also be applied directly in the field during a deployment to assess risk in response to changes in situation. These benefits are the reasons the proposed fuzzy-based risk analysis framework is pragmatically useful for future Antarctic AUV deployments.

Sensitivity analysis enables the user to tune the model for particular risk scenarios. Our sensitivity analysis has considered five risk factors, but more variables could have been included in this analysis. We could have included other environmental and operational variables such as the distance between the AUV and the seabed, the presence of icebergs and others. We could also have included more detailed characteristics of the launch and recovery systems. The variables considered in this analysis were those deemed more important in the deployment under the Sørsdal Glacier in the Antarctic.

Advancement of this work can potentially further its application outside the AUV domain. For complex new technology there is often an absence of hard data and of expertise. This uncertainty is present in risk matrices used by organizations that are now adopting AUVs. We have proposed a method to homogenize the risk analysis used by organizations with those used for quantifying AUV risk. In doing so, a new methodology for AUV under-ice mission risk calculation is proposed. The fuzzy risk analysis framework can be adopted for other complex technologies such as other unmanned marine surface vessels or unmanned aerial vehicles [161][162], where there is an apparent lack of data. The difference between the AUV applications and other are in the variables considered and their dependencies. For example, with respect to AUV mission under-ice the mission profile risk must be calculated based on the Distance of mission, Max depth of Mission and Duration under-ice. If we apply this methodology to other technology, for example, to an unmanned ship the mission profile risk would have to consider other variables.

CHAPTER 3: ADDRESSING DYNAMIC BEHAVIOR AND INTERRELATIONSHIPS WITH SYSTEM DYNAMICS

The content of this chapter is drawn mainly from the paper “Human error in autonomous underwater vehicle deployment: A system dynamics approach.” The paper was submitted on the 22 May 2018 to the *journal of risk analysis* and accepted on 14 Feb 2020. The following authors have also contributed in the preparation of the paper; Mario P. Brito, Neil Bose, Jingjing Xu and Kiril Tenekedjiev.

The aim of this chapter is to introduce a systems-based risk analysis approach, with a structured framework, for Antarctic AUV programs. This represents an extension of the work by Brito and Griffiths [105] on the use of system dynamics in the AUV domain. The work by Brito and Griffiths [105], based on a generic “rework cycle” system archetype, represents a proof of concept for using system dynamics in risk analysis of AUV operations. Here, we proposed an additional framework to facilitate application of system dynamics for risk analysis as well as different ways to tests the model to ensure robustness.

3.1 INTRODUCTION TO SYSTEM DYNAMICS

The use of a systems approach for analysing risk was first suggested by Reason [163] when he found most accidents are the result of underlying system flaws. Since then, there has been a gradual shift in risk analysis focus, from static chain of event models to complex dynamic risk models which are more representative of real-world systems [164][165]. The importance of adopting a systems approach for risk analysis was further recognised after investigations of several high-profile industrial accidents. For instances, the Three Mile Island accident [166], Bhopal gas tragedy [167] and the Chernobyl nuclear disaster [168]. All three accidents were attributed, at least partially, to human errors of operators who played a supervisory controller role with passive monitoring of the system state. However, these human errors were the long-term effect of other systemic issues such as production pressure, poor workforce planning, weak governance, lack of communication channels, poor resource planning or placing priority on productivity over safety [111]. An AUV operator plays a very similar supervisory controller role during an Antarctic deployment. The main difference between conventional systems and AUV systems is the level of autonomy, with the interactions between human operator and autonomous system being more complex to understand. This chapter adopts valuable lessons from past industrial incidents to propose a systems-based risk analysis framework using system dynamics.

The field of system dynamics was established by Jay Forrester [169] for analysis of dynamic complex systems. Sterman [1] described system dynamics as a method to learn about dynamic complexity, understand the sources of policy resistance and design of more effective policies. System dynamics uses concepts from the field of feedback control to demonstrate how the structure of the system with its feedback loops are responsible for its dynamic behaviour.

Central to system dynamics are models representing feedback processes, expressed through reinforcing and balancing loops (Figure 3.1), stock and flow structures (Figure 3.2) and time delays [1].

A reinforcing loop is one where an initial change influences more of the same change while a balancing loop seeks equilibrium by counteracting change. In the hypothetical example shown in Figure 3.1, schedule pressure increases the occurrence of human error, which slows down mission completion rate and causes a higher incident rate. This adds further schedule pressure in a reinforcing loop (R). On the contrary, schedule pressure can also increase team productivity, which increases the mission completion rate and reduces schedule pressure in a balancing loop (B).

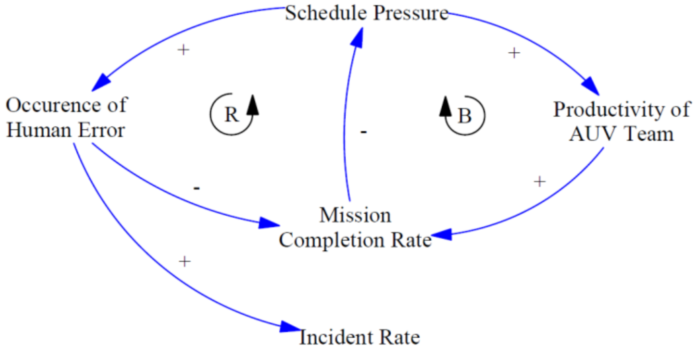


Figure 3.1: An example of a causal loop diagram showing both reinforcing feedback (R) and balancing feedback loop (B).

Stocks are referred to as entities that accumulate or deplete over time while flows define the rate of change in a stock. Stocks characterise the system state by providing inertia and memory, which can also lead to time delays when a difference between inflow and outflow rate exist. As the example in Figure 3.2 shows, the number of AUV engineers in an organisation is a stock that is increased through hiring inflow and is reduced by attrition outflow. The clouds represent boundaries of the model environment.

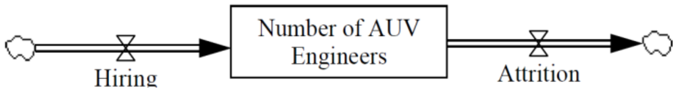


Figure 3.2: An example of a stock and flow diagram.

The widespread application of system dynamics modelling transcends disciplinary boundaries from politics to healthcare. Cooke [170] modelled the systemic issues leading to the Westray mine disaster using system dynamics methodology. The models revealed that organisational factors such as putting a priority on productivity over safety accelerated incident rates at the mine. Bouloiz et al. [171] demonstrated the use of system dynamics models to formalise causal interdependencies between safety factors in the context of a chemical storage unit. The study also shows that integration of safety factors from technical, organisational and human dimensions allow for better risk analysis, leading to improved organisational decision making. The use of system dynamics in the AUV domain was first attempted by Brito and Griffiths [105]. In their work, system dynamics models were used to analyse the impact of multiple AUVs deployments on risk mitigation efforts. Based on a generic “rework cycle” system archetype, the risk model focused on human resource management with suggestions made to investigate organisational, cultural and stress factors using the same approach. Their study represents a proof of concept for using system dynamics in risk analysis of AUV operations. However, there is no proposal of a structured framework and the study also lacks validation of the risk model.

To our best knowledge, a systems dynamics framework has never been proposed for analysing risk of AUV loss. As an extension of the work by Brito and Griffiths [105], the approach is then demonstrated through an example to examine human errors, the most common 'fault' during AUV deployments [6]. Policy recommendations are then provided to improve risk control of Antarctic AUV operations. This chaper is organised as follows: section 3.2 introduces the proposed risk analysis framework based on system dynamics. section 3.3 presents a well-developed example of the application of the framework. Finally, section 3.4 concludes the chapter with a discussion of the benefits, limitations and scope for future work.

3.2 METHODOLOGY

3.2.1 Overview

The generic risk analysis framework proposed in this paper and shown in Figure 3.3 consists of three main iterative steps with further description of each step presented in subsequent sections.

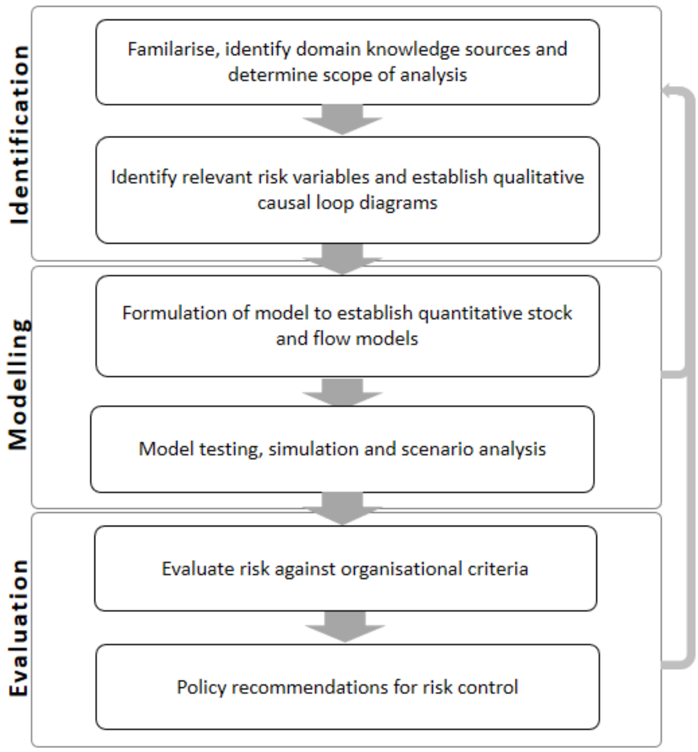


Figure 3.3: A broad overview of the proposed risk analysis framework based on system dynamics methodology.

3.2.2 Identification

The objectives of this step are to acquaint with the AUV program objectives, expected performance requirements, as well as finding and recognising causes that can lead to the loss of the AUV during Antarctic deployment. The first task is to establish available sources of knowledge about the AUV of interest. Experts' knowledge is often regarded as the best source of information [(172)], and this can come from AUV engineers, AUV program owner as well as manufacturer or contractors. Important considerations for experts' elicitation are the choice and number of experts necessary to capture both spatial and temporal risk variables of interest. While there is no formal procedure tailored specifically to risk assessment of AUV operations, guidance can be taken from the recommended selection criteria published by Pulkkinen and Simola [(124)] and Kotra et al. [(173)]. The number of experts to interview lies between 6 - 12 as recommended by Cooke and Probst [(125)]. In addition to experts' knowledge, information can also be sought from organisational documentation such as technical specifications of the AUV, safe work procedures, fault logs, risk assessment records, program schedule, budget plan, previous audit findings, organisation charts and previous incident reports. Future deployment plans and expected performance requirements also contain important information for the risk analysis.

The second task involves the investigation of context, systemic issues, existing risk controls and risk variables that can cause or culminate the loss of the AUV in the Antarctic. To address the shortfall of existing risk analysis approaches (Section 1.2) where focus very much lies on the technical dimension of an AUV, risk variables from other aspects should be considered. This includes human, organisational and external factors. As the use of AUVs is a relatively new domain, publicly available incident data are unavailable or very limited. Therefore, to faciliate a more comprehensive analysis of risk, a generic risk structure with some of the most frequently cited grouping of factors adopted from [(4)] and [(5)] is proposed (Figure 3.4). This risk structure, the first of its kind tailored for risk analysis of AUV operations, was the result of iterations of unstructured discussions and revisions with the AUV team at the University of Tasmania. Based on intuition and judgemental evaluation, the qualitative risk structure offers an indication of how the interactions between risk variables of different dimensions can influence the risk of AUV loss. It serves as a useful guide, supporting earlier established sources of knowledge. The output of this task is a list of risk variables, which may influence the risk of AUV loss.

The third task to be performed for this step is to scope the risk analysis, which includes the setting of a realistic time horizon for the risk models. A realistic scope ensures relevancy of the models and yet avoids overwhelming both model users and the analyst. To do so, considerations on the availability of resources, knowledge and time had to be made. The analysis time horizon should be sufficient enough to capture both the emergence of systemic issues leading to the risk of losing AUV and the delayed effects of potential policies. This may encompass the entire AUV program period, from design through construction and operational phase to decommissioning. The determination of scope should follow the general decision analysis principles of defining decision context [(174)(175)].

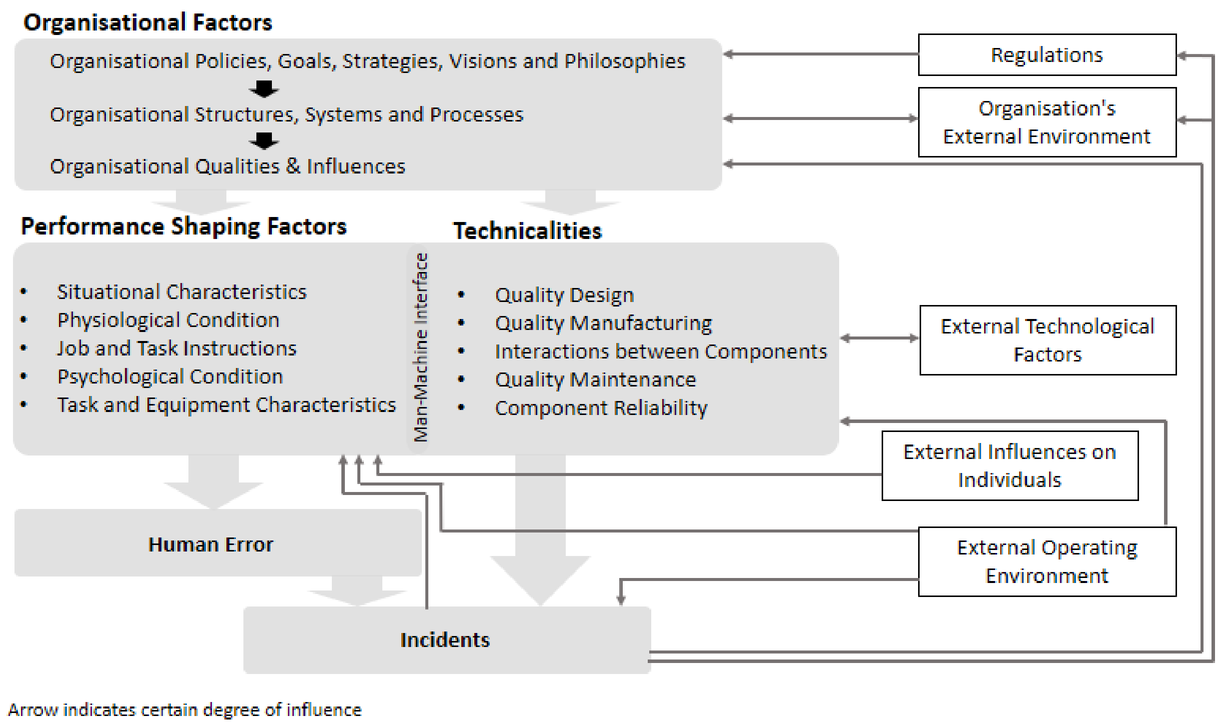


Figure 3.4: Generic risk structure influencing the risk of AUV loss with some taxonomies adapted from [4] and [5].

The last task of this step is to establish causal relationships between the identified risk variables. Using the available sources of knowledge established earlier, this step involves multiple iterations between interviews, data collection, data comparisons and causal loop diagram modelling.

Although the concept of causation is ubiquitous in every branch of theoretical science [176], one of the most commonly used criteria to determine causation was proposed by Sir Austin Bradford Hill [177]. The same criteria can be adapted to establish causality in the context of AUV risk analysis. However, it is important to note that these criteria do not provide definitive causality conclusions and a certain level of judgement is still necessary.

Once causality has been established, it can be represented in a causal loop diagram. Causal loop diagram is a qualitative graphical tool that enables the visualisation of causal relationships, describes the causal mechanism and represent feedback structure of the system [178]. In a causal loop diagram, risk variables are connected by arrows with a polarity of either positive (+) or negative (-). The polarity is positive when the effect of the first variable will cause an effect in the same direction for the linked variable. The polarity is negative when the effect of the first variable will cause an effect in the opposite direction for the linked variable [1]. Where the causal effects take time to manifest, the delay is represented by a double line (//) on the arrow. In the example shown in Figure 3.5, quality of maintenance practices affects the occurrence of technical faults for the AUV, albeit a delay effect. As the number of technical faults increases, as does the risk of AUV loss, which reduces overall trust in the AUV systems. A lack of trust reduces complacency of the AUV team, which leads to an increase in the quality of maintenance practices to complete the balancing loop. These causal loop diagrams will be the foundation for further in-depth risk analysis in the next step.

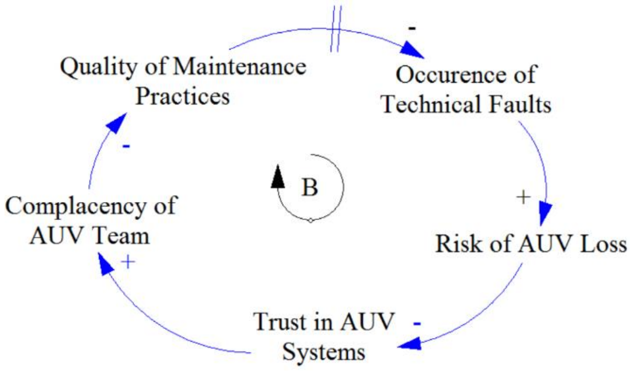


Figure 3.5: Example of positive, negative polarity, and delay effects in a causal loop diagram.

3.2.3 Modelling and Validation

Building on the causal loop diagrams developed in the previous step, the objective of this step is to further specifications of the model structures, estimate parameters, formulate causal relationships, and establish initial conditions. This yields quantifiable stock and flow models which describes the system with integral or differential equations.

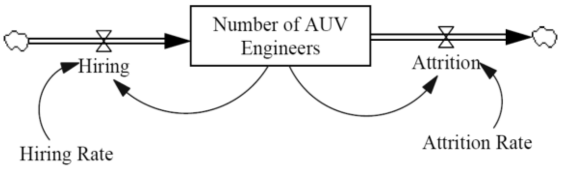


Figure 3.6: An example of stock and flow diagram, developed from Figure 3.2.

For example, consider a stock and flow model as shown in Figure 3.6. The model consists of two flows determining the stock of '*Number of AUV engineers' (Engr)*. *'Hiring'* is the inflow and *'Attrition'* is the outflow, which are influenced by parameters *'Hiring Rate' (HR)* and '*Attrition Rate' (AR)* with the following equations (3.1) and (3.2):

$$Hiring = HR \times Engr \qquad (3.1)$$

$$Attrition = AR \times Engr \qquad (3.2)$$

To simulate the model, the rate of change of the stock and the level of stock at time *(t)* is required. This corresponds to the differential and integral equation of the model as:

$$\frac{d(Engr_t)}{dt} = (HR - AR) \times Engr_t \qquad (3.3)$$

$$Engr_t = Engr_0 + \int_0^t (\boldsymbol{HR} - \boldsymbol{AR})\ x\ Engr_t\ x\ \boldsymbol{dt} \qquad (3.4)$$

Where $Engr_t$ stands for equivalent full-time AUV engineers at time t and $Engr_0$ stands equivalent full-time AUV engineers at the start of the program.

The formulation of stock and flow models consist of multiple iterations between interviews, data collection, data comparison and fine-tuning of models. Other data sources such as publications, direct observations, organisational documents or additional interview sessions can be sought to fill information gaps. The conduct of interviews at this step focuses more on the testing and formulation of the stock and flow models. Any conflicting information provided by the interviewees should be reviewed and supported by other empirical sources of data as far as possible. The outcome of this step is a set of models demonstrating how risk of loss can culminate for an Antarctic AUV program.

To test the developed models, three main approaches were taken. First, local knowledge and available historical data were used to calibrate the model. Second, a series of tests were undertaken to uncover model errors and areas for improvement. Examples of key tests to be carried out are summarised in Table 3.1, adapted from Sterman [(1)]. The testing must be performed through discussion with stakeholders until the models converge sufficiently to be deemed reflective of the real-world system by those involved in the modelling. Last, simulation results from the model were discussed and compared with domain experts' opinion.

Table 3.1: Key tests to be carried out on the developed models, adapted from [(1)].

Test	Purpose
a. **Dimensional Consistency**	Ensure that equations within the models are dimensionally consistent.
b. Extreme Conditions	Check whether models respond plausibly when subjected to extreme inputs.
c. Behavioural Reproduction	Ensure that the models are a good representation of the behaviour of real-world systems.
d. Sensitivity Analysis	Check for numerical, behavioural and policy sensitivity when assumptions about parameters, boundary and aggregation are varied over a plausible range of uncertainty.

Once sufficient confidence is gained on the developed models, simulation of the models for scenario analysis can be undertaken. Scenarios to be analysed can be derived primarily from earlier interviews and should be performed in close discussion with decision makers in preparation for the final step of the risk analysis. The finality of this step is to establish a set of systemic behaviours based on various risk scenarios which influence the risk of AUV loss.

3.2.4 Evaluation

Simulation results from the analysis can then be evaluated against pre-determined organisational criteria with eventual risk control policy recommendations. For instance, this can be an acceptable risk rating level based on the semi-quantitative risk matrix of the organisation. Insights attained through analysis of the risk models can also be used for policy recommendations through the following:

a. Improving the mental models of decision makers, experts and stakeholders of the AUV program. According to Sterman [1] and Forrester [179][180], the performance of an organisation and its systems will improve when there is a better understanding of system behaviour;

b. Identifying leverage points to institute new management strategies or decision rules for risk controls; and ;

c. Identifying leading indicators which may suggest a potential migration of risk from low to high level. This involves recognising measurable and observable risk variables in the AUV program which influences the risk of AUV loss. The AUV team's average experience for Antarctic deployment, number of technical changes on the AUV per year or AUV engineer's turnover rate are examples of possible leading indicators.

Effectiveness of recommendations can only be achieved if they are adequately implemented by organisational leaders. It is therefore critical that this step is conducted in close consultation and consideration of feedbacks from decision-makers, experts and other key stakeholders in the AUV program. Although this is the last step of the proposed risk analysis framework (Figure 3.3), the process is iterative in nature. Analysis of new information and filling of data gaps must be performed on a regular basis to ensure relevancy and more refined analysis of risks.

3.2.5 System Dynamics Modelling Software

A number of software packages facilitating system dynamics modelling and simulation is available. Three commonly used software are Stella®, Vensim® and PowerSim®. All three software promotes the development of system dynamics model with visual clarity. For this work, Vensim® is chosen due to its user-friendly interface, dimensional checks, the clear visual output of system behaviour and system status.

3.3 APPLICATION EXAMPLE

3.3.1 Overview

To demonstrate the application of the proposed framework, it is used to examine the occurrence of human error for an actual Antarctic AUV program. Although being able to operate autonomously, humans still play an important role in AUV deployments. They take control during an emergency, determine mission plans and perform the launch and recovery of the vehicle. Notably, during a four years deployment of the Autosub AUV from 1996 to 2000, Griffiths et al. [6] identified human error as the most common 'fault' instead of technological failures (Figure 3.7). These included the lack of attention, poor error checking, poor handling, distraction and wrong configuration setting. Thieme et al. (106) presented the use of a qualitative BBN to assess the role of human factors in the monitoring of an AUV during missions. Trust, workload, fatigue and situation awareness were some of the factors mentioned to affect the performance of an AUV operator. Manley (94) highlighted the importance of managing human errors during AUV operations and suggested that the best strategy to mitigate operational risk is to have an experienced and well trained AUV team. Several other studies had also found human errors playing a significant role in contributing to the overall risk of AUV loss (107)(108). The extremities of the Antarctic further amplifies the importance of managing human error not just during any mission, but also throughout the entire Antarctic AUV program. The proposed system approach is also aligned to Reason's (181) suggestion that human error originates from systemic factors and are consequences rather than causes of incident.

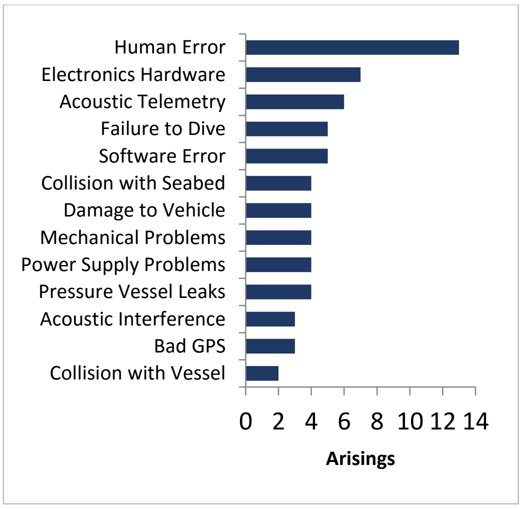


Figure 3.7: Pareto diagram of Autosub AUV failure modes during missions 1-240 by Griffiths et al. (6).

The AUV program in this example is funded by the Antarctic Gateway Partnership initiative and managed by the University of Tasmania (UTAS) in Australia. Readers are referred to section 5.1 on details of the *nupiri muka* AUV program.

3.3.2 Identification

Delivered in May 2017 to UTAS, the *nupiri muka* AUV is relatively new at the time of writing and has very limited historical failure fault log data. The task of familiarisation was therefore performed using data from trial runs, information from manufacturer's operating manual, discussions with AUV engineers, direct observations and organisational documents such as standard operating procedures and risk assessments records. Literature on other AUVs also proved to be valuable references, such as those of *Autosub* AUV, developed and operated by the National Oceanography Centre, Southampton.

The primary AUV team in UTAS consists of four personnel; a facility coordinator, an engineer, a technician and a researcher. Out of the four, only two had previous Antarctic under-ice operating experience working on other AUVs. This lack of operating experience on the new AUV was therefore identified as one key risk factor. It can increase the likelihood of human error leading to higher incident rate and consequently, a higher risk of AUV loss [182][183]. Presented with a high incident rate due to human error, the AUV owner may be reluctant to deploy the AUV to the Antarctic. Yet without actual deployment of the AUV, the team gains limited operational experience. Such a situation is analogous to the dilemma facing new job seekers where employers prefer to hire people with experience but new job seekers cannot gain that experience if nobody hires them. To mitigate the lack of experience, a series of trials were planned for and performed in a relatively benign environment (Tamar River, Tasmania) before actual deployment in the Antarctic.

Through semi-structured interviews with the AUV team which was guided by the generic risk structure shown in Figure 3.4, experience of the team, as well as other key risk variables relating to human error were identified below:

a. Human Resource (e.g Hiring and Attrition)

b. AUV Utilisation Rate

c. Management Risk Appetite

d. Average Experience of AUV Team

e. Experience Decay during Lull

f. On-the-Job Experience Gain

For this work, the scope of the analysis focuses on the incidence of human error. The time horizon for the analysis was set as 10 years, the expected operating life of the *nupiri muka* AUV.

To establish causal relationships between the identified risk variables, feedback was sought through interviews with the primary AUV team in UTAS, as well as taking reference from literature, risk assessment records and standard operating procedures. The resultant causal loop diagram is presented in Figure 3.8.

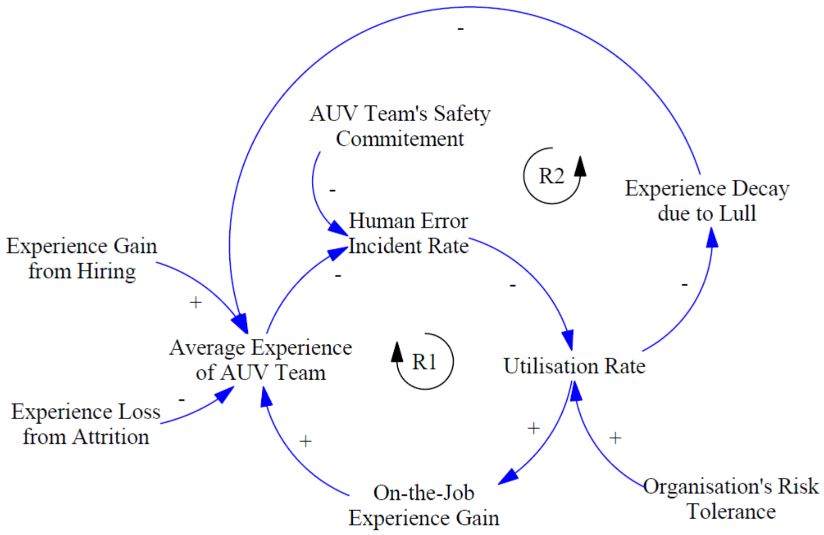


Figure 3.8: Causal loop diagram showing the influence of operating experience on human error incident rate.

The causal loop diagram shows two reinforcing loops R1 and R2. In both of them, the risk variable 'Average Experience of AUV Team' has a causal relationship to 'Human Error Incident Rate'. This causality was supported both by interviews and the literature [182][5]. In addition, the 'AUV Team's Safety Commitment' level also influences the 'Human Error Incident Rate'. Depending on the level of risk tolerance by the organisation, 'Human Error Incident Rate' then affects the 'Utilisation Rate' of the AUV with a negative polarity. A decrease in utilisation of the AUV will result in less on-the-job experience gain which decreases the average experience of the AUV team, completing the R1 feedback loop. Conversely, a decrease in utilisation of the AUV will increase the amount of experience decay due to lull and decrease the average experience of the AUV team, completing the R2 feedback loop. This decay of experience is supported by several research on memory, which has shown that a significant amount of forgetting takes place naturally over time [184][185].

The two reinforcing loops seem to aggravate the problem of the lack of operating experience through utilisation rate of the AUV. Quantification of the model is carried out in the next step.

3.3.3 Modelling and Validation

To construct quantifiable stock and flow model, figures and equations used were elicited through multiple discussions with the primary AUV team, supported by other information sources as discussed previously. Interviews were carried out in semi-structured format using the questionnaire presented in Appendix G and went through *several iterations*, with the risk model updated after each cycle. The derived stock and flow diagram consist of four stocks; 'Total Experience of AUV Team', 'Number of AUV Team Members', Human Error Incident Rate' and 'Utilisation Rate', as shown in 3.9. Details of the formulation, definitions and initial conditions used are listed in Table 3.2.

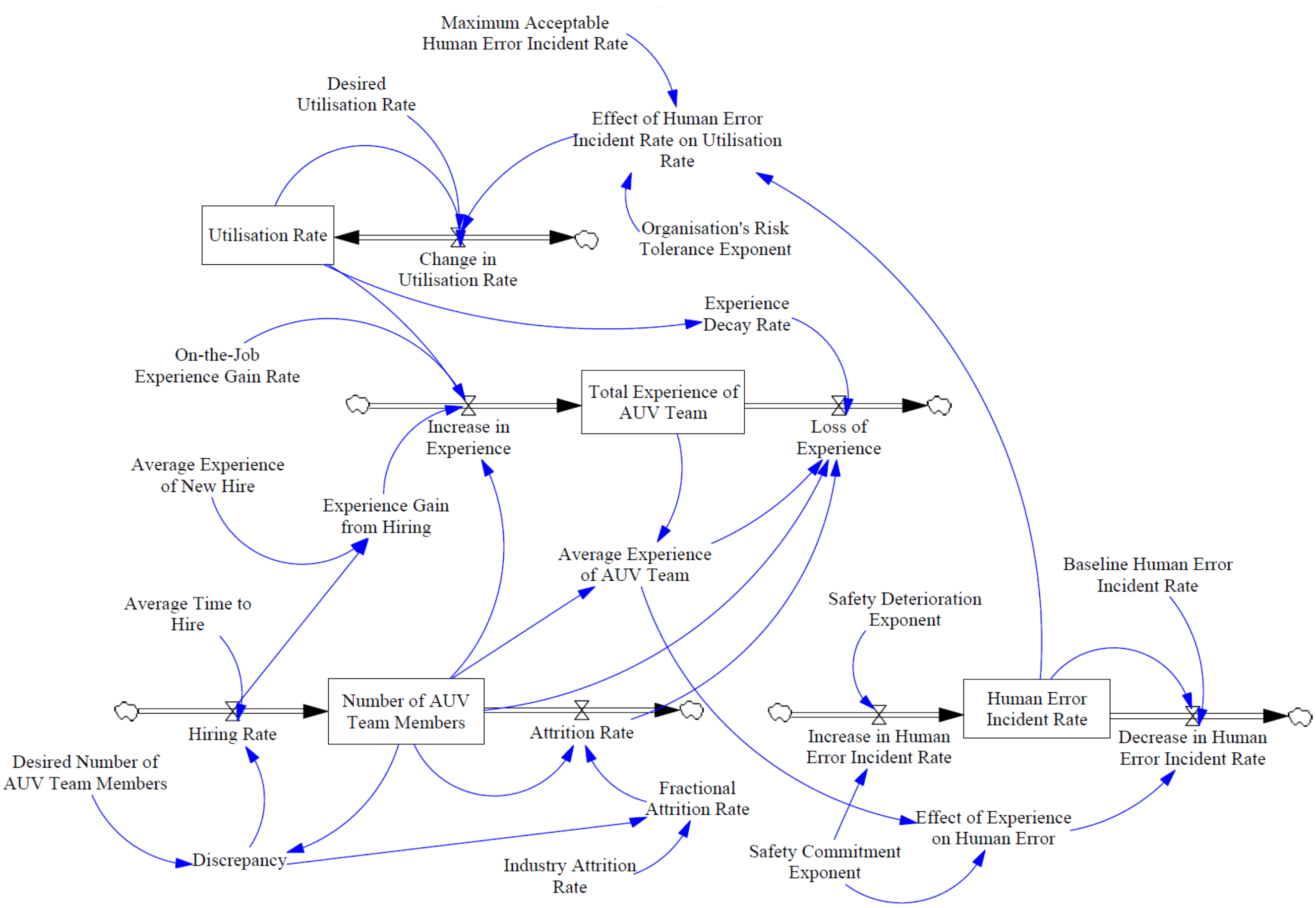


Figure 3.9: Stock and Flow diagram with four stocks.

Table 3.2: Details of the formulation, definitions and initial conditions used in the stock and flow model.

Risk variable	Definition	Equation	Remarks
Total Experience of AUV Team	The total experience of the primary AUV team in Antarctic under-ice deployment.	INTEG (Increase in Experience-Loss of Experience); Initial value = 4 Years	INTEG: Numerical Integration. Initial value is based on experience of existing AUV team.
Increase in Experience	The amount of experience gained on-the-job and from hiring.	("On-the-Job Experience Gain Rate"*Utilisation Rate*Number of AUV Team Members)+Experience Gain from Hiring	
Loss of Experience	The amount of experience loss through decay during lull and attrition.	(Experience Decay Rate*Number of AUV Team Members)+(Attrition Rate*Average Experience of AUV Team)	
Experience Gain from Hiring	The amount of experience gained from hiring.	Average Experience of New Hire*Hiring Rate	

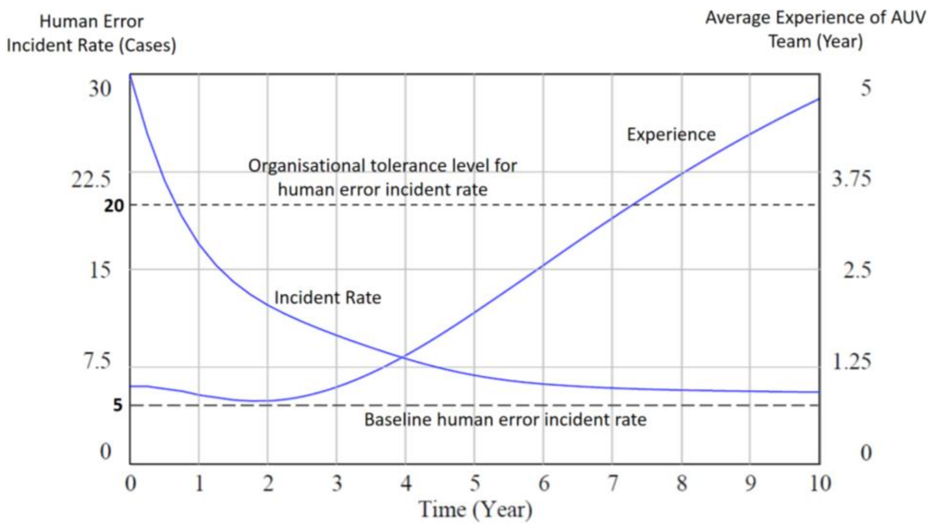
Table 3.2: (Continuation) Details of the formulation, definitions and initial conditions used in the stock and flow model.

Risk variable	Definition	Equation	Remarks
On-the-Job Experience Gain Rate	The amount of experience gained on-the-job. Set at 3 times the utilisation rate to account for preparation and planning of deployment.	3	A constant value subject to change by model user. Current value is based on existing deployment plan for the AUV. I.e. A one-week AUV mission requires at least 2 weeks of planning and preparation.
Average Experience of New Hire	The amount of relevant experience of new hire.	1 Year	A constant value subjected to change by model user. Current value is based on average experience of existing AUV team when they joined.
Experience Decay Rate	Amount of experience decay during lull. Assumed that time will be spent on non-AUV related activities during lull.	1-Utilisation Rate*3	Based on existing deployment plan for the AUV.
Average Experience of AUV Team	Average experience of the primary AUV team in Antarctic under-ice AUV deployment.	MAX (0,Total Experience of AUV Team/Number of AUV Team Members)	MAX: Maximum of two alternatives
Number of AUV Team Members	The total number of personnel in the primary AUV team.	INTEG (Hiring Rate-Attrition Rate) Initial value = 4 Personnel	Based on the number of crew in existing AUV team.
Hiring Rate	Rate at which new AUV team members are hired when there is a shortfall.	MAX (0, Discrepancy/Average Time to Hire)	
Discrepancy	Difference between desired number of AUV team members and current number.	Desired Number of AUV Team Members-Number of AUV Team Members	
Desired Number of AUV Team Members	Target number of personnel in the primary AUV team.	6	A constant value subject to change by model user. Current value is based on interviews with the existing AUV team.
Attrition Rate	Rate at which AUV team member leaves the organisation.	Number of AUV Team Members*Fractional Attrition Rate	
Industry Attrition Rate	Reported annual attrition rate by industry and region.	0.15	A constant value subject to change by model user. Current value is based on the average of best estimate by the AUV team.
Fractional Attrition Rate	The expected percentage of AUV team member leaving the organisation annually. Each excess in manpower increases attrition rate by 0.05 on top of industry attrition rate.	IF THEN ELSE(Discrepancy<0 , 0.05*Discrepancy+Industry Attrition Rate, Industry Attrition Rate)	
Average Time to Hire	Average time needed to fill a position in the AUV team.	2 Months	A constant value subject to change by model user. Current value is based on best estimate by the AUV team.
Human Error Incident Rate	Number of recorded human error related incidents.	INTEG (Increase in Human Error Incident Rate-Decrease in Human Error Incident Rate) Initial value = 30 Cases	Initial value is based on best estimate arising from trial runs in Tamar river.
Increase in Human Error Incident Rate	Rate at which new human error incidents are reported.	(1-Safety Commitment Exponent)*Safety Deterioration Exponent	

Table 3.2: (Continuation) Details of the formulation, definitions and initial conditions used in the stock and flow model.

Risk variable	Definition	Equation	Remarks
Decrease in Human Error Incident Rate	Rate at which human error incidents reduces.	(Human Error Incident Rate-Baseline Human Error Incident Rate)*Effect of Experience on Human Error	
Effect of Experience on Human Error	The degree of influence that average experience of the primary AUV team had over human error incident rate.	Average Experience of AUV Team*Safety Commitment Exponent	
Safety Commitment Exponent	Safety commitment level of the primary AUV team. Represents strength of the relationship between average experience and human error incident rate. Ranges from 0 to 1.0 with higher value indicates higher commitment level.	0.8	A constant value obtained through average values of interview inputs with the existing AUV team.
Safety Deterioration Exponent	Baseline deterioration of safety commitment by the primary AUV Team due to lack of safety initiatives. Higher value indicates more deterioration.	10 / Year	A constant value subject to change by model user. Current value is based on the average of best estimate by the AUV team.
Baseline Human Error Incident Rate	Baseline human error incidents attributed to other reasons other than experience of the team.	5 Cases	A constant value subject to change by model user. Current value is based on the average of best estimate by the AUV team.
Effect of Human Error Incident Rate on Utilisation Rate	The degree of influence that human error incident rate had over utilisation rate.	(Maximum Acceptable Human Error Incident Rate-Human Error Incident Rate)*Organisation's Risk Tolerance Exponent	
Maximum Acceptable Human Error Incident Rate	The number of recorded human error related incidents before the organisation begins to reduce utilisation of the AUV.	20 Cases	A constant value subject to change by model user. Current value is based on the average of best estimate by the AUV team.
Organisation's Risk Tolerance Exponent	Risk tolerance level of the organisation. Represents strength of the relationship between human error incident rate and utilisation rate. Ranges from 0 to 1.0 with higher value indicates risk aversion.	0.4, based on interviews with the existing AUV team.	A constant value obtained through average values of interview inputs with the existing AUV team.
Desired Utilisation Rate	Target percentage of time the AUV spends at the Antarctic in a year.	0.33	A constant value subject to change by model user. Current value is based on objectives for the AUV program.
Change in Utilisation Rate	The amount of change in utilisation rate of the AUV.	(Desired Utilisation Rate-Utilisation Rate)*Effect of Human Error Incident Rate on Utilisation Rate	
Utilisation Rate	The percentage of time the AUV spends at the Antarctic in a year.	IF THEN ELSE ((Utilisation Rate<=0, 0, INTEG (Change in Utilisation Rate)) Initial value = 2 Months	IF THEN ELSE: Alternative formulations based on condition. Initial value is based on existing deployment plans.

The model was checked for violations of physical law. For instance, real quantities such as number of AUV team members, utilisation rate and human error incident rate do not go into a negative value. Similarly, outflows from these stocks have shown to be zero if the stock is zero. The model was also checked for dimensional consistency using inbuilt <Check Units> function within the software. Any inconsistencies with units of measure were reflected by the software when the equations were checked. Extreme condition tests were performed extensively to assess its robustness. By randomly changing variables to realistic maximum and minimum values while monitoring model behaviour, these tests ensure that the model behaves in a realistic manner even with extreme inputs. After performing these tests, simulation of the model was carried out with the result shown in Figure 3.10.



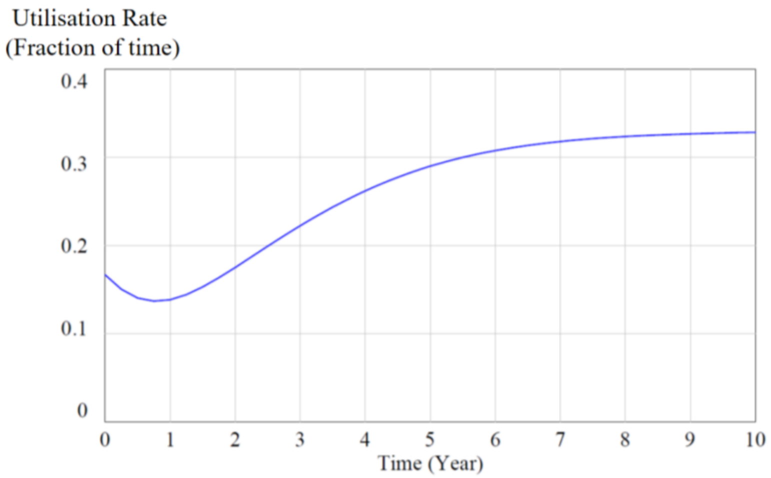


Figure 3.10: Simulation results showing the trend of human error incident rate, average experience of AUV team (Top) and utilisation rate (Bottom).

The simulation result showed that in the first 7 months of operation, the lack of Antarctic operating experience resulted in an incident rate which was above the organisation's tolerance level of 20 cases. As a result, deployment of the AUV was reduced which caused some loss of experience due to decay up to second year of the program. However, as the team gradually gain more experience through practice runs and training, the incident rate continues to decline towards the baseline level of 5 cases. This resulted in an increase in the utilisation rate. Overall, the simulation shows an overall declining human error incident rate with the increase in experience of the primary AUV team. With coherent results obtained thus far from the base model, three scenarios were simulated next to facilitate policy recommendations.

In the first scenario, the effect of having regular training and practice runs during lull periods was examined. Based on best estimate elicited from the AUV team, 'Experience Decay Rate' was reduced by half to represent having such practices during lull period to mitigate the effect of lack of actual Antarctic deployment. The assumption here is that both training and practice runs remain consistently and equally effective throughout the span of the program for each person in the AUV team. Despite this simplification, many studies across industries have shown that effective training and practice runs do reduces the occurrence of human error [(186)(187)]. Consequently, the simulation results show that there was no initial loss of experience as compared to the base scenario (Figure 3.11). In addition, there is also an apparent reduction of human error incident rate as compared to the base scenario, especially in the second and third year of operation (Figure 3.11).

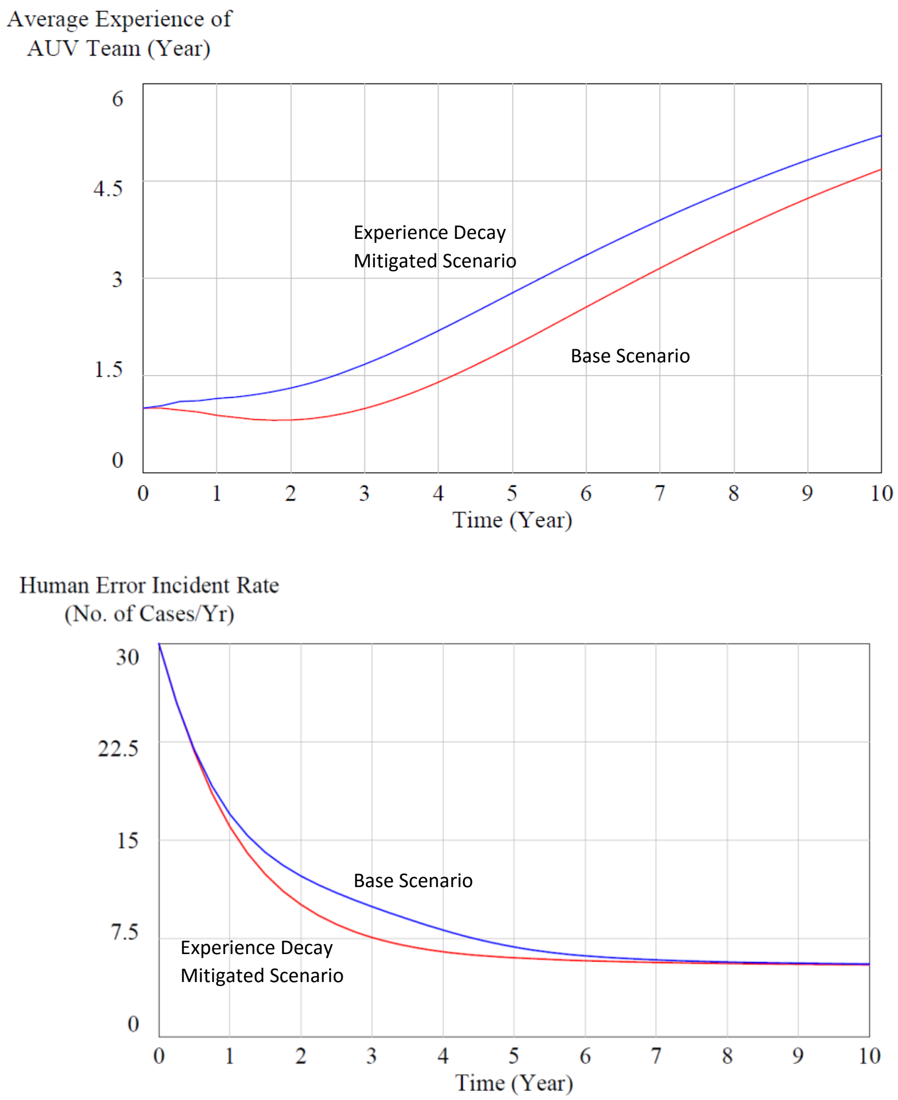


Figure 3.11: Simulation results showing the trend of average experience of AUV team (Top) and human error incident rate (Bottom) in an experience decay mitigated scenario.

The second scenario examines the impact of hiring and attrition on human error incident rate by varying the 'Average Experience of New Hire' (Figure 3.12). When recruitment policy requires new hires to the primary AUV team to have two years of relevant experience, an apparent reduction of human error incident rate as compared to the base scenario is observed. On the contrary, when there is no such requirement, the simulation shows a gradual decline in the average experience of the AUV team. This decline eventually leads to an increase in human error incident rate after the second year of the AUV program due to delays in the system. Faced with an increasing incident rate, the organisation reduces the utilisation rate of the AUV, further exacerbating the situation with even lesser opportunity for the team to gain experience. As a result, the rate of decay exceeds the rate of gain, with average experience of the team reduced to zero by the third year. Without the consideration of other factors, this may be an oversimplification of human cognitive function. However, the lack of utilisation has an undeniable negative impact on experience of the AUV team, which eventually leads to a premature end to the AUV program.

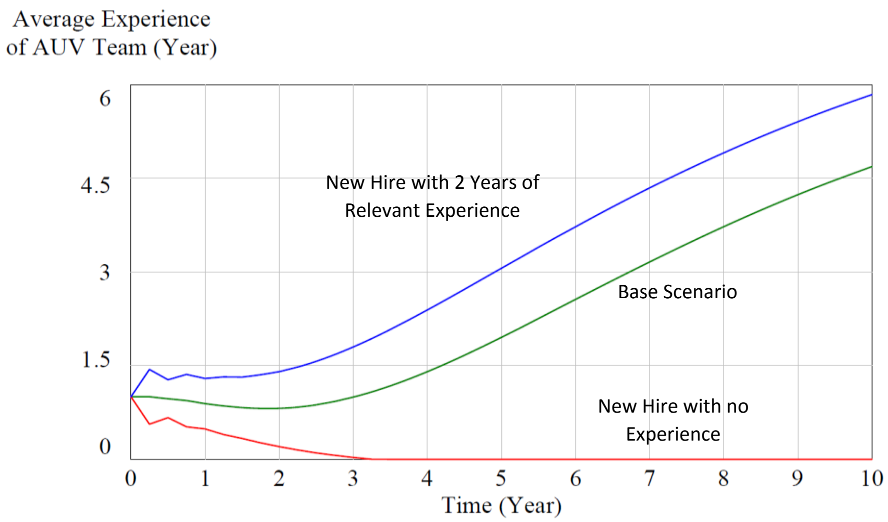


Figure 3.12: Simulation results showing the trend of human error incident rate (Top), average experience of AUV team (Middle) and utilisation rate (Bottom) in different recruitment policy.

In the third scenario, the impact of the organisation's risk appetite on human error incident rate was examined (Figure 3.13). Maximum acceptable human error incident rate, which represents either a risk-averse or risk-prone culture within the organisation was varied by ±20% for the analysis. This figure was elicited from the AUV team based on the best highest and lowest estimate of future changes in organisational risk appetite. In the risk-prone scenario, utilisation rate of the AUV was higher than the base scenario. This allows the primary AUV team to gain valuable experience which translates to lower human error incident rate after first year of the program. In the risk-averse scenario, maximum acceptable human error incident rate was decreased by 20%. With the organisation being less likely to take risks, utilisation rate of the AUV was lower than the base scenario. Consequently, the primary AUV team gains little experience if not losing experience to decay throughout the operating lifetime of the AUV. This eventually leads to a higher human error incident rate as compared to the base scenario. Although the simulation results seem to suggest that a risk-prone culture is desirable for reducing risk of loss, it is clearly not a rational recommendation without considering other factors. Instead, the simulation demonstrates the importance of establishing an optimal risk tolerance level from the beginning of the AUV program.

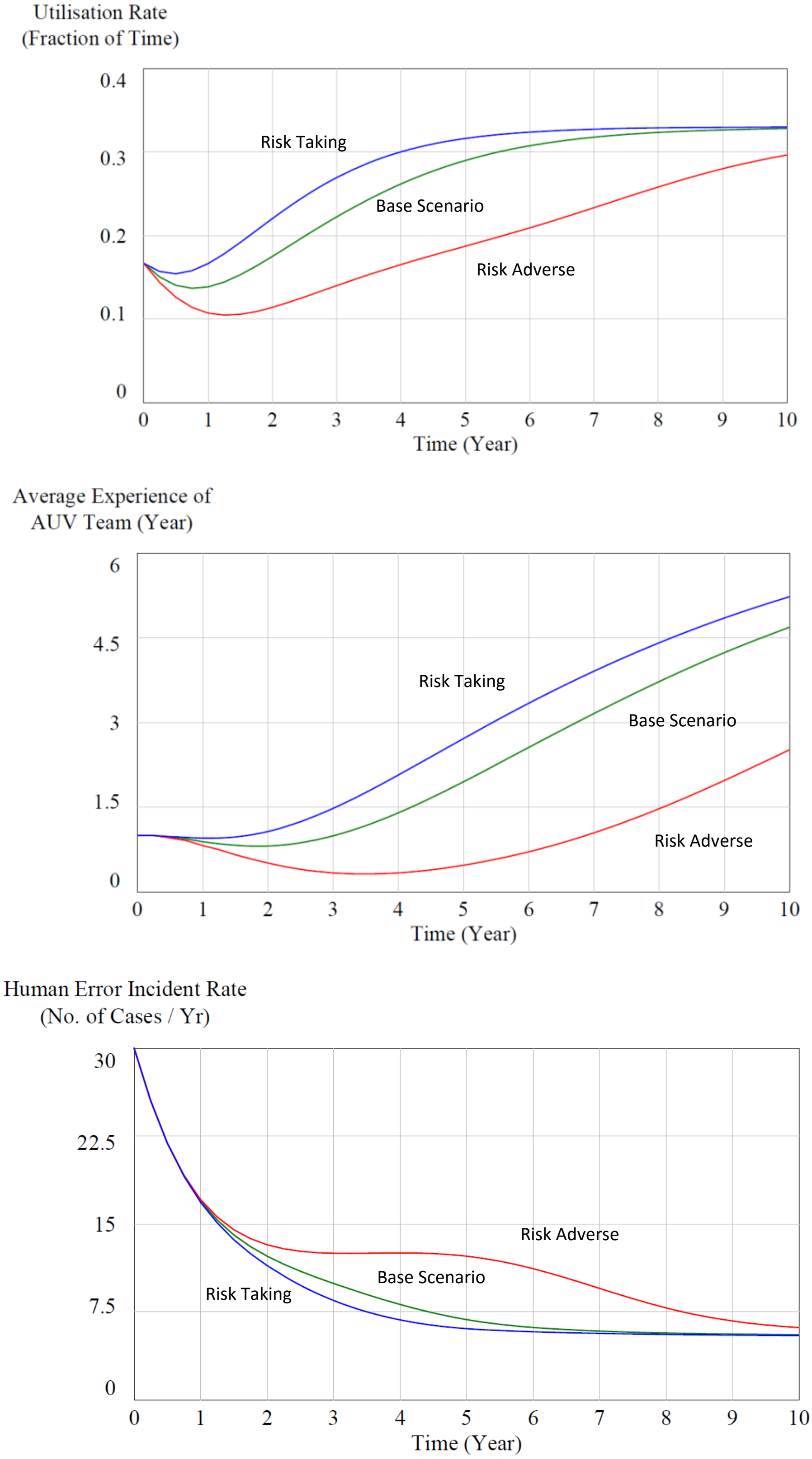


Figure 3.13: Simulation results showing the trend of utilisation rate (Top), average experience of AUV team (Middle) and human error incident rate (Bottom) in different risk culture.

The last scenario analysis consisted of having different input combinations of the above three scenarios to reflect possible real-life situations. These combinations are presented in Table 3.3 with the corresponding graph presented in Figure 3.14.

Table 3.3: Different input combinations of earlier presented scenarios, with corresponding graph number indicated in Figure 3.14.

Graph Number	1	2	3	4	5	6	7	8	9	10	11	12	13	**14 (Base)**	15	16	17	18
Training and Practice during lull Y:Yes N:No	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N
Average Experience of new hire (Yrs)	0	0	O	1	1	1	2	2	2	0	0	0	1	1	1	2	2	2
Organisation's risk appetite RP: Risk Prone, RN: Risk Neutral, RA: Risk Averse	RP	RN	RA	RP	RN	RA	RP	RN	RA	RP	RN	RA	RP	RN	RA	RP	RN	RA

The results showed that the lowest level of human error incident rate occurs when the organisation provides training and practice runs during lull, requires new hires to the primary AUV team to have two years of relevant experience and is generally risk-prone (Graph 7). On the contrary, a risk-averse environment with no training or practice runs and a team without experience will incur the highest human incident rate (Graph 12). Notably, while training and a risk-prone culture do mitigate some effect from a lack of experience in new hires (See Graph 2 and Graph 10), the human error incident rate remains higher than the base scenario (Graph 14). However, the provision of training and the requirement for new hires to have 2 years of experience in a risk-averse culture reduces human error incident rate below the base scenario (see Graph 6 and Graph 18). More importantly, the simulation shows that the order of effectiveness in reducing human error incident rate is: having 2 years of experience for new hire (Graph 17), availability of training (Graph 5) and a risk-prone culture (Graph 13).

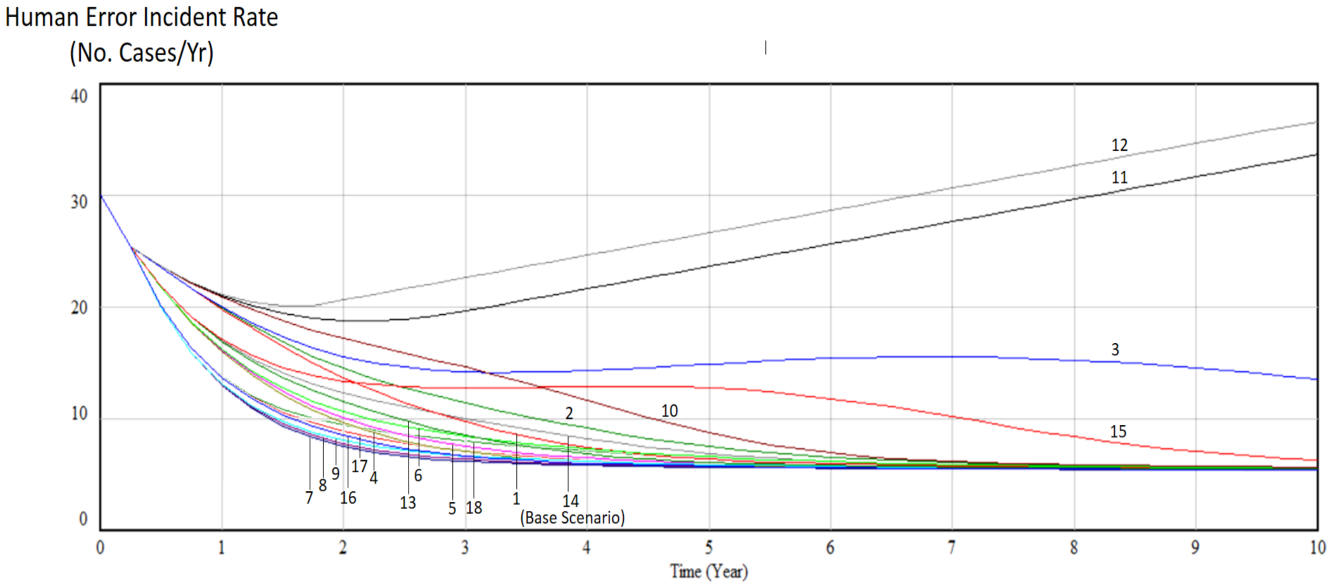


Figure 3.14: Simulation result showing human error incident rate for various combinations of scenarios.

3.3.4 Evaluation

Although simulation results from the analysis can be used to evaluate against a pre-determined evaluation criterion, an exact set of evaluation criterion has yet to be established as the program is still relatively new. Despite so, results from the scenario analysis can still be used to facilitate the formulation of risk control policies.

Simulation results from the first scenario analysis emphasise the importance of implementing a regular training regime and practice runs during lull periods which are similar to actual Antarctic deployment. This mitigates experience decay of the AUV team and consequently, reduces the risk of AUV loss during actual deployment [(188)]. It is, therefore, also logical that utilisation rate of the AUV, amount of practice run and relevant training are monitored as leading indicators to risk of AUV loss. The second scenario analysis demonstrated the impact of new hire's relevant experience on human error incident rate. Optimising the recruitment criteria on the amount of required relevant experience can, therefore, be an ideal leverage point for reduction of risk of AUV loss. Conversely, the impact of staff turnover or attrition on the risk of loss can also be analysed with the model. While it is tempting to recommend recruiting as many experienced AUV engineers as possible, considerations have to be made on the effects of team dynamics and the amount of available resources [(186)]. The third scenario analysis demonstrated that an excessively risk-averse culture may, ironically exacerbate the risk of AUV loss. This occurs when the primary AUV team loses experience through decay during lull period. While it is also illogical to ignore risks in Antarctic AUV deployment, the key to further risk reduction is to establish an optimal risk tolerance level. Finally, the combined scenario analysis shows 2 years' experience for new hire, training and a risk-prone culture are ranked in order of effectiveness in mitigating risk of AUV loss.

3.4 DISCUSSIONS AND LIMITATIONS

Despite the advantages of applying system dynamics for risk analysis of AUV operations, it also has its drawbacks. The multidimensional, dynamic and sometimes fuzzy nature of risk [(189)] can make the modelling process a challenging and time-consuming task. Trying to model all identified issues faced by an Antarctic AUV program often result in models which are too complex for any practical analysis. As shown in the example, in the consideration of just a few risk variables relating to human error can result in a relatively complex risk model. Yet, the reduction of complexity meant working with assumptions which may be subjected to differing interpretations by different people. In addition, these assumptions may deteriorate relevance of the model to actual real-world situation. Other issues encountered are the poor availability of data as well as incomplete and episodic knowledge of domain experts. Lastly, the structural view of system dynamics models is often viewed as being too deterministic in nature [(190)]. However, the origin of risk stems from uncertainties [(111)], which may not be explicitly taken into account by deterministic system dynamic models. This problem becomes especially evident when the number of uncertainties in the causal relationships between risk variables becomes very large [(191)].

To these drawbacks and improve the analysis of risk, further research can follow two tracks. First, further research can explore complimenting system dynamics with fuzzy set theory to develop a hybrid risk analysis approach. The main advantage of doing so is to account for the stochastic uncertainties in the system. This would overcome the constraint that system dynamics models are too ‘deterministic’ and result in a more robust risk analysis methodology. Additional research can explore means of effective data aggregation, especially for disparate information acquired during the risk analysis process. This can facilitate and expedite the identification of relevant risk variables, improve the clarity of assumptions and aid quantification of the risk models.

The proposed generic framework (Figure 3.3) and novel risk structure (Figure 3.4) can be adopted by any organisations that operates AUV. However, there are different types of AUV, operated by different organisations for different purposes. This implies that the issues and risk variables influencing the risk of AUV loss also varied widely. For instance, the parameters used in the application example were elicited from the AUV team and would be different for another team from a different organisation. It is important then, to tailor the system dynamics models according to the problem and intent of the organisation when applying the proposed framework. As a result, the risk profile may also differ significantly from this work.

3.5 CONCLUSION TO CHAPTER

This work presents a systems-based risk analysis approach for an Antarctic AUV program. Presented as a framework, the use of system dynamics enables a comprehensive analysis of risks for more effective policy recommendations. It overcomes drawbacks of existing risk analysis approaches, which are generally based on a chain-of-events paradigm with focus inclined towards the technical aspects of an AUV. Application of the proposed framework facilitates modelling of the complex, interrelated and dynamic systems behind an Antarctic AUV program, which may lead to increased risk of AUV loss. An example based on an actual Antarctic AUV program is presented, examining the occurrence of human error in the program.

Traditional human error analysis techniques such as Human Error Assessment and Reduction Technique (HEART) [(192)], Technique for Human Error Rate Prediction (THERP) [(193)] and others [(194)] have proven useful for estimating human error generation rate for well-defined and constrained tasks. Such techniques can also be applied to estimate human error incident rate for particular phases of the AUV deployment and operation, for example piloting. However, these techniques would not allow estimating the risk of AUV loss due to human error as a function of organisational factors. Application of the proposed framework showed an overall declining human error incident rate with the increase in experience of the primary AUV team. Three scenarios were then simulated with the following findings: First, implementing a regular training regime and practice runs similar to actual operation during lull periods mitigates the effect of lack of actual Antarctic AUV deployment. Second, the amount of new hire's relevant experience is an important leverage point for reducing human error incident rate. Last, an optimal risk tolerance level must be established by the organisation as being excessively risk-averse may ironically exacerbate the risk of AUV loss. Despite the seemingly intuitive policy recommendations, this example demonstrates how the proposed framework could be pragmatically useful for analysing more complex issues in future AUV programs.

Further advancement of this work to enhance the risk analysis framework can focus on two areas. First, to incorporate secondary methodologies such as fuzzy logic to overcome the 'deterministic' nature of system dynamics, which is presented in Chapter 4. Secondly, to work on means of effective data aggregation, especially for disparate information. The generic nature of the proposed risk analysis framework allows for application in other areas apart from risk of loss in an Antarctic AUV program. It can be relevant to different organisational needs, AUV types and usage purposes. In addition, it may also be useful for analyzing risk of other complex technological systems, such as the budding field of autonomous cars, unmanned aerial vehicles and unmanned vessels.

CHAPTER 4: CREATING A HYBRID FUZZY SYSTEM DYNAMICS RISK ANALYSIS (FuSDRA) FRAMEWORK

The content of this chapter is drawn mainly from the paper "Fuzzy System Dynamics Risk Analysis (FuSDRA) of autonomous underwater vehicle operations in the Antarctic". The paper was submitted on the 29 Jul 2018 to the *journal of risk analysis*, accepted on 12 Nov 2019 and published on 4 Dec 2019. The following authors have also contributed in the preparation of the paper; Mario P. Brito, Neil Bose, Jingjing Xu and Kiril Tenekedjiev.

The aim of this chapter is to build on the strengths while overcoming limitations of fuzzy logic as presented in Chapter 2, and system dynamics as presented in Chapter 3. The resulting hybrid FuSDRA approach aims to provide a structured, robust and effective solution for risk analysis of Antarctic AUV deployment. As presented in Chapter 3, system dynamics was used to model the complex, interrelated and dynamic systems behind an AUV program which may influence the risk of AUV loss during an Antarctic deployment. Fuzzy logic, as presented in Chapter 2, was then integrated into the system dynamics models to overcome limitations due to the lack of empirical data and accounts for the uncertainties about causal relationships between risk factors.

4.1 INTRODUCTION TO FUZZY SYSTEM DYNAMICS

This chapter presents a hybrid FuSDRA approach which addresses limitations of existing risk analysis methods in AUV deployments (Section 1.3.6). System dynamics is an objective-oriented deterministic approach. It can overcome existing risk analysis shortfalls of AUV operations in the Antarctic by modelling the complex inter-relationships between risk variables of different risk dimensions. In addition, the use of stock and flow models expressed using differential equation notation also takes into account the dynamism of time-dependent risk factors. This strength of system dynamics is well recognised outside of the AUV domain and demonstrated in risk studies across various disciplinary boundaries, from chemical (195), mining (170) to aerospace (196). However, the deterministic nature of system dynamic models does not explicitly account for uncertainties in causal relationships and soft factors. This limitation has resulted in the recent development of various hybrid system dynamics approaches (197)(198)(199) as well as qualitative system dynamics models (191). Here, we propose the integration of fuzzy logic with system dynamics to overcome this limitation.

Despite being proposed as early as 1994 (121), the use of fuzzy system dynamics remained relatively uncommon. Khanzadi et al. (200) applied the approach to determine an optimal concession period for build-operate-transfer infrastructure projects. Nasirzadeh et al. (201) used fuzzy system dynamics models to establish an optimum percentage of risk allocation between owners and contractors which helps to minimize construction project cost. Mutingi and Mbohwa (202) demonstrated how fuzzy system dynamics approach has the ability to solve real-world manpower planning problems and help organisations design more effective manpower management strategies. To our best knowledge, this is the first time the use of fuzzy system dynamics has been proposed for analysing operational risk of autonomous systems. In addition, a systematic and structured framework to facilitate application and understanding of the approach is also novel.

Utilising the strengths while overcoming weaknesses of system dynamics and fuzzy logic, the proposed approach addresses existing risk analysis shortfalls. The application of FuSDRA reveals a set of systemic behaviours influencing the risk of AUV loss. Through these insights, risk control policies can be recommended, with the eventual goal of achieving both better control and monitoring of risks. This chapter is organised as follows: Section 4.2 describes the FuSDRA approach. Section 4.3 presents an example of FuSDRA application on an Antarctic AUV program. Section 4.4 discusses the benefits, limitations and scope for future work. Lastly, Section 4.5 concludes the chapter.

4.2 METHODOLOGY

The proposed FuSDRA approach follows a three-stage iterative framework, comprising the identification of risk variables, risk modelling and risk evaluation (Figure 4.1).

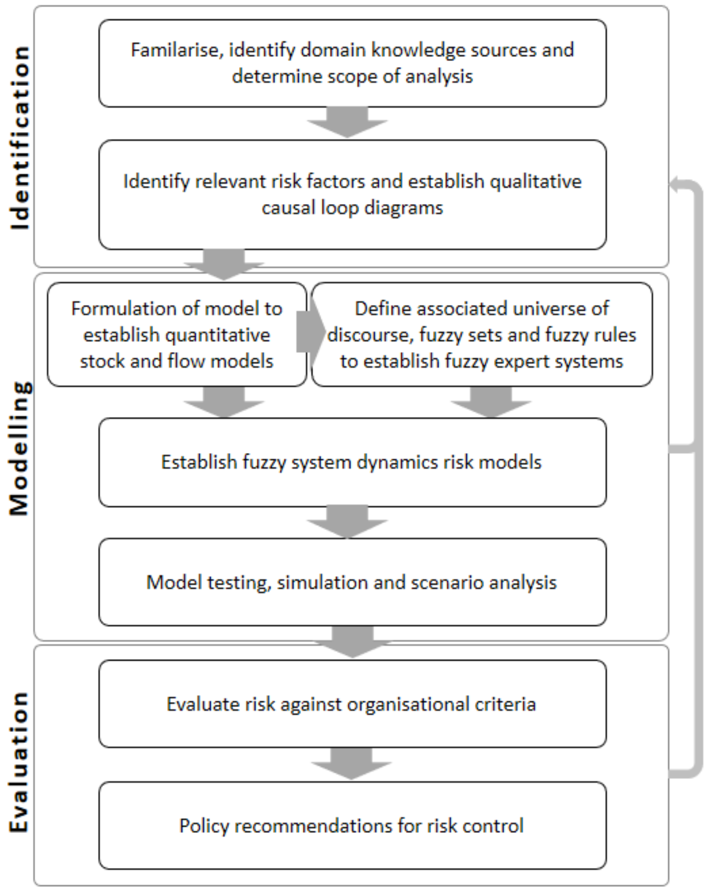


Figure 4.1: An overview of the FuSDRA framework.

4.2.1 Identification

The first task is to become familiar with the Antarctic AUV program, the subject area under consideration and to identify domain knowledge sources. Experts' knowledge is often the only and the best source of information for this process [172]. As far as possible, the number of experts to interview should lie between 6 - 12 as recommended by Cooke and Probst [125]. Experts should have different roles and specialism in the AUV domain and this can come from AUV engineers, the program owner, the manufacturers or contractors. Additional information can also be sought from organisational documents such as the safe work procedures, technical specifications of the AUV, fault logs, risk assessment records, program schedules, budget plans, Antarctic deployment plans and expected performance requirements.

Tapping into the established domain knowledge sources, the second task involves identification of risk variables that can cause or culminate in the loss of the AUV during an Antarctic deployment. To ensure comprehensiveness, risk variables from different dimensions such as human, organisational, technical and external influences should be considered. Using semi-structured interviews with experts and other identified knowledge sources, causal relationships between risk variables are then identified and represented in a qualitative causal loop diagram (CLD). A CLD enables clear visualisation of the overall feedback structure influencing the risk of AUV loss during an Antarctic deployment.

4.2.2 Modelling

4.2.2.1 Establish FuSDRA Model

The next task aims to quantify the risk of loss by constructing quantitative stock and flow models from the qualitative CLDs. This is carried out through parameters' estimation, formulation of causal relationships and establishing initial conditions. For causal relationships between risk factors which are vague and ambiguous, fuzzy logic is applied through a fuzzy expert system. The use of fuzzy expert system has many advantages. It provides consistent and objective results, help support and verify expert's opinions and allows for modelling based on data and knowledge banks [152]. More importantly, it allows for a combination of hard and soft factors as well as uncertain causal relationships to be modelled. The generic architecture of a fuzzy expert system is shown in Figure 4.2 [7]. It involves determining the universe of discourse, defining fuzzy sets and membership functions, and constructing fuzzy rules. The universe of discourse is the numerical range of possible values associated with the risk variable. To ascertain a fuzzy set, a list of typical adjectives associated with the risk variable is identified. The membership function then defines the degree to which a parameter belongs to a particular fuzzy set. Additional details on the terminologies and process involved was presented in earlier Chapter 2. An example of universe of discourse, fuzzy sets and membership functions for the risk factor 'AUV Annual Utilisation Rate' is shown in Table 4.1. Fuzzy rules, usually elicited from experts, then infer information using linguistic variables and fuzzy sets to produce an output in a process called fuzzy inference. Two of the most commonly used fuzzy inference methods are the Mandani [141] and Sugeno [142] inference. Lastly, a crisp output value is derived through defuzzification using methods such as the centroid method, weighted average method, centre of sums, centre of largest area, mean-max membership or max-membership principal [145][146].

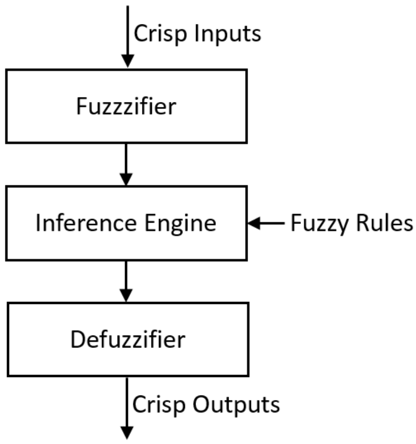


Figure 4.2: The generic architecture of a fuzzy expert system adapted from Mendel [7].

Table 4.1: An example of the universe of discourse, fuzzy sets and triangular membership function for the risk factor 'Annual Utilisation Rate'.

Risk factor	**Universe of Discourse (Units)**	**Fuzzy Sets**	**Membership Function**		
			Min	**Most Likely**	**Max**
AUV Annual Utilisation Rate (Time in water)	0 – 0.5 (Year)	Minimal	-	0	0.125
		Low	0	0.125	0.25
		Average	0.125	0.25	0.375
		High	0.25	0.375	0.5
		Extreme	0.375	0.5	-

The resultant fuzzy expert systems are incorporated with the stock and flow models to construct integrated fuzzy system dynamics risk models. To do so, the stock and flow model is first converted into a block diagram. To demonstrate this, consider the stock and flow diagram given in Figure 3.6. The stock variable *'Number of AUV Engineers' (Engr)* changes via flow variables *'Hiring'* and *'Attrition'* which are influenced by parameters *'Hiring Rate' (HR)* and '*Attrition Rate' (AR)*. The corresponding differential and integral equation of the model up to this point is given in equation 3.3 and 3.4.

Now, consider a situation where hiring rate is further influenced by *'Supply of Labour'* and *'Workload in AUV Team'* (Figure 4.3a), where causal relationships are harder to quantify deterministically due to uncertainty. To model this, a fuzzy expert system can be established through the elicitation of expert's opinion and integrated into the stock and flow model using a block diagram. Using Simulink to build the block diagram, the resultant fuzzy system dynamics model is shown in Figure 4.3b.

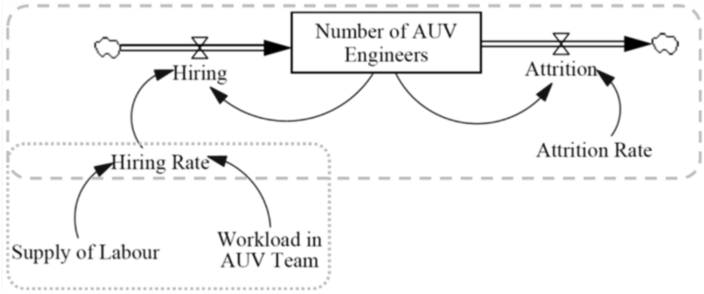


Figure 4.3a: An example of stock and flow diagram to be modelled with fuzzy system dynamics.

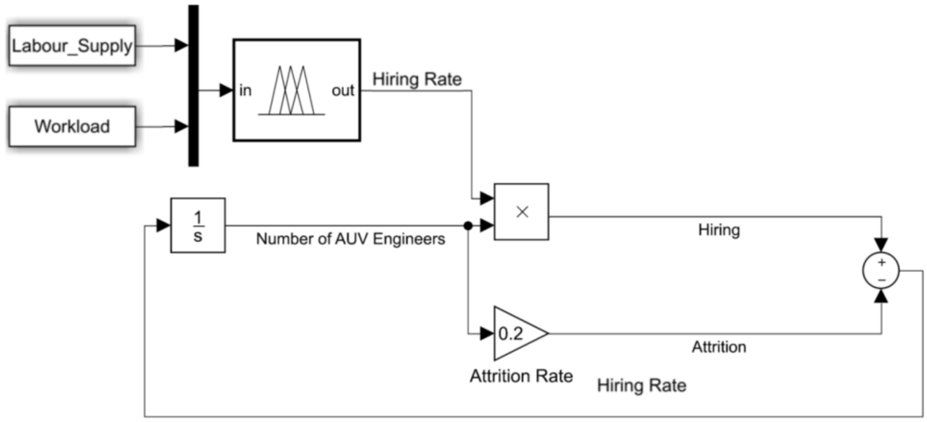


Figure 4.3b: Corresponding fuzzy system dynamics block diagram of Figure 4.3a.

4.2.2.2 Model Testing, Simulation and Scenario Analysis

To ensure relevance and suitability for its intended purpose, the established FuSDRA models should then be tested, reviewed and calibrated. A wide variety of tests are available in the literature for both system dynamics models and fuzzy expert systems. These can be broadly classified into model structure, model behaviour and policy implications tests [(1)]. The choice of tests often depends on several factors such as time and resource availability, size of the model and purpose of the model. Any unexpected behaviour revealed during the tests must be investigated and improvements made to the model accordingly. Once sufficient confidence is gained, simulation and scenario analysis can be undertaken. The types of scenarios to be analysed are selected based on discussion with the AUV team and decision maker in the AUV program; the result of which is a set of systemic behaviour influencing the risk of AUV loss in the Antarctic.

4.2.3 Evaluation

To evaluate risk, simulation results are compared against pre-determined organisational evaluation criterion. For instance, this can be an acceptable probability of AUV loss based on the capital and operating cost of the AUV [(2)]. Insights attained through analysis of the risk models can improve mental models of decision-makers and lead to the identification of leverage points. For example, the causal loop diagram can be used to communicate risk, identify missing information and dispell misconception [203]. The eventual aim is to derive and recommend risk control policies to prevent loss of AUV in the long run. To ensure the effectiveness and pragmatism of the recommended risk control policies, it is critical that decision-makers, experts and other key stakeholders in the AUV program are closely involved in the entire FuSDRA process.

The FuSDRA approach does not end in this last step of the iterative framework. During the analysis process itself, new risk factors and information can surface during both the modelling and evaluation stage of the framework. As a result, the analysis must return to the task of identification to enhance the risk model. Even upon completion of the analysis, the inclusion of new information, filling of data gaps and review of models need to be performed on a regular basis to maintain relevancy and more refined analysis of risks. Revisiting the analysis also helps to refresh knowledge and facilitate open discussions. This will ensure the effectiveness and sustainability in controlling the risk of AUV loss for future Antarctic deployments.

4.2.4 Software

For this work, Vensim® [204] was chosen for system dynamics modelling, which includes both causal loop diagrams and stock and flow diagrams. It has the advantage of a user-friendly interface, dimensional checks and visual clarity. The fuzzy expert systems were developed using the MATLAB® fuzzy logic toolbox 2017 [154]. This tool provides a comprehensive and user-friendly environment to build and evaluate fuzzy systems.

System dynamics models from Vensim® were converted into block diagrams to construct the fuzzy system dynamics models with the MATLAB® Simulink toolbox 2018 [205]. This tool allows for the construction of mathematically complex systems involving many risk factors. More importantly, it enables the incorporation of fuzzy expert systems with system dynamics models with relative ease.

4.3 APPLICATION EXAMPLE

4.3.1 Overview

To demonstrate the application of the proposed framework, an example based on the *nupiri muka* AUV program is presented. Readers are referred to section 5.1 on details of the *nupiri muka* AUV program. Delivered in May 2017, the first Antarctic deployment to the Sørsdal Glacier took place during the summer field window, between December 2018 and February 2019. The *nupiri muka* AUV is relatively new at the time of writing, with very limited historical data. Without sufficient data for any meaningful probabilistic risk quantification, the high level of uncertainty makes the FuSDRA approach highly suitable for analysing the long term risk of AUV loss.

4.3.2 Identification

The AUV operating team in the University of Tasmania consists of a facility manager, a research engineer and an engineer. They serve as the primary information source throughout the entire risk analysis process and were elicited through a series of both individual and group interviews. The semi-structured interview for individual consist of 11 questions including both open and closed questions. The group interviews were unstructured discussions focused on reviewing conflicting information provided by the interviewees to better understand the different perspectives, and to achieve a consensus. Other knowledge sources included data from trial runs, information from the manufacturer's operating manual, direct observations, standard operating procedures, risk assessments records and literature on under-ice missions of other AUVs. Two common issues which may affect long term survivability of the AUV were brought up by all members of the AUV team. They are, the securing of funding to ensure the long-term sustainability of Antarctic deployments and the hiring of niche talent who are experienced in polar AUV operations. For example, an interviewee mentioned:

> *"Getting our finances right is one of the biggest risks. If we do not have the right finance, we will not be able to run the vehicle in the first place. The vehicle costs a lot of money to run and so that money has to come from somewhere."*

The FuSDRA approach was applied to examine the impact of these two issues on the risk of AUV loss. Other risk variables associated with the two issues were also identified through the interviews, as presented in Table 4.2.

Through the interviews, causal relationships between the risk variables were also identified. For instance, an interviewer highlighted the causal relationship between "Effective AUV Age", "Technical and System Faults" and "Reactive maintenance cost":

> *"We have to be able to maintain the vehicle, have the budget, because in three to five years' time, some things need to be replaced or keep up to date."*

Table 4.2: Identified risk variables influencing the risk of AUV loss for the *nupiri muka* AUV.

Risk Dimension	Risk Variable (s)
Organisational	1. Utilisation Rate 2. Allocated Annual HR Budget 3. Reputation in AUV Operations 4. Third Party AUV Hire Contracts 5. Research Demand
Human	6. Average Experience of AUV Team 7. Human Error Incidents
Technical	8. Technical and System Faults 9. Effective AUV Age 10. Reactive Maintenance Costs 11. Preventive Maintenance Costs 12. Total Expenses of Maintenance
External	13. Commercial Demand

Each causal link was verified by the AUV team during group discussions and supported with literature when possible. The final diagram (Figure 4.4.), gradually established through the series of interviews, had a resultant reinforcing loops R1 and R2, and balancing loops B1 and B2. This diagram was reviewed and validated through group discussions, with frequent reassessment of the model until the models converge sufficiently to be deemed reflective of the real-world system by all members of the AUV team.

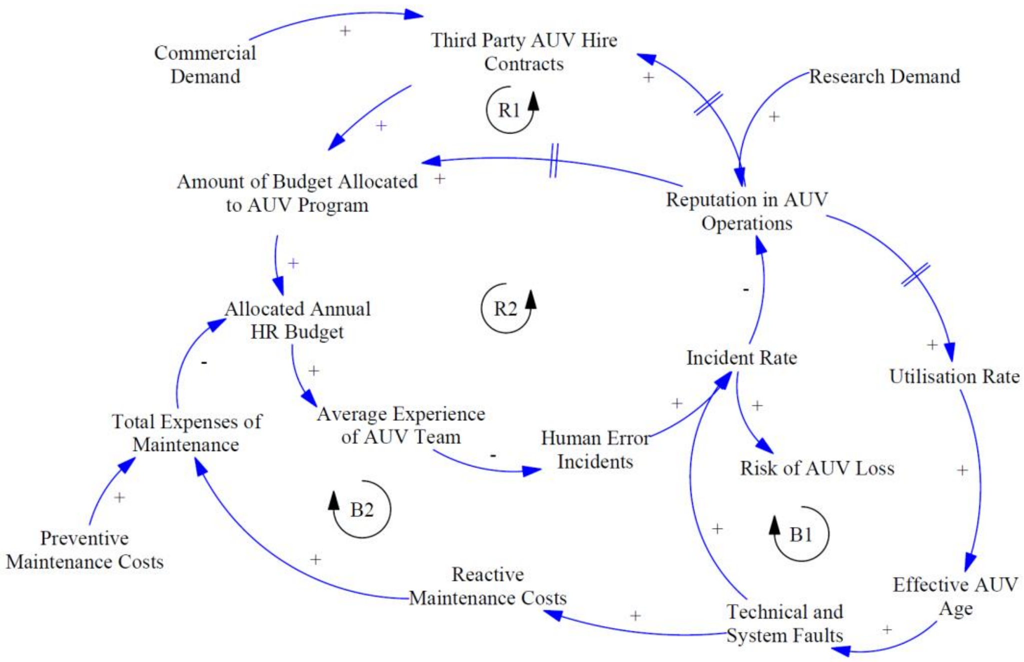


Figure 4.4: CLD showing causal relationships between identified risk factors and feedback loops.

In the reinforcing loops R1 and R2, average experience of the primary AUV operating team influences the number of human error incidents during a deployment. This causality is also supported in the literature [182][5]. Human error incidents determine partially, the overall incident rate, which reflects the risk level of losing the AUV in the Antarctic. Supporting this causality are several studies which found that human errors play a significant role in contributing to the overall risk of AUV loss [6][107][108]. The occurrence of incidents during deployments can cause delays and adversely impact reputation of the organisation in AUV operations. The level of research demand also influences the reputation of the organisation through research output such as the number of research publications. Subjected to a time delay, reputation of the organisation has an influence over the number of third-party AUV hire contracts, albeit limited by external commercial demand. Based on the amount of revenue generated from AUV hire contracts and gain in reputation contributed by the AUV program, senior management of the University then determines the amount of budget to be allocated for the AUV program in the next work year. This includes budget for human resources (HR), which can impact management strategies in areas such as recruitment, turnover and training. Logically, a higher amount of budget allocation for human resources translates to higher average experience of the AUV team, thus completing the two reinforcing feedback loops.

In the B1 balancing loop, reputation of the organisation in AUV operations determines the level of future AUV utilisation. Higher AUV usage will result in a higher rate of ageing, *vice versa*. The effective age of the AUV then directly influences technical and system failure rate with a typical ‘bathtub’ curve relationship consisting of three phases: a relatively short infant mortality phase with a decreasing failure rate, a normal operating period with low, relatively constant failure rate and a wear-out phase that exhibits an increasing failure rate. Technical and system failures determine, partially, the overall incident rate, which affects reputation of the organisation and completes the feedback loop.

In the B2 balancing loop, the level of technical and system failures affects reactive maintenance costs. Together with preventive maintenance costs, they make up the total expenses for overall maintenance. With a lump-sum budget allocation to the AUV program, higher spending on maintenance reduces the amount of budget allocated to human resources and *vice versa.*

To better analyse the interactions between feedback loops and quantify the risk of AUV loss, construction of the FuSDRA model was carried out next.

4.3.3 Modelling

Using the CLD as a basis, a stock and flow model was constructed and shown in Figure 4.5. Formulations, definitions and initial conditions were established using information sought from domain knowledge sources, as shown in Appendix C.

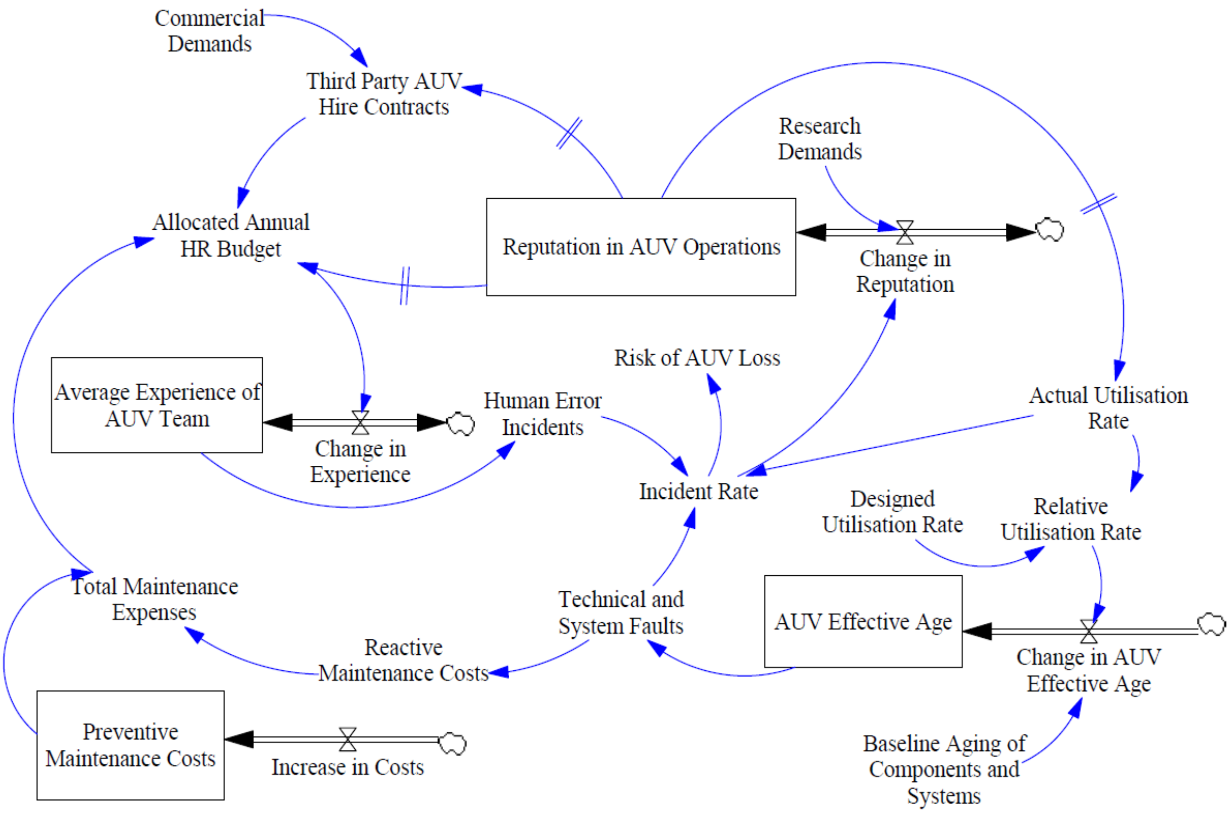


Figure 4.5: Stock and flow diagram with four stocks.

The formulations of causal relationships between several risk variables in the stock and flow model were uncertain due to a lack of data points and the presence of soft factors. These require the application of fuzzy logic through fuzzy expert systems to represent practical scenarios, which is the next step of the FuSDRA approach.

To develop fuzzy expert systems, the universe of discourse, fuzzy sets and membership function of the risk variables were identified through the semi-structured interviews with each member of the AUV team. Both triangular and trapezoidal membership functions were used as they are suited to effectively capture subjective and imprecise information, as well as being simple to compute (129). Aggregation of opinions was performed using the lowest and greatest value provided by experts as the lower bound and upper bound. The average value is then used as the modal value (130). Elicitation of fuzzy rules was then performed through group discussions with the AUV team using a hypercube matrix. A hypercube is a geometric shape of *n*-dimensions, determined by the number of input risk variables (136). For instance, a 4D hypercube can be used for a fuzzy system consisting of four input risk variables and a 3D hypercube for a three-input risk variable fuzzy system. The fuzzy rules were elicited from experts in the form of IF-THEN rules such as:

IF Research Demand is High **AND** Incident Rate is Average

THEN Reputation in AUV Operations is Good

The universe of discourse, fuzzy sets, membership functions and fuzzy rules are presented in Appendix D. Fuzzy inference was then performed using the Mandani approach as it is widely accepted for capturing experts' knowledge (143). Finally, defuzzification was carried out using the centroid method by finding a point representing the centre of gravity of the aggregated fuzzy set. It is chosen over other methods as it has the advantage of being well-balanced, sensitive to the height and width of the fuzzy output, and provides consistent results (153). The fuzzy inference and defuzzification process were implemented using MATLAB® fuzzy logic toolbox 2017 (154).

The established fuzzy expert systems were incorporated into the system dynamics model by converting the stock and flow model into a block diagram, with the resultant model shown in Figure 4.6.

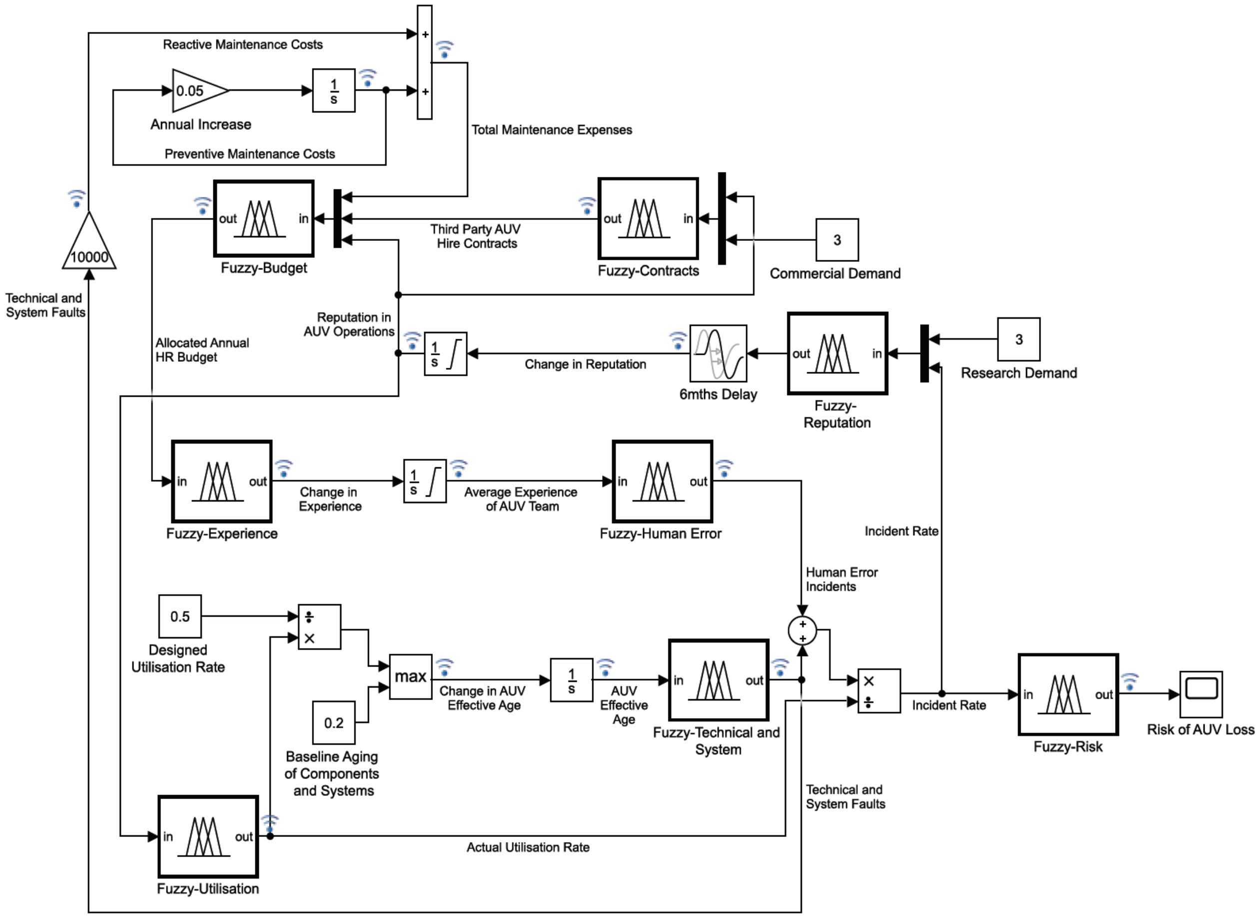


Figure 4.6: The Fuzzy System Dynamics model

The main components of the FuSDRA model include eight fuzzy logic blocks, representing the eight uncertain causal relationships formulations in the stock and flow model. There are four integrator blocks which compute the level of stock variables, 'AUV Effective Age', 'Average Experience of AUV Team', 'Reputation in AUV Operations' and 'Preventive Maintenance Costs'. Despite the *nupiri muka* being relatively new in operation, the primary AUV team had experience working on other AUVs such as the *UBC-Gavia* and the Memorial University Explorer AUV. Therefore, the initial average experience for the team was set at two years. Initial conditions for reputation in AUV operations was set as average, at 50%, due to positive publicity of the *nupiri muka* AUV program despite limited historical track record. For ‘Preventive Maintenance Costs’, the initial value was set at 50,000 AUD with a 5% annual increase to account for inflation, component deterioration and outdated technology. The integrator block outputs the integral of its input based on the following equation 4.1,

$$\boldsymbol{y(t)} = \int_0^t \boldsymbol{u(t)dt} + \boldsymbol{y_o} \quad \text{--- } (4.1)$$

where y is the output at simulation time t with input u and initial condition y_o. There are also four constant blocks and two gain blocks representing ‘Commercial Demand’, ‘Research Demand’, ‘Designed Utilisation Rate’, ‘Baseline Aging of Components and Systems’, ‘Annual Increase in Preventive Maintenance Costs’ and ‘Average Reactive Maintenance Cost per Technical and System Fault’. After discussion with the primary AUV team, both research and commercial demand were set at an average value of 5 out of 10 due to limited awareness, high cost, regulatory requirements and geographical limitations. An AUV that is kept in storage will continue to age and deteriorate. Therefore, ‘Baseline Aging of Components and Systems’ was set at an equivalent of 20% utilisation rate. ‘Designed Utilisation Rate’, the amount of time the AUV is expected to be operating in the water was set at 50%, based on a best estimate. Lastly, the ‘Annual Increase in Preventive Maintenance Costs’ and ‘Average Reactive Maintenance Cost Per Technical and System Fault’ were set at 5% and 10,000 AUD respectively. These constants and gain blocks also allow for easy future calibration of the risk model for more accurate reflection of reality.

To build confidence in the developed FuSDRA model, three main approaches were taken. First, local knowledge and available historical data were used to calibrate the model. Second, a series of tests were undertaken to uncover model errors and areas for improvement. Last, simulations results from the model were discussed and compared with domain experts’ opinion. Some key tests were carried out on the resultant FuSDRA model, including boundary adequacy, structure assessment, dimensional consistency, extensive extreme conditions and behaviour anomaly tests. To check for completeness of the fuzzy rule bases, the completeness measure approach by Jager [206] was applied. Any unexpected behaviour revealed during the tests were investigated and improvements made to the model accordingly. Once sufficient confidence was gained in the FuSDRA model through extensive model testing, custom scenarios can be created and analysed through the model.

Results from simulation of the FuSDRA model showed a declining risk of loss from 0.293 in the early years of the Antarctic AUV program, reaching a minimal of 0.206 before increasing again in later years. (Figure 4.7a). As the AUV team gradually gains experience with utilisation of the AUV (Figure 4.7b), human error incidents declined steadily towards a ‘baseline’ human error incident rate (Figure 4.7c). Number of technical and system faults exhibited a ‘bathtub’ curve, common to reliability engineering, with higher failure rates in the early phase and late phase of the AUV program (Figure 4.7d).

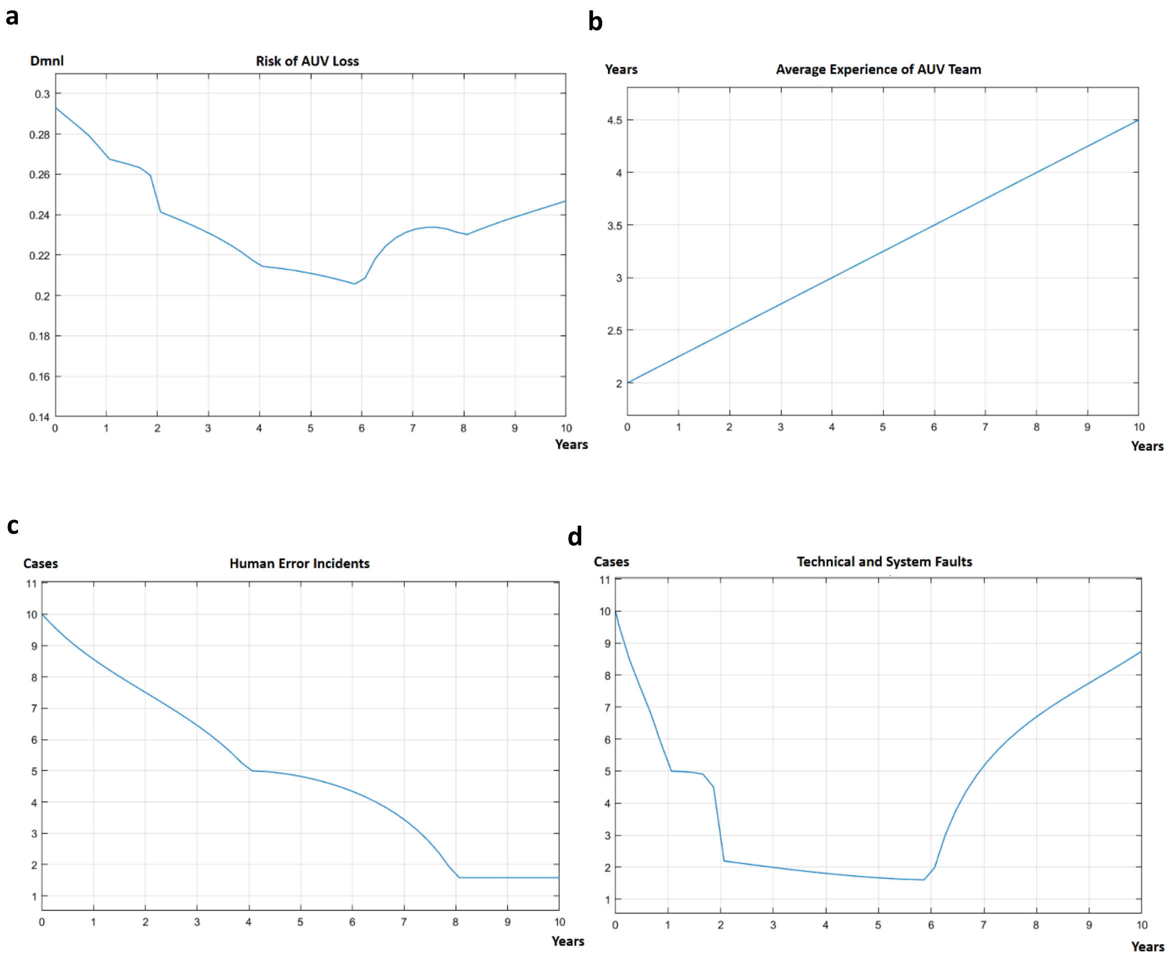


Figure 4.7: Simulation results showing the trend of a: 'Risk of AUV Loss', b: 'Average Experience of AUV Team', c: 'Human Error Incidents' and d: 'Technical and System Faults'.

To facilitate policy recommendations for risk control, various scenarios were simulated in the next step of the risk analysis. The first few scenarios concurrently checked for coherent results, useful in evaluating the accuracy of the model. Various input combinations of risk factors were then simulated next to reflect various possible real-life scenarios.

The first scenario examines how initial 'Average experience of AUV team' can affect risk of AUV loss (Figure 4.8). The initial value of 'Average experience of AUV team' was increased from two to three years to reflect hiring of additional experienced AUV engineers in the initial phase of the AUV program. Results showed an apparent lower risk of loss as compared to the base scenario, although the difference is less pronounced in later years of the AUV program. On the contrary, if the initial value for 'Average experience of AUV team' was decreased from two to one year to reflect the departure of experienced AUV engineers, risk of AUV loss became higher throughout the entire timespan of the AUV program as compared to the base scenario.

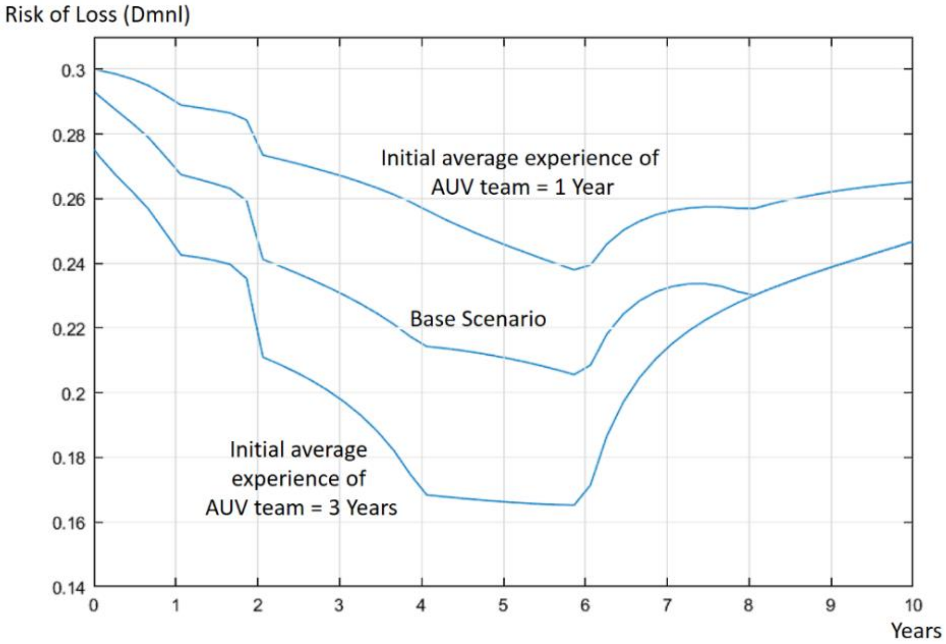


Figure 4.8: Simulation results showing the trend of risk of AUV loss for different initial average experience of AUV team.

The next scenario analyses how varying both research and commercial demand on the use of *nupiri muka* can impact the risk of AUV loss in the Antarctic (Figure 4.9a). Higher demand for the use of *nupiri muka* can occur due to increase in oceanographic activities, awareness of AUV capabilities and a favourable regulatory framework. To simulate 'average-high' demand, a value of 7.5 instead of 5.0 out of 10 were used as inputs to both 'Commercial demand' and 'Research demand'. Simulation results showed a lower risk of loss as compared to the base scenario. The contrary effect of 'poor-average' demand to reflect a situation such as technological obsolescence or unfavourable regulatory framework on the use of AUVs was simulated using a value of 2.5 as the inputs. Results showed a higher risk of risk throughout the entire timespan of the AUV program, being more pronounced in the later years. It is also noteworthy that under 'poor-average' demand, average experience of the AUV team reaches a peak between the third and fourth year of the AUV program before a steady decline (Figure 4.9b). This decline caused an increase in human error incident rates, thus exacerbating the problem further as explained in Figure 4.4 in reinforcing loops R1 and R2.

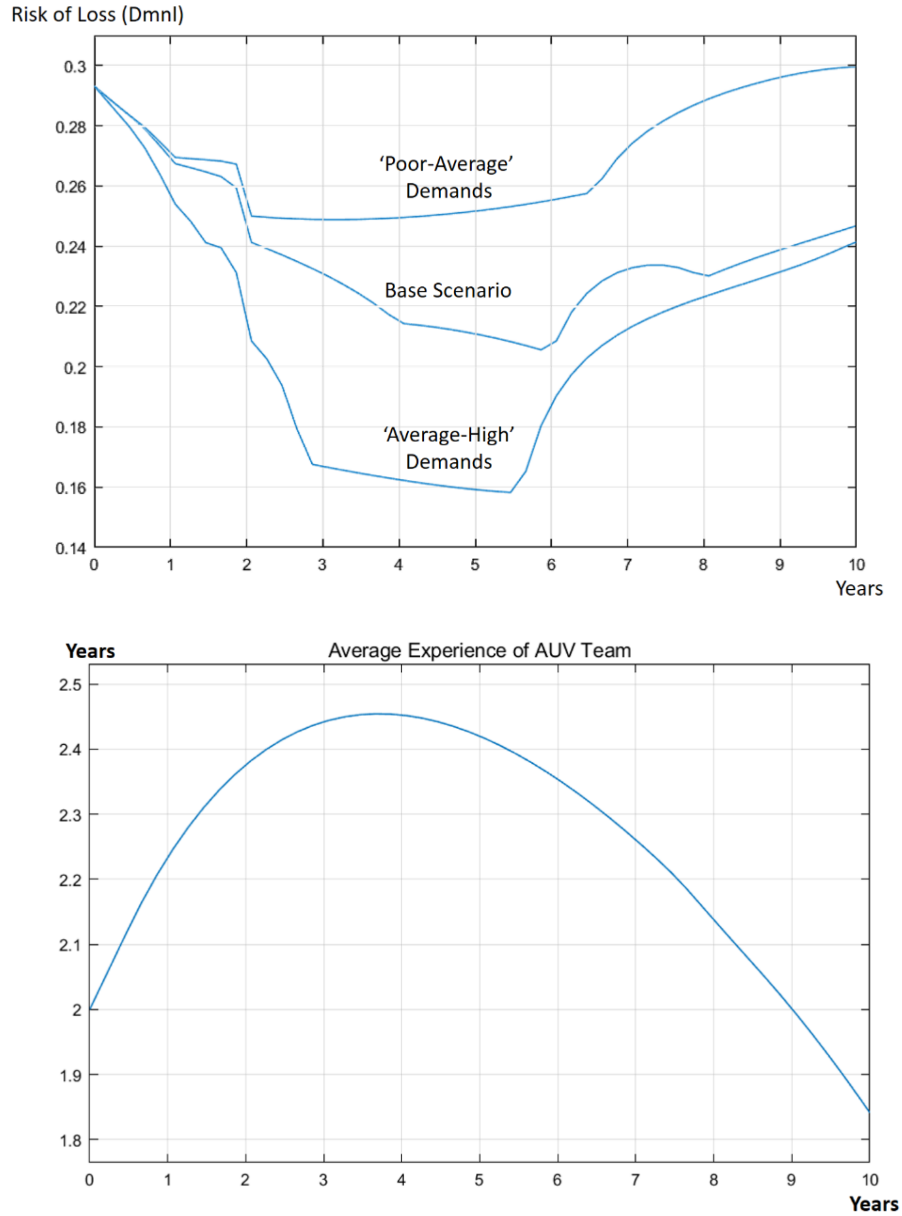


Figure 4.9: Simulation results showing (a) the trend of risk of AUV loss under different research and commercial demand and (b) average experience of AUV team under 'poor-average' demand.

With coherent results obtained thus far, the next scenario analysis consisted of having different input combinations of 'Initial average experience of AUV team', 'Research demand' and 'Commercial demand' to reflect different possible real-life scenarios. The resultant range for 'risk of AUV loss' is presented in Figure 4.10.

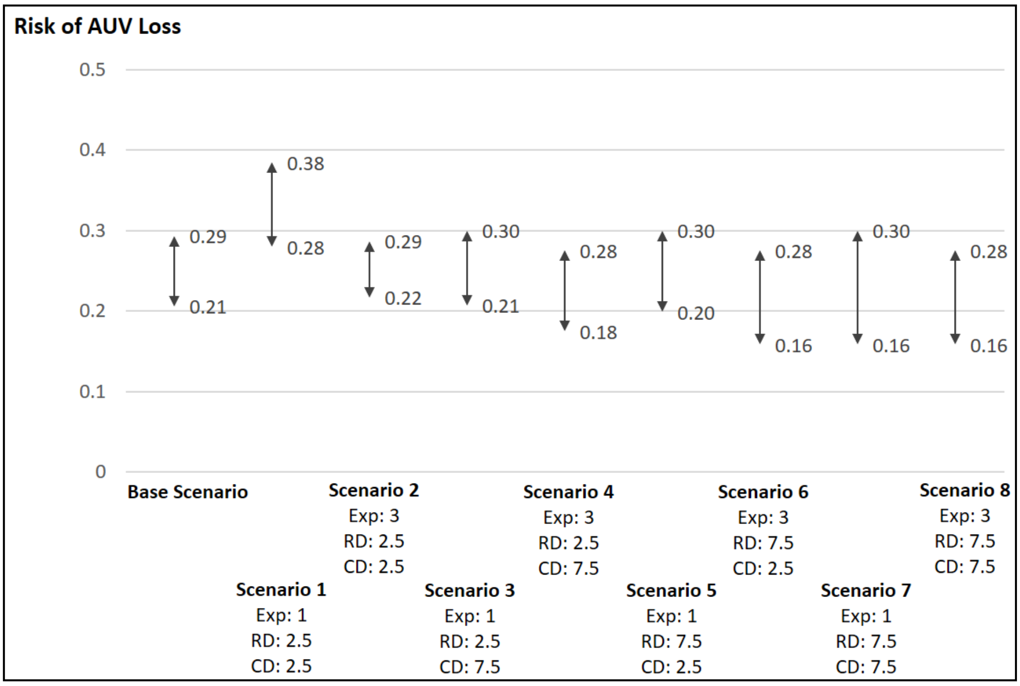


Figure 4.10: Simulation results showing range of 'risk of AUV loss' for various combinations of scenarios. Exp: Initial value for 'Average Experience of AUV Team' RD: 'Research Demand' CD: 'Commercial Demand'.

Results from the simulations showed that the lowest range for risk of AUV loss occurred in scenario 6 and scenario 8. In both scenarios, the initial average experience of the AUV team is 3 years and research demand being 'average-high' on a scale of 7.5 out of 10. Commercial demand for scenario 6 is 'poor-average' at 2.5 and 'average-high' in scenario 8 at 7.5. The significance of these results was evaluated in the next phase of the FuSDRA framework.

4.3.4 Evaluation

In principal, simulation results from the base scenario can be used to evaluate against a pre-determined evaluation criteria put forward by the AUV owner or higher management. However, the *nupiri muka* AUV program is still in its early phases with many uncertainties, such as the precise operating costs and level of value creation. Therefore, an exact set of evaluation criterion has yet to be established. The focus currently lies in ensuring the risk of loss to be as low as reasonably practicable before the first Antarctic deployment.

Despite lacking evaluation criterion, results from the scenario analysis can still be used to facilitate the formulation of risk control policies. For instance, the initial average experience of the AUV team has an apparent impact on the risk of AUV loss throughout the entire AUV program, as shown in Figure 4.8. and Figure 4.10. Therefore, it is an useful leverage point for risk control and more experienced crews should be recruited at the onset of the AUV program. Although such recommendation may seem intuitive, the FuSDRA model can support the optimising of recruitment strategy, taking into consideration other factors such as team dynamics and availability of resources. Alternatively, an intensive training regime and practice runs similar to the actual Antarctic operation should be implemented to increase hands-on-experience of the existing AUV team. Policies to boost morale and increase engagement with the AUV team may also help to reduce turnover of experienced crew and ensure knowledge retention.

The importance of having both long-term research and commercial demand to ensure ongoing utilisation of the AUV was demonstrated in both Figure 4.9 and Figure 4.10. It is therefore recommended that sustainable and effective communication channels are established both internally and externally to facilitate research collaboration. Figure 4.10 also shows that research demand seems to have more influence in reducing the risk of AUV loss than commercial demand. A higher research demand on use of the AUV would result in more research publications and a better reputation for the organisation, translating to better research funding opportunities. While commercial demand also builds upon the reputation of the institution (207), it is an external variable which can change rapidly due to momentous political, economic, sociological and technological changes (208). However, in a realistic context of limited funding sources, it is not practical to recommend using the AUV solely for pure research or commercial works. Instead, the simulation result suggests that priority should be given for research purposes over commercial works. The AUV owner should also constantly support and encourage its own internal use of the AUV. High internal demand can also help to mitigate the effects of poor commercial demand and an AUV team with low experience. Finally, it is also logical to monitor the average experience of the AUV team and the level of demand for both internal and external use as leading indicators to risk of AUV loss.

4.4 DISCUSSION AND LIMITATIONS

The multidimensional, dynamic and sometimes fuzzy nature of risk (189) makes the FuSDRA approach highly effective in analyzing risk of AUV loss in the Antarctic. It overcomes the shortcomings of existing risk analysis methods by taking into account complexity of the system, dynamic nature of risk variables, uncertainties in causal relationships as well as soft factors which are difficult to quantify. Therefore, the resultant risk control policy recommendations, if implemented, are expected to be more reliable and effective than those put forward by existing risk analysis approaches. As demonstrated in the application example, the FuSDRA approach, being without complex mathematical computations is relatively easy to understand and apply. The risk analysis process itself presents an invaluable learning opportunity for the involved stakeholders. Iterative discussions revealed insights on possible leverage points, indicators and decision rules to better manage the risk of AUV loss. In addition, regular review of the risk model not only helps to ensure relevance and sustainability of risk control efforts, but these sessions also act as refreshers on risk mitigation strategies for the stakeholders.

In our application example, the FuSDRA approach makes an attempt to capture the impact of funding and recruitment on the AUV risk, providing means to inform the implementation of risk management strategies. This enables AUV owners to adapt risk management strategies to the environment in which the department operates.

Despite the advantages of the FuSDRA approach in analyzing risk of AUV loss in the Antarctic, we also recognise that there are limitations. One major limitation is that the approach is dependent on expert judgement, which is subjected to bias. AUV experts come with a varied level of experience working with different types of AUVs. Even those who have had Antarctic experience may have worked for different organisations with various objectives. As a result, assumptions, perceptions and expectations differ between experts, often resulting in inconsistent or conflicting opinions during construction of the FuSDRA model. Similar issue was also encountered in other studies involving fuzzy logic (209)(210). Exacerbating this problem is the fact that risk of AUV loss is a complex problem involving many risk variables. Attempts to include all suggested risk variables in a single risk model often results in models which are too complex for any practical analysis. To reduce the complexity of the risk model meant that assumptions had to be made, which may be subjected to differing interpretations. Lastly, the inability of the FuSDRA model to self-learn means that regular review is required to ensure the relevance and sustainability of risk control efforts. Despite these limitations, the long-term reduction to risk of AUV loss arising from implementation of the recommended policies justifies the effort for the modelling.

To overcome some of the mentioned challenges to further improve risk analysis of AUV operations in the Antarctic, further research can follow two tracks: First, to account for varying degrees of trust in experts in the risk model. This can be done with the use of intuitionistic fuzzy logic, which is an extension of classical fuzzy logic. It deals with vagueness by assigning to each element a membership degree and non-membership degree. Inputs provided by each individual experts can then be assigned a 'certainty degree' based on the level of trust (211). Secondly, to explore means of optimising fuzzy rules and facilitating self-learn by applying optimisation methods such as a genetic algorithm, neural networks or simulated annealing among others.

There are many different types of AUVs and organisations use them for different purposes in the Antarctic. This implies a wide variety of risk variables may influence the risk of AUV loss depending on the context. It is therefore important, to tailor the FuSDRA approach according to the identified problem and intent of the organisation. As a result, the output may also differ vastly depending on the organisations, vehicle characteristics or deployment types, and should only be compared with caution.

4.5 CONCLUSION TO CHAPTER

The deployment of AUVs in the Antarctic is of relatively high risk due to the extreme environment, which pushes the limits of both human and AUV technology. However, the risk of AUV loss is a dynamic and complex problem, influenced not only by Antarctic's operating environment but also other risk variables. It is under such situations that the AUV owner often has to devise risk control measures and make difficult deployment decisions. Existing risk analysis approaches tend to be discrete-based and focus more on technicalities of the AUV, often neglecting risk variables from other risk dimensions including soft factors which are often neglected due to difficulties in quantification.

To overcome existing shortfalls, this chapter presents an integrated FuSDRA approach to achieve both better control and monitoring of long term risk of AUV loss in the Antarctic. System dynamics was used to model the dynamic complex inter-relationships between risk variables influencing the risk of

AUV loss. Fuzzy logic was then integrated into the system dynamics models to account for uncertainties in causal relationships and soft factors. The proposed hybrid FuSDRA approach follows a three-stage iterative framework comprising of identification of risk variables, risk modelling and risk evaluation.

To demonstrate the application of FuSDRA, it was applied to the *nupiri muka* AUV program, managed by the University of Tasmania. A risk model was constructed, and simulation of the resultant risk model showed a declining risk of loss in the early years of the AUV program, reaching a minimal level before increasing again in later years. Scenario analysis was then performed to validate the risk model and facilitate policy recommendations. Results showed that the initial 'Average experience of the AUV team' is a suitable leverage point for reducing risk of AUV loss, which can be increased or maintained through recruitment, staff retention, as well as training and practice runs. Also demonstrated was the importance of having both external commercial and internal research demand on the use of the AUV for reducing risk of loss. As commercial demand may fall outside the control of the organisation, priority should be placed on internal research demand. AUV owners should continuously support and encourage their own use of AUV for research purposes as increased usage can help control risk of AUV loss in the long run. It is also recommended that the average experience of the AUV team and the level of demand for both internal and external use of the AUV be monitored as leading indicators to risk of AUV loss. These results arising from FuSDRA translates into policy recommendations to manage and control the risk of loss. For example, the University can implement an operation policy which places a priority on internal research use of the AUV over commercial use. There can also be a recruitment policy which requires new AUV crew to have a minimal of 3 years relevant experience. In addition, the risk analysis process, which revealed and analyses new risk variables, helped to improve mental models of decision-makers. For example, the role of organisational reputation and demand on AUV use have never been considered in other risk studies on AUV operations.

In summary, the FuSDRA framework provides a systematic and structured approach for risk analysis of AUV operations in the Antarctic, facilitating the building and customizing of risk models in accordance with the context of circumstances. It overcomes limitations of existing AUV risk analysis approaches, improves comprehensiveness of the analysis and can be used as a decision support tool. In the face of increasingly complex AUV operations such as higher autonomy and multi-vehicle missions, FuSDRA can help to understand the effectiveness of different risk management strategies. Due to the generic nature of the approach, the framework can also be applied to other types of AUV operations apart from Antarctic deployment. It may also be relevant to similar complex technological systems, such as the budding field of autonomous cars, unmanned aerial vehicles and unmanned vessels. The commonalities that they share is the apparent lack of data and the potential for low probabilities and high consequences accidents [212][213][214]. The only foreseeable difference between application of the FuSDRA approach to AUV and other technological systems lies in the risk variables being considered.

The proposed FuSDRA framework is not only useful to practitioners for analysis of risk. Academically, it also explores further into the concepts of non-probabilistic risk modelling, which is often challenging in real-life problems. Therefore, the FuSDRA approach provides both contribution to knowledge, as well as a pragmatic tool for the AUV community for better analysis of risks. Further advancement of this work to enhance the FuSDRA approach can focus on data aggregation, intuitionistic fuzzy logic as well as optimization and self-learning of the risk model.

CHAPTER 5: CASE STUDY – RISK ANALYSIS OF THE *NUPIRI MUKA* AUV PROGRAM

The content of this chapter is partially presented in two paperss. The first paper, “A hybrid fuzzy system dynamics approach for risk analysis of AUV operations.” was submitted to *Journal of Advanced Computational Intelligence and Intelligent Informatics* on 15 Mar 2019, accepted on 29 Aug 2019 and published on 20 Jan 2020. The following authors have also contributed in the preparation of the paper; Mario P. Brito, Neil Bose, Jingjing Xu, Natalia Nikolova and Kiril Tenekedjiev. The second paper, “Policy Recommendations for Autonomous Underwater Vehicle Operations Through Hybrid Fuzzy System Dynamics Risk Analysis (FuSDRA).” was accepted for publication in the Proceedings of the *International Association of Maritime Universities Conference (IAMUC) 2019* on 26 Aug 2019 with in press date 29 Oct 2019.The following authors have also contributed in the preparation of the paper; Mario P. Brito, Neil Bose, Jingjing Xu and Kiril Tenekedjiev.

This chapter aims to demonstrates application of the FuSDRA framework on an Antarctic AUV program. The case study is grounded on the *nupiri muka* AUV program, which is funded by the Australian Research Council (ARC) Special Research Initiative for Antarctic Gateway Partnership and the Australian Maritime College (AMC), University of Tasmania. The chapter starts with an overview of the *nupiri muka* AUV program, presenting relevant background information useful for analysing the risk of AUV loss. Thereafter, the stepwise FuSDRA framework and outcome models are presented, followed by model testing and scenario analysis. Simulation results were then evaluated against organisational criteria with eventual risk control policy recommendations. Lastly, the chapter closes with a conclusion to the case study.

5.1 OVERVIEW OF THE *NUPIRI MUKA* AUV PROGRAM

The name *nupiri muka* means ‘Eye of the Sea’ in *palawa kani,* the language of Tasmanian Aborigines. Funded by the Antarctic Gateway Partnership and the University of Tasmania, the primary objective of the *nupiri muka* program is to develop a polar capable AUV for the acquisition of high-quality underwater data. Apart from bathymetry and physical oceanography surveys beneath Antarctic’s ice, the vehicle is also equipped with a suite of other scientific instruments to support the four research themes of the Antarctic Gateway Partnership. The program itself falls under theme 4 (Marine Technology and Polar Environments) of the partnership. The interested reader is referred to Appendix E for additional details on the Antarctic Gateway Partnership initiative.

5.1.1 Program Objective and Timeline

The dynamic nature and complexity of risk meant that factors that can cause or culminate in the loss of *nupiri muka* AUV in the Antarctic may reside in different phases of the program. It is, therefore useful to have an understanding on the project timeline to account for time-dependent risks factors and setting a time horizon for the risk analysis.

At the beginning, the original project synopsis aimed to produce a baseline AUV which is versatile and modular in nature. This would allow for future enhancement to sensors and tooling capabilities on the AUV for tailoring to specific mission requirements. The tender process for such a state of the art AUV started back in 2015. The contract was subsequently awarded to International Submarine Engineering (ISE) from Canada at approximately 5 million AUD. Apart from the physical AUV, the contract also included sea trials and acceptance, handling equipment such as cradle and dollies, and launch and recovery lines/slings. The explorer-class AUV was eventually delivered in May 2017 to UTAS and underwent a series of trials in a relatively benign environment, mostly in the Tamar River, Tasmania. The first Antarctic deployment to the Sørsdal Glacier took place during the field season of December 2018 to March 2019. Being more of an engineering trial than scientific survey, the Antarctic deployment demonstrated the capabilities of *nupiri muka* AUV in under-ice missions and helped improve the operational model for future similar deployments. The overall project timeline is presented in Figure 5.1, with a target AUV service life of 10 years.

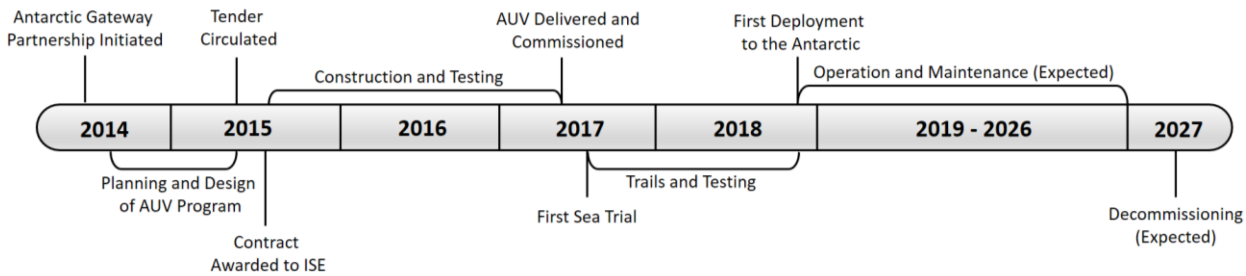


Figure 5.1: Planned timeline of the *nupiri muka* AUV program.

5.1.2 International Submarine Engineering Ltd. (ISE)

As one of the leading companies in the AUV business, ISE has delivered more than 30 AUV systems globally since its formation in 1974. Over the years, the company has received various awards from international bodies such as the Marine Technology Society, the IEEE Oceanic Engineering Society and the Offshore Energy Center Hall of Fame. Apart from AUVs, ISE also develops and manufactures ROVs, towed bodies (towfish) and human-occupied submersibles.

ISE AUV's were the first to carry out operation under the Arctic icecap and have conducted the longest missions of any AUV in both under-ice and open water environment. Apart from the *Theseus* AUV and two Arctic *Explorer* vehicles owned and operated by Natural Resources Canada, the *nupiri muka* is ISE's fourth under-ice capable AUV. This Explorer-class AUV is the core of ISE's AUV product line, with the first Explorer AUV delivered in 2003 to Ifremer, a French oceanographic agency. Including the *nupiri muka*, there are currently more than ten Explorer-class AUV in operation, owned by various scientific agencies, ocean survey companies and government organisations. This track record for reliability and quality manufacturing plays a critical role in influencing the risk of AUV loss and is taken into consideration during the risk analysis.

5.1.3 Technical Specifications of nupiri muka AUV

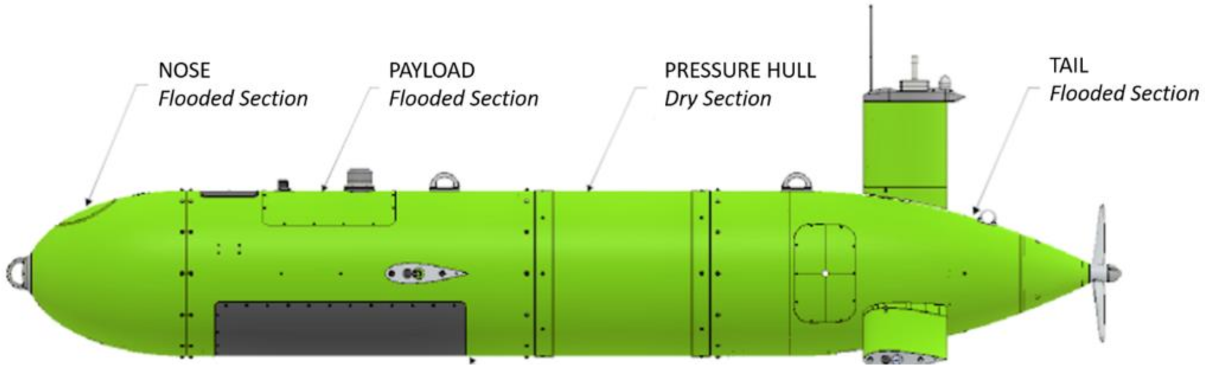


Figure 5.2: Overview of a typical explorer-class AUV.

The *nupiri muka* is a 6.3m long, 1.6 tonnes and 5000m depth rated AUV. It consists of a torpedo-shaped body with four aft control planes, two forward control planes, a propeller, and surface features in the form of transducers, antenna, and a strobe light. A typical explorer-class AUV is shown in Figure 5.2. The main body of the AUV comprises of a pressure hull and free-flooding payload sections. Within the pressure hull lies all the batteries and dry electronic components such as the Vehicle Control Computer (VCC). The free-flooding sections, including the nose and tail, house all the wet electronics and sensors, including payloads, acoustic sensors, Doppler velocity log, bottom avoidance sonar and depth sensor. The bottom avoidance sonar resides in the nose of the vehicle while the aft section houses the propulsion unit. The modular design of the vehicle allows easy access to components and sensors, which also enables a user to upgrade the vehicle without the need for re-engineering, reducing the risk of technical failures (92). A brief description of the critical systems relevant to the risk of AUV loss are presented below, with additional technical specifications based on the manufacturer's manual located in Appendix F

a. **Power System:** Currently powered by rechargeable lithium-ion battery modules in the pressure hull. It has a present cruising range of approximately 140 km with a standard charging time of approximately 10-12 hours.
b. **Control System:** The four aft planes and rudder control pitch and yaw while the forward planes enhance stability and provide heave and roll control. The vehicle control computer (VCC) inside the pressure hull provides guidance and control using information from the AUV sensors and actuators. The surface control computer (SCC) displays the primary Graphical User Interface (GUI) used for piloting the AUV on the water surface, performing pre-dive testing and managing mission downloads to the vehicle. The SCC receives telemetry data, either by radio or acoustic communications ports. A separate mission planning workstation (MPW) runs the navigation chart display and mission planning software, as well as miscellaneous diagnostic utilities provided by the various equipment manufacturers.
c. **Navigational System:** Highly accurate positioning and navigation systems which include a fibre-optic inertial navigation system, fibre-optic gyroscopes and accelerometers, a

downward facing RDI Doppler Velocity Log (DVL), an obstacle avoidance sonar, an Ultra Short Baseline System (USBL), a temperature compensated depth sensor and lastly, a Global Positioning System (GPS).

d. **Communication System:** Four systems enable communications with the AUV during mission: the on-deck Ethernet cable, a radio for surface communication before and after diving, an Iridium modem for long-range surface communication, and an acoustic telemetry system for underwater communications of up to 15 km. Additionally, the acoustic telemetry system also works as an emergency locator.

e. **Emergency System:** An inbuilt fault manager is designed to address a wide range of exceptions in a way that will enable the AUV to continue with the mission with full or reduced capabilities. Fault responses are pre-determined and configured during the mission planning stage and may change throughout the mission. In addition to the fault manager, *nupiri muka* is equipped with a Watchdog Timer system. The hardwired Watchdog Timer system acts as a safeguard against the AUV running with the thruster engaged but without computer control. Another safety device is the drop weight, activated either by the VCC, the watchdog timer or an acoustic command. The drop weight consists of a lead weight that changes the buoyancy of the AUV enough to make it surface without propulsion. Once on the water surface, a high-intensity strobe light is activated and can be seen from approximately 5 km from the air. Additionally, a radio beacon provides a radio locator signal that can be tracked using a hand-held radio locator with a maximum detection range of 42 km.

5.1.4 nupiri muka's AUV Crew and Organisational Structure

The *nupiri muka* AUV is maintained and operated by a team of specialist research and technical staff at the University of Tasmania AMC's Autonomous Maritime Systems Laboratory, an engineering research facility. At the time of writing, the primary team responsible for operations and maintenance of the AUV consists of a facility manager, a research engineer and an engineer. The team reports to both the principal of AMC, who took on the role as the AUV owner, and to the director of the Antarctic Gateway Partnership (AGP) initiative. While the AMC principal has accountabilities to the AMC board, the director of AGP works closely with the Australian Research Council (ARC), who is under the direct responsibility of Australia's Minister for Education and Training.

Notably, the AUV team also work closely with the following entities; AMC Search Ltd, the commercial arm of the Australian Maritime College, who support liaison with external parties on potential commercial use of the AUV; Research scientists from the Institute for Marine and Antarctic Studies (IMAS), a teaching and research institute of the University of Tasmania, and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), an independent Australian federal government agency responsible for scientific research. The Australian Antarctic Division (AAD), part of the Australian Government's Department of the Environment and Energy that leads Australia's Antarctic Program, supports the *nupiri muka* program by coordinating activities from scientific research through to logistics and transport. Last but not least, with ISE Ltd, for post-delivery support of the AUV. An overview of the personnel and organisations closely associated with the *nupiri muka* AUV program is presented in Figure 5.3.

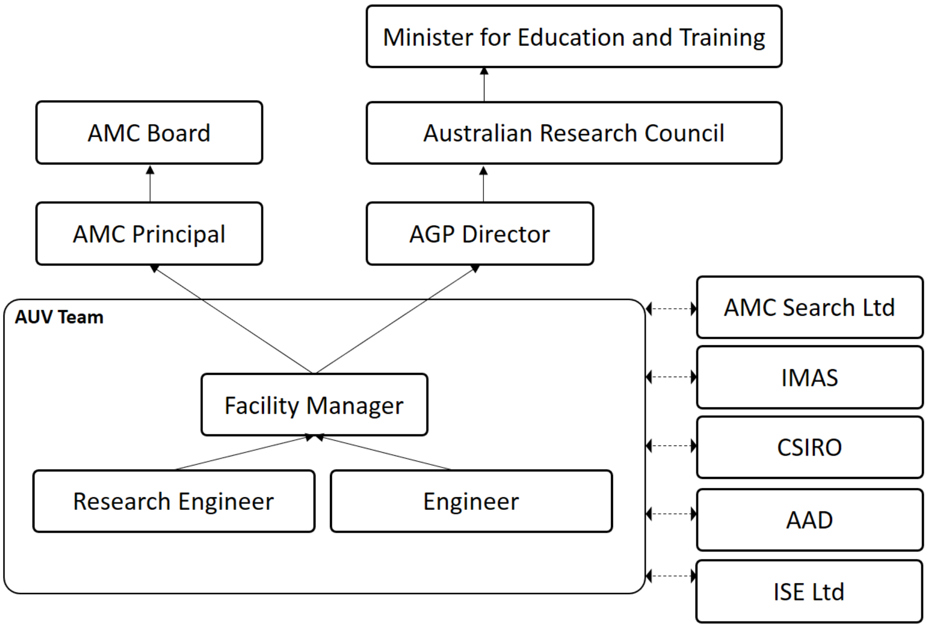


Figure 5.3: Personnel and organisations closely associated with the *nupiri muka* AUV program.

5.1.5 Existing Risk Management

Since conceptualisation of the AUV program back in 2014, the AUV team had adopted a proactive approach to managing risk of loss. The risk management process was guided primarily by UTAS's risk management policy (148), which articulates the University's commitment to establishing a robust risk management framework based on the Australian and New Zealand Standard for risk management, AS/NZS ISO 31000:2009 (75). Under the framework, risks were analysed using a semi-quantitative risk matrix (Appendix J), which was discussed earlier in Chapter 2. The main outputs were a series of recommended control measures, such as having a comprehensive set of Standard Operating Procedures (SOPs) and familiarising the team through a series of trials. Additionally, the manufacturer's manuals also provided valuable information and procedures on safe use of the AUV. This included pilot checklists, mechanical checklists, mission planning manual, maintenance manual and operations manual.

Apart from compliance to the University's risk management policy and manufacturer's manuals, several workshops were conducted to solicit peer review from AUV experts. Through the workshops, AUV experts from different organisations shared best practices and provided feedback regarding the readiness of the *nupiri muka* AUV program. For an example, the interested reader can refer to (215) for details of a recent workshop hosted by ISE.

5.2 FuSDRA - IDENTIFICATION

Using the presented background information on the *nupiri muka* AUV program, the next few sections demonstrates application of the FuSDRA framework to the program. The identification phase of the framework consists of several tasks, which includes scoping of the analysis, familiarisation, identification of knowledge sources, identification of risk factors and representing possible causal relationships in qualitative causal loop diagrams (CLDs). Additional details of this phase can be found in earlier section 4.2.1.

5.2.1 Scope of Analysis

The operation of the *nupiri muka* program involves several levels of abstraction, from Australian federal legislation down to detailed technical specifications of the AUV. The focus of this risk analysis lies in the management of the *nupiri muka* AUV program at the organisational level. This included factors associated with the performance of the AUV team, UTAS's policies, processes and systems, as well as relevant external influences. The time horizon for the analysis is set at 10 years, the pre-determined target service life of the AUV.

5.2.2 Familiarization and Knowledge Sources

For the most part, the task of familiarization and establishing domain knowledge sources were conducted concurrently. The following sections describe the various sources of information that were used to familiarize with the *nupiri muka* AUV program, as well as to facilitate the creation of subsequent risk models.

5.2.2.1 Organisational and Manufacturer Documents

Useful information relating to the risk of AUV loss was found to be scattered throughout various organisational documents such as:

a. UTAS's risk management policy and framework
b. Standard operating procedures
c. Risk assessment records
d. The business case for procurement of AUV
e. Fault logs
f. Insurance policy
g. Budget plans and costing models
h. Meeting minutes

Additionally, documents provided by the manufacturer (ISE Ltd) also contained valuable information for identifying risk factors and their possible causal structures. This includes various manuals, checklists and technical specifications associated with the *nupiri muka* AUV. Both organisational and manufacturer documents were mainly utilised as secondary sources of information, for calibrating the risk models and complementing the interviews of domain experts.

5.2.2.2 Literature

Several books and journal articles were used to identify possible risk factors and their causal structures. This included the recommended code of practice on the operation of AUVs [61], risk research articles, such as those from the *Autosub* AUV program (Section 1.3.5), as well as others which had been reviewed in earlier chapters.

5.2.2.3 Domain Experts

Although available documentation and literature provided useful information for the risk analysis, they often lack sufficient details, especially about the causal relationships between risk factors. Such information was, therefore, sought through a series of elicitation interviews with domain experts involved in the *nupiri muka* AUV program. They consist of the University's AUV team (Figure 5.3) and an AUV researcher (Scientist) who works closely with the team. These domain experts had a combined experience of 24 years working with AUVs and are currently responsible for, or are familiar with:

a. Implementing control measures based on the results of risk analysis
b. Resource allocation
c. Operation strategies and objectives of the *nupiri muka* program
d. *nupiri muka's* operating systems
e. Technical training, experience, knowledge of data and theory on AUV
f. Analysis of risk through both qualitative and quantitative judgement
g. Various aspects of the AUV program, either directly or indirectly

Prior to the actual interview, a brief description of the FuSDRA methodology was sent to the interviewees for pre-reading. The interviews were conducted primarily face to face, with some follow ups over phone calls as well as through email correspondence to suit the convenience of the interviewees. These were carried out in both unstructured and semi-structured format, with questions focusing in the following areas:

a. Background of the interviewee, including roles and responsibilities as well as relevant experience.
b. Risk factors influencing the risk of losing *nupiri muka* during under-ice missions in the Antarctic (Guided by the generic risk structure presented in Figure 3.4, with changes and external influences added based on inputs from interviewees.).
c. Causal relationships between the identified risk factors (Guided by the generic risk structure, Figure 3.4).
d. Membership functions of risk factors

e. Fuzzy rules governing fuzzy causal relationships of risk factors.
f. Current situation and possible future scenarios
g. Other relevant issues relating to the study

The interviews went through several iterations, with the risk models updated after each cycle. Early interviews focused on identifying risk factors and causal structures while later sessions focused on establishing fuzzy rules used to define model behaviour. Transcripts of each interview and the developed risk models with descriptions to aid understanding were sent to the interviewees for validation. To minimise the intrusion of biases in the interviews, constant comparisons were made with information provided by other interviewees and data sources to check for consistencies and account for differences. The developed risk models were reviewed, calibrated and tested through discussion with the interviewees until the models converge sufficiently to be deemed acceptable by the those who are interviewed. In total, these sessions generated close to 100 pages of interview transcripts and observation notes which were used as the basis to construct the FuSDRA model and subsequent testing exercises. Additionally, a research journal was kept to document both verbal and non-verbal responses of interviewees to check for signs of bias or heuristics.

Specific details of the interview, including the ethics approval, consent form and interview protocol are presented in Appendix G.

5.2.3 Causal Loop Diagram

Using the information gathered through the interviews and other knowledge sources as discussed earlier, risk factors, as well as their causal relationships were identified. These were used to establish the causal loop diagram which describes the causal mechanism and represent feedback structure of the system. Details about causal loop diagram modelling including the conventions used can be found in section 3.2.2.

The causal loop diagram for the *nupiri muka* AUV program consists of four main subsystems which directly and indirectly influences the risk of loss. They are the ‘budget’, ‘utilisation’, ‘technical reliability’ and ‘human reliability’. Figure 5.4 shows an overview of the subsystems and their interrelatedness, with the arrows indicating causal relationships.

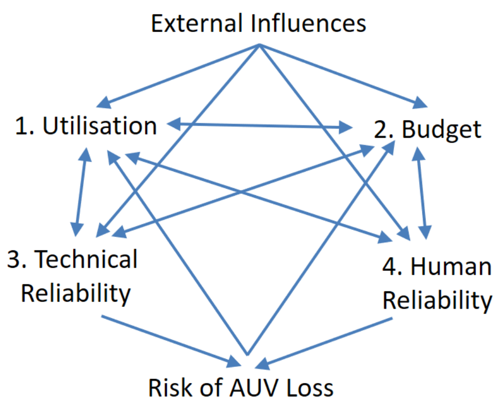


Figure 5.4: Overview of the causal loop diagram for the *nupiri muka* AUV program.

The human reliability subsystem captures the contribution of human error to the risk of loss, including possible underlying causes of these errors. Similarly, the technical reliability subsystem considers the contribution of technical failures to the risk of loss and factors influencing the technical reliability of the *nupiri muka* AUV. Both technical and human reliability are affected by other subsystems, namely the utilisation of the AUV and annual allocated budget to the AUV program. For example, “Experience gain rate” of the AUV team, which is a function of the AUV’s “Utilisation”, influences human reliability during an Antarctic deployment. Similarly, “Budget allocation” has a direct bearing on the “Quality of maintenance and repair”, which influences the technical reliability of the AUV. In addition, the University does not operate in a vacuum and there are several identified external influences which can impact both utilisation of the *nupiri muka* and the allocated budget for the program.

The interactions between the four subsystems, risk of AUV loss and external influences resulted in a causal loop diagram which is presented in Figure 5.5. The dotted boxes broadly marked the four main subsystems and their associated risk factors. To reduce complexity of the model for analysis, these subsystems will be examined separately as stock and flow models in the next few sections.

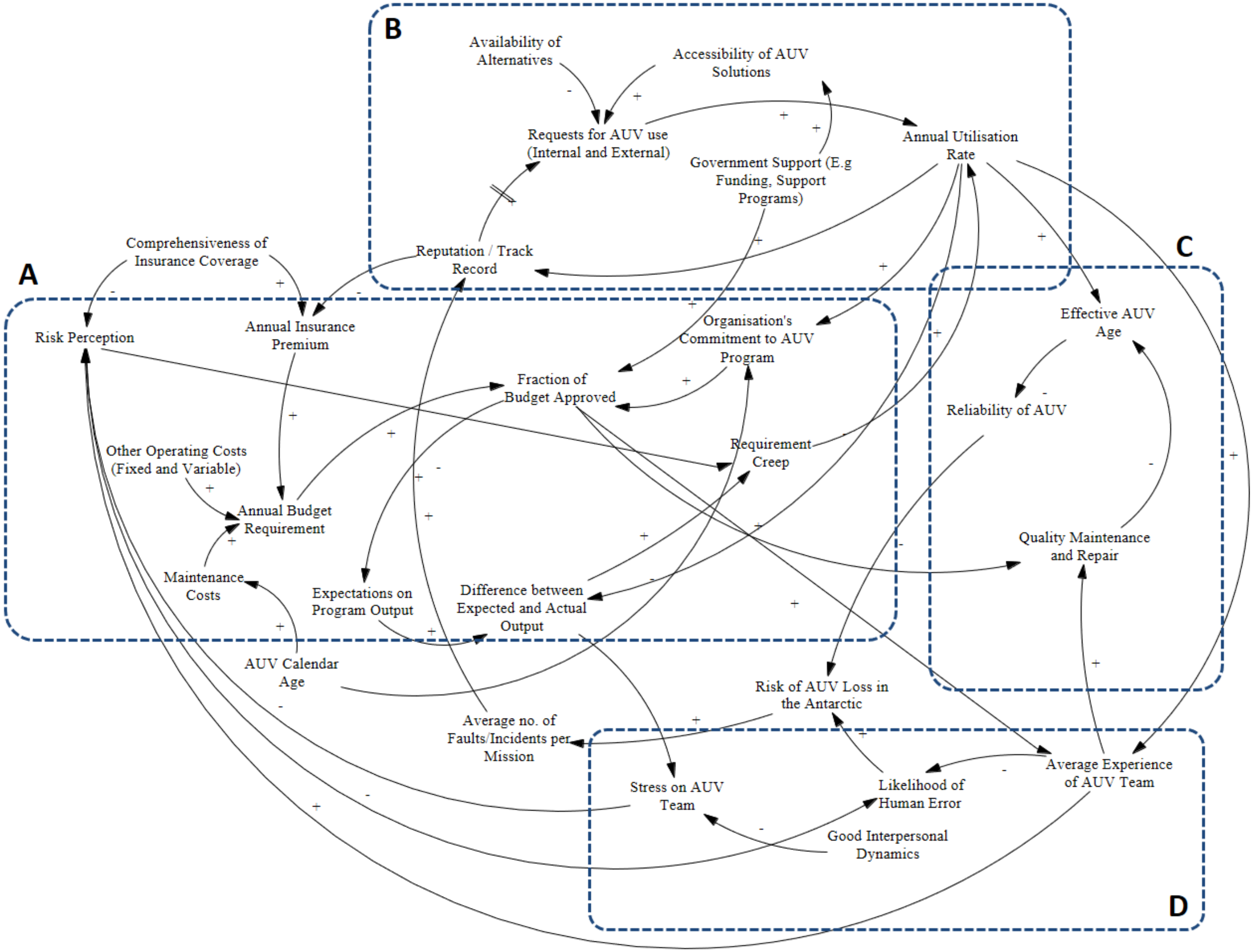


Figure 5.5: Overview of the causal structure relating to risk of AUV loss for the *nupiri muka* AUV program, categorised broadly into four sub-models. **A:** Budget **B:** Utilisation **C:** Technical reliability **D:** Human reliability.

5.3 FuSDRA - RISK MODELLING

The next step, which is the risk modelling phase of the three-stage iterative FuSDRA framework (Figure 4.1), aims to quantify the risk of loss through constructing fuzzy system dynamics models. Based on the established qualitative causal loop diagram (Figure 5.5), the next task aims to quantify the risk of loss by constructing quantitative stock and flow models. This is carried out through parameters' estimation, formulation of causal relationships and establishing initial conditions.

5.3.1 Stock and Flow Models

First, stock and flow models of the four subsystems, their interactions with external influences and relationship with the risk of AUV loss are presented. Details about stock and flow models including the conventions used can be found in section 3.2.3.

5.3.1.1 Technical Reliability

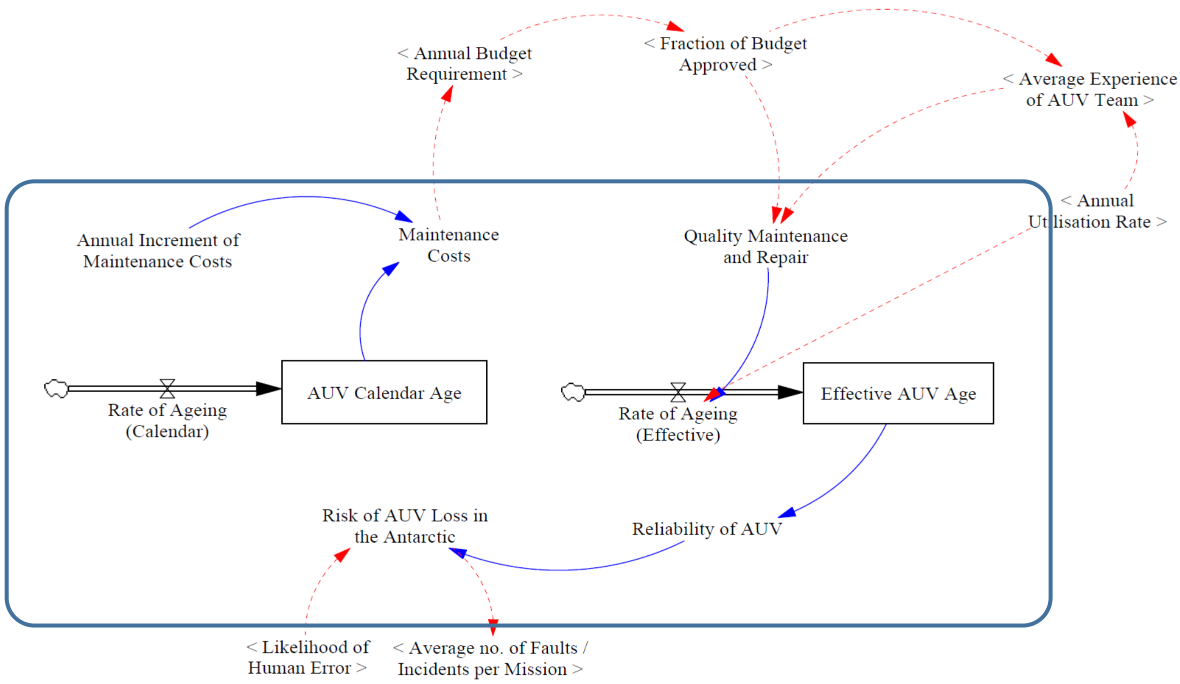


Figure 5.6: Stock and flow model for 'technical reliability' sub-model.

The technical reliability sub-model is presented in Figure 5.6. Almost all interviewees, except for one, mentioned overall reliability of *nupiri muka* as one of the two main risk factors influencing the risk of loss. An interviewee puts it:

> *“Mechanical issues such as the loss of forward-looking obstacle avoidance sonar through either leak or collision could lead to the loss of the vehicle. There are also the ‘regular stuff’ like water ingress into the pressure hull or power issues.”*

Not surprisingly, the causal relationship between reliability and effective age of the AUV was also brought up by several interviewees:

> *“Surely in a few years time, things will start to age. But as we are sitting now, the vehicle is quite new and running very well.”*

Without sufficient historical data for statistical analysis, this causal relationship between effective age and reliability was modelled to exhibit a ‘bathtub’ curve trend, commonly used in reliability engineering. The higher likelihood of failure in the early and late operational life of an AUV was explained in the earlier section of 4.3.2. Also supported by the literature [216][217], the rate of ageing (effective) was modelled to depend both on the utilisation rate of the AUV, and also the quality of maintenance and repair.

In another technical aspect, the calendar age of the *nupiri muka* is predicted to influence the cost of maintenance. An interviewee puts it:

> *“We have to be able to maintain the vehicle, have the budget, because in three to five years’ time, some things need to be replaced or keep up to date.”*

This is also supported by studies in the aviation industry, such as the US Airforce [218] and Boeing [219], where a positive causal relationship has been found between calendar age of an equipment and its maintenance and operating costs. The increasing maintenance costs constitute part of the overall budget requirement for the AUV program, which will be further examined in the budget allocation sub-model.

5.3.1.2 Human Reliability

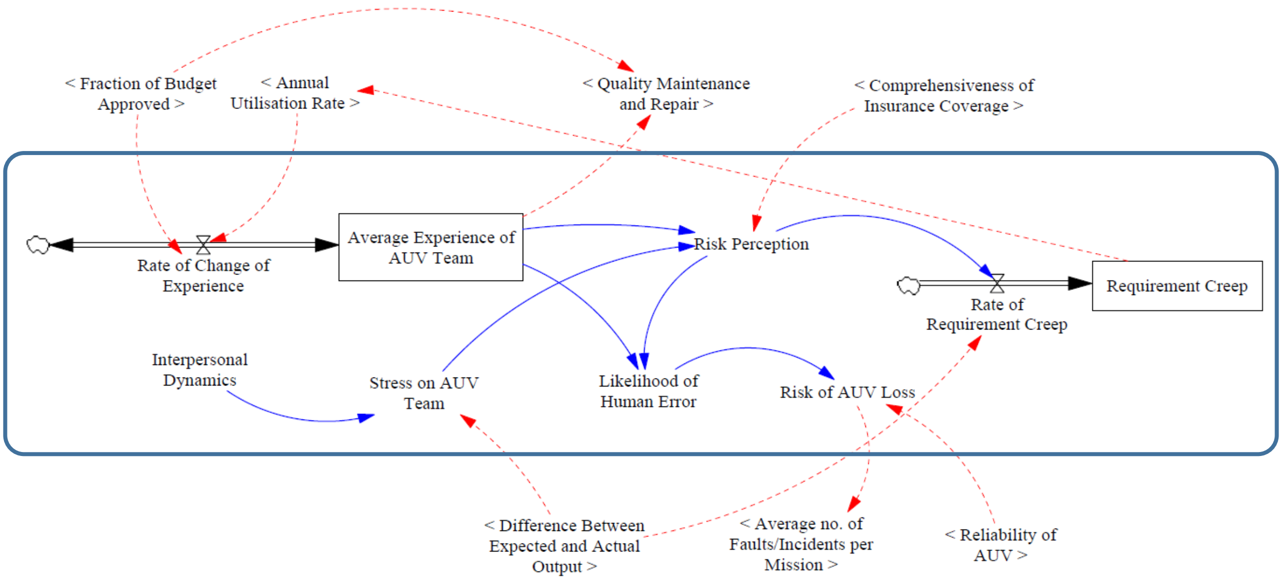


Figure 5.7: Stock and flow model for the ‘human reliability’ sub-model.

Human error was mentioned by all interviewees as one of the main contributing factors to the risk of AUV loss, which gave rise to the human reliability sub-model (Figure 5.7). Some examples of human errors were provided by an interviewee:

> *“I think the primary thing that would cause the AUV to be lost would be human error in the vehicle configuration or response. For example, something was misconfigured or not set up correctly so that it did not function, and that could be one of the sensors for avoiding the bottom. Or a mistake made in the mission planning fault response where the vehicle reacts to something in a wrong way.”*

Also mentioned during the interviews were two main factors influencing the likelihood of human error; operating experience and the risk perception of the AUV team, with the latter being influenced by the level of stress the team is working under. The evidence of a causal relationship between stress level, risk perception and human error is supported by many published research articles on stress and human performance. For example, Brito and Griffiths found that stress factors played a role in risk mitigating activities for missions involving multiple AUVs [105]. Baradell & Klein found reductions in the amount of information used in reaching decisions when people work under stress [220]. Hocket et. al. reported an increase in riskiness for people under stress due to fatigue [221]. Dhillon et al. [222] listed some of the factors which may result in stress, many of which are relevant to deployment in the Antarctic (Table 5.1).

Table 5.1: Stress factors and example of scenarios relevant to an Antarctic deployment.

No.	Stress Factors	Examples
1	Environment	Deprivation of sunlight in winter and continuous daylight in Antarctic summer. Cold temperature.
2	Equipment Design	Quality and reliability of equipment including both the AUV and the surface control computer (SCC).
3	Equipment Layout	The location and labelling of spares and tools.
4	Procedures	The quality of standard operating procedures and the effectiveness of maintenance and checks.
5	Skill	Training and experience of AUV team in Antarctic deployment.
6	Complexity of Task	The difficulty of deployment, including the duration, location and number of missions.

While a thorough analysis on the cause and effect of stress on the AUV team may be necessary, it is beyond the scope of this case study and dissertation. Using information provided by interviewees as the basis, the sub-model considers interpersonal dynamics and AUV program outputs to have a causal relationship with stress on the AUV team, influencing the level of risk perception. An interviewee puts it:

> *"Interpersonal dynamics can be broadly split into inter-team dynamics and intra-team dynamics. Inter-team dynamics includes communication with other stakeholders such as boat operators, station support and other scientific groups. Miscommunication or conflict may arise due to competition for resources, time or fatigue due to the Antarctic environment. Intra-team dynamics may be affected by a lack of clarity on roles and responsibility as a team. For example, scope of mission, maintenance and deployment plan. These issues may magnify in the Antarctic environment."*

The role of interpersonal dynamics in influencing stress level is further supported by the literature [223]. In addition to stress and experience of the AUV team, comprehensiveness of insurance coverage was also included in the model to have a causal relationship with the level of risk perception. Although not explicitly mentioned, the topic of insurance was brought up by several interviewees and the causal relationship is well documented in the literature [224][225][226]. A reduced risk perception can cause requirement creep leading to decision biases, such as taking on additional missions of higher risks in an attempt to produce more outputs from the AUV program. A couple of interviewees provided further explanation of requirement creep:

"If you don't have a clear set of objectives, then you might get into a situation when you do something down at the Antarctic and then think that maybe you need to do more, and that is when things start to get extra risky."

"The current AUV team is appropriately conservative. The line we often hear is, can the vehicle do this? And we will say of course it can, but are we willing to take the risk? At the moment, the team is less influenced by external pressure, but we are human."

Another key risk factor in the human reliability sub-model is the average experience of the AUV team. As mentioned by an interviewee:

"*Another big risk is that only 50% of the team have polar experience. However, as a team operating a large AUV, we've had 18 months of operational experience, which is not tiny but not massive either."*

It is reasonable to consider that relevant experience can be gained through utilisation of the vehicle or employing and retaining skilled personnel. Contrariwise, it can also be lost due to attrition, turnover or low utilisation of the vehicle. While the human resource is primarily influenced by the budget, the optimal period between utilisation was further explained by an interviewee:

"You have to be running regularly. If the vehicle sat for two years without being deployed, the risk will go up because the familiarity is not there anymore. So you need to operate regularly to keep the team trained and familiar. Almost monthly or bi-monthly, you really want to get out, like half a dozen or ten times a year not only to practice and to keep the state of readiness, but also to check the condition of the vehicle."

5.3.1.3 Utilisation

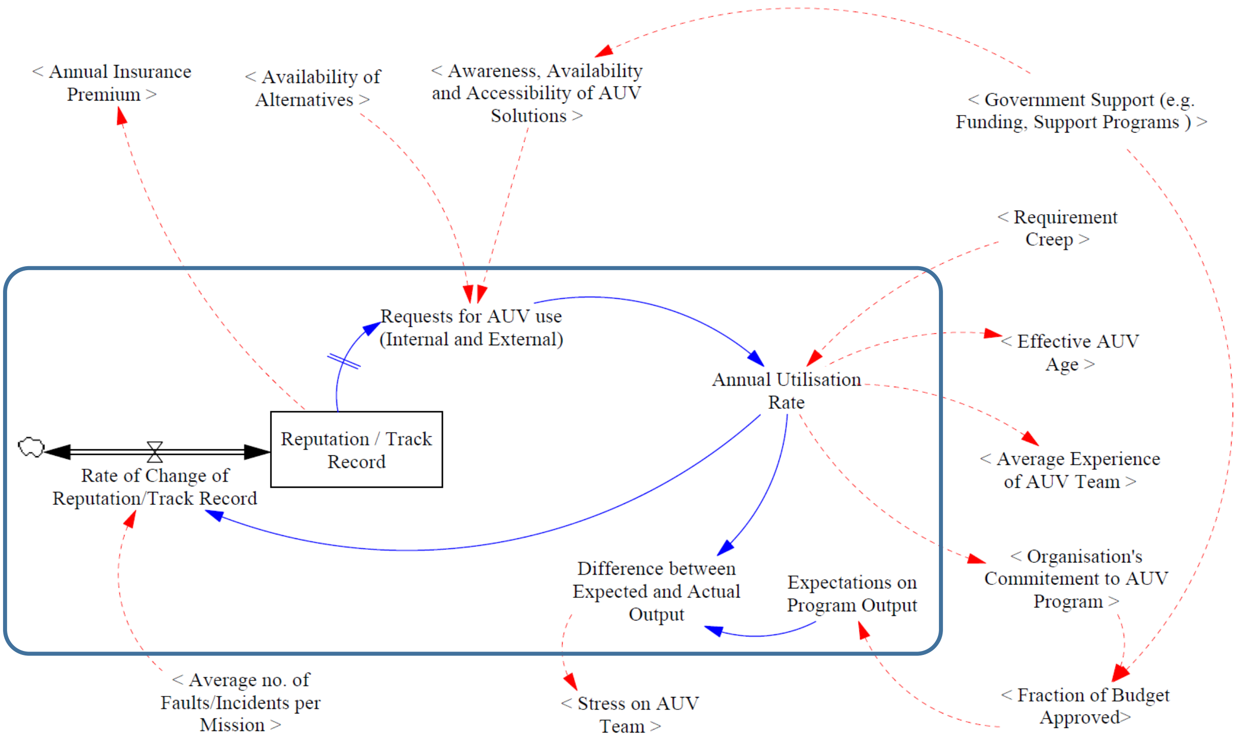


Figure 5.8: Stock and flow model for the 'utilisation' sub-model.

The utilisation sub-model (Figure 5.8) focused on the utilisation level of the *nupiri muka* AUV, which is an indication of the time that the AUV is in use while available. All interviewees mentioned the importance of utilising the *nupiri muka* to generate output to the program. For example, an interviewee puts it:

> *"If the vehicle isn't seen as providing value, people will stop spending money on it. Both commercial and research aspects are important. Either the vehicle has to bring in real money to offset the cost or be producing a lot of relevant research that allow justification."*

Here, the interviewee also suggested that there are expectations on the AUV program to be met in terms of providing value, which can represent both commercial and research outputs. Although not explicitly mentioned, it is reasonable to assume that the amount of output will then influence the organisation's commitment to the AUV program and the reputation/track record of the organisation. Any improvement to the reputation and track record of the organisation will further increase demand for use of *nupiri muka,* albeit at a delay. This forms a reinforcing loop as shown in Figure 5.9. However, utilisation of the AUV does not increase indefinitely and will eventually be constrained by other risk factors. These include the 'Availability of Alternatives', 'Government Support', 'Awareness, Availability and Accessibility of AUV Solutions', 'Requirement Creep' and 'Average no. of Faults/Incidents per Mission'. These risk factors serve to stabilise and limit growth of the *nupiri muka* AUV program, or in severe cases, lead to the failure of the program. For instance, a high utilisation rate may increase ageing of the AUV, reducing its reliability, leading to a higher risk of loss and consequently reduces its utilisation.

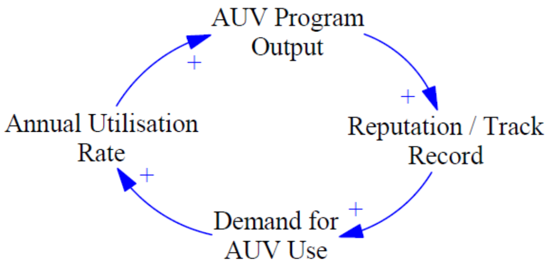


Figure 5.9: Reinforcing loop involving utilisation of the *nupiri muka* AUV.

5.3.1.4 Budget

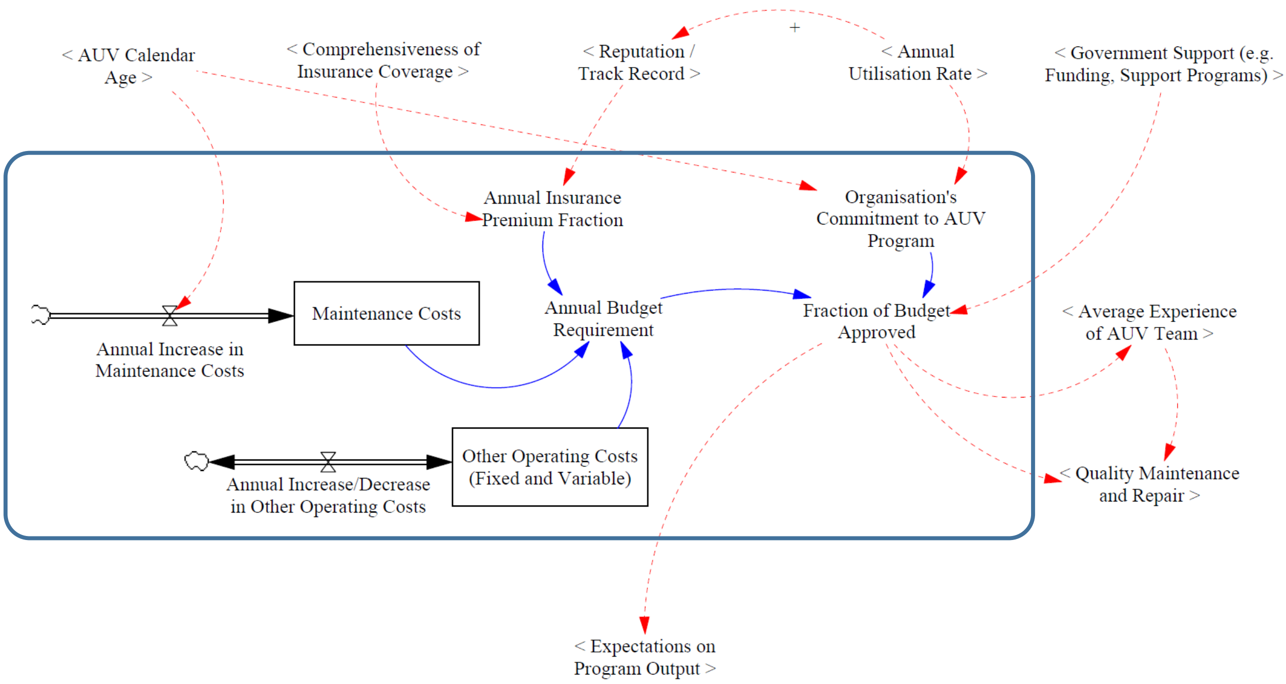


Figure 5.10: Stock and flow model for the 'budget' sub-model.

The importance of budget preparation and administration in influencing the risk of AUV loss was mentioned by all interviewees. This gave rise to the budget sub-model as shown in Figure 5.10. An interviewee explained the current funding situation for the *nupiri muka* program:

> *"At the moment, the program is funded by AMC and AGP. Facility is funded by AMC, staff cost is funded by AGP and then there is an ongoing depreciation cost and insurance cost which is currently under AMC. At the moment, some of the money comes directly from government through the ARC via AGP. But where does AMC gets the money to pay for facility and insurance, which is quite a large line-up on AMC's*

budget, that is an open question. So it could be AGP is very successful in its funding but AMC isn't. That is a risk.

Without delving into specific budgeting details, the annual budget requirement for the AUV program was consolidated in the model into three broad inputs of; 'Insurance premium', 'Maintenance costs' and 'Other operating costs'. Operating costs refers to the recurring costs of operating the AUV, such as staff cost, facility expenses, depreciation costs, wear and tear of the AUV and license or fees imposed by the government for deployment. Another interviewee elaborated on the insurance cost:

> *"We have insurance for open water operation but not yet for under-ice operation. The current ball-park premium is about 200,000 AUD a year. They take the replacement cost of the vehicle, comes out with a risk profile and then comes out with some percentage. If anything, the premium should improve overtime because one of the things they ask you when you go for insurance is they want to know your experience. So the longer you go without incidence, the more reliable you appear. It's like car insurance."*

With the AUV program currently funded primarily by the Australian government and the University, a reduction in commitment from either party over time could adversely impact sustainability of the program, leading to higher risk of loss. Also, according to the interviewees, areas of maintenance and repair, and staffing for the AUV program will be most adversely impacted by budgetary constraints. An interviewee puts it:

> *"Resource is not too bad at the moment, but I guess if there is a risk, it's the risk of reducing commitment from the University, to tighten the budget belt and therefore reduce the maintenance schedule. But I guess also, is the lack of personnel because we are still running the vehicle as brand new and doesn't require regular maintenance at the moment. But between three of us, it's at the upper limit of what we are capable of without doing overtime."*

The impact of the budget on staffing was modelled to influence 'AUV team experience', representing the hiring, attrition or turnover of personnel. Although other intangible aspects, such as compensation satisfaction could be involved in human resource management, these were not explicitly mentioned by the interviewees and therefore, excluded in the model.

5.3.2 FuSDRA *Model Parametrization and Construction*

To construct the FuSDRA model from the stock and flow diagrams, formulations, definitions and initial conditions had to be set in the model. Such information was sought primarily from interviews and supported by other domain knowledge sources, with the parameters presented in Appendix H. Like the example presented in Chapter 4, uncertain causal relationships due to vagueness or ambiguity were represented through the application of fuzzy logic using fuzzy expert systems. The fuzzy rules are presented in Appendix I. Triangular and trapezoidal membership functions were used for both input and output variables in the fuzzy expert systems. Fuzzy inference was performed with the Mamdani approach and defuzzification carried out using the centroid method. The established fuzzy expert systems were subsequently incorporated into the system dynamics model by converting the stock and flow models into a block diagram (Section 4.2.2). Each individual block in the diagram transforms the input signal(s) into an output signal, with the entire block diagram representing the dynamic relationship between input(s) and output(s) of a system. Using MATLAB® Simulink toolbox 2018 [205], the resultant fuzzy system dynamics model was constructed and is shown in Figure 5.11.

In an overall sense, the FuSDRA model consisted of four sub-models, namely, 'utilisation', 'budget', 'human reliability' and 'technical reliability'; Sixteen fuzzy logic blocks, each representing causal relationships which are vague or ambiguous; Seven integrator 'blocks' which transform rate of change into the level of stock variables, and; Lastly, six constant and four gain blocks for ease of user inputs to allow for calibration and testing of the model.

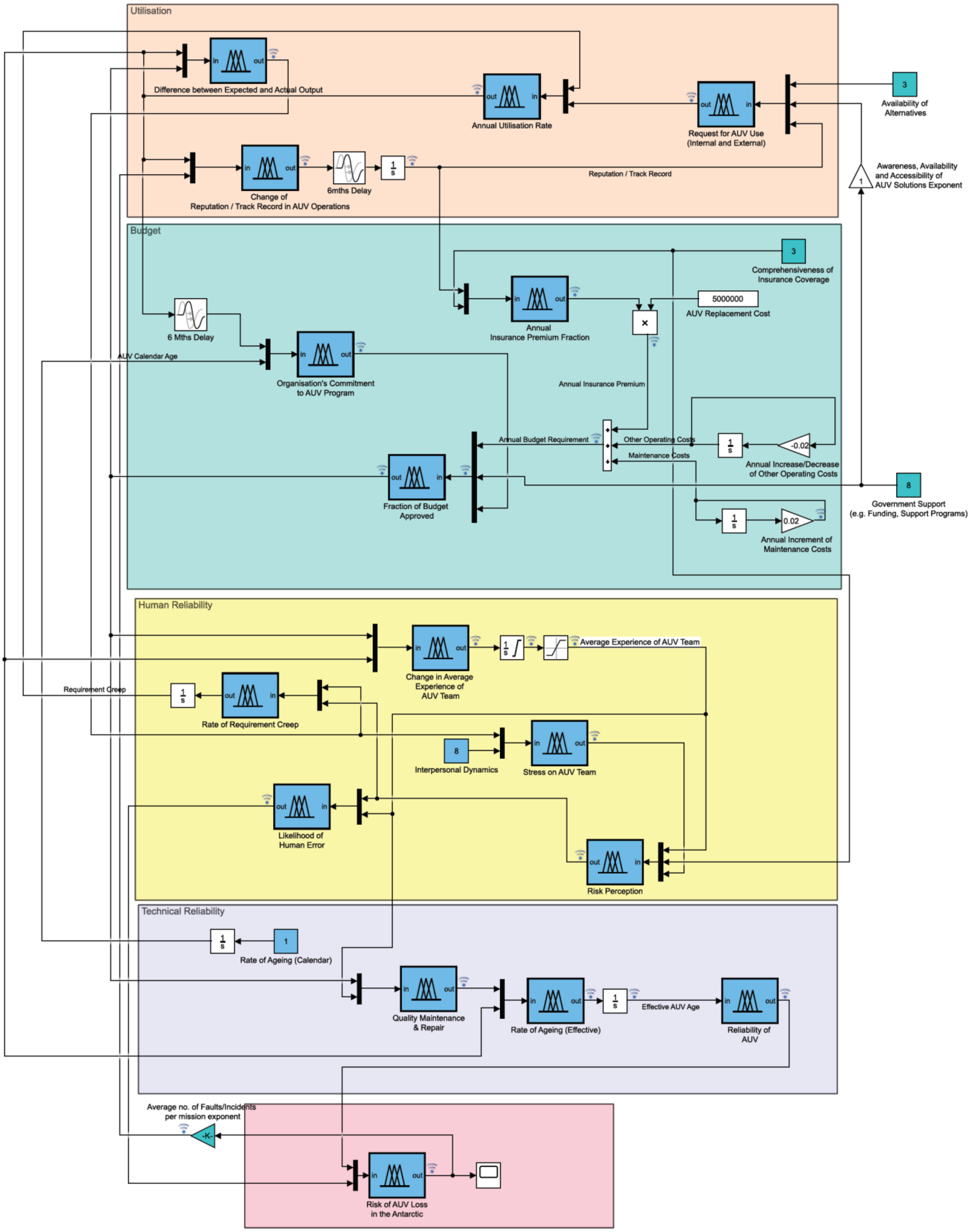


Figure 5.11: The resultant FuSDRA model, categorised into four sub-models.

5.3.3 Assumptions

Models are an attempt to understand some aspect of the varied world through a selection of perceptions and experience associated with the problem [227]. Consequently, an ordered set of underlying assumptions lie at the heart of all risk models. In this respect, the assumptions used in development of the FuSDRA model play a critical role in ensuring a realistic reflection of the real-world scenario. Conversely, poor or overly optimistic assumptions can result in an inaccurate picture of the risk exposure, potentially resulting in flawed recommendations.

The FuSDRA model of this case study was built on five major assumptions, which are stated as below:

a) The use of time as the basis for determining the risk of AUV loss, which requires accurate parameterization of causal relationships between risk factors.
b) Both the formulation and fuzzy rules used to represent the causal relationship between risk factors, remained similar throughout the time horizon of the model.
c) Domain experts, which are the primary source of information for the risk analysis, have an adequate grasp of what are the key issues in relation to the *nupiri muka* AUV program.
d) The use of the incident rate, including faults, as an accurate lagging indicator for the risk level of AUV loss.
e) The mission profiles, including the number of under-ice missions for each deployment remains relatively similar for each Antarctic deployment throughout time horizon of the analysis.

5.3.4 Model Testing - An Introduction

To build confidence in the developed FuSDRA model, three main approaches were taken. First, local knowledge and available historical data were used to calibrate the model. Second, a series of tests were undertaken to uncover model errors and areas for improvement. Last, simulations results from the model were discussed and compared with domain experts' opinion. In this section, details of model testing are presented.

FuSDRA models, like any other risk models, are simplified representations of the real world and always differ from reality, no matter how large or small the difference may be. This difference arises from imperfectly measured data, abstractions, aggregations and simplifications[1]. Therefore, this dissertation is inclined towards the belief that complete validation and verification of a risk model is impossible, a claim based on concepts presented by Sterman[1] and supported by others[169][228]. Unfortunately, the terms testing, validation and verification are often used interchangeably, leading to confusion. To avoid a lengthy discussion on fitting definitions, the term testing will be used here to represent the iterative process of checking and uncovering errors.

The objective of model testing is to increase confidence, in both soundness and usefulness of the FuSDRA model through uncovering errors and improvement. Some important questions that should be asked when testing the FuSDRA model include:

- Whether the FuSDRA model fulfils its primary purpose of facilitating understanding and controlling of risk factors that can cause or culminate in the loss of an AUV during deployment in the Antarctic?
- Are important risk factors being included in the model?
- Are the time horizon and model boundaries relevant to the problem?
- Does the FuSDRA model conform to basic physical laws such as conservation laws where inflows into the system either accumulate or become outflow?
- Are the fuzzy rules within the fuzzy expert system complete and logical?
- How does the FuSDRA model behave under specific conditions for which its inputs take on extreme values?
- Are the policy recommendations arising from the model pragmatic and sensitive to plausible variations in assumptions?
- Are the results of the FuSDRA model reproducible?

A wide variety of tests are available in the literature for both system dynamics models and fuzzy expert systems. These can be broadly classified into model structure, model behaviour and policy implications tests [(1)]. A summary of these tests, adapted from [(1)] are presented in Table 5.2. The choice of tests often depends on several factors such as time and resource availability, size of the model and purpose of the model. Although it may be tempting to perform as many tests as possible on the risk model, doing so can be excessively time-consuming and resource intensive. For this case study where there is limited historical data for model development, most problems were revealed during the risk analysis process through discussion with domain experts. This triggered frequent reassessment of the model, resulting in a time-consuming iterative cycle of model analysis, testing and analysis. Nevertheless, some key tests were carried out on the resultant FuSDRA model, including boundary adequacy, structure assessment, dimensional consistency, extensive extreme conditions and behaviour anomaly tests. Any unexpected behaviour revealed during the tests were investigated and improvements made to the model accordingly. Details of these tests will be discussed in subsequent sections.

Table 5.2: List of recommended tests that can be performed on the developed FuSDRA model.

No.	Test	Purpose (s)
		Model Structure Tests
1.	Boundary Adequacy	• Assess whether important concepts associated to the risk of AUV loss is included in the model. • Assess whether behaviour of the model and risk control policy recommendations change significantly when the boundary is changed?
2.	Structure Assessment	• Check that the model structure is consistent with descriptive knowledge of risk of AUV loss in the Antarctic. • Assess whether the FuSDRA model conforms to basic physical laws such as conservation laws where inflows into the system either accumulates or becomes outflow.

		• Assess fuzzy expert systems for inconsistencies, conflicts, redundant or missing rules.
3.	Dimensional Consistency	• Check that equations used in the model, including fuzzy systems are dimensionally consistent.
4.	Parameter Assessment	• Assess parameter values on consistency with descriptive and numerical knowledge of risk of AUV loss in the Antarctic.
	Model Behavior Tests	
6.	Extreme Conditions	• Assess how the FuSDRA model behaves under specific conditions for which its inputs take on extreme values.
7.	Integration Error	• Assess sensitivity of simulation results to the choice of time step or integration method.
8.	Behaviour Reproduction	• Check that the model reproduces behaviour of risk factors associated with an AUV program, with influence over the risk of AUV loss.
9.	Behaviour Anomaly	• Assess the behaviour of FuSDRA model when assumptions or the model are changed or deleted.
10.	Family Member	• Evaluate behaviour of the FuSDRA model to other types of *nupiri muka* operations or that of other AUVs.
11.	Surprise Behavior	• Assess whether are there discrepancies between model behaviour and expectations. It checks for previously unobserved or unrecognised behaviour.
12.	Sensitivity Analysis	• Assess whether the outcome of the risk analysis changes significantly when assumptions are varied over a plausible range of uncertainty.
	Policy Implications Tests	
13.	System Improvement	• Assess whether the eventual goal of the FuSDRA model to facilitate risk control is met. To pass the test, policy recommendations derived from the FuSDRA model must be implemented and risk of AUV loss prove to actually reduce.

5.3.4.1 Model Structure Tests

To determine the boundaries of the FuSDRA model, a generic risk structure associated with the risk of AUV loss (Figure 3.4) was established during early phase of the risk analysis. Based mainly on literature review and preliminary informal discussions with the AUV team, the structure acts as a model boundary chart. It depicts the scope of the model and facilitates identification of likely endogenous and exogenous risk factors, as well as important feedback loops. The risk structure was subsequently used to guide formal discussions with the domain experts, with the construction of the FuSDRA model based on refinement to the structure. Additionally, the resultant FuSDRA model was presented to the domain experts for iterative improvements and the eventual consensus on the final model.

The FuSDRA model was also checked for violations of physical law. For instance, real quantities such as annual utilisation rate of *nupiri muka*, calendar age, operating and maintenance costs, effective age, and experience of the AUV team do not go into a negative value. Similarly, outflows from these stocks have shown to be zero if the stock is zero.

Parameters assessments were performed using the knowledge sources described earlier (Section 5.2.2), except for cases where opinions had to be elicited from domain experts in the form of fuzzy rule bases. To check for completeness of the fuzzy rule bases, the completeness measure approach by Jager (206) was applied. According to Jager (206), the measure of completeness of a fuzzy rule base is defined as:

$$CM\ (\boldsymbol{x}) = \sum_{K=1}^{N_r} \{ \prod_{i=1}^{N_X} \mu_{A_{i,k}}(x_i) \} \qquad \text{---------------}\ (5.1)$$

Where $\boldsymbol{x}$ is a numerical data vector, N_r the number of rules and N_x the number of fuzzy sets. A completeness measure (CM) value of 0 means incomplete, where there are combinations of input where no output is defined. A CM value of < 1 means subcomplete, CM value of 1 means strict complete and CM value of > 1 means overcomplete, where there are presence of redundant rules. For all sixteen fuzzy expert systems in the FuSDRA model, a CM value of 1 were achieved, inferring strict completeness of the fuzzy rule bases.

All stock and flow models of the four subsystems were checked for dimensional consistency using inbuilt <Check Units> function within the Vensim® (204) Software. Any inconsistencies with units of measure were reflected by the software when the equations were checked. Details on the units of measure for each risk factor is listed in Appendix H.

5.3.4.2 Model Behavior Tests

Extreme condition tests were performed extensively on the FuSDRA model to assess its robustness. By randomly changing variables to realistic maximum and minimum values while monitoring model behaviour, these tests ensure that the FuSDRA model behaves in a realistic manner even with extreme inputs. Here, three examples of extreme condition test are presented.

In the first example, a simple extreme condition test was applied by changing the value of one risk factor. The level of ‘interpersonal dynamics’ was set to extreme values of 0 (Very Poor) and 10 (Very High) to observe its impact on stress level of the AUV team. Since they have a negative causal relationship, it is expected that as the level of interpersonal dynamics increases or decreases, stress level of the AUV team changes in the opposite direction. Simulation of the FuSDRA model showed results consistent with the expected outcomes (Figure 5.12). The stepwise reduction of the stress level can be traced back to ‘organisation’s commitment to the AUV program’. The antagonistic effect of an increase in AUV calendar age and utilization rate resulted in a stepwise reduction of commitment level, which translates downstream to other risk variables.

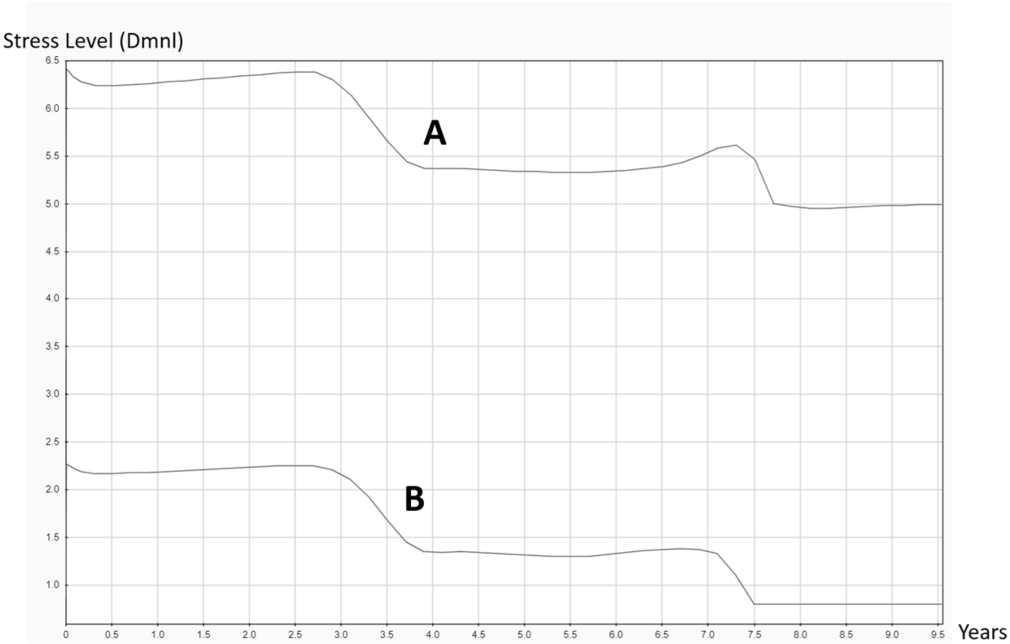


Figure 5.12: Impact on stress level with extreme input of interpersonal dynamics. **A:** Interpersonal dynamics = 0 (Very Poor), **B:** Interpersonal dynamics = 10 (Very High)

For the second extreme condition test, the values of two risk factors were changed to examine their impact on the risk of AUV loss. They are the level of government support for the AUV program and the availability of alternatives to AUVs for Antarctic research. Intuitively, it is expected that a high level of government support with low availability of alternatives to AUVs would result in greater commitment to the program and consequently, a lower risk of AUV loss and vice versa. To test the model, the level of government support was set to 0 (very low) and the availability of alternatives to AUVs set at 10 (very high) for one extreme, with the reverse for the opposite extreme. Simulation results presented in Figure 5.13 showed that the risk of AUV loss behaved as per expectation. It is also noteworthy that the presence of delays within the system resulted in a noticeable difference in risk level only after a year into the AUV program. In the scenario of very low government support and very high alternatives to AUVs, the risk of loss shows a sharp increase in the last year of the AUV program. This can be attributed to a lack of quality maintenance and repair due to budget limitation.

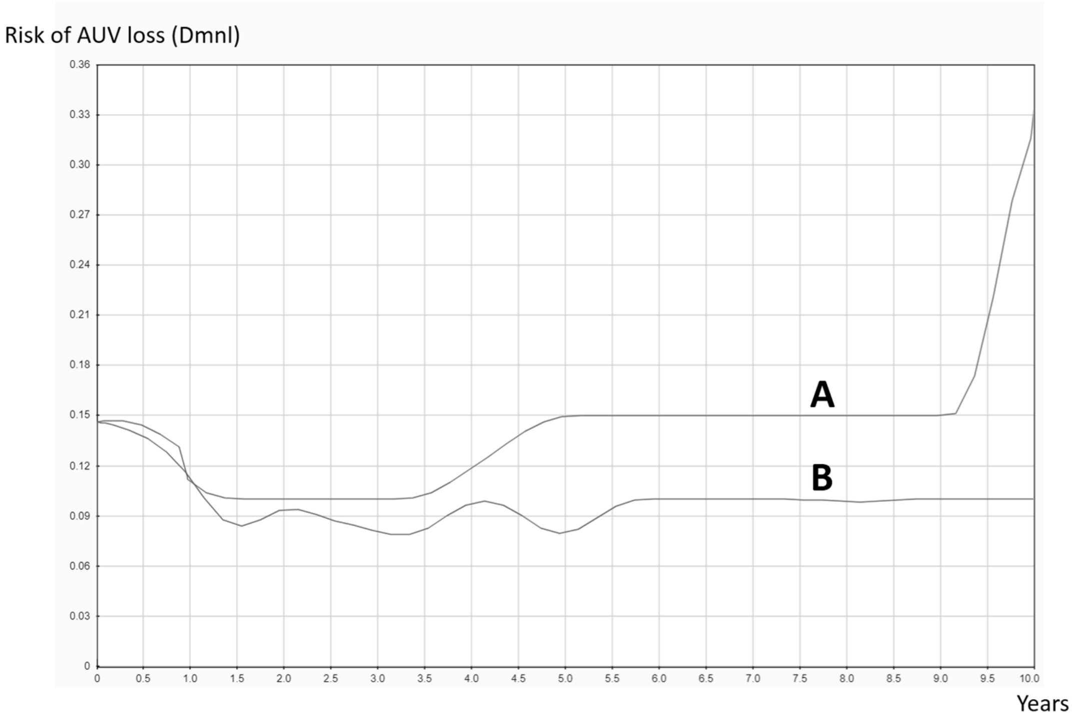


Figure 5.13: Impact on the risk of AUV loss with extreme input of government support and the availability of alternatives. **A:** Government support = 0 (Very Low), availability of alternatives = 10 (Very High) **B:** Government support = 10 (Very High), availability of alternatives = 0 (Very Low).

The last example of extreme condition test examines the positive relationship between the risk of AUV loss and both the budget requirement for the AUV program and the level of government support. Three risk factors were varied for this test, namely ‘government support’, ‘annual increment of maintenance costs’ and ‘annual increase/decrease of other operating costs’. It is expected that a higher budget requirement together with low government support would adversely affect the availability of resources, consequently leading to a higher risk of AUV loss and vice versa. At one extreme, the annual increment of maintenance costs was set at 1% with an annual decrease of other operating costs set as 5% and a government support value of 10 (very high). At the other extreme, the annual increment of maintenance costs was set at 5% with an annual increase of other operating costs of 5% and government support value of 0 (very low). The simulation results are presented in Figure 5.14. Unsurprisingly, the results showed a lower risk of loss with lower budget requirement and higher government support. With more funding available, resources can be channelled into quality maintenance and repair of the AUV, as well as the retention or recruitment of experienced personnel. The risk of AUV loss between the two extreme scenarios diverges as the AUV program progresses, once again reflecting the presence of delays within feedbacks in the system. In the scenario of higher budget requirement with low government support, the risk of loss again shows a sharp increase in the last year of the AUV program, with reason similar to the previous extreme condition test.

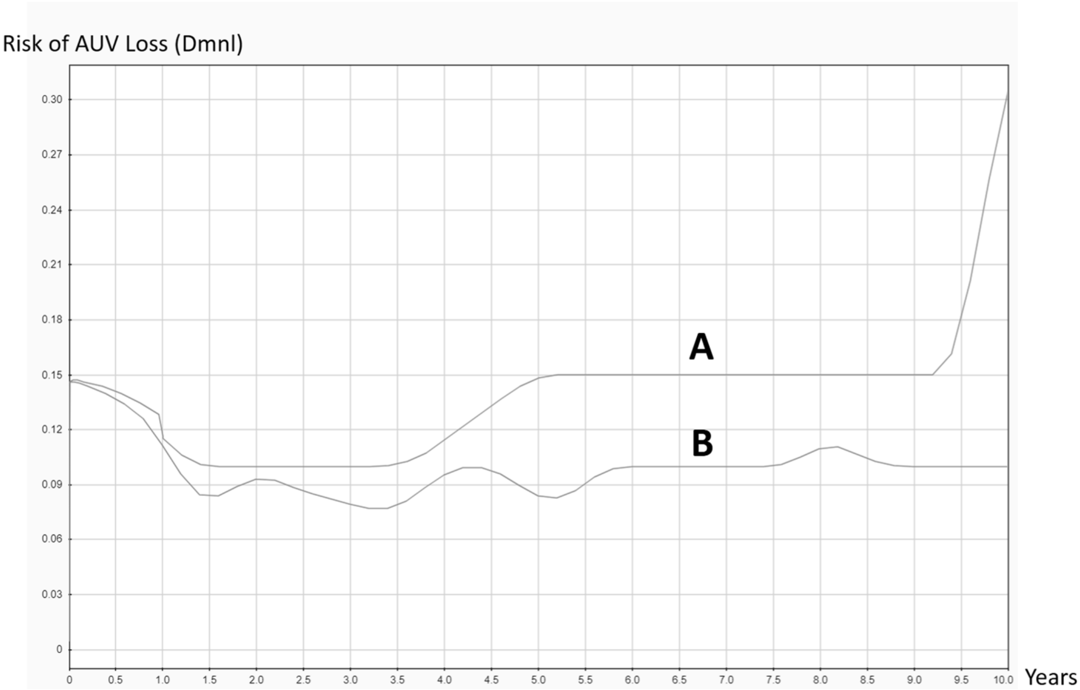


Figure 5.14: Impact on risk of AUV loss with extreme input of budget requirement for the AUV program and the level of government support. **A:** Annual increment of maintenance costs = 1%, annual decrease of other operating costs = 5% and government support = 10 (very high). **B:** Annual increment of maintenance costs = 5% annual increase of other operating costs = 5% and government support = 0 (very low).

5.3.4.3 Sensitivity Analysis

Sensitivity analysis aims to examine how varied assumptions over a plausible range of uncertainty can influence the risk of AUV loss. It helps to evaluate the reliability of simulation results and provide additional insights into the FuSDRA model structure, revealing surprise and anomaly behaviour, potential errors, and areas for improvement. Additionally, results from the analysis can help to identify leverage points for risk control by identifying the risk factors which the risk of AUV loss be most sensitive towards.

A series of "one-at-a-time" [229] univariate analyses were performed on risk factors identified during interviews as having a significant impact on the risk of AUV loss. For example, an interviewee suggested the importance of 'initial average experience of AUV team', saying:

> *"I guess one of the big risk is that only one-third of the team is experienced. Likely an engineer from ISE will be joining us in the upcoming Antarctic mission and that puts the experience to 50:50, with polar AUV operators and non-polar AUV operators. So it sort of even the odds a little bit more."*

The univariate sensitivity analysis of three risk factors, namely the 'initial average experience of AUV team', 'government support' and 'comprehensiveness of insurance coverage' are presented here. Different input values of these risk factors were used to examine their effect on risk of AUV loss. For 'initial average experience of AUV team', values ranging from 0.5 to 2 years were used. The simulation results are presented in Figure 5.15 and Table 5.3, followed by a discussion on the results. For 'government support', values of 2 (Low), 5 (Average) and 8 (High) out of an arbitrary scale of 10 were used, with the results presented in Figure 5.16 and Table 5.4. Last, for 'comprehensiveness of insurance coverage', values of 1 (Low), 5 (Average) and 9 (High) out of an arbitrary scale of 10 were used, with the results presented in Figure 5.17 and Table 5.5.

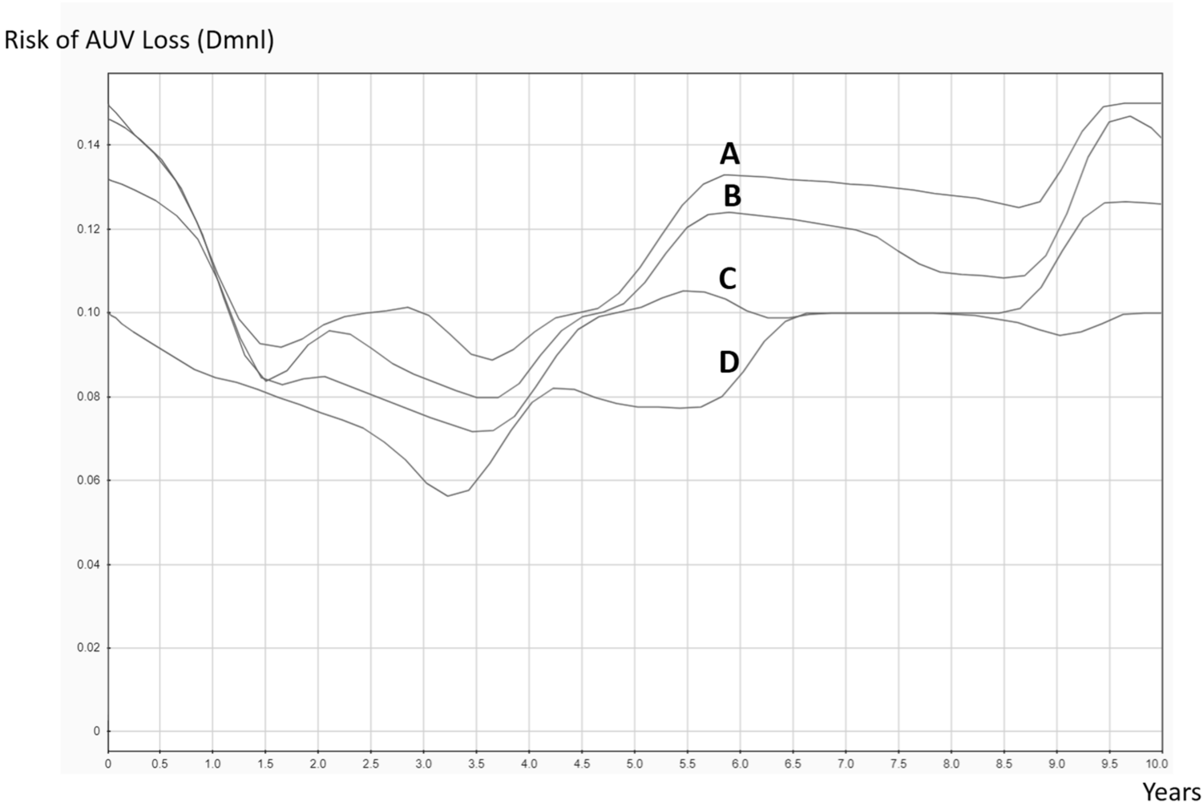


Figure 5.15: Risk of AUV loss for different 'Initial average experience of AUV team'. **A:** 0.5 yr. **B:** 1 yr **C:** 1.5 yr **D:** 2 yr.

Table 5.3: Risk of AUV loss for different 'Initial average experience of AUV team'.

IE: Initial experience.

Year	Risk of AUV Loss			
	IE = 0.5	IE = 1	IE = 1.5	IE = 2
0	0.150	0.146	0.132	0.100
1	0.112	0.111	0.110	0.085
2	0.096	0.094	0.085	0.077

3	0.100	0.084	0.076	0.060
4	0.095	0.086	0.080	0.078
5	0.109	0.105	0.101	0.078
6	0.133	0.124	0.101	0.085
7	0.131	0.120	0.100	0.100
8	0.128	0.109	0.100	0.100
9	0.134	0.120	0.114	0.095
10	0.150	0.142	0.126	0.100

Results from the simulation showed apparent differences in the ‘risk of AUV loss’ with varied ‘initial average experience of AUV team’, with higher initial experience leading to lower risk of loss. However, the general oscillatory behaviour of the risk of loss remained the same for all four simulations, showing an overall initial decrease in risk, followed by an increase in the middle phase and in later phase of the AUV program. This can be attributed to higher likelihood of human error in the early phase of the AUV program due to lack of experience and poorer reliability of the AUV in the later phase of the program due to aging of the vehicle. While all the simulations showed an increase in risk from 3.5 years to 5.5 years into the AUV program, the peak risk level for ‘initial average experience of AUV team’ of 0.5 yr and 1 yr is notably higher than that of 1.5 yr and 2 yr. There is also a significant difference in risk of loss right at the start of the AUV program, especially between an AUV team of initial average experience of 1.5 yr and 2 yr. It is therefore recommended that new AUV team members recruited at the start of the AUV program should ideally possess 2 years of relevant experience. Additionally, the simulations showed the risk level plateauing between 6.5 and 8.5 years into the program. This is the period where both technical reliability of the AUV and human reliability remains relatively stable in the mature AUV program.

The simulation results appear to differ slightly from the application example as presented in Figure 4.8. This is the result of additional risk factors and feedbacks in the system. However, the bathtub curve behaviour is still apparent, especially in the first six years of the AUV program. These simulation results have important implications for human resource management, such as optimising recruitment criteria in terms of desirable experience level or assessing the impact of staff turnover or attrition.

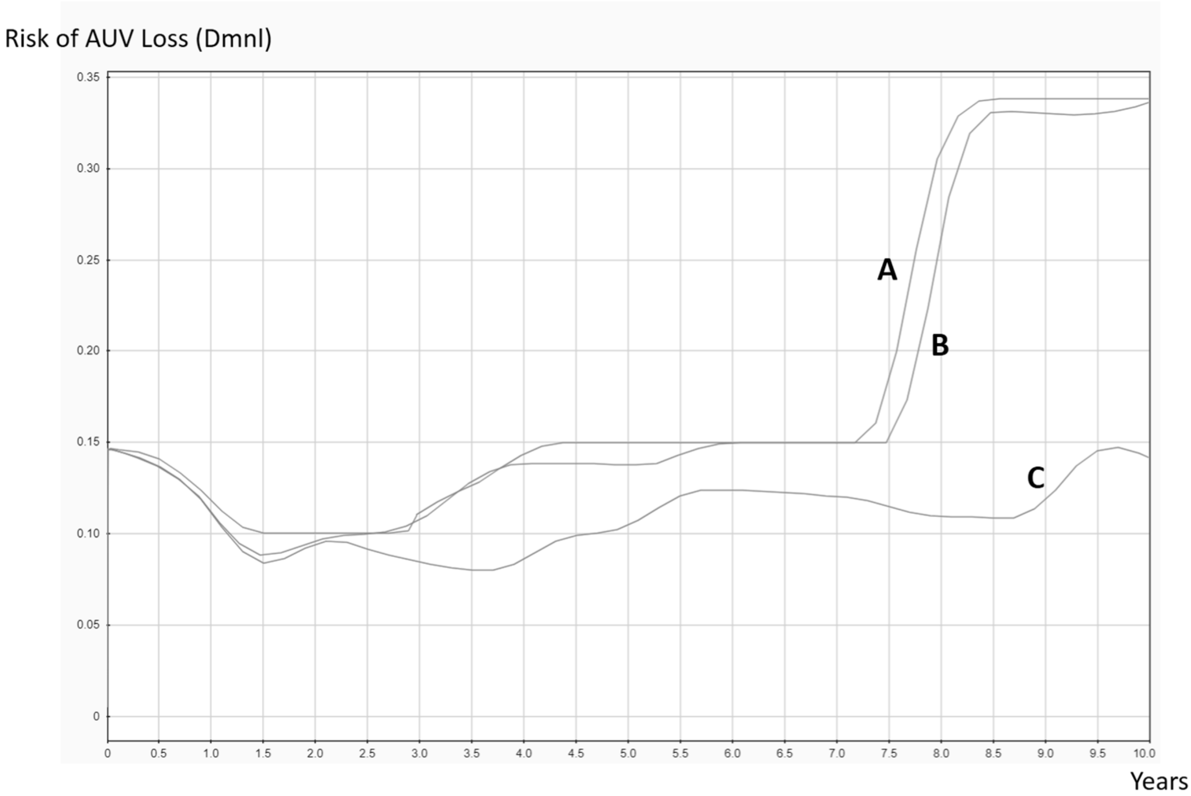


Figure 5.16: Risk of AUV loss for different levels of ''government support'. **A:** 2 (Low). **B:** 5 (Average) **C:** 8 (High).

Table 5.4: Risk of AUV loss for different levels of ''government support'.

GS: Government support

Year	Risk of AUV Loss		
	GS = 2	GS = 5	GS = 8
0	0.146	0.146	0.146
1	0.118	0.111	0.111
2	0.100	0.096	0.094
3	0.111	0.107	0.085
4	0.143	0.138	0.085
5	0.150	0.138	0.104
6	0.150	0.150	0.124
7	0.150	0.150	0.120
8	0.305	0.235	0.110
9	0.338	0.331	0.117
10	0.338	0.337	0.142

The impact of varied level of government support on the risk of AUV loss ressembled earlier sensitivity analysis example, where the general behaviour of the risk of loss remained relatively similar for all simulations. The difference to risk of loss only starts to become evident after 2.5 years into the AUV program. Apart from a negative relationship between the level of government support and risk of AUV loss, a considerable increase in the risk of loss near the end of the AUV program under low (value of 2) and average (value of 5) government support was observed. A lack of government support can adversely impact the amount of budget for the AUV program, which is important for both proper maintenance and repair of the AUV and retention of experienced personnel. Once the budget falls below a threshold level, experienced personnel may leave the team and critical AUV components such as the navigational or control systems starts to fall into disrepair. This increases the risk of loss significantly when the components start to age in later phase of the AUV program. Although the level of government support may be beyond the organisation's control, understanding its impact on risk of AUV loss can allow UTAS to better anticipate and respond to changing government policies. For instance, to seek diversity in funding base, such as commercial contracts.

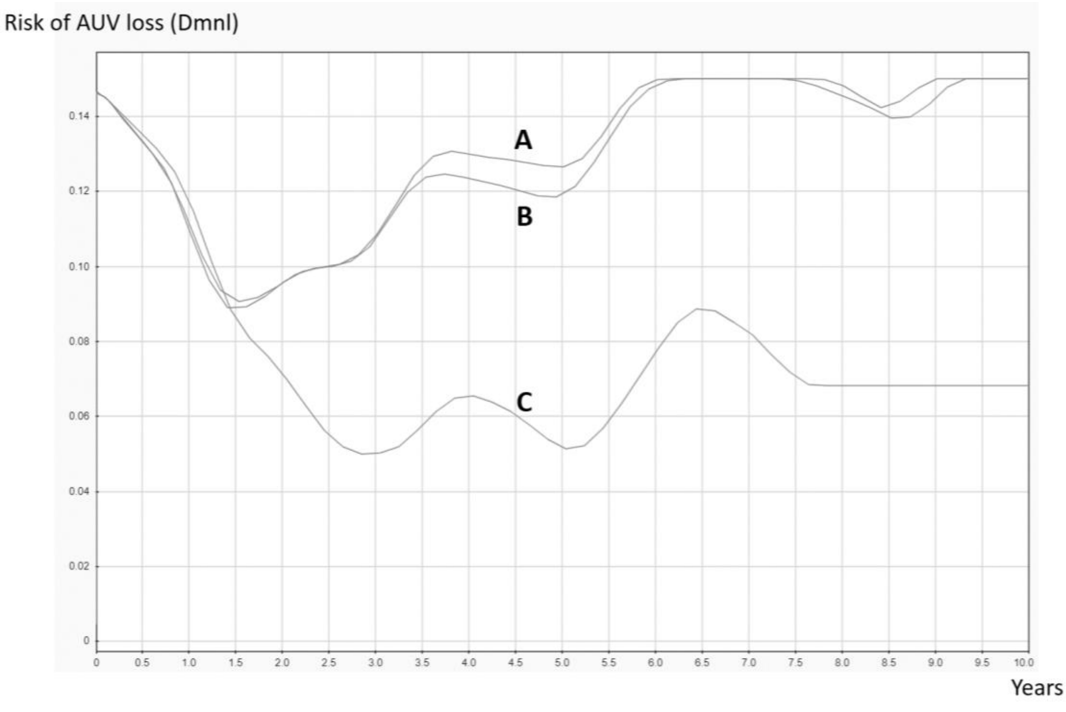


Figure 5.17 Risk of AUV loss for different 'comprehensiveness of insurance coverage'. **A:** 9 (High). **B:** 5 (Average) **C:** 1 (Low).

Table 5.5: Risk of AUV loss for different ‘comprehensiveness of insurance coverage’.

IC: Insurance coverage

Year	Risk of AUV Loss		
	IC = 9	IC = 5	IC = 1
0	0.146	0.146	0.146
1	0.116	0.110	0.109
2	0.096	0.096	0.070
3	0.108	0.108	0.050
4	0.130	0.123	0.065
5	0.126	0.120	0.052
6	0.150	0.148	0.077
7	0.150	0.150	0.082
8	0.148	0.145	0.068
9	0.150	0.145	0.068
10	0.150	0.150	0.068

The effects of varied comprehensiveness of insurance coverage showed an apparent impact on the risk of AUV loss. The presence of delays within feedbacks in the system resulted in the difference being evident only after first year of the AUV program. Contradictory as it seems, a higher insurance coverage translates to higher risk of loss. This is due to the negative relationship between insurance coverage and risk perception of individuals within the AUV team and the management, which eventually affects the risk of AUV loss. Although such relationship between insurance and risk perception is well supported in the literature [(224)(225)(226)], many other factors, such as social and cultural influences also play important roles in influencing an individual’s perception of risk [(230)]. Therefore, obtaining direct evidence on individual beliefs of the AUV team may be important for assessing risk perception. This however, warrants further investigation which is beyond the scope of this dissertation. Although the simulation results seem to suggest that lower insurance coverage is desirable for reducing risk of loss, it is clearly not a pragmatic recommendation. Instead, it is recommended that measures should be taken to improve the perception of risk among the AUV team and relevant stakeholders, such as enhancing training and risk communications. To increase effectiveness, such measures should be implemented in the early stages (<2 years) of the AUV program.

5.3.5 Scenario Analysis

Once sufficient confidence was gained in the FuSDRA model through extensive model testing, custom scenarios can be created and analysed through the model. There are numerous scenarios involving different risk factor combinations and permutations that can lead to an increased risk of AUV loss. A thorough analysis of all scenarios is onerous, impractical and time-consuming. Therefore, the choice of scenarios for analysis was based primarily on issues highlighted by the interviewed domain experts.

The following sections present three of these scenarios, accompanied by an analysis of the FuSDRA model and risk control recommendations.

5.3.5.1 Scenario 1: Experience Loss due to Departure of Critical Employee.

5.3.5.1.1 Scenario Motivation

The scenario of experience loss due to the departure of critical employee was inspired by the concerns of several interviewees, who highlighted strong reliance on the facility manager for the current *nupiri muka* AUV program. The following quote was taken from one of the interviews:

> *"One thing that we have talked about in the past, is the risk of over-reliance on one person. It highlights the issue, like being one person deep across the board, like so many organisations are. His approach is to make sure the training and knowledge of how to run the vehicle is passed on the operational team. But it is a risk we have been vocal about but what are we going to do? Are we going to hire two people? Three people?"*

It is also noteworthy that the facility manager is currently employed on a biennial contractual basis, thus being offered less job security as compared to a permanent arrangement. Experience loss due to the departure of employees is a natural part of a business in any industry. In the mid-1990s, the departure of many experienced mechanics from Delta Air Lines Inc. resulted in flight delays and cancellations due to longer diagnosis and repair time [(231)]. In Australia's context, a recent survey by specialist recruiter Robert Half in 2018 showed that 15% of Australian workers are likely to seek a new job in the coming year, and 67% of Australian employers saying they have seen an increase in staff departures in the last three years [(232)]. It is thus imperative that UTAS understand the impact of employee turnover, the facility manager for this scenario, to implement effective employee and knowledge retention strategies and attract quality employees into the organisation.

5.3.5.1.2 Scenario Simulation

To simulate departure of the facility manager, a loss of 2 years 'average experience of the AUV team' was introduced at the 2nd, 4th, 6th and 8th year of the AUV program in the FuSDRA model. To do so, a 'transport delay' block was added, as shown in Figure 5.18. Simulation results showing the impact of the departure to 'average experience of AUV team' and the 'risk of loss' are presented in Figure 5.19 and 5.20. As intended, the 'average experience of AUV team' decreases sharply at the point where the facility manager departs, with the 'risk of AUV loss' showing a sharp increase. Notably, the risk of loss remained elevated as compared to the base scenario for the remaining of the AUV program. Also, the departure of the facility manager caused a snowball effect which resulted in a jump in the risk of loss in later stages of the AUV program.

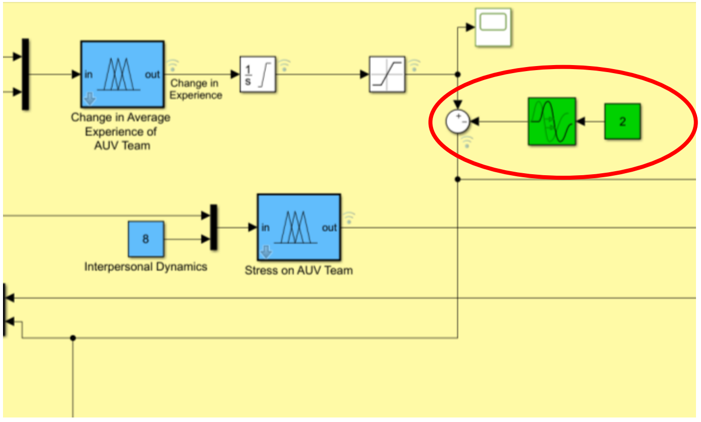


Figure 5.18: Addition of the ‘transport delay’ block in the human reliability sub-model (Circled) to simulate loss of average experience at different timing of the AUV program.

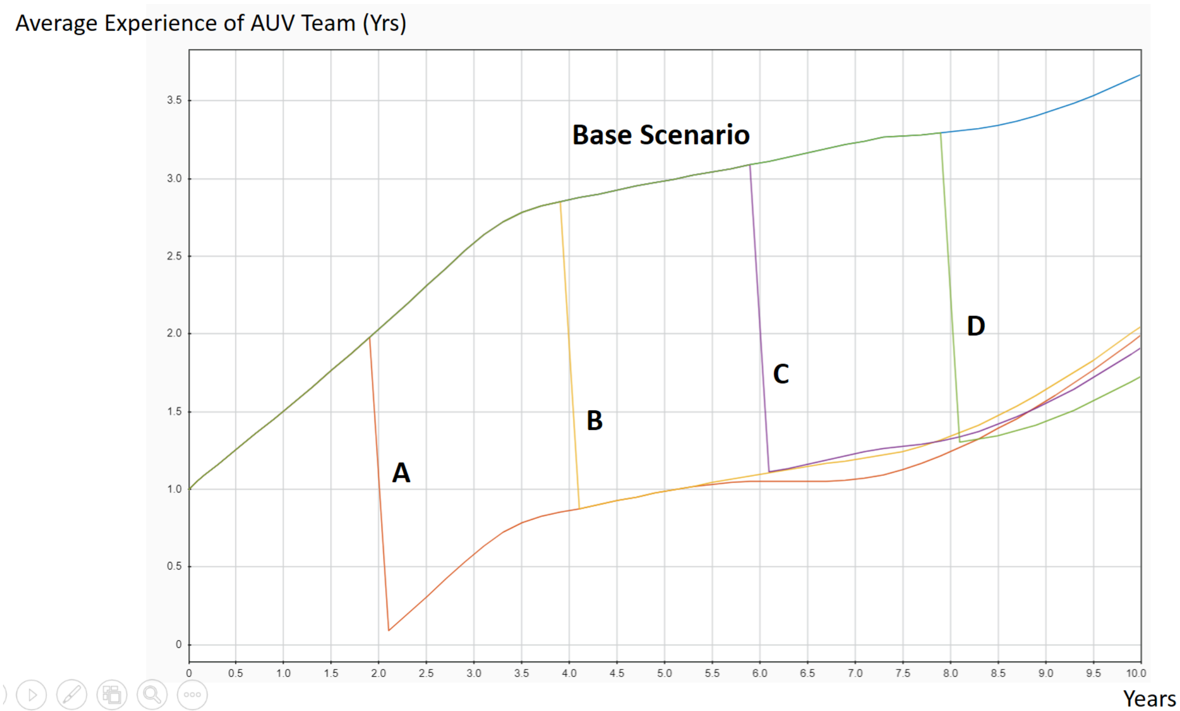


Figure 5.19: The ‘average experience of AUV team’ when the facility manager leaves at different time points of the AUV program. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr

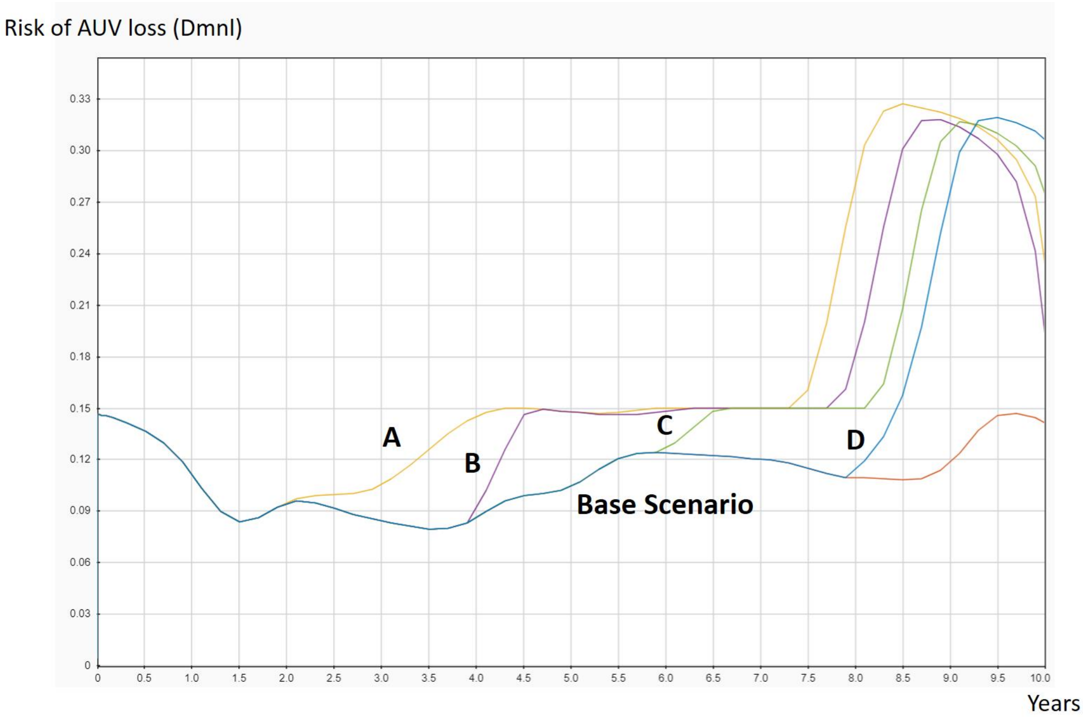


Figure 5.20: The impact on 'risk of AUV loss' when the facility manager leaves at different time points of the AUV program. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr

The above results assumed that there is no replacement for the facility manager, which is highly unlikely given the criticality of this position and the existing lean AUV team. However, finding appropriate replacement candidates with such niche skills and specific experience is understandably complicated and time-consuming. Therefore, a hiring period of one year was used in the model for recruiting a replacement of similar experience level, to model turnover of the facility manager. The simulation results are shown in Figure 5.21 and 5.22.

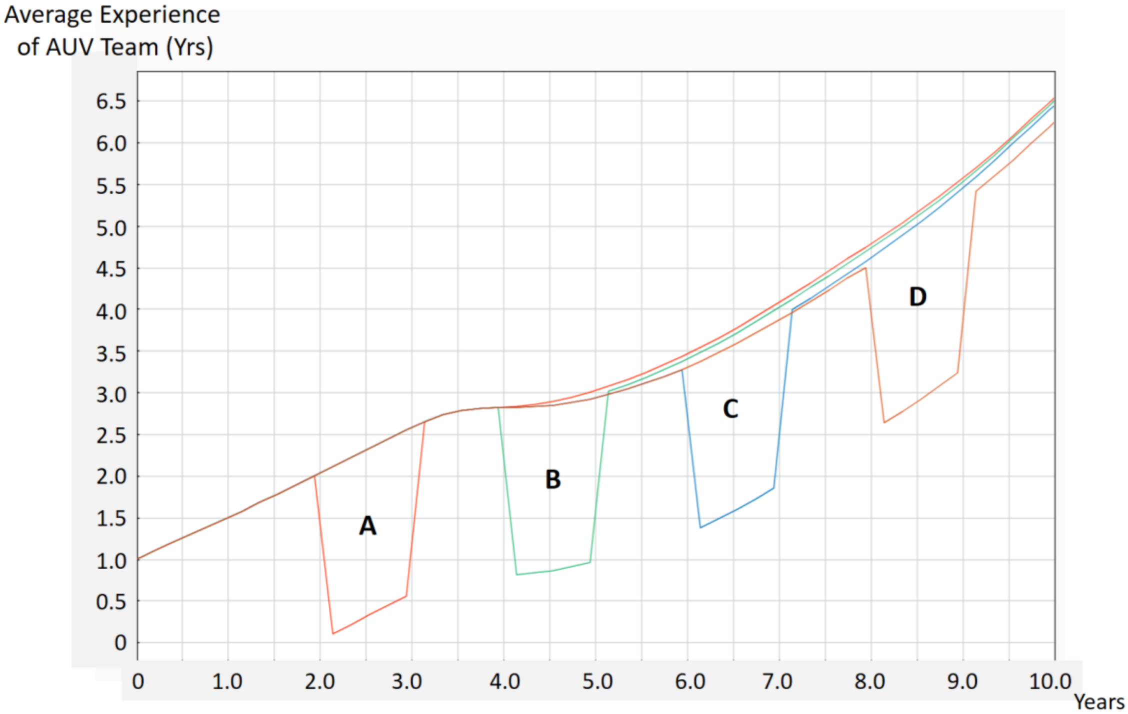
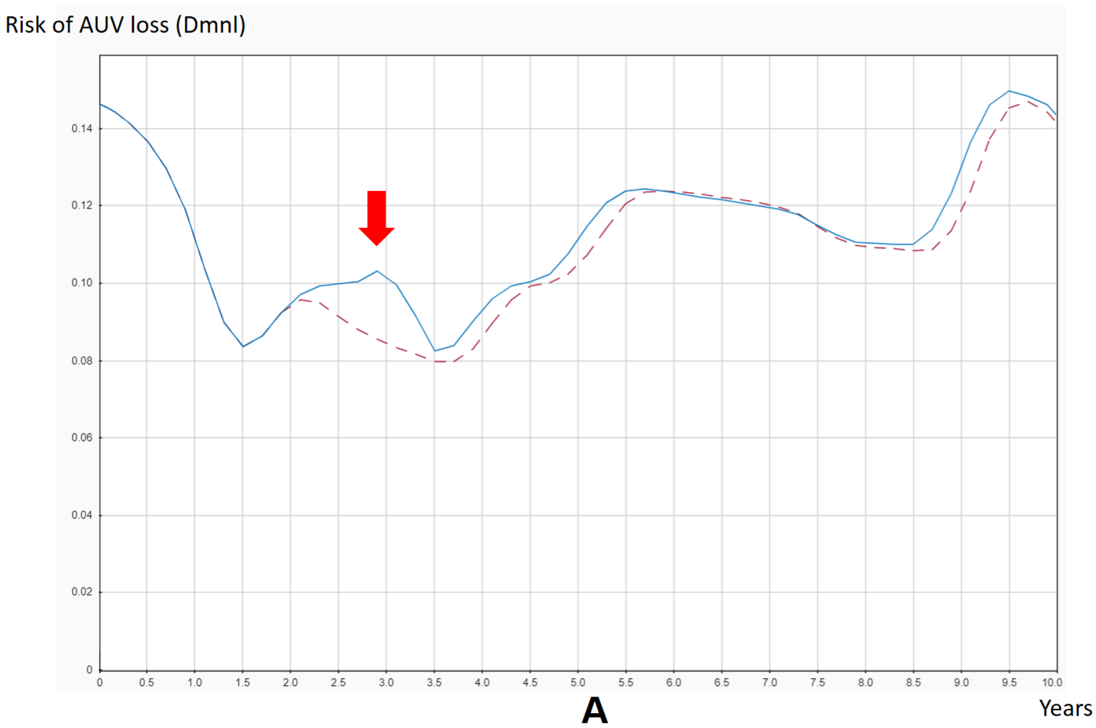
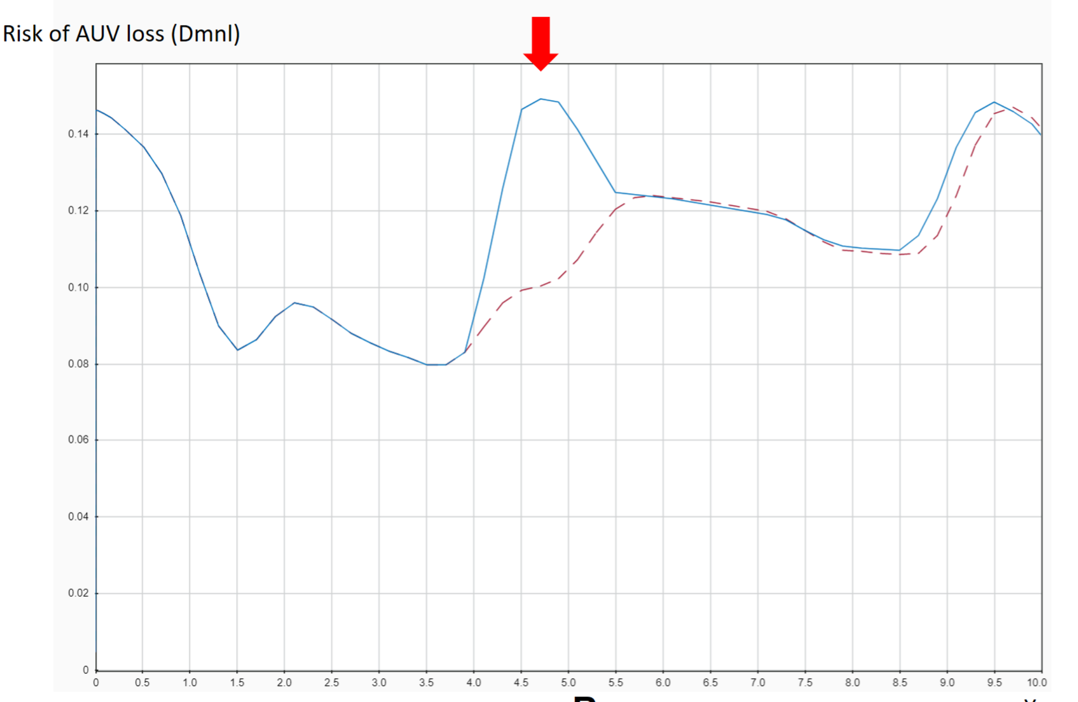


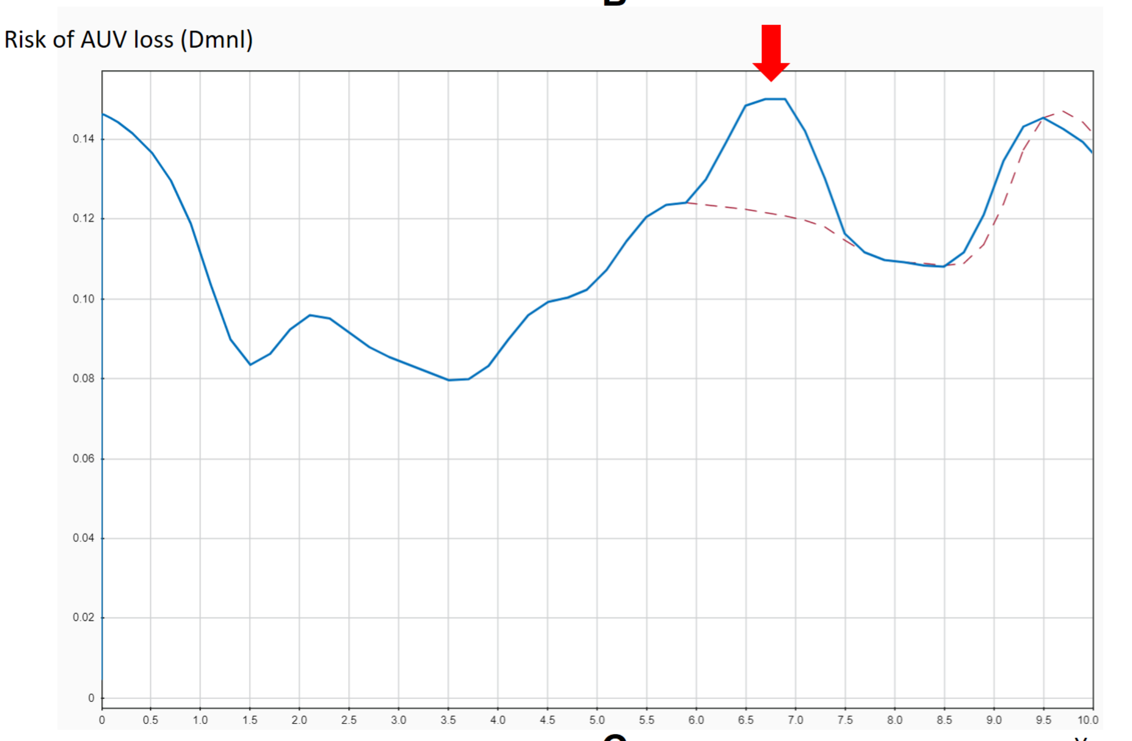
Figure 5.21: The ‘average experience of AUV team’, with a 1 yr replacement period for the departed facility manager at different time points of the AUV program. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr



A


Risk of AUV loss (Dmnl)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Years

B


Risk of AUV loss (Dmnl)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
Years

C

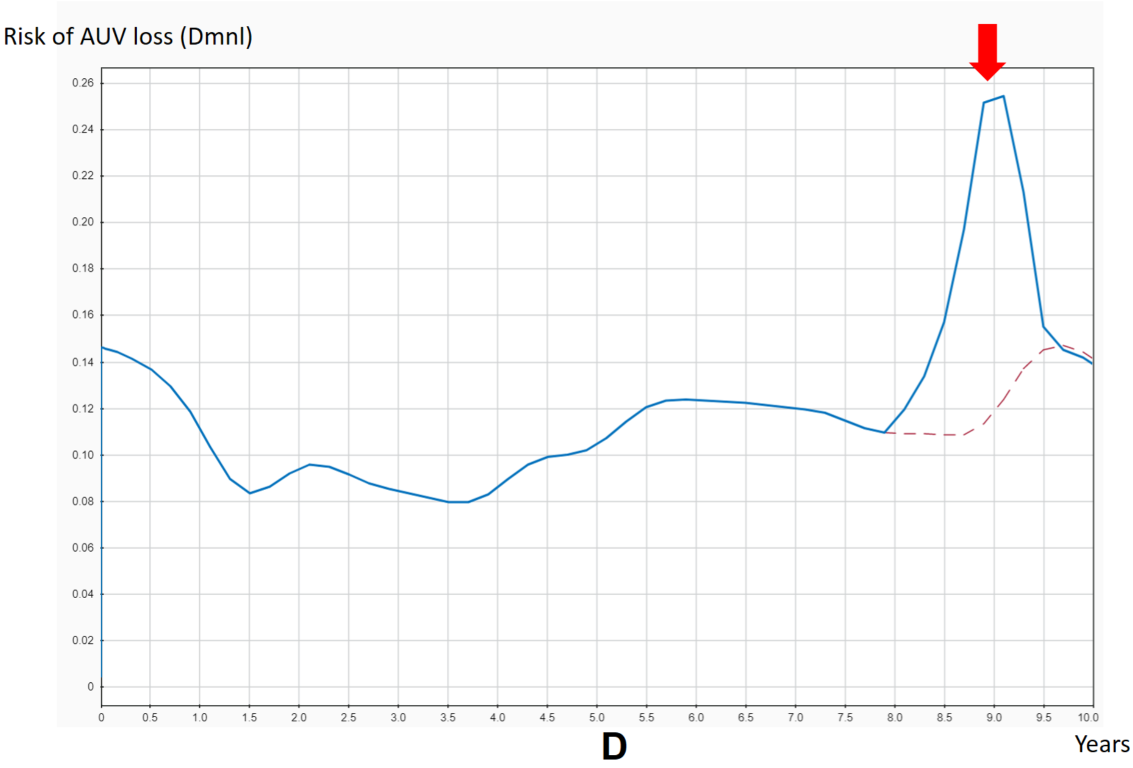
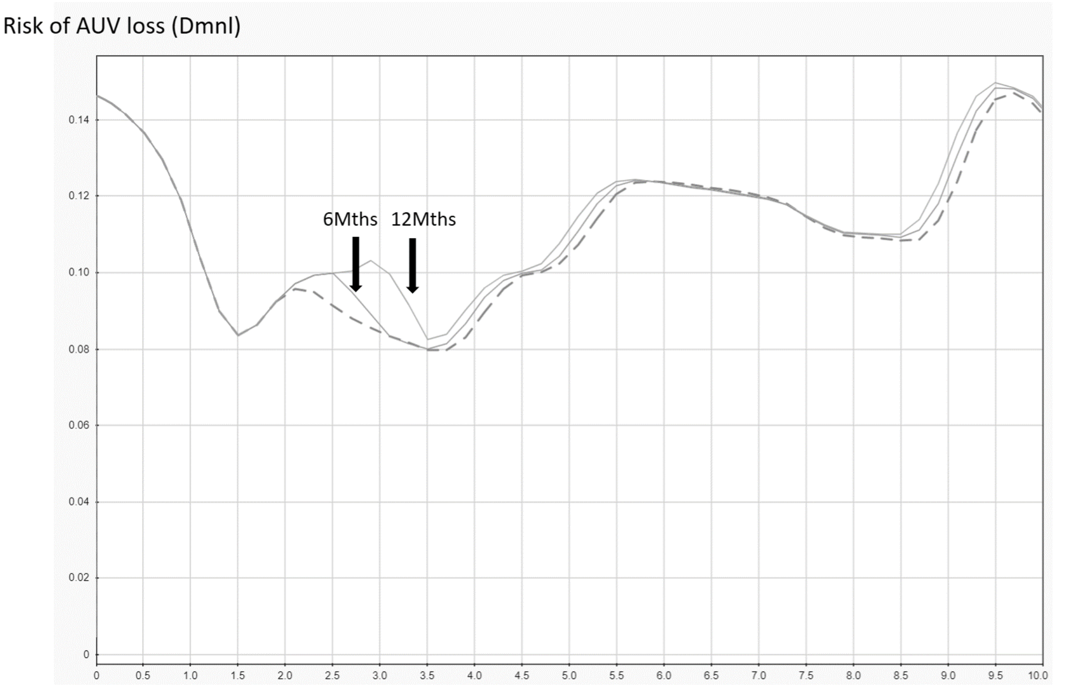


Figure 5.22: Impact on 'risk of AUV loss' (arrow) as compared to the base scenario (dotted) with a 1 yr replacement period for the departed facility manager at different time points of the AUV program. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr

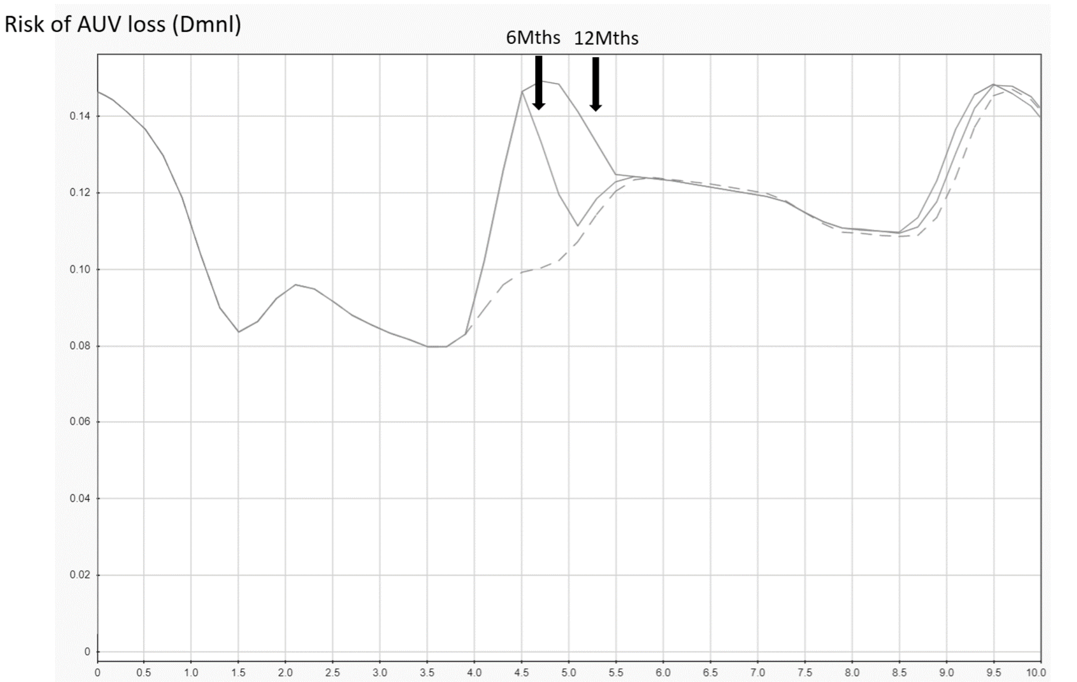
Figure 5.21 shows the 'troughs' in 'average experience of AUV team' with the turnover of the facility manager at different point of the AUV program. Figure 5.22 shows the impact on the risk of loss as compared to the base scenario, with the increase in risk highlighted by an arrow. Notably, the turnover in the earlier stages (2nd year) of the AUV program appears to have a lesser impact to the risk of loss as compared to the later stages (4th, 6th and 8th year). The extensive amount of feedback loops and fuzzy rules makes it challenging to pinpoint the exact reason for such a behavior. However, it is likely that departure of the facility manager in mature stages (> 4 years) of the AUV program has a greater impact to the risk of loss due to increasing maintenance activities and budgetary constraints.

In the next simulation, the turnover period for the facility manager was shortened from a year to 6 months to simulate a reduction of hiring time. The simulation results are shown in Figure 5.23.



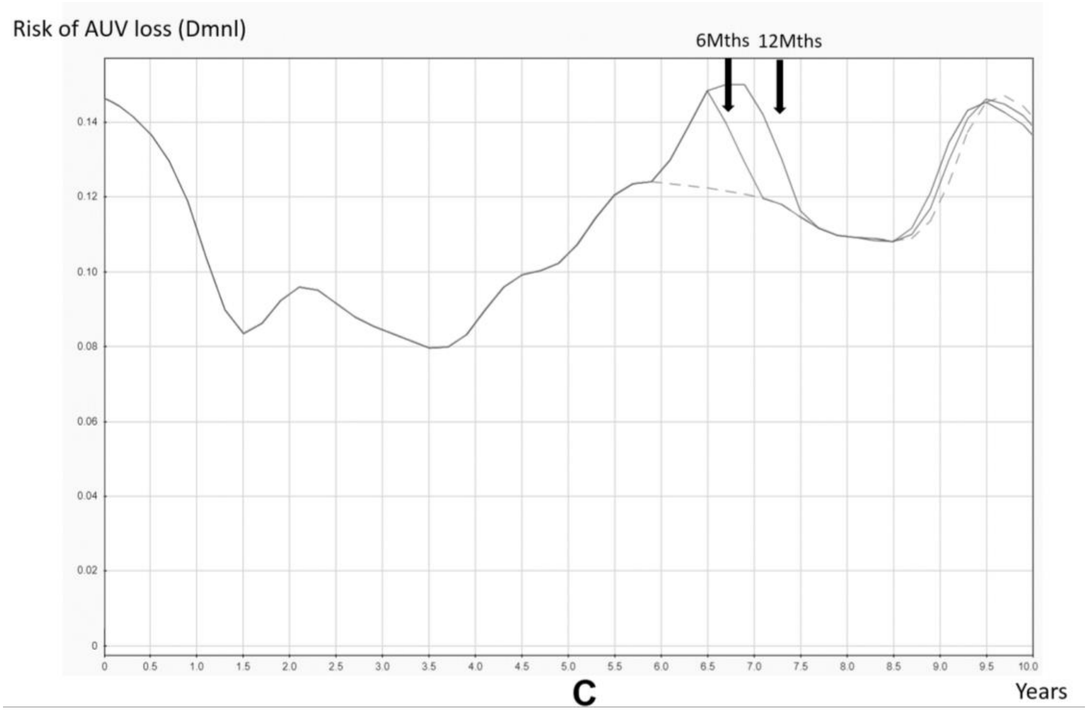
Risk of AUV loss (Dmnl)
6Mths
12Mths
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0
Years

A



Risk of AUV loss (Dmnl)
6Mths
12Mths
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5 10.0
Years

B



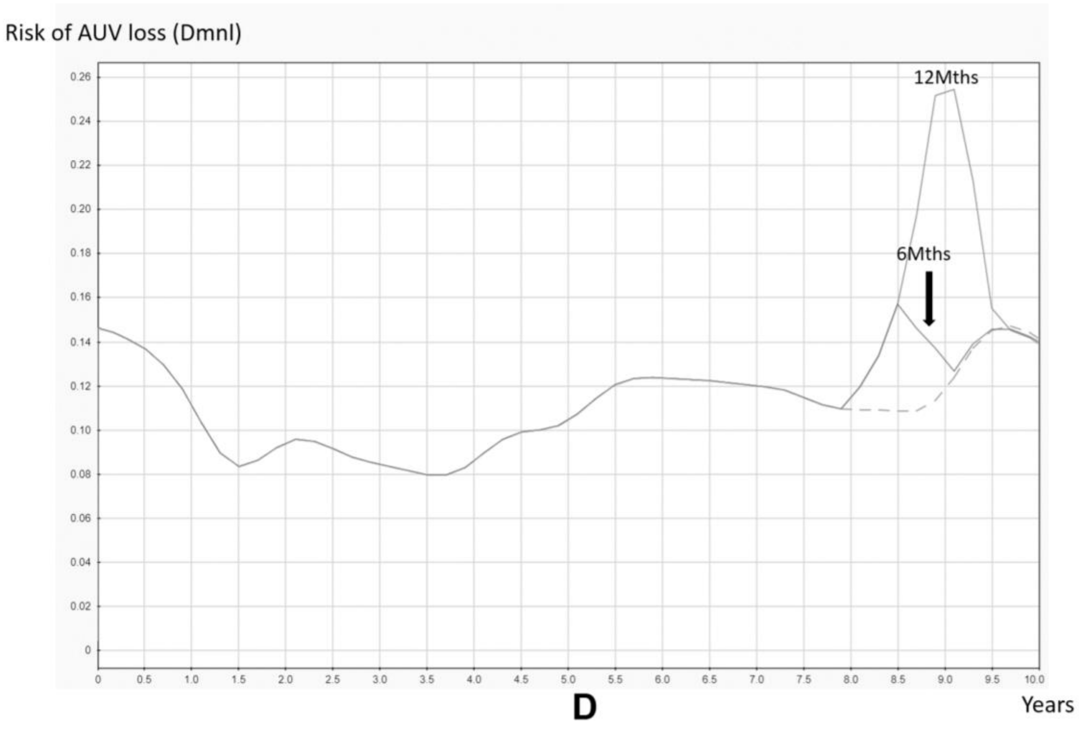


Figure 5.23: Impact on 'risk of AUV loss' (arrow) with 6 months and 1 yr replacement period for the departed facility manager at different time points of the AUV program. The base scenario (dotted) is also included for reference. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr

Simulation results showed that reducing the replacement period for the facility manager mitigates impact of the turnover on risk of loss. This is especially apparent when the reduction in hiring period was simulated in the 8th year of the AUV program. In addition, the risk of loss was also noted to exhibit a sharper decline upon recruitment of the replacement in a 6 months period as compared to a year.

5.3.5.1.3 Recommendations

Simulation results from both the sensitivity analysis (Figure 5.16) and scenario analysis suggested that average experience of the team plays a critical role in influencing the risk of AUV loss. In particular, the current facility manager is influential over the current *nupiri muka* program because of his relevant and extensive polar AUV experience. The following recommendations are therefore offered with the aim of retaining an experienced employee, secure replacement in a shorter period, and promote an effective knowledge transfer process.

With the current program supported primarily by a lean team of three, the departure of any crew can negatively impact the workload and morale of the team. Therefore, it is recommended that an effective employee retention program be implemented to improve retention. This may include open lines of communication, provision of training and professional development and fostering of teamwork. In addition, considerations can be made to provide an option for the facility manager to convert existing contractual arrangement into a permanent role, under the condition that the facility manager is found to be suitable for the job. Providing such an option to the facility manager, especially in later stages of the AUV program (>4 years) may improve retention and consequently, a lower risk of AUV loss.

Sourcing for an employee replacement specialising in AUV operations means dipping into a very niche talent pool. To reduce hiring time and achieve a lower risk of loss (Figure 5.23), strategies are recommended to attract niche talents. This may include sourcing internationally with competitive relocation packages, hosting AUV-related conferences to create networking opportunities and offering flexibility in working arrangements. It is also important to note that a more experienced team at the beginning of the program translates to a lower risk of loss throughout the entire program (Figure 5.15). Therefore, recruitment criteria in terms of desirable experience level can be established early in the program using the simulation results.

Last, an ongoing effective knowledge transfer plan should be executed to mitigate the risk of experience loss in the event of employee departure. The transfer of both tacit knowledge and explicit knowledge should be included in the plan, which may include mentorship, training, work shadowing, knowledge repository or rotational assignments. This will increase the pool of knowledgeable personnel who can take on each other’s role whenever the need arises. It is also critical to evaluate and measure effectiveness of the knowledge transfer regularly to identify gaps and make improvement to the plan.

Although these recommendations may seem intuitive and obvious to any organisations, they can be overlooked in routine organisational practices, especially in the event where commitment to the AUV program decreases over time. The next scenario analyses examine such a reduction in commitment, with a resulting cutback in government support.

5.3.5.2 Scenario 2: Reducing Government Support and Increasing Alternatives to AUV.

5.3.5.2.1 Scenario Motivation

The current *nupiri muka* AUV program is co-funded by both AMC and AGP. Broadly speaking, AMC supports the infrastructure and insurance fees while AGP funds the staff cost. However, it is worth highlighting that the funding arrangement by AMC and AGP is not independent of each other, with both parties working in close collaboration to support the program. A reduction in government support to the *nupiri muka* AUV program is arguably one of the most pressing concerns raised by many of the interviewees. Apart from directly influencing the risk of AUV loss through budgetary pressure, several interviewees also expressed concerns on how such reduction can affect the continued renewal of their employment contracts. An interviewee highlighted the possibility of a future funding reduction:

> *"It is fine because the vehicle is new now and everybody is excited but next year, people will take a very hard look and go, we are spending a lot of money but not everybody will probably feel that they have gotten value from it."*

And another interviewee mentioned the risks of a funding reduction:

> *"Getting our finances right is one of the biggest risks. If we do not have the right finance, we will not be able to run the vehicle in the first place. The vehicle costs a lot of money to run and so that money has to come from somewhere."*

Apart from government support, another risk factor external to the organisation is the availability of alternatives to AUVs for Antarctic data collection. The obsolescence of technological equipment with increasingly shorter lifecycles is a continual challenge faced by many industries. The exponential rate of technological evolution can render old AUV technologies less practical and competitive either against newer AUVs or other means of data collection. With more options available, Scientists and other users will naturally choose the most effective and cost-efficient means of data collection, adversely impacting the quantity of output from the *nupiri muka* AUV program. As one scientist openly mentioned:

> *"I don't care about AUVs, it is useless to me until it provides a data set, and then it is the data set I care about. To a large part, the actual concern for failure rates, I am interested only as a curious person. But strictly as a scientist, a seagoing oceanography focused scientist, it is not really my problem. Just like if I am on a ship, it is not really my problem if it is using a propeller with five blades or four as long as it meets specific requirements."*

Currently, alternatives to AUVs include polar profiling floats, ice-tethered profilers, subsurface moorings, oceanographic instruments deployed on marine mammals and satellite technology (21). With rapidly developing technologies, future Antarctic under-ice observation systems may also include pop-up storage capsules and data telemetry, airborne observation platforms, low-cost expendable buoys, oceanographic mooring deployment using ROVs and enhanced acoustic capabilities (21). Therefore, it is conceivable that alternatives to AUVs may render the *nupiri muka* obsolete for Antarctic marine science research in the future.

5.3.5.2.2 Scenario Simulation

To simulate a scenario of government support reduction and an increasing number of alternatives to the *nupiri muka* AUV, two integrator blocks were added to replace the constant blocks of 'government support' and 'availability of alternatives' in the FuSDRA model (Figure 5.24). The output of the integrator block is equal to the time-integral of the input, plus the initial value (at t = 0) of the output. The first simulation examines the effect of gradual government support reduction on the risk of AUV loss, at a rate of 10% each year (On the arbitrary scale of 10). The simulation result is presented in Figure 5.25. The second scenario examines a more abrupt reduction in government support at various time points of the AUV program. To do so, a 'transport delay' block was used, similar to the one shown in Figure 5.18. 'Government support' was simulated to reduce from a level of 8 (High) to 2 (Low) out of an arbitrary scale of 10 at the 2nd, 4th, 6th and 8th year of the AUV program in the FuSDRA model. Results of the simulation are presented in Figure 5.26. The next simulation analyses the effect of increasing alternatives to the *nupiri muka* AUV on the risk of AUV loss, at a rate of 10% each year (On an arbitrary scale of 10). Lastly, a combination of gradual reduction in government support (rate of 10% each year) and an increasing number of alternatives (rate of 10% each year) to the AUV were simulated to determine their combined impact on the risk of AUV loss.

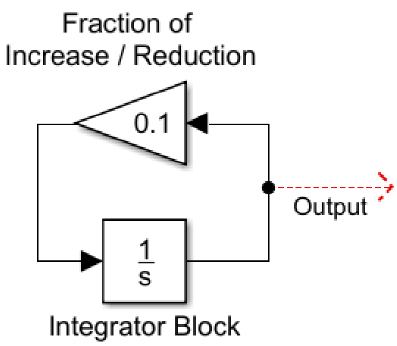


Figure 5.24: Addition of the 'integrator block' in the FuSDRA model to simulate increasing or decreasing time-dependent risk factors.

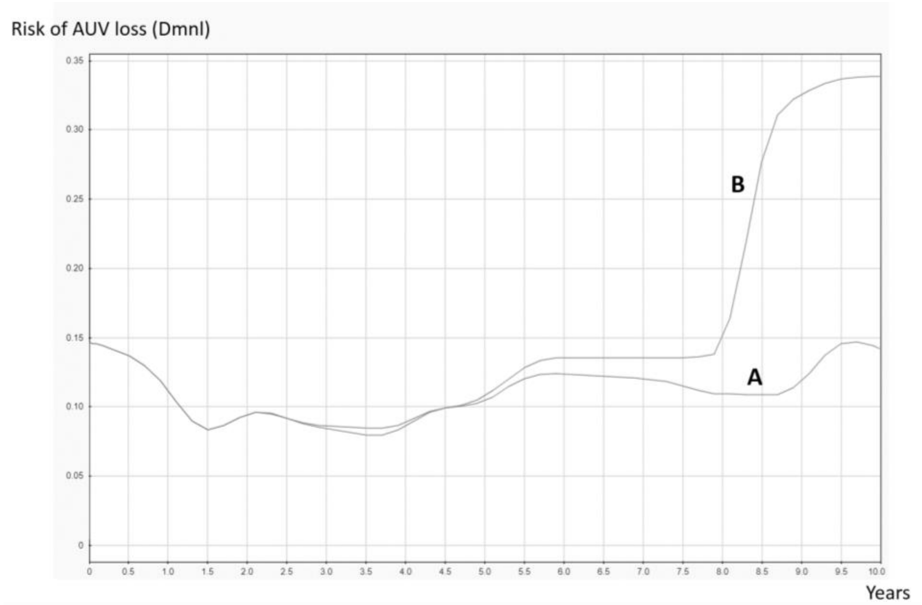


Figure 5.25: Impact on ‘risk of AUV loss’ with a 10% annual reduction in government support, as compared to the base scenario. **A:** Base scenario. **B:** Reducing government support.

The simulation results showing the impact of gradual government support reduction on the risk of AUV loss is presented in Figure 5.25. Initial reduction in government support does not appear to impact the risk of AUV loss, due to a latency period represented by delays in the system. However, as government support continue to decline, a difference in risk of loss emerges from the third year of the AUV program when compared to the base scenario. The subtle difference of mostly less than 0.01 continues till 5.5 years into the program before becoming more apparent in the last 2 years of the simulation.

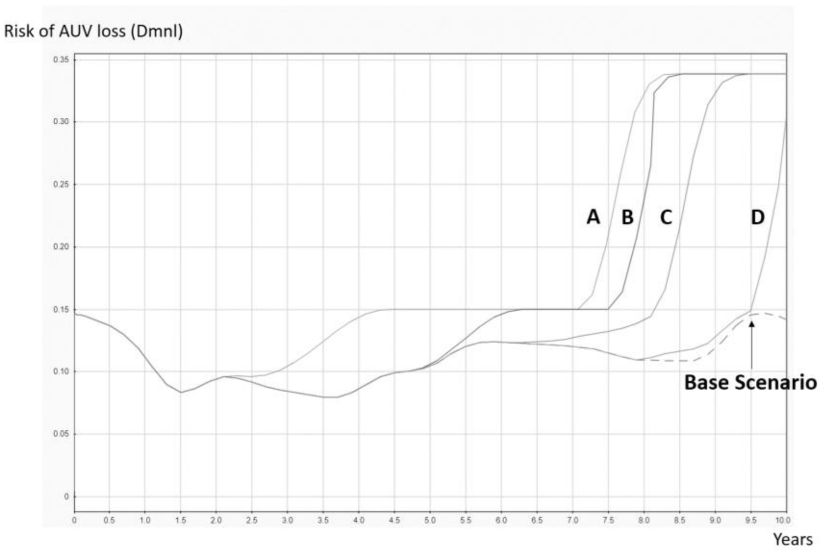


Figure 5.26: Impact on ‘risk of AUV loss’ with a more abrupt reduction in government support from a level of 8 (High) to 2 (Low) out of an arbitrary scale of 10 at various time points of the AUV program. The base scenario (dotted) is also included for reference. **A:** 2 yr **B:** 4 yr **C:** 6 yr **D:** 8 yr

As shown in Figure 5.26, the risk of AUV loss increases correspondingly when the level of government support reduces abruptly at various points of the AUV program. Similar to the earlier simulation of gradual reduction in government support, the risk of loss increases significantly in late phase (>7 years) of the AUV program in all four reduction scenarios. Notably, reduction of government support at 2nd year of the program resulted in an earlier peak in the risk of loss as compared to a reduction at 8th year of the AUV program.

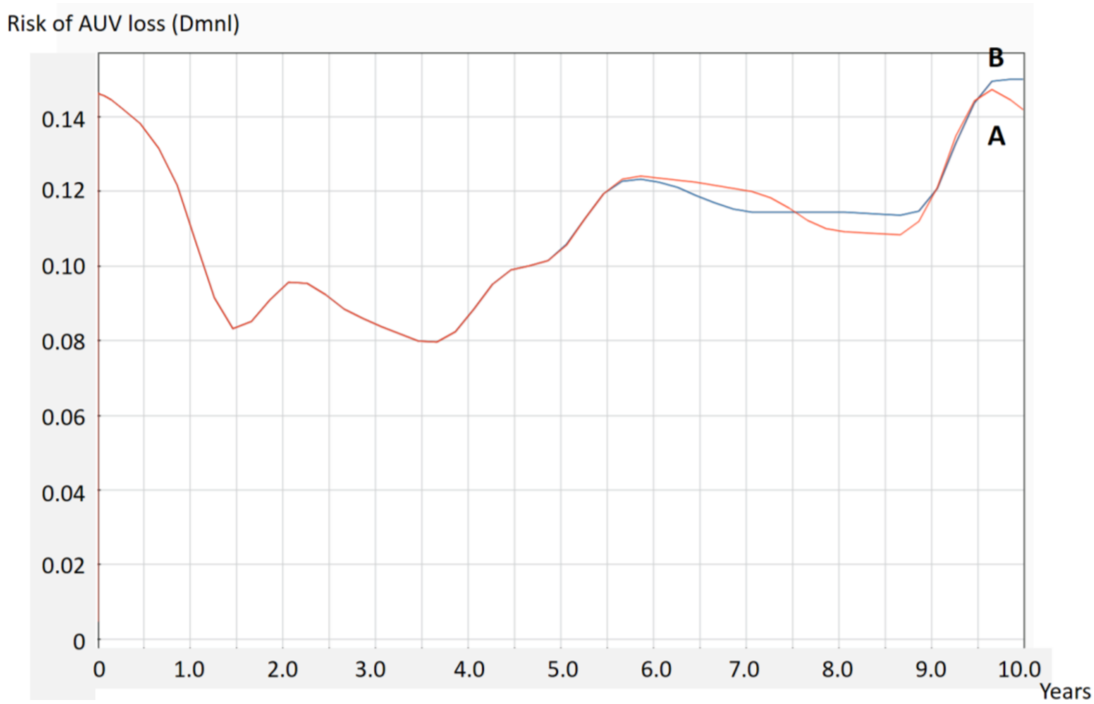


Figure 5.27: Impact on 'risk of AUV loss' with a 10% annual increment in alternatives to the *nupiri muka* AUV, as compared to the base scenario. **A:** Base scenario. **B:** Increasing alternatives to the *nupiri muka* AUV.

Simulation results showing the impact of increasing alternatives to the *nupiri muka* AUV on the risk of AUV loss is presented in Figure 5.27. For the most part of the AUV program, the increasing number of alternatives do not appear to impact the risk of AUV loss as compared to the base scenario. The difference only becomes apparent in the last year of the AUV program, with the reason for this being twofold. First, the *nupiri muka* adopts newest AUV technologies and is considered state-of-the-art, manufactured by one of the leading company in AUV business (Refer to section 5.1.2 and Appendix F). Second, the use of AUV for Antarctic marine science research is a relatively new development with many potentials and advantages over other means of data collection (Refer to section 1.2.5). Therefore, the obsolescence rate for the *nupiri muka* AUV is currently deemed to be very low, thus having an impact on the risk of loss only in the late stages of the AUV program.

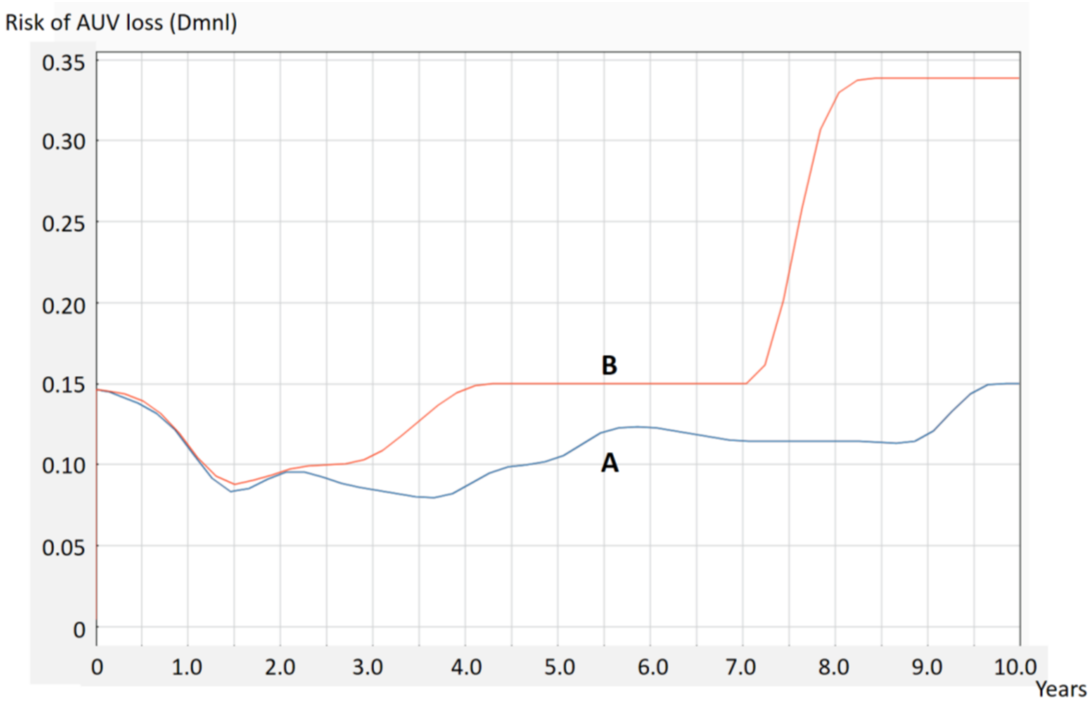


Figure 5.28: Combined impact on 'risk of AUV loss' with a 10% annual increment in alternatives to the *nupiri muka* AUV and 10% annual reduction in government support, as compared to the base scenario. **A:** Base scenario. **B:** Combined effect.

Results from simulations of the final scenario, which examines the combined effect of a gradual reduction in government support and increasing number of alternatives, is presented in Figure 5.28. When compared to the base scenario, the risk of AUV loss noticeably deviates after the second year of the AUV program. After 7 years into the program, the risk of loss exhibited a sharp increase and diverges significantly from the base scenario. The jump in risk can be attributed to the reduction of budget below a threshold level, where experienced personnel may leave the team and critical AUV components fall into disrepair (See section 5.3.4.3). Interestingly, the combination of reducing government support and increasing alternatives has a synergistic effect on the risk of AUV loss, resulting in a greater increase in the risk of loss than the sum of their individual effects. Although the extensive amount of feedback loops and fuzzy rules makes it challenging to pinpoint the reason behind this synergistic effect, the significant increase in risk clearly requires attention for tightened controls.

5.3.5.2.3 Recommendations

Based on the scenario analysis, measures are required to dampen the combined effect of reducing government support and increasing number of alternatives to the *nupiri muka* AUV. To better prepare for the possibility of reduced government support, measures to consider may include: (1) Having a robust system for monitoring budgets and forecast future additional funding requirements. (2) Actively seek diversity in funding base, such as commercial contracts and establish strong stakeholder relationships. (3) Establish a robust finance strategy, with regular review, which is aligned to the strategic plan. The strategy should include plans to maintain or build funds to ensure sustainability of the AUV program, and. (4) Implement a process for reviewing and updating strategic or operational plans in response to changes in government support. These measures are especially crucial from early stages of the AUV program as reduction in government support at any point can have a consequential effect on the risk of loss later in the program (Figure 5.26 and Figure 5.25).

. While competitive market pressures and rapid evolution of technologies may be outside the organisation's control, measures can be adopted to better manage the risk of obsolescence. This includes: (1) Ensure a comprehensive repair and preventive maintenance program is in place. An effective maintenance program can increase the reliability and availability of the *nupiri muka* AUV over the long run. (2) Implement a process for regular review of published literature and other information sources to spot emerging trends in both AUV technologies and alternative technology to AUVs. (3) Develop a strong partnership with ISE Ltd. The company should be well-aware of any impending obsolescence and have a migration or upgrade strategy. (4) Establish a robust and clear long-range plan for the *nupiri muka* AUV program. This plan should assign a return of investment, state cost avoidance strategies, process optimization and best practices, and (5) To position the AUV program as a multipurpose research program going beyond the AUV itself, such as battery capabilities or adaptive controls. This should lead to a strong underwater robotics research program at AMC UTAS, exploring next generation alternatives to AUVs. As Figure 5.27 shows, these measures are especially important in later stages of the AUV program (>7.5 years).

5.3.5.3 Scenario 3: Increasingly Dysfunctional Interpersonal Dynamics

5.3.5.3.1 Scenario Motivation

The last scenario analysis examines the impact of increasingly dysfunctional interpersonal dynamics on the risk of AUV loss. The concern on interpersonal dynamics, particularly inter-team dynamics was raised by several interviewees, as one of them put it:

> *"Having four to six people in a very small enclosed space (boat) for numerous hours in a very cold conditions is a recipe for conflicts. Having boat operators that are not part of the team is a risk as far as I'm concern because there is usually discrepancy in understanding. Because they are not part of our team day-to-day, they would otherwise be very unfamiliar with how we operate and what needs to be done slightly differently."*

And from another interviewee:

> *"An operational team would be focused on making sure the vehicle survives while a science team is less interested in that and more interested in getting its shot. So if it's now or never, might as well be now if you are a user. Because if the vehicle doesn't come back, I wasn't to get my data anyway, it's worth the risk. That is not true for the*

guys who have to plan for the next trip. So you got two very different incentives around users and operators. That is the inter-team difficulty."

An increasingly dysfunctional interpersonal dynamic can be caused by several reasons, such as weakening leadership, deterioration in communication, decreasing trust, groupthink and excessive deference to authority. The relationship between interpersonal dynamics and risk is also well documented in the literature. For instance, Morphew [233] found that interpersonal dynamics between crew members in long-duration space flight is one of the main human-related stressors that can impact mission safety and risk. Of closer relevance to operations in the Antarctic, Robertson [234] shared her account of leading a team through four months of Antarctic winter at Davis station. She highlighted the challenges in managing human interactions over the harsh physical conditions and recalled an incident over a stand-off over whether the bacon should be cooked crispy or soft. The bacon argument nearly derailed the $20 million Antarctic science program.

5.3.5.3.2 Scenario Simulation

To simulate the effect of increasingly dysfunctional interpersonal dynamics on the risk of AUV loss, an integrator block similar to that shown in Figure 5.24 was added to replace the constant block of 'interpersonal dynamics' in the FuSDRA model. The first simulation examines the effect of reducing interpersonal dynamics at a rate of 10% each year (On the arbitrary scale of 10). The second simulation analyses the same reduction, but at a higher rate of 20% each year (On an arbitrary scale of 10). Results of both simulations are shown in Figure 5.29, with the main difference to the risk of AUV loss highlighted in the circle and further shown in Figure 5.30.

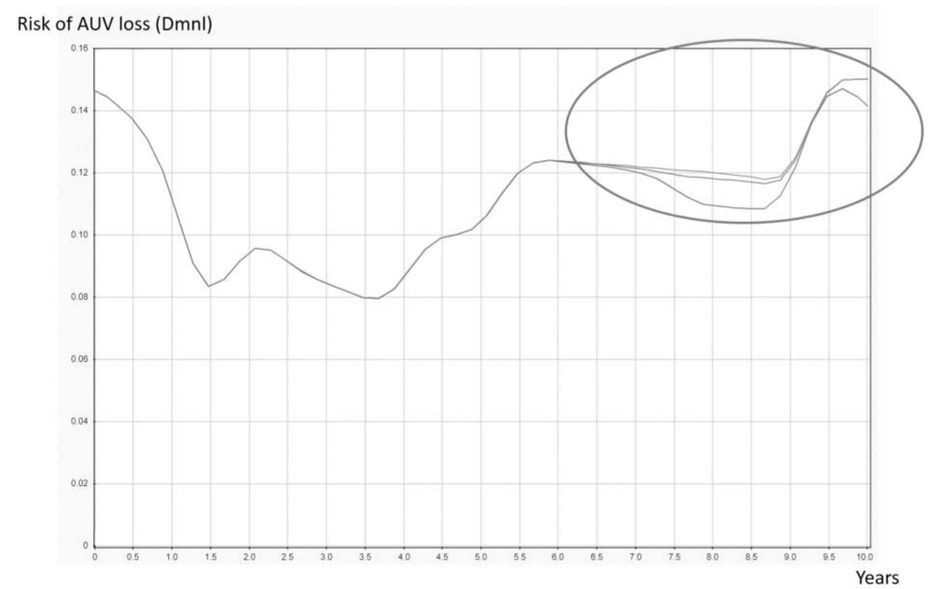


Figure 5.29: Minimal impact on 'risk of AUV loss' with the reduction of 'interpersonal dynamics', as compared to the base scenario.

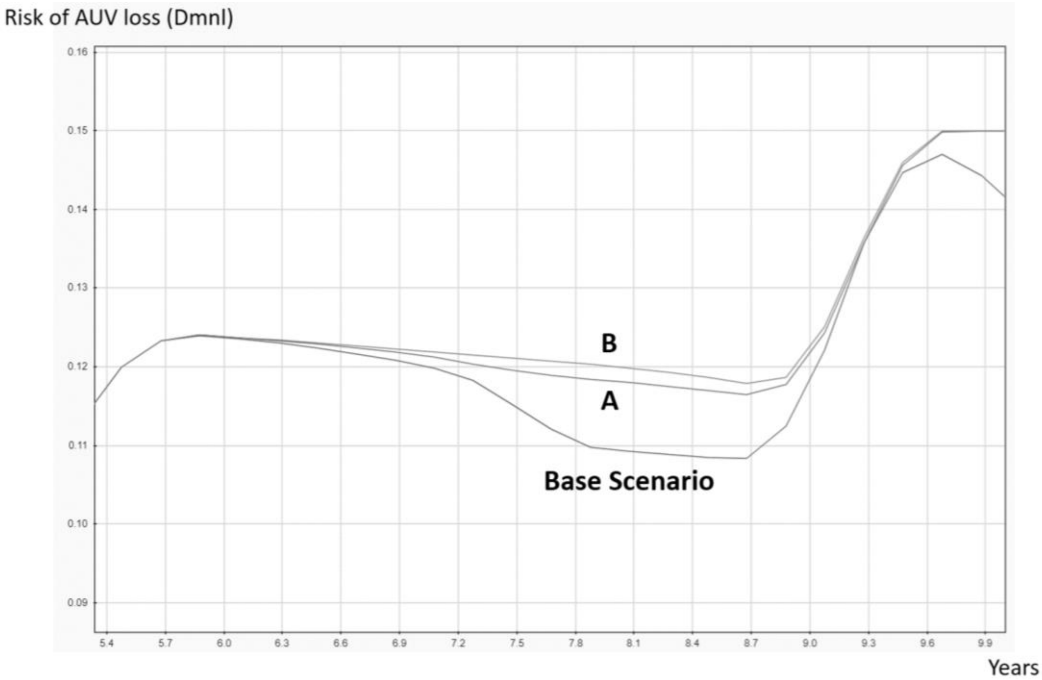


Figure 5.30: Impact on 'risk of AUV loss' with an annual reduction in 'interpersonal dynamics', as compared to the base scenario (dotted). **A:** 10% annual reduction. **B:** 20% annual reduction.

When compared to the base scenario, reduction in interpersonal dynamics increases risk of loss by causing a higher stress level leading to an increase in likelihood of human error. However, both simulations appear to increase the risk of loss minimally, of less than 0.015. Additionally, the difference in risk of AUV loss was observed only after 6 years into the AUV program. This result is unexpected but not surprising. In the FuSDRA model, the level of interpersonal dynamics influences the stress level of the AUV team directly, which is one of the risk factor influencing risk perception of the AUV team. The other two risk factors identified as having influence over risk perception are the average experience of the AUV team and comprehensiveness of insurance coverage. As compared to stress level, the experience of the team and comprehensiveness of insurance coverage presents more immediate and quantifiable concerns. Stress itself is a complex and subjective phenomenon which is highly dependent on individual's perception (235). Therefore, it is not surprising that during elicitation of fuzzy rules, a relatively lower emphasis was given to stress level of the AUV team as compared to the average experience of the AUV team and comprehensiveness of insurance coverage. As a result, any fluctuations in the level of interpersonal dynamics would have produced minimal impact on the risk of AUV loss. Although a greater emphasis on stress level of the AUV team will produce a different set of simulation results, it is difficult to ascertain the exact weightage without further quantitative studies, such as using the Hassles Scale (236) or the Perceived Stress Scale (237).

5.3.5.3.3 Recommendations

Despite the simulation results, the importance of interpersonal dynamics should not be underestimated. Therefore, it is recommended to further investigate the impact of changing interpersonal dynamics on stress level and risk perception of the AUV team. Additionally, initiatives to improve interpersonal dynamics and stress awareness should still be considered. This may include increasing awareness through workshops, defining clear roles and responsibilities during deployment, and improving both inter and intra-team communications through meetings or group messaging systems.

5.4 FuSDRA - EVALUATION

5.4.1 Organisational Criteria

As highlighted in the earlier section 4.3.4, an exact set of evaluation criterion has yet to be established for the *nupiri muka* AUV program. Therefore, risk evaluation was performed using UTAS's semi-quantitative risk matrix (Appendix J), which was discussed earlier in Chapter 2. The base scenario of the FuSDRA model showed that the risk of AUV loss lies between 0.147 and 0.080. Using the evaluation criteria associated with UTAS's semi-quantitative risk matrix, this falls between the likelihood scale of likely and possible. With the loss of the *nupiri muka* AUV falling under the consequence scale of <Major>, the overall risk level was therefore evaluated to be <Extreme>, as circled in Figure 5.31.

	Consequence				
Likelihood	Insignificant	Minor	Moderate	Major	Catastrophic
Almost Certain	Mod 11	High 13	Ext 20	Ext 23	Ext 25
Likely	Mod 7	High 12	High 17	Ext 21	Ext 24
Possible	Low 4	Mod 8	High 16	Ext 18	Ext 22
Unlikely	Low 2	Low 5	Mod 9	High 15	Ext 19
Rare	Low 1	Low 3	Mod 6	Mod 10	High 14

Figure 5.31: Risk evaluation based on UTAS's semi-quantitative risk matrix.

Using the Risk Management Standard from the University of Tasmania as shown in Appendix J [148], any activity of extreme risk requires the senior management team for risk acceptance before it can proceed. In addition, the University's audit and risk committee of council needs to be communicated on the requirements of the AUV program, with all risk control measures to be reviewed at least bi-annually. Additional control measures are also to be implemented within a year.

5.4.2 Policy Recommendations

To reduce the risk of loss for the nupiri muka AUV program, a set of effective control measures are required. Using simulation results from model testing and scenario analysis, a series of policy recommendations are suggested. These are summarised as follows:

a) Any new AUV team members recruited during the current early phase of the AUV program should ideally possess 2 years of relevant experience (Figure 5.15).
b) Establish an effective budget management system with regular review, based on Figure 5.13 and scenario 2 (Section 5.3.4.2). This includes built in contingencies, a robust system for monitoring budgets and forecast of future additional funding requirements, and a robust finance strategy.
c) Implement a process for reviewing and updating strategic or operational plans in response to changes in government support (Scenario 2, section 5.3.4.2). Additionally, diversity in funding base is recommended to reduce reliance on government support. This includes commercial contracts and establishing strong stakeholder relationships. In particular, these measures should be implemented in early stages of the AUV program as any reduction in government support has a considerable impact on the risk of loss later in the program (Figure 5.16, 5.25 and 5.26).
d) Improve management on the risk of obsolescence (Scenario 2, section 5.3.4.2). This includes a comprehensive repair and preventive maintenance program, regular review of emerging technological trends, a strong partnership with ISE Ltd, having a robust and clear long-range plan for the *nupiri muka* AUV program and building of a strong underwater robotics research program at AMC UTAS. These measures are important for later stages of the AUV program (>7.5 years).
e) Provide an option for the facility manager to convert existing contractual arrangement into a permanent role, under the condition that the facility manager is found to be suitable for the job. Providing such an option to the facility manager, especially in later stages of the AUV program (>4 years) may improve retention and consequently, a lower risk of AUV loss.
f) Optimize recruitment strategy in terms of desirable experience level and attracting niche talents. Additionally, human resource policies to improve retention and knowledge transfer should be implemented. These suggestions, together with an intensive training regime and practice runs should reduce the risk of AUV loss, as shown in Figure 4.8, 4.10, 5.14 and scenario 1 (Section 5.3.4.1).
g) Improve the perception of risk among the AUV team and relevant stakeholders, such as through enhancing training and risk communications. Such measures should be implemented in the early stages (<2 years) of the AUV program to increase effectiveness (Figure 5.17)
h) Implement initiatives to improve interpersonal dynamics and stress awareness, such as workshops, defining clear roles and responsibilities, and improving communications. Additionally, further investigation on the impact of changing interpersonal dynamics is necessary due to the inconclusive simulation results shown in scenario 3 (Section 5.3.4.3).

5.5 CASE STUDY CONCLUSION

One of the main goals of this dissertation is to improve existing risk management of AUV operations in the Antarctic, to prevent, as far as reasonably practicable, loss of the AUV. This case study shows that application of the FuSDRA approach not only facilitates effective quantitative analysis of risk, but also allows for deeper qualitative understanding on the overall system of an AUV program. The risk analysis process itself presents an invaluable learning opportunity for both the risk analyst and the involved personnel. Meaningful discussions revealed insights on possible leverage points, indicators and decision rules to better manage the risk of AUV loss. In this chapter, the FuSDRA approach was applied to the *nupiri muka* AUV program, with the following demonstrated:

a) The ability to build and customise risk models using the three-stage iterative FuSDRA framework in accordance to context of the circumstances.
b) The identification, modelling and evaluation of risk associated with an AUV program, with improved comprehensiveness of the risk analysis.
c) The ability to account for the dynamic nature of risk factors, thus improving the understanding and control of time-dependent risks such as those presented in the scenario analysis.
d) The ability to account for the complex interrelationships between risk factors within the AUV system, as well as the uncertainties involved in these relationships through fuzzy logic.
e) An improvement to the analysis of risk using a combination of domain knowledge sources in addition to expert’s opinion.
f) The attainment of insights from the analysis which improves mental models for better decision making. These insignts also helps to identify both leading indicators and leverage points for risk monitoring and risk control recommendations.
g) The ability to derive and test policy recommendations for improving the control of risks in an Antarctic AUV program.

CHAPTER 6: CONTRIBUTIONS, FUTURE WORK AND CONCLUSIONS

6.1 SUMMARY

The deployment of AUVs in the Antarctic for under-ice marine science research is a complex operation, involving multiple stakeholders, adverse environmental conditions and often fraught with logistical, financial and technical challenges. It is, therefore, indisputable that the risk of AUV loss during missions in the Antarctic is higher when compared to open water missions in other relatively benign environments. There are shortfalls to be addressed in existing risk analyses methods to reduce the risk of loss, such as; overcoming the chains of events perspective, improving the comprehensiveness of analysis and accounting for the complex dynamic interactions between risk factors. Additionally, complexities in risk analysis of AUV deployment is often exacerbated by imprecise or lack of data regarding the performance of an AUV. In this dissertation, the use of fuzzy logic, system dynamics and eventually, a hybrid fuzzy system dynamics approach were proposed to address these shortfalls. In particular, the fuzzy system dynamics framework facilitates identification of relevant risk factors, modelling of systemic behaviour and evaluation of the risk of AUV loss. It leverages on strengths and overcoming limitations of both fuzzy logic and system dynamics by accounting for the dynamic nature of risk, interrelationships between risk factors within the system, as well as the uncertainties of these relationships. The practicality of these approaches were demonstrated on the *nupiri muka* AUV program, producing a set of policy recommendations for effective risk control.

6.2 CONTRIBUTIONS

The following sections present a summary of the contributions made in this dissertation.

6.2.1 Generic Risk Structure Associated with an AUV Program

A generic static risk structure associated with the risk of AUV loss was established and presented in Figure 3.4, improving the comprehensiveness of the risk analysis. The structure presents an overview of the explicit causal links between various risk factors associated with an AUV program, including organisational factors, performance shaping factors, AUV technicalities and external factors. The generic components serve as a useful guide to identify possible areas of concerns influencing the risk of loss, facilitating the risk analysis process to those with limited knowledge of risk analysis methodologies. It applies to different types of AUV deployment, augmenting established sources of knowledge to improve analysis of risk. The *nupiri muka* case study presented in Chapter 5 of this dissertation illustrated the usefulness of the risk structure for facilitating the elicitation process and the creation of complex risk models.

6.2.2 A Fuzzy-Based Risk Analysis Framework for AUV Operations

An AUV program in its early phases lacks historical data and any assessment of risk may be vague and ambiguous. In Chapter 2, a fuzzy-based risk analysis framework is proposed for quantifying the risk of AUV loss in such circumstance. The framework utilises the knowledge, prior experience of available subject matter experts and the widely used semi-quantitative risk assessment matrix, albeit in a new form.

The use of a fuzzy-based approach accounts for the vagueness and ambiguity of many risk variables which are difficult to quantify and are commonly described in natural language. The proposed framework also facilitates the capturing of knowledge and experience from domain experts, with the evaluation of risk either against a set of criteria or relatively to compare the level of risk for different missions. Additionally, the framework can also be applied directly in the field during a deployment to assess risk in response to changes in situation. An application example presented in Chapter 2 guides the reader through the framework and further supports the usefulness of the fuzzy-based risk analysis framework for future Antarctic AUV deployments. A sensitivity analysis carried out on the fuzzy risk model shows that the risk level of an Antarctic mission is most sensitive to ‘Time Duration Under-Ice’. Therefore, it acts as a good leverage point for risk control. For instance, a reduction of ‘Time Duration Under-Ice’ from 6 hours to 5 hours reduces the eventual risk rating for AUV loss from 11.5 to 9.9.

6.2.3 A Dynamic and Systems-Based Risk Analysis Framework for AUV Operations

In Chapter 3, a dynamic systems-based risk analysis framework was proposed for Antarctic AUV operations. The framework accounts for the dynamic behaviour of systems and the complex interrelationships between risk factors through a system dynamics approach. The approach enables an inclusive and broad analysis of risks by considering other aspects of risk apart from technical specifications, such as human errors. It is also well suited to model empirical data about known risk factors, such as information gathered from historical fault logs of an AUV. Simulation results from the resultant risk models can be used to enhance risk controls through more effective policy recommendations. Additionally, the generic nature of the proposed risk analysis framework allows for broad application to different organisations, AUV types and usage purposes. It may also be relevant to other complex technological systems which are similar to the AUV.

An example was presented in the chapter, demonstrating the step-by-step application of the proposed systems-based risk analysis framework. Scenario analysis performed on the risk model resulted in the following recommendations:

- To implement a regular training regime and practice runs similar to actual operation during lull periods. This mitigates experience decay of the AUV team which consequently reduces the risk of AUV loss during actual under-ice deployment [188]. In addition, utilisation rate of the AUV, amount of practice runs, and relevant training should be monitored as leading indicators to risk of AUV loss.

- To utilise recruitment criteria on the amount of required relevant experience as a leverage point to control risk of AUV loss. However, considerations have to be made on the effects of team dynamics and the amount of available resources.
- To determine an optimal risk tolerance level for deployment of AUV. While it is illogical to take blind risks in the deployment of AUV, being excessively risk-averse may, ironically exacerbate the risk of AUV loss.

Although the policy recommendations may seem intuitive, they demonstrate how the proposed framework could be pragmatically useful for risk analysis of more complex issues for future AUV programs.

6.2.4 A Hybrid Fuzzy System Dynamics Risk Analysis (FuSDRA) Framework for AUV Operations

The effective management of the risk of AUV loss in the Antarctic is a challenge characterised with dynamic, fuzzy risk factors and their complex interrelationships. Therefore, the formulation of risk control policies requires an analysis tool which addresses both the dynamic and fuzzy characteristics of the problem. The main contribution of this dissertation is the development of such a tool, a risk analysis methodological framework based on the integration of system dynamics and fuzzy logic. Leveraging on the strengths of both fuzzy logic and system dynamics, the proposed approach addresses shortfalls of existing risk anaysis approaches to reveal a set of systemic behaviours influencing the risk of AUV loss. The use of fuzzy logic allows human perceptions to be incorporated in the system dynamics models, offering robust human judgements useful in situations where historical data may be imprecise or lacking. In summary, the contributions arising from the FuSDRA framework include:

a) Providing a systematic and structured approach for risk analysis of AUV operations, facilitating the building and customizing of risk models in accordance with the context of circumstances.
b) Improving the comprehensiveness of the analysis by incorporating risk factors associated with various dimensions of an AUV program
c) Accounting for the dynamic nature of risk, improving the ability to understand and control time-dependent risks.
d) Allowing for the use of linguistic variables instead of crisp precise variables which may not always be possible, thus appealing to decision makers and facilitating elicitation process with domain experts
e) Offering a decision support tool for decision makers to analyse various scenarios, and experiment with different policies to derive the most effective risk control strategies.
f) Facilitating the identification of both leverage points and leading indicators associated with the risk of AUV loss, to achieve better control and monitoring of risk.
g) Facilitating a reasonable risk modelling timeframe with the use of readily available software.
h) Providing applications not only for deployment of AUVs in the Antarctic but also other types of AUV operations. Due to the generic nature of the approach, it may also be relevant to other complex technological systems similar to that of the AUV.

The proposed FuSDRA framework is not only useful to practitioners for analysis of risk. Academically, it also explores further into the concepts of non-probabilistic risk modelling, which is often challenging in real-life problems. Therefore, FuSDRA approach provides both contribution to knowledge, as well as a pragmatic tool for the AUV community for better analysis of risks. An application example (Chapter 4) and a case study (Chapter 5) provided step-by-step guidance on the risk analysis process, which further demonstrates usefulness of the FuSDRA framework.

In the application example, scenario analysis of the risk model identified the initial average experience of the AUV team having an apparent impact on the risk of AUV loss throughout the entire AUV program. Therefore, recruitment strategy should be optimised with the consideration of other factors such as team dynamics and availability of resources. In addition, training regime and practice runs similar to the actual Antarctic operation should be implemented, as well as policies to boost morale and increase engagement with the AUV team to reduce turnover and ensure knowledge retention.

The risk model also demonstrated the importance of the ongoing AUV utilisation. Therefore, a sustainable and effective communication channels should be established both internally and externally to facilitate research collaboration. Although the simulation shows research demand having more influence in reducing the risk of AUV loss as compared to commercial demand, it is not practical to recommend using the AUV solely for pure research or commercial works. Instead, the simulation result suggests that priority should be given for research purposes over commercial works. The AUV owner should therefore constantly support and encourage its own internal use of the AUV, and build a research program around the AUV, such as in areas of battery capabilities or adaptive controls.

6.2.5 Case Study Related Insights

The application of the FuSDRA framework to the *nupiri muka* AUV program was presented in Chapter 5. After sufficient confidence was gained in the FuSDRA model through extensive model testing, custom scenarios were created and analysed through the model. The result of which, are insights that facilitates the formulation of risk control policy recommendations, summarised as follows:

Policies to Implement from Early Stages of the AUV Program:

- To institute as a requirement, that the recruitment of new AUV team members should ideally possess 2 years of relevant experience.
- To establish an effective budget management system with regular review. This includes built in contingencies, a robust system for monitoring budgets and forecast of future additional funding requirements, and a robust finance strategy.
- To establish a process for reviewing and updating strategic or operational plans in response to changes in government support. Additionally, diversity in funding base is recommended to reduce reliance on government support. This includes commercial contracts and establishing strong stakeholder relationships.
- To optimize recruitment strategy in terms of desirable experience level and attracting niche talents at different stages of the AUV program. Additionally, human resource policies to improve

retention and knowledge transfer should be implemented. These suggestions, together with an intensive training regime and practice runs should reduce the risk of AUV loss.

- To improve the perception of risk among the AUV team and relevant stakeholders, such as through enhancing training and risk communications.
- To implement initiatives to improve interpersonal dynamics and stress awareness, such as workshops, defining clear roles and responsibilities, and improving communications.

Policies to Implement from Middle to Late Stages of the AUV Program:

- To Improve management on the risk of obsolescence. This includes a comprehensive repair and preventive maintenance program, regular review of emerging technological trends, a strong partnership with ISE Ltd, having a robust and clear long-range plan for the *nupiri muka* AUV program and building of a strong underwater robotics research program at AMC UTAS.
- To provide an option for the facility manager to convert existing contractual arrangement into a permanent role, under the condition that the facility manager is found to be suitable for the job. Providing such an option to the facility manager may improve retention and consequently, a lower risk of AUV loss.

More importantly, the case study shows that application of the FuSDRA approach not only facilitates analysis of risk, but also allows for deeper qualitative understanding on the overall system of the AUV program. The risk analysis process itself presents an invaluable learning opportunity to reveal insights on possible leverage points, indicators and decision rules to better manage the risk of AUV loss in the Antarctic.

6.3 FUTURE WORK

This section presents some areas of possible future research to improve the FuSDRA framework, with the aim of achieving better risk control for AUV operations in the Antarctic.

6.3.1 FuSDRA Software Tools

The proposed FuSDRA framework facilitates the risk analysis process within a reasonable modelling time through readily available software. However, model building requires the use of multiple software, namely Vensim® [204] for system dynamics modelling, MATLAB® fuzzy logic toolbox 2017 [154] for developing fuzzy expert systems and MATLAB® Simulink toolbox 2018 [205] to construct the final FuSDRA risk model. This makes application of the framework challenging for those without experience and knowledge of these software. The lack of an all-inclusive multifunctional software can impede the extensive use of the FuSDRA approach in real-world systems, regardless of how effective the proposed approach may be. Therefore, a commercial quality software should be developed to facilitate the three-stage iterative FuSDRA process. The software should include a repository of generic risk factors and allow for easy addition of new ones to customise risk models without extensive software knowledge.

Furthermore, either automated or manually input tests of the FuSDRA model (Section 5.3.4) can be integrated into the software, to gain confidence in the developed model. Users should also be able to customise evaluation criteria and perform various scenario analysis with relative ease to aid decision-making and policy formulations. Lastly, intuitive graphical user interface and clear interactive visualization are necessary in the software, to improve the model building process and understanding of the risk model.

6.3.2 Improvement to Elicitation of Fuzzy Rules

One of the main challenges encountered in application of the FuSDRA framework lies in the elicitation of fuzzy rules. First, domain experts may have incomplete and episodic knowledge from their experience, causing incorrect or incomplete fuzzy rule bases. Second, various experts holding different assumptions can result in inconsistent or conflicting opinions during the elicitation process. Last, the inability of the FuSDRA model to self-learn means that regular review of fuzzy rules is required to ensure relevance. Therefore, further research should focus on two areas. First, to improve the elicitation of fuzzy rules by considering varied degrees of trust in the domain experts. The use of intuitionistic fuzzy logic is one way of achieving this. An extension of classical fuzzy logic, it is able to deal with vagueness by assigning a 'certainty degree' on inputs, based on the level of trust on each domain expert. The second focus area is to explore possible means of self-learning to ensure long-term relevancy of fuzzy rules. This can be carried out through optimisation methods such as a genetic algorithm, neural networks or simulated annealing among others.

6.3.3 Further Applications of the FuSDRA Approach

The FuSDRA framework was created based on AUV operations in the Antarctic. However, the generic nature of the approach will be useful to other types of AUV operations. It may also be applicable to managing risks of other complex technological systems similar to that of the AUV, such as the budding field of autonomous cars, unmanned aerial vehicles and unmanned vessels. It is anticipated that further research in this direction will significantly expand the repository of risk factors found to be relevant in other systems, providing cross-disciplinary insights which are useful for both practitioners and academics.

Another possible area of further research is to augment FuSDRA with real-world data. Empirical data, if available, can be used to test robustness of the developed FuSDRA models and to calibrate the models to improve its performance. Comparison can also be made between conventional probabilistic risk analysis methodologies and the proposed FuSDRA *approach*.

6.3.4 Observations from Case Study

Simulation results and the ensuing policy recommendations from the case study presented in Chapter 5 may be suggestive of similar behaviour for different types of AUV operations in the same organisation.

However, it may or may not reflect the issues encountered by other organisations operating an AUV program, regardless of vehicle characteristics. Therefore, further research is required to verify some of the observations made in the case study and to determine generality of the findings. Once determined, these generic risk components and their causal relationships can be integrated into the repository of a FuSDRA Software to facilitate future risk analysis process. The following section list some areas of potential further research arising from the case study presented in Chapter 5.

6.3.4.1 Significance of Risk Perception

In the FuSDRA model presented in Figure 5.11, risk perception was modelled to be influenced by three main factors, namely the comprehensiveness of insurance coverage, experience and stress level. However, risk perception is a complex multidetermined phenomenon influenced by many other factors, such as social and cultural influences. Therefore, further research on the influence of individual's risk perception on the overall risk of AUV loss will prove invaluable to improve risk control.

6.3.4.2 Synergistic Effect of Poor Support and Technological Obsolescence

In the scenario analysis 5.3.5.2.2, simulations showed that a combination of reducing government support and increasing alternatives has a synergistic effect on the risk of AUV loss (Figure 5.26). Reducing support and technological obsolescence is a concern commonly shared by other organisations operating technological equipment and systems. Therefore, additional investigation to bolster our understanding of this synergistic effect can prove to be relevant not only within the AUV domain, but also in other areas.

6.3.4.3 The Role of Stress Level in Risk of AUV Loss

In the last scenario analysis, reduction in interpersonal dynamics increases risk of loss minimally due to the lower emphasis given to stress level of the AUV team during elicitation of fuzzy rules. To improve accuracy of the risk model, further quantitative studies on stress such as using the Hassles Scale (236) or the Perceived Stress Scale (237) should be considered.

6.3.4.4 Review and Calibration of FuSDRA Risk Models

With planned annual deployment to the Antarctic, there is a constant inflow of new information to the nupiri muka AUV program. For instance, the most recent deployment to the Sørsdal Glacier saw minor damage to the AUV hull due to collision with ice during manoeuvring of the AUV at the water surface. Such information can be used to review and calibrate existing FuSDRA risk models, such as the effectiveness of training in AUV manoeuvring. When carried out on a regular basis, this iterative process ensures relevancy and effectiveness of the risk analysis.

6.4 CONCLUSION

The methodological frameworks presented in this dissertation provided a systematic and structured approach to risk analysis of AUV operations in the Antarctic. One of the main contributions is the development of a hybrid risk analysis approach. One which leverages on the strengths and overcoming limitations of both fuzzy logic and system dynamics. The system dynamics aspect of the FuSDRA approach facilitates comprehensive risk analysis and improves the ability to understand and control time-dependent risks. It does so by accounting for the dynamic nature of risk and interrelationships between risk factors within the system. The fuzzy logic aspect of the FuSDRA approach is appealing with its use of linguistic variables which are easily comprehensible. Furthermore, it also accounts for vagueness and ambiguity due to imprecise or lack of empirical data.

Application of the FuSDRA framework facilitates the identification, modelling and evaluation of risk associated with an AUV program. The process of the risk analysis itself offers a learning opportunity, revealing areas of concern and possible risk control measures. Outputs from the analysis offer insights to improve mental models of decision makers and aid the identification of leverage points and leading indicators for risk control and monitoring. Furthermore, established risk models can be used as a decision support tool to analyse various scenarios and experiment with different policies to derive the most effective risk control strategies.

Through application on the *nupiri muka* AUV program, the FuSDRA approach demonstrated effectiveness and potential in revealing risk behaviour and possible risk control measures. Many of these observations would not have been possible with the use of existing risk analysis approaches. Therefore, the FuSDRA approach lays the foundation for a risk analysis framework to support the AUV community in reducing the risk of AUV loss during Antarctic deployment. The approach may also be relevant to other types of AUV operations or other complex technological systems similar to that of the AUV. Further work is proposed to enhance both the usability and ability of the FuSDRA methodology to solve real-world problems and to advance our understanding to the knowledge of risk analysis.

APPENDIX A: LIST OF ACRONYMS

AAD	Australian Antarctic Division
AGP	Antarctic Gateway Partnership
AMC	Australian Maritime College
AMSA	Australian Maritime Safety Authority
ARC	Australian Research Council
AUD	Australian Dollar
AUV	Autonomous Underwater Vehicle
BBN	Bayesian Belief Network
CAM	Consistency Aggregation Method
CLD	Causal Loop Diagram
CM	Completeness Measure
CSIRO	Commonwealth Scientific and Industrial Research
DVL	Doppler Velocity Log
FuSDRA	Fuzzy System-Dynamics Risk Analysis
FDM	Fuzzy Delphi Method
GPS	Global Positioning System
GUI	Graphical User Interface
HEART	Human Error Assessment and Reduction Technique
IEEE	Institute of Electrical and Electronics Engineers
IMAS	Institute for Marine and Antarctic Studies
ISE	International Submarine Engineering Ltd.
ISO	International Organization for Standardization
MATLAB	Matrix Laboratory Software
MPW	Mission Planning Workstation
MSR	Marine Science Research
MTBF	Mean Time Between Failure
NASA	National Aeronautics and Space Administration
OAM	Optimal Aggregation Method
QRA	Quantitative Risk Analysis
REMUS	Remote Environmental Monitoring Units
RMP	Risk Management Process
ROV	Remotely Operated Vehicles
SAM	Similarity Aggregation Method
SCC	Surface Control Computer
SPAR-H	Standardised Plan Analysis Risk – Human
SRA	Society of Risk Analysis
STAMP	Systems-Theoretic Accident Model and Processes
TDR	Time Delay Relay

THERP	Technique for Human Error Rate Prediction
UNCLOS	The United Nations Convention on the Law of the Sea
USBL	Ultra Short Baseline System
UTAS	The University of Tasmania
UUV	Unmanned Underwater Vehicle
VCC	Vehicle Control Computer

APPENDIX B: COMMON RISK ANALYSIS METHODS

Hazard and Operability (HAZOP) Study

Widely used within the chemical process industry, HAZOP study is a structured and systematic qualitative technique which analyses risks of processes or operations. It breaks down overall complexity into simpler sections to investigate potential deviations from norms. Usually carried out by a multi-disciplinary team over a series of meetings, the study aims to uncover potential risks through the use of guide words.

Although initially developed for the chemical process industry, it has since branch out to many other domains such as aviation, mining and software engineering.

What-If Analysis

What-if analysis is a structured brainstorming approach based on expert's judgement. A series of questions in the form of 'What If' are used to determine possible deviations from operational norms, the likelihood and magnitude of undesired events. Once identified, these concerns can be evaluated against a risk acceptability level to determine the necessary follow up actions.

Despite being subjective and relies heavily on experience of the experts, what-if analysis offers simplicity and quick analysis results. Special tools are not required, and experts can participate meaningfully even with little risk analysis knowledge.

Checklist

Checklist contains a detailed list of pre-defined evaluation criteria for an operator to assess status of the system or perform a desired action. The list, usually constructed based on historical data or expert's judgment, enables identification of critical steps within a process or important component parameters.

In the AUV domain, checklists are often used to facilitate preventive maintenance, deployment logistics, pre-launch checks, in-water pre-mission checks, post mission checks and post recovery checks. An example of a pre/post dive checklist is presented below.

UTAS Pilot's Checklist ISER-E634-FRM-002-01

VESSEL		EXPLORER PILOT PRE/POST DIVE CHECKLIST	CRUISE DATE / #	

Acoustic Drop Weight & Pop-Up Buoy Release

- [ ] Set-up the surface acoustic modem to be able transmit to / receive from AUV acoustic transducer in air (life jacket makes a good acoustic baffle)
- [ ] Request deck personnel to ensure pop-up buoy is removed, but pin is still in the attached position
- [ ] Request deck personnel to support drop weight for the purpose of the acoustic test
- [ ] Verify acoustic drop weight release
- [ ] Coordinate drop weight attachment with deck crew
- [ ] Verify acoustic pop-up buoy release
- [ ] Request re-install pop-up buoy
- [ ] Request surface acoustic modems to be deployed into water; AUV modems OFF until later

Mission Plan, Fault Limits & Fault Responses

- [ ] Verify mission plan text file with mission planner & operations manager; Record file name

  ____
- [ ] Load any parameter settings for ping schedules or sonars
- [ ] Load mission text file; Verify no errors
- [ ] Load fault response table required for operations; Verify no errors; Record file name

  ____
- [ ] Verify all fault limits are acceptable for mission plan and operations area

Fault Limits

Max Depth		Min Altitude	
Min Pitch		Max Pitch	
Low Energy		Min Battery	
Max Offline Distance		Acoustic Telem TO	

Maneuvering Limits

Max Depth		Min Pitch	
Ice Avoid Range		Max Pitch	
Obs Fore Range		Obs Vert Range	
Bottom Avoid Range		Min Altitude	

Task Readiness

- [ ] Batteries charged and ready for operations
- [ ] Deck cables removed
- [ ] Drop Weight safety pin removed
- [ ] Radio telemetry verified
- [ ] Connectors & vacuum port capped
- [ ] Strobe & USBL ON; Xeos beacon ON
- [ ] Hull hatches closed
- [ ] Deck crew have rigged the AUV for launch
- [ ] Pilot console ready for launch
- [ ] AUV On-Deck Pre-Dive Complete with no problems

AUV IS READY FOR PRE-LAUNCH BRIEFING

LAUNCH / RECOVERY #		SIGNATURE	

4

Bayesian Belief Network (BBN)

Bayesian Belief Network (*BBN*) is a semi-quantitative approach that uses graphical statistical model used to describe probabilistic dependencies between random variables. The approach conceptualises a model of interest as a set of interconnected nodes representing variables and the causal relationships between them.

Griffiths and Brito [97] explored the use of BBN for quantifying the probability of AUV loss during under-ice missions. A model was established based on expert judgement on historical faults of the AUV, past sea ice data, probability distributions of ice thickness and concentration, and ships of differing ice capabilities. The output was a probability distribution for risk of AUV loss during under-ice missions. This work demonstrated the use of BBN as a structured approach to manage risks of AUV deployments.

The deployment of AUVs, especially in the Antarctic, involves high level of uncertainties, particularly from the operating environment. BBNs allows these uncertainties to be addressed by incorporating data from different sources such as expert judgement or observations. However, feedback effects are not accounted for due to the acyclic property of BBNs (Barton et al, 2008). It is also a time intensive process due to the iterative elicitation of expert judgement.

Fault Tree Analysis (FTA)

FTA is a top-down deductive failure analysis method which visually depicts the pathways that can lead to failures or undesired events. Starting from the top at a single point, it branches downwards in sequences of either series relationships (OR Gates) or parallel relationships (AND Gates) till it reaches the basic events. The structured and graphical fault tree allows for easy interpretation and communication, facilitating the prioritization of risks for follow up actions or creates the foundation for further analysis. However, FTAs may not be able to capture complex problems with multiple levels of causes and feedback loops. FTA can be used either qualitatively or quantitatively for risk analysis and has been applied in the AUV domain [(103)(104)].

Event Tree Analysis (ETA)

Similar to FTA, ETA is a graphical approach which is set up left to right starting from the failure or undesired event. The event tree then splits at stages which are significant events that may arise during the event chain. The event is either true or false, and each is associated with a certain probability. At the end of the event tree, the consequences and the cumulative probability are listed, representing the risk arising from the specific hazardous event. Through ETA, design and procedural weaknesses can be identified. ETA was the methodology used for the assessment of possible causes leading to the loss of Autosub2. Through analysis, the board of inquiry established that the cause of Autosub2 loss was most likely to be due to a fault introduced during the manufacturing/assembly phase [(32)].

Markov Analysis

Markov Analysis uses models which represents possible chains of events to forecast the activity of a random variable at a given point in time based on current circumstances. Markov analysis is often used as a decision aid for decision makers by providing probabilistic information about a situation. It is well-suited for systems which exhibit probabilistic changes from one state to another. For instance, to predict the probability of failure for an equipment.

In the AUV domain, Brito & Griffiths [101] demonstrated the use of Markov chains to model the sequential steps of an AUV deployment, from pre-launch to recovery. Based on the AUV's historical performance data and experts' judgement, the resultant model allowed the overall risk of loss for a deployment to be estimated.

Monte Carlo Simulation (MCS)

MCS performs risk analysis by is widely used for generating random numbers for any factor which has inherent uncertainty. Carried out numerous times, the result is a probability distribution of all possible outcomes. This way, MCS facilitates a comprehensive risk analysis and provides decision makers on information about the range of possible outcomes and their probabilities of occurrence. Because of its advantages, MCS is used in various industries for risk analysis, from engineering, manufacturing, oil and gas to finance.

In the AUV domain, Griffiths and Brito [97] uses MCS to generate faults for inputs into a non-parametric Kaplan-Meier estimator to analyse probability of mission survival with distance. Xu et al. [104] demonstrated the use of a qualitative fault tree analysis, together with Monte Carlo simulation to handle the lack of data.

APPENDIX C: DETAILS OF STOCK AND FLOW MODEL (FIGURE 4.5)

Table I. Formulations, definitions and initial conditions for the stock and flow diagram presented in Figure 4.5.

Risk variable	Definition	Equation
Allocated Annual HR Budget	Amount of budget to be allocated for human resources in the AUV program. Affects recruitment, turnover and training.	*Function of* (Third Party AUV Hire Contracts), (Reputation in AUV Operations) and (Expenditure) Uncertain[1]
Average Experience of AUV Team	Average experience of the primary AUV team in AUV operations.	INTEG (Change in Experience) Initial value = 2 Years INTEG = Numerical Integration
Baseline Aging of Components and Systems	Aging of AUV components and systems which are independent of usage.	0.2 years per year (For each year in operation)
Change in AUV Effective Age	Rate at which the effective age of the AUV increases.	MAX (Baseline Aging, Relative Utilisation Rate) MAX= Maximum of two alternatives
Change in Experience	The amount of experience gained or lost due to turnover or training of staff.	*Function of* (Allocated Annual HR Budget) Uncertain
Change in Reputation	Changes to reputation of the University of Tasmania in AUV operations.	Function of (Research Demand) and (Incident Rate) Uncertain
Commercial Demand	Pool of potential customers hiring the AUV at a specific period considering the costs, awareness, regulations, geographical limitations and economic conditions. Utilises an arbitrary range of 0 – 10 where higher number indicates higher demand.	5.0: Average commercial demand
Designed Utilisation Rate	The expected utilisation rate considered by the AUV manufacturer during design and production of the AUV. Measured in time spent in water.	50% annually

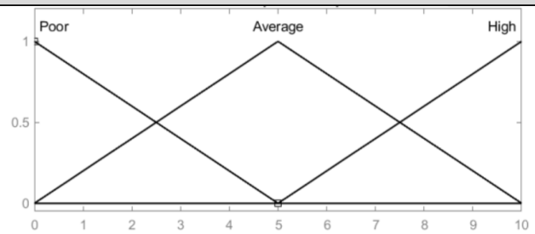
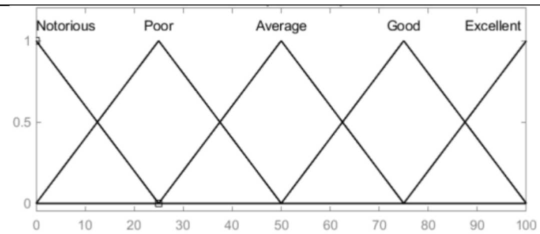
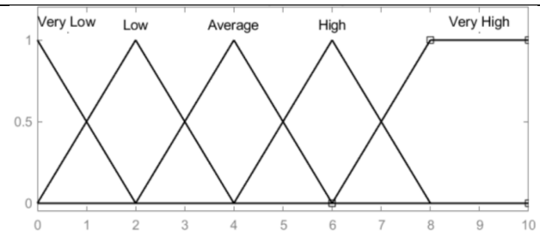
Effective AUV Age	Basis of remaining useful life, which can be less than actual calendar age of the AUV	INTEG (Rate of Aging) Initial value = 0
Human Error Incidents	Number of recorded human error related incidents.	*Function of* (Average Experience of AUV Team) Uncertain
Incident Rate	Overall recorded incident rate, per AUV year in water.	(Human Error Incidents + Technical and System Faults) / Utilisation Rate
Increase in Costs	Increase in costs of preventive maintenance as AUV components and systems deteriorates or become obsolete with time.	5% Annual Increase
Preventive Maintenance Costs	Amount of spending on routine preventive maintenance.	INTEG (Increase in Costs) Initial value = 50,000 AUD
Reactive Maintenance Costs	Amount of spending on repairs in response to breakdown, fault or defect.	10,000 AUD x Technical and System Faults
Relative Utilisation Rate	Actual utilisation rate as compared to designed utilisation rate.	Utilisation Rate / Designed Utilisation Rate
Research Demand	Amount of internal scientific or engineering research requests on use of the AUV. Utilises an arbitrary range of 0 – 10 where higher number indicates more requests.	5.0: Average research demand
Reputation in AUV Operations	Perceived level of reputation of the University of Tasmania in AUV operations. Utilises an arbitrary range of 0 – 100 where higher number indicates better reputation.	INTEG (Change in Reputation) Initial value = 50: Average reputation
Risk of AUV Loss	Likelihood of losing the AUV during a deployment to the Antarctic.	*Function of* (Incident Rate) Uncertain
Technical and System Faults	Number of recorded technical and system related faults	*Function of* (Effective AUV Age) Uncertain

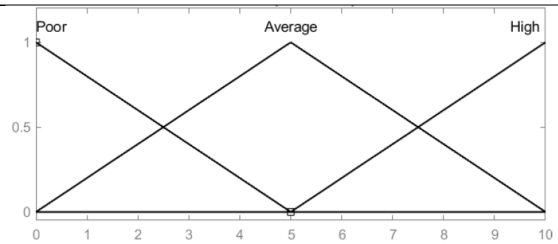
Third Party AUV Hire Contracts	Perceived level of annual third-party AUV hire contracts. Utilises an arbitrary range of 0 – 10 where higher number indicates more contracts	*Function of* (Reputation in AUV Operations) and (Commercial Demand) Uncertain
Total Expenses of Maintenance	Total expenditure on both preventive and reactive maintenance.	Reactive Maintenance Costs + Preventive Maintenance Costs
Utilisation Rate	The amount of time the AUV spends in water in a year.	*Function of* (Reputation in AUV Operations) Uncertain

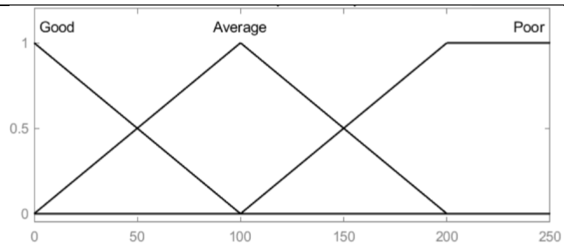
[1] Bolded uncertain represents presence of random factors somewhere in the functional relationships which may not be deterministically defined at this point in time.

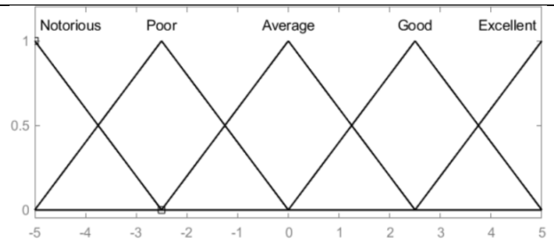
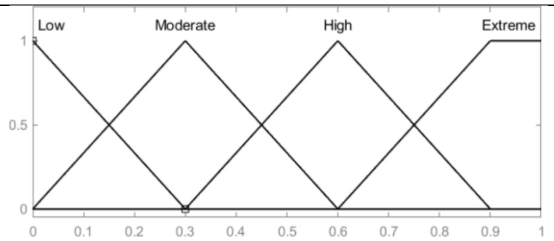
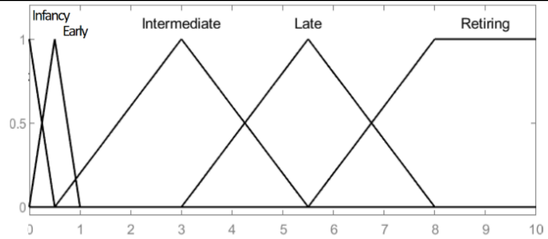
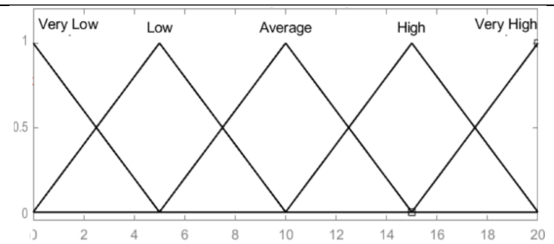
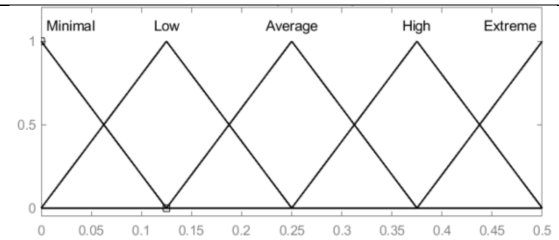
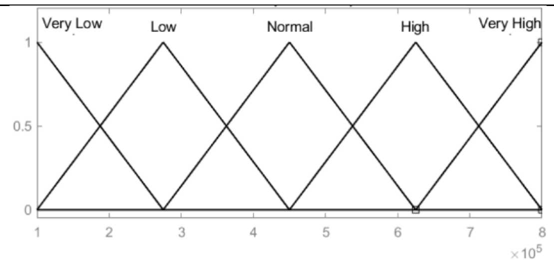
APPENDIX D: UNIVERSE OF DISCOURSE, FUZZY SETS, MEMBERSHIP FUNCTION AND FUZZY RULES (FIGURE 4.6)

Table II-A. Risk factors and their associated universe of discourse, fuzzy sets and membership functions.

<table>
<tr><th>Risk factors</th><th>Universe of Discourse (Units)</th><th>Fuzzy Sets and Membership Function</th></tr>
<tr><td>Commercial Demand</td><td>0 to 10 (Dimensionless)</td><td>
</td></tr>
<tr><td>Reputation in AUV Operations.</td><td>0 to 100 (Dimensionless)</td><td>
</td></tr>
<tr><td>Third Party AUV Hire Contracts</td><td>0 to 10 (Dimensionless)</td><td>

Very Low</td></tr>
<tr><td>Research Demand</td><td>0 to 10 (Dimensionless)</td><td>
</td></tr>
<tr><td>Incident Rate</td><td>0 to Positive Infinity, in practice usually ranges from 0 to 250

(No. of Cases / Year in Water)</td><td>
</td></tr>
</table>

Change in Reputation.	-5 to 5 (Dimensionless)	
Risk of AUV Loss	0 to 1 (Dimensionless)	
AUV Effective Age	0 to 100, in practice usually ranges from 0 to 10 (Years)	
Technical and System Faults	0 to Positive Infinity, in practice usually ranges from 0 to 20 (Cases per Year)	
Actual Utilisation Rate	0 to 0.5 (Percentage of time operational in water)	
Allocated HR Budget	0 to Positive Infinity, in practice usually ranges from 100,000 to 800,000 (AUD)	

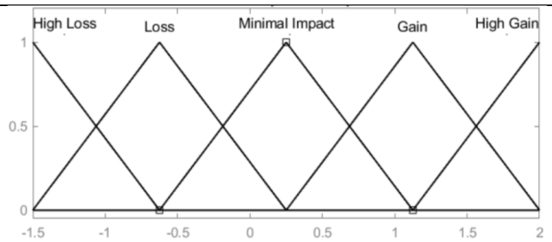
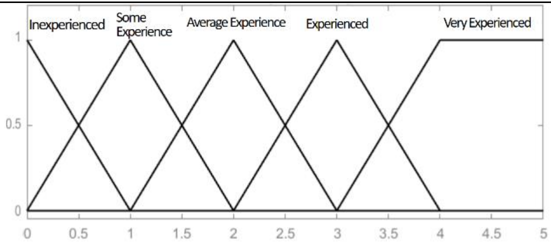
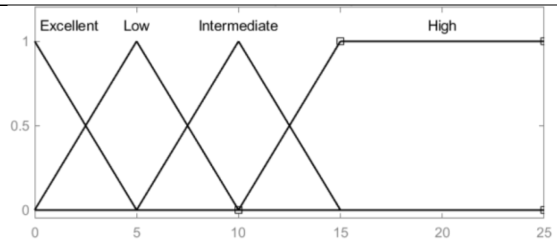
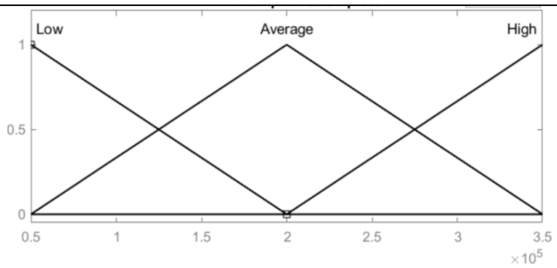
Change in Experience	-1.5 to 2 (Years)	
Average Experience of AUV Team	0 to 50, in practice usually ranges from 0 to 10 (Years)	
Human Error Incidents	0 to Positive Infinity, in practice usually ranges from 0 to 25 (Cases per Year)	
Total Expenses of Maintenance.	0 to Positive Infinity, in practice usually ranges from 50,000 to 350,000 (AUD per Year)	

Table II-B. Elicited fuzzy rules.

Table II-B (a). Fuzzy rules for 'Third Party AUV Hire Contracts' depending on 'Commercial Demand' and 'Reputation in AUV Operations'

		Commercial Demand		
		Poor	Average	High
Reputation in AUV Operations	Notorious	Very Low	Low	Low
	Poor	Very Low	Low	Average
	Average	Low	Average	High
	Good	Low	Average	High
	Excellent	Low	High	Very High

Table II-B (b). Fuzzy rules for 'Reputation in AUV Operations' depending on 'Research Demand' and 'Incident Rate'

		Research Demand		
		Low	Average	High
Incident Rate	Poor	Notorious	Poor	Average
	Average	Poor	Average	Good
	Good	Average	Good	Excellent

Table II-B (c). Fuzzy rules for 'Risk of AUV Loss' depending on 'Incident Rate'

		Risk of AUV Loss
Incident Rate	Poor	High
	Average	Moderate
	Good	Low

Table II-B (d). Fuzzy rules for 'Technical and System Faults' depending on 'AUV Effective Age'

		Technical and System Faults
AUV Effective Age	Infancy	Average
	Early	Low
	Intermediate	Very Low
	Late	Average
	Retiring	Very High

Table II-B (e). Fuzzy rules for 'Actual Utilisation Rate' depending on 'Reputation in AUV Operations'

		Actual Utilisation Rate
Reputation in AUV Operations	Notorious	Minimal
	Poor	Low
	Average	Average
	Good	High
	Excellent	Extreme

Table II-B (f). Fuzzy rules for ‘Change in Experience’ depending on ‘Allocated Annual HR Budget’

		Change in Experience
Allocated Annual HR Budget	Very Low	High Loss
	Low	Loss
	Normal	Minimal Impact
	High	Gain
	Very High	High Gain

Table II-B (g). Fuzzy rules for ‘Human Error Incidents’ depending on ‘Average Experience of AUV Team’

		Human Error Incidents
Average Experience of AUV Team	Inexperienced	High
	Some Experience	Intermediate
	Average Experience	Intermediate
	Experienced	Low
	Very Experienced	Excellent

Table II-B (h). Fuzzy rules for 'Allocated Annual HR Budget' depending on 'Total Expenses of Maintenance', 'Third Party AUV Hire Contracts' and 'Reputation in AUV Operations'

Total Expenses of Maintenance = Low		**Third Party AUV Hire Contracts**				
		Very Low	Low	Average	High	Very High
Reputation in AUV Operations	Notorious	Low	Low	Low	Normal	Normal
	Poor	Low	Low	Normal	Normal	Normal
	Average	Low	Normal	Normal	High	High
	Good	Normal	Normal	High	High	Very High
	Excellent	High	Very High	Very High	Very High	Very High

Total Expenses of Maintenance = Average		**Third Party AUV Hire Contracts**				
		Very Low	Low	Average	High	Very High
Reputation in AUV Operations	Notorious	Very Low	Low	Low	Low	Normal
	Poor	Low	Low	Low	Normal	Normal
	Average	Low	Normal	Normal	Normal	High
	Good	Normal	Normal	High	High	High
	Excellent	High	High	Very High	Very High	Very High

Total Expenses of Maintenance = High		**Third Party AUV Hire Contracts**				
		Very Low	Low	Average	High	Very High
Reputation in AUV Operations	Notorious	Very Low	Very Low	Low	Low	Low
	Poor	Very Low	Low	Low	Low	Low
	Average	Low	Low	Low	Normal	Normal
	Good	Low	Normal	Normal	Normal	Normal
	Excellent	Normal	Normal	High	High	Very High

APPENDIX E: THE ANTARCTIC GATEWAY PARTNERSHIP INITIATIVE

Funded by the Australian Research Council's (ARC) Special Research Initiatives Scheme, the Antarctic Gateway Partnership (AGP) is a collaboration between the University of Tasmania (UTAS), centred at the Australian Maritime College (AMC); the Institute for Marine and Antarctic Studies (IMAS); the Australian Antarctic Division (AAD) and the Commonwealth Scientific and Industrial Research (CSIRO). Led by the administering organisation, UTAS, the AGP focussed on Antarctic and Southern Ocean research.

Commencing in 2014, the program provides funding of $24 million over a three years period to successful initiatives. Apart from enhancing Australia's existing research efforts in the Antarctic, the partnership also aims to reinforce Tasmania's place as a global leader in Antarctic and Southern Ocean science. In collaboration with researchers from over ten countries, research will be undertaken across four integrated themes of:

1. Cryosphere-Ocean Interaction,
2. Open Water and Under Ice Foodwebs,
3. Solid Earth Cryosphere Interaction and;
4. Marine Technology and Polar Environments.

One primary objective under the theme of <Marine Technology and Polar Environments> is to develop an innovative, next-generation, polar Autonomous Underwater Vehicle (AUV) to acquire high-resolution data under sea ice and ice shelves in the Antarctic. Central to achieving this objective lies the effective management of risks, which is one of the main objective of this research.

APPENDIX F: TECHNICAL SPECIFICATIONS OF THE NUPIRI MUKA AUV

Principal Vehicle Data

Characteristic:	Specification:
Total Vehicle Weight	~1600kg
Displacement	~1600 kg
Overall Length	6.25 m
Height	1.4 m (including antennas)
Beam	1.5 m (Including fore planes)
Main Body Diameter	0.74 m
Turning Radius	10 m
Maximum Operating Depth	5000 m
Normal Operating Speed	1.5 m/s
Maximum Speed	2.6 m/s

Navigation

INS

Characteristic:	Specification:
Manufacturer	iXBlue
Type	Fiber Optic Gyroscope
Model #	OI PHINS 3

DVL

Characteristic:	Specification:
Manufacturer	Teledyne RDI
Type	300 kHz DVL
Model #	WHN300-I-UG22

GPS Receiver

Characteristic:	Specification:
Manufacturer	Hemisphere
Type	L1 10Hz GNSS Receiver
Model #	R330 GNSS

Obstacle Avoidance Sonar

Characteristic:	Specification:
Manufacturer	Imagenex
Type	Delta T Multibeam Sonar, 260 kHz 120° x 10° Beam
Model #	837A-000-405

Depth Sensor

Characteristic:	Specification:
Manufacturer	Paroscientific
Type	RS232
Model #	8B7000-I

Ultra Short Baseline

Characteristic:	Specification:
Manufacturer	iXBlue
Type	OCEANO Miniature Transponder
Model #	MT862S/HD-R

NTP Server

Characteristic:	Specification:
Manufacturer	Masterclock
Model #	GMR1000

Scientific Payload

Conductivity Temperature and Depth Sensor (CTD)

Characteristic:	Specification:
Manufacturer	Sea Bird
Type	FastCAT
Model #	SBE49

Sidescan Sonar/Sub-Bottom Profiler

Characteristic:	Specification:
Manufacturer	EdgeTech
Type	ICD, Ducer, SideScan, 2205, 230-550 KHz 550Khz Bathy with Preamp Box, 6000M
Model #	2205

Energy

Main Battery

Characteristic:	Specification:
Manufacturer	EXIDE Technologies
Model	Onyx +48V M70X48V034P
Energy capacity per module (9 installed)	1.6 kWh
Material	Lithium Ion
Voltage minimum per module	42 VDC
Voltage maximum per module	54.0 VDC
Maximum current discharge per module	20 Amp per module
Number of modules	11
Total energy capacity	28.8 kWh

Communication

Ethernet Radio

Characteristic:	Specification:
Manufacturer	Encom
Type	Ethernet Radio Modem
Frequency	2.4 GHz ISM Band
Model #	Commpak EP-BB24NC
Emissions Designator	DSSS

Acoustic Modem: Communication

Characteristic:	Specification:
Manufacturer	Sercel
Type	MATS 3G 12 kHz
Model #	AUV Top: 10003037 AUV Bottom: 10003037 Ships Modem: 10003041

Ethernet Deck Cable

Characteristic:	Specification:
Manufacturer	ISE Ltd.
Type	Industrial Waterproof
Model #	EL9999-001-77-01
Length	25 m

Satellite Modem

Characteristic:	Specification:
Manufacturer	Iridium
Type	L-Band modem data transceiver
Model #	9522B

Emergency Devices

Strobe Light / Iridium Beacon

Characteristic:	Specification:
Manufacturer	Apollo
Power Source	7 of “AA” size alkaline batteries
Model #	Apollo RH

Drop Weight

Characteristic:	Specification:
Weight	44.5 kg
Model #	EE5634-100-00-01

Emergency Battery

Characteristic:	Specification:
Manufacturer	Magnavolt
Model	SLA12-20 (12V20AH)
Battery Type	Rechargeable Sealed Lead Acid
Voltage per module	12VDC
Current	20Ah
Number of modules	2
Total energy capacity	24 VDC

APPENDIX G: EXPERT ELICITATION (ETHICS APPROVAL, CONSENT FORM AND INTERVIEW PROTOCOL)

Social Science Ethics Officer
Private Bag 01 Hobart
Tasmania 7001 Australia
Tel: (03) 6226 2763
Fax: (03) 6226 7148
Katherine.Shaw@utas.edu.au

UTAS

HUMAN RESEARCH ETHICS COMMITTEE (TASMANIA) NETWORK

09 July 2018

Professor Kiril Tenekedjiev
AMC Governance Office
Private Bag 1395

Dear Professor Tenekedjiev

Re: MINIMAL RISK ETHICS APPLICATION APPROVAL
Ethics Ref: H0017392 - Risk Analysis of Autonomous Underwater Vehicle (AUV) Operations in the Antarctic

We are pleased to advise that acting on a mandate from the Tasmania Social Sciences HREC, the Chair of the committee considered and approved the above project on 09 July 2018.

This approval constitutes ethical clearance by the Tasmania Social Sciences Human Research Ethics Committee. The decision and authority to commence the associated research may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or review by your research governance coordinator or Head of Department. It is your responsibility to find out if the approval of other bodies or authorities is required. It is recommended that the proposed research should not commence until you have satisfied these requirements.

Please note that this approval is for four years and is conditional upon receipt of an annual Progress Report. Ethics approval for this project will lapse if a Progress Report is not submitted.

The following conditions apply to this approval. Failure to abide by these conditions may result in suspension or discontinuation of approval.

1. It is the responsibility of the Chief Investigator to ensure that all investigators are aware of the terms of approval, to ensure the project is conducted as approved by the Ethics Committee, and to notify the Committee if any investigators are added to, or cease involvement with, the project.

A PARTNERSHIP PROGRAM IN CONJUNCTION WITH THE DEPARTMENT OF HEALTH AND HUMAN SERVICES

2. Complaints: If any complaints are received or ethical issues arise during the course of the project, investigators should advise the Executive Officer of the Ethics Committee on 03 6226 7479 or human.ethics@utas.edu.au.

3. Incidents or adverse effects: Investigators should notify the Ethics Committee immediately of any serious or unexpected adverse effects on participants or unforeseen events affecting the ethical acceptability of the project.

4. Amendments to Project: Modifications to the project must not proceed until approval is obtained from the Ethics Committee. Please submit an Amendment Form (available on our website) to notify the Ethics Committee of the proposed modifications.

5. Annual Report: Continued approval for this project is dependent on the submission of a Progress Report by the anniversary date of your approval. You will be sent a courtesy reminder closer to this date. **Failure to submit a Progress Report will mean that ethics approval for this project will lapse.**

6. Final Report: A Final Report and a copy of any published material arising from the project, either in full or abstract, must be provided at the end of the project.

Yours sincerely

Ailin Ding
Ethics Officer
Tasmania Social Sciences HREC

UNIVERSITY of TASMANIA | AMC Australian Maritime College

Consent Form

Risk Analysis of Autonomous Underwater Vehicle (AUV) Operations in the Antarctic

First and foremost, we sincerely thank you for agreeing to take part in this research study. Your contribution will make a difference in ensuring the success of this research. The purpose of this consent form is for you to understand and agree to the terms and conditions of participation. If you agree to the terms and conditions, please sign at the bottom of this form and scan a copy to Tzuyang.Loh@utas.edu.au or pass the signed hard copy to Loh Tzu Yang.

The purpose of this research is to understand better the systemic process risks behind an AUV program, which influences the risk of losing an AUV during operations in the Antarctic. Through a better understanding of the risks involved, we aim to design and propose recommendations for safer operations of AUVs in the Antarctic.

You have been chosen because of your notable experience, knowledge or involvement in AUV operations. Your participation is entirely voluntary, and you have the right to stop or withdraw from the study at any time. By signing at the bottom of this form, you agree to the following:

1. I agree to take part in the research study named above.
2. I have read and understood the Information Sheet sent earlier to me.
3. I am aware of the nature of the study and the scope of my involvement.
4. I understand that this research involves an iterative modelling process and I will likely be elicited more than once. Each session will last no longer than one hour and for face-to-face or phone calls, it will be recorded. I will receive summarised transcripts to correct any factual errors.
5. I understand that participation does not involve any foreseeable risk. However, I may choose to stop or not answer any particular question if I am uncomfortable.
6. I understand that all research data will be kept in a password secured drive in a UTAS issued laptop and in the One drive server of UTAS. Additional password protection will be in place for interview data files which includes identity of participants. Data will be deleted from the drives five years from the publication of study results.
7. Any questions that I have asked pertaining to this research have been answered to my satisfaction.
8. I understand that the researcher(s) will maintain confidentiality and that any information I supply to the researcher(s) will be used only for this research.
9. I understand that the results of the study will be published in academic publications or other academic outlets. However, I will be anonymised and care will be taken so that I cannot be identified as a participant.
10. I understand that the final results of the study will be made available on a website with links sent to me. I can choose to access these results if I wish to.
11. I understand that my participation is voluntary and that I may withdraw at any time without any adverse consequences. I may also request that any data which I have supplied to be withdrawn from this research.

Contact Information

If you have any further questions or concerns about this study, please communicate with the research investigator:

Loh Tzu Yang
Tzuyang.Loh@utas.edu.au

Alternatively, you can contact the investigator's supervisor Prof Kiril Tenekedjiev at kiril.tenekedjiev@utas.edu.au

Or if you have concerns or complaints about how it is being conducted, please contact the Executive Officer of the HREC (Tasmania) Network on +61 3 6226 6254 or email human.ethics@utas.edu.au. The Executive Officer is the person nominated to receive complaints from research participants. Please quote ethics reference number __________."

Participant's name: ____

Participant's signature: ____

Date: ____________________

To be completed by investigator

Statement by Investigator

☐ I have explained the project and the implications of participation in it to this volunteer. I believe that the consent is informed and that he/she understands the implications of participation.

If the Investigator has not had an opportunity to talk to participants prior to them participating, the following must be ticked.

☐ The participant has received the Information Sheet where my details have been provided. Participants have had the opportunity to contact me prior to consenting to participate in this project.

Investigator's name: ____

Investigator's signature: ____

Date: ____________________

Elicitation Protocol/

Risk Analysis of Autonomous Underwater Vehicle (AUV) Operations in the Antarctic

Introduction

We sincerely thank you for agreeing to take part in this research study. Your participation will make a difference in ensuring the success of this research. Please feel free to clarify any questions which you may have at any point in this study.

Background

- The use of Autonomous Underwater Vehicles (AUVs) for marine science research in the Antarctic has grown with maturing technology and improved accessibility. With more prevalent use of AUVs, effective management of risks, especially the risk of losing an AUV during operations, becomes a key focus area for the AUV community. The loss of an AUV is not only financially costly due to the higher insurance premium, but it can also delay research projects, damage the reputation of the AUV community, cause the loss of valuable research data and a possibility of harming the delicate Antarctic environment.
- Existing risk management approaches focus mainly on the technical dimension of the AUV, with much attention on immediate risks to an AUV during deployment and less on systemic risks. Systemic risks arise from inadequate or failed internal processes, human errors or external events.
- The purpose of this research is to understand better the systemic process risks behind an AUV program, which influences the risk of losing an AUV during operations in the Antarctic. Time pressure, poor workforce planning, weak governance, lack of communication channels and poor resource planning are some examples of systemic process risks. Through a better understanding of the risks involved, we aim to propose risk control recommendations for safer operations of AUVs in the Antarctic.
- Fuzzy system dynamics is the chosen modelling methodology for this research.

Methodology

We will elicit your perspectives on risk factors influencing the risk of AUV loss during under-ice missions in the Antarctic. As this research involves an iterative process, you are likely to be elicited more than once to assist in reviewing, fine-tuning and validating the risk models.

Confidentiality

We will take steps to preserve the confidentiality of your identity. Results from this study will be released in academic publications or other academic outlets. However, you will be anonymised, and care will be taken to ensure that your identity will not be revealed through any forms of information. This interview session will be recorded, and you will receive summarised transcript to correct any factual errors. You may also choose to stop or not answer any particular question if you feel uncomfortable.

PART 1

Background

1. Please describe in detail, your experience in the operations of AUVs, including duration, organisations, types of AUVs involved and types of deployments. Please also state the amount of experience in under-ice AUV operations.

2. Please provide a description either in words or diagram of the organisational structure involved in running the AUV program in your organisation. For example, who is the AUV owner and the number of personnel in the AUV team?

3. What are your roles, responsibilities and expertise in the above organisational structure?

Risk Identification

4. In your opinion, what are the main risk factors or scenarios influencing the risk of losing an AUV during under-ice mission in the Antarctic? You may wish to consider the following areas:

Human Factors e.g. Operating Experience of Team

AUV Technicalities e.g. Reliability of Components

Organisational Factors e.g. Resource Allocation

External Influences e.g. Insurance Coverage, Regulations, Operating Environment

Other Risk Factors

5. Based on the risk factors, please provide some recommendations to improve the survivability of AUVs during under-ice mission in the Antarctic.

6. Please provide a description either in words or diagram of some possible causal relationships and the strength of these relationships between the risk factors you have stated earlier?

7. What are the assumptions, if any, that you have made for the above opinions?

Open Discussion

8. Please share any other comments or thoughts relating to the risk of losing an AUV during under-ice mission in the Antarctic.

- End of Part 1 -

PART 2

Review of Fuzzy Rule Bases and Models

1. Based on earlier interviews and other information sources, causal relationships in the form of rule bases were established. Please review and comment on these rule bases between the identified risk factors.

2. Please review and comment on the risk models developed partly from your earlier contribution. This represents our current understanding of potential issues influencing the risk of AUV loss during deployment in the Antarctic. Do not hesitate to let us know if you think that the model or specific parts of the model is wrong.

3. We have established several recommendations for risk control based on the risk models. Please provide us with feedback on these recommendations. For example, ease of implementation of these measures?

4. Please share any other comments or thoughts relating to the risk of losing an AUV during under-ice mission in the Antarctic.

- End of Part 2 -

We have come to the end of this interview session and will like to again, thank you for your valuable contributions to this research study. We will be sending you the transcript shortly and be in touch with you. If you have any further questions or concerns about this study, please reach me at:

Tzuyang.Loh@utas.edu.au

Or if you have concerns or complaints about how it is being conducted, please contact the Executive Officer of the HREC (Tasmania) Network on +61 3 6226 6254 or email human.ethics@utas.edu.au. The Executive Officer is the person nominated to receive complaints from research participants. Please quote ethics reference number H0017392

To be filled by investigator											
Interviewee:	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**
	L	**M**	**N**	**O**	**P**	**Q**	**R**	**S**	**T**	**U**	**V**
Elicitor: Loh Tzu Yang											
Date:	____/_____/_____										
Time Start:	________________			**Time End:**		_____________					
Venue:	________________										
Session No.:	___										

APPENDIX H: FuSDRA MODEL PARAMETERS AND FORMULATIONS (FIGURE 5.11)

Table III. Formulations, definitions, units and initial conditions.

Risk factor	Definition	Equation
Utilisation Sub-model		
Annual Utilisation Rate	Time that the AUV is underwater over the time which the AUV is available to operate, in a year.	*Function of* (Requirement Creep) and (Request for AUV Use) **Fuzzy Logic[1]**
Availability of Alternatives	Newer AUVs or other means of data collection available to scientists and other users of the *nupiri muka*.	3.0 (Low) on an arbitrary scale of 0 (Very Low) – 10 (Very High)
Request for AUV Use (Internal and External)	Quantity of request received for use of the *nupiri muka* AUV. Consists of both internal research and external commercial requests at a specific period considering the costs, awareness, regulations, geographical limitations and economic conditions.	*Function of* (Availability of Alternatives), (Awareness, Availability and Accessibility of AUV Solutions) and (Reputation/Track Record) **Fuzzy Logic[1]**
Difference Between Expected and Actual Output	Difference between expected output from the AUV program and actual output. Outputs may include income, journal articles, books, book chapters, conference publications.	*Function of* (Annual Utilisation Rate) and (Fraction of Budget Approved) **Fuzzy Logic[1]**
Change of Reputation/Track Record in AUV Operations	Rate of change to the reputation of UTAS in Antarctic AUV operations.	*Function of* (Annual Utilisation Rate) and (Average no. of High Impact Faults/Incidents Per Mission) **Fuzzy Logic[1]**
Reputation/Track Record	Overall perception of UTAS in Antarctic AUV operations, held by both internal and external stakeholders based on its track records and predicted future behavior.	INTEG (Change in Reputation/Track Record in AUV Operations) Initial value = 50
Awareness, Availability and Accessibility of AUV Solutions	Level of awareness, availability and accessibility to the use of nupiri muka AUV by both internal and external stakeholders. This may include *geographical* limitations, cost of deployment and knowledge of AUV capabilities.	1 x Government Support, On an arbitrary scale of 0 (Poor) – 10 (Very High).
Budget Sub-model		
Comprehensiveness of Insurance Coverage	Types of situation which falls under insurance coverage. From relatively low risk to high risk situations such as damage or loss whilst in storage, being transported, open water operations, under-ice operations etc.	3.0: Average-Low. on an arbitrary scale of 0 (Low) – 10 (High). At time of writing, *nupiri muka* has insurance coverage for open water missions.
Annual Insurance Premium	The amount of money UTAS have to pay annually for the insurance policy on loss of *nupiri muka.*	Annual Insurance Premium Fraction x AUV Replacement Cost
AUV Replacement Cost	The actual cost to replace the *nupiri muka* at its pre-loss condition.	AUD$ 500,0000
Annual Insurance Premium Fraction	Fraction of replacement value for the *nupiri muka* AUV which translates into annual insurance premium.	*Function of* (Comprehensiveness of Insurance Coverage) and (Reputation/Track Record) **Fuzzy Logic[1]**

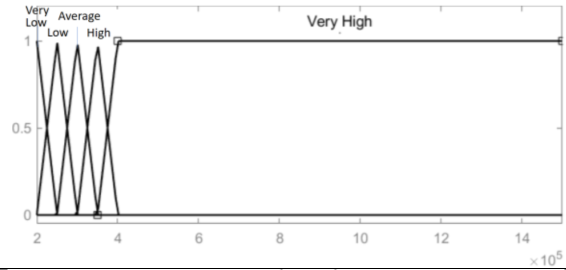
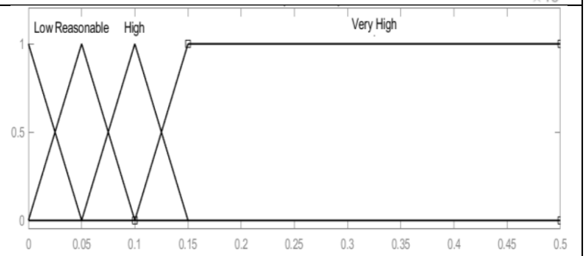
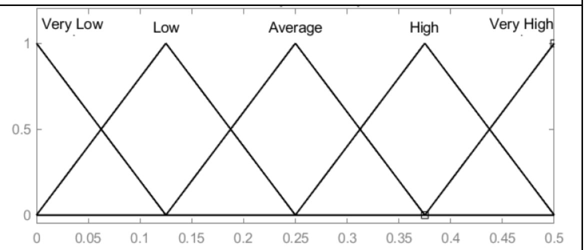
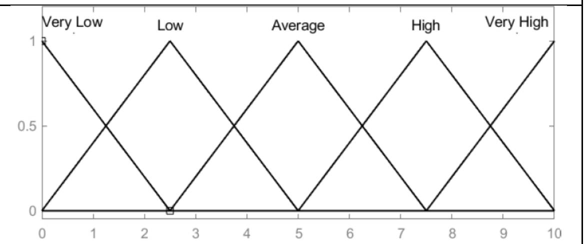
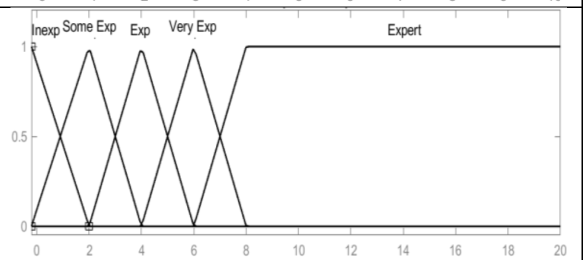
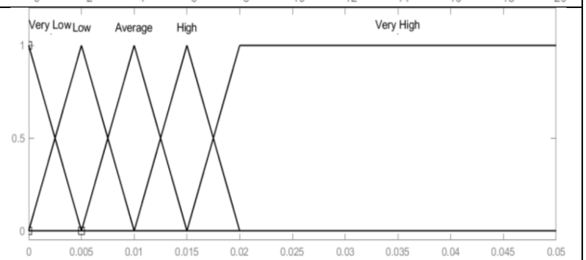
Government Support	The level of Australia's government support for the nupiri muka AUV program. For instance, in terms of funding or support programs.	8.0: High. On an arbitrary scale of 0 (Poor) – 10 (Very High).
Annual Increase/Decrease of Other Operating Costs	Increase or decrease in operating costs other than maintenance.	-2.0%
Other Operating Costs	The recurring costs of operating the *nupiri muka*, such as staff cost, facility expenses, depreciation costs, wear and tear of the AUV and license or fees imposed by the government for deployment.	INTEG (-0.02 x Other Operating Costs) Initial value = AUD $150,000
Annual Increment of Maintenance Costs	Increase in costs of maintenance and upgrades as AUV components and systems deteriorates or become obsolete with time.	2.0%
Maintenance Costs	Costs of maintenance and upgrades.	INTEG (0.02 x Maintenance Costs) Initial value = AUD $20,000
Annual Budget Requirement	Forecast annual budget requirement to operate the *nupiri muka* AUV program.	Annual Insurance Premium + Maintenance Costs + Other Operating Costs
Fraction of Budget Approved	Fraction of annual budget approved by management for the *nupiri muka* AUV program.	*Function of* (Annual Budget Requirement), (Government Support) and (Organisation's Commitment to the AUV Program) **Fuzzy Logic**[1]
Organisation's Commitment to the AUV Program	Management's psychological attachment to the nupiri muka AUV program, which translates into resource allocation for the program.	*Function of* (Annual Utilisation Rate) and (Calendar Age of AUV) **Fuzzy Logic**[1]
Human Reliability Sub-model		
Change in Average Experience of AUV Team	The amount of experience gained or lost due to turnover, recruitment policies or hands-on experience from deployments.	*Function of* (Fraction of Budget Approved) and (Annual Utilisation Rate) **Fuzzy Logic**[1]
Risk Perception	Overall risk perception of the primary AUV Team, which is the subjective judgement the team estimates about occurrence and severity of a risk.	*Function of* (Average Experience of AUV Team), (Comprehensiveness of Insurance Coverage) and (Stress on AUV Team) **Fuzzy Logic**[1]
Rate of Requirement Creep	Rate of change to the original risk evaluation criteria.	*Function of* (Risk Perception) and (Difference Between Expected and Actual Output) **Fuzzy Logic**[1]
Requirement Creep	Changes to the original risk evaluation criteria, to undertake AUV missions of higher risk without accounting for additional risk control measures.	INTEG (Change in Requirement Creep) Initial value = 0
Average Experience of AUV Team	Average experience of the primary AUV team in Antarctic AUV operations.	INTEG (Change in Average Experience of AUV Team) Initial value = 1
Interpersonal Dynamics	Refers to the quality of relationships and interactions that the AUV team has within the team as well as with other stakeholders.	8.0: High. On an arbitrary scale of 0 (Very Poor) – 10 (Very High).

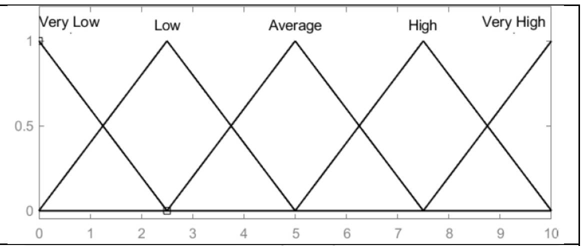
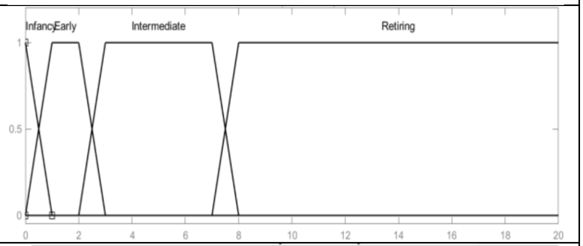
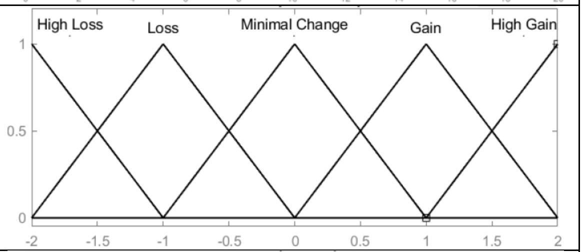
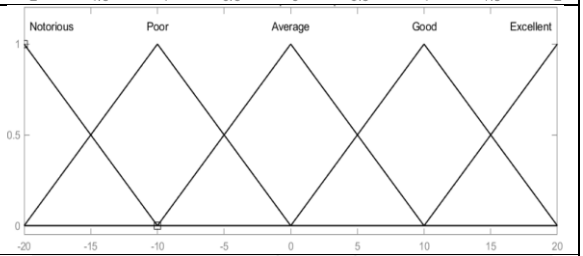
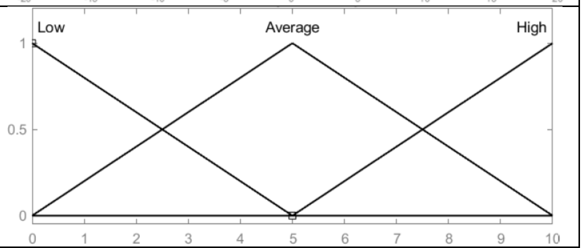
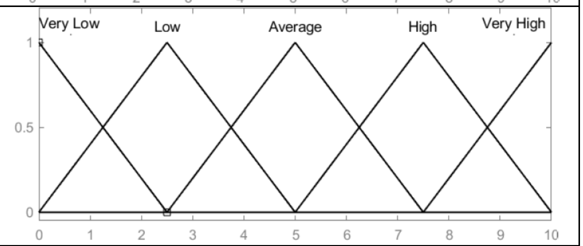
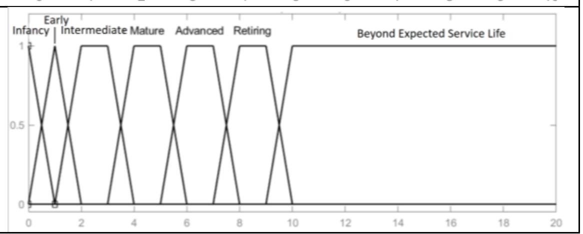
Stress on AUV Team	The adverse reaction experienced by the AUV team due to expectations and responsibilities which may be greater than what is comfortably manageable.	*Function of* (Interpersonal Dynamics) and (Difference Between Expected and Actual Output) **Fuzzy Logic**[1]
Likelihood of Human Error	The likelihood of unintentional action or decision which may lead to loss of the *nupiri muka* AUV in the Antarctic	*Function of* (Risk Perception) and (Average Experience of AUV Team) **Fuzzy Logic**[1]
Technical Reliability Sub-model		
Effective AUV Age	Basis of remaining useful life, which can be less than actual calendar age of the AUV	INTEG (Rate of Effective Ageing) Initial value = 0
Rate of Calendar Ageing	Rate of increase in the chronological age of the nupiri muka AUV.	1.0
Calendar Age of AUV	The actual age of the AUV.	INTEG (1) Initial value = 0
Rate of Effective Ageing	Rate at which the effective age of the AUV increases.	*Function of* (Quality Maintenance and Repair) and (Annual Utilisation Rate) **Fuzzy Logic**[1]
Reliability of AUV	The ability of the *nupiri muka* AUV to operate without technical faults for a stipulated period.	*Function of* (Effective AUV Age) **Fuzzy Logic**[1]
Quality Maintenance and Repair	The level of high quality maintenance and repair which includes both reactive and preventive maintenance of the AUV	*Function of* (Average Experience of AUV Team) and (Fraction of Budget Approved) **Fuzzy Logic**[1]
Risk of Loss		
Risk of AUV Loss in the Antarctic	Likelihood of losing the *nupiri muka* AUV during a deployment to the Antarctic.	*Function of* (Likelihood of Human Error) and (Reliability of AUV) **Fuzzy Logic**[1]
Average Number of Faults/Incidents per Mission	Average number of high impact faults and incidents encountered per mission. High impact faults could potentially lead to the loss of the AUV, such as major pressure vessel leak or battery short circuit. Incidents include both near-misses and accidents such as collision with vessel.	0.089 x Risk of AUV Loss. (Using the risk study on Autosub (6) as the reference)

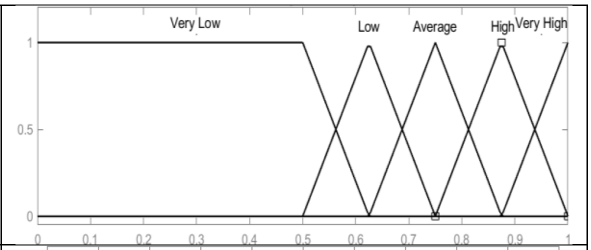
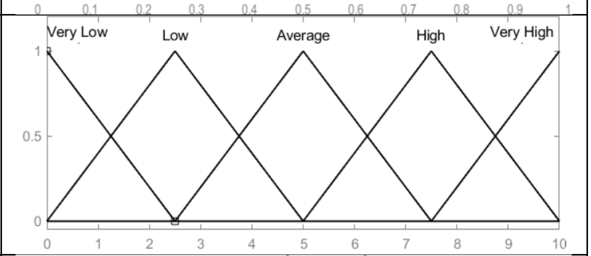
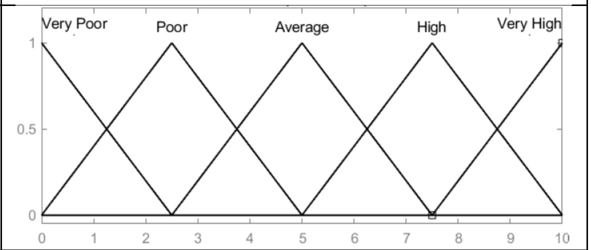
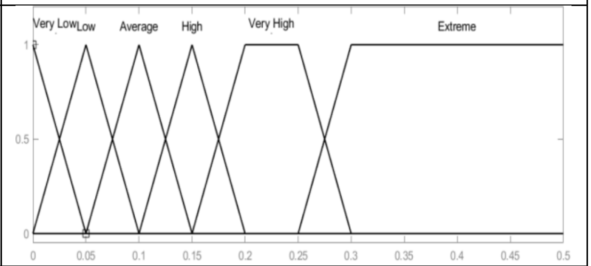
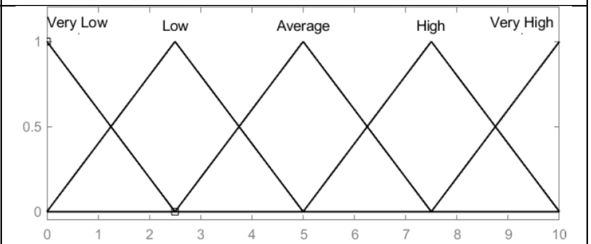
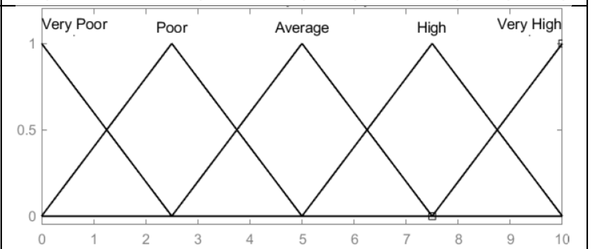
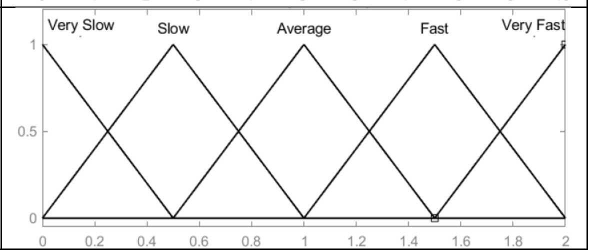
[1] Represents the likely presence of random factors in the functional relationships which may not be deterministically defined at this point in time. Causal relationships are therefore modelled with fuzzy logic, with inputs from domain experts in the form of fuzzy rule bases.

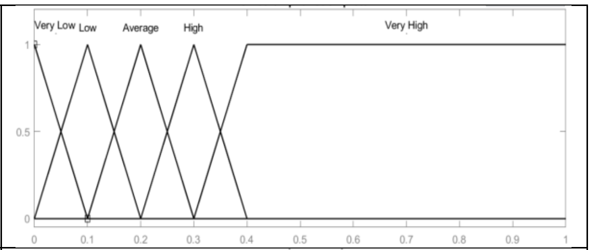
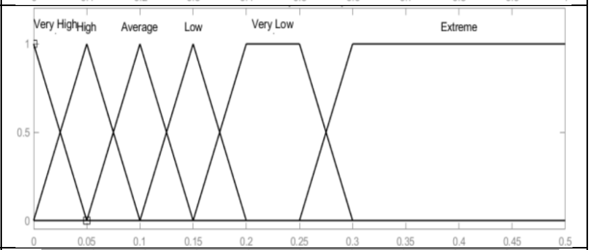
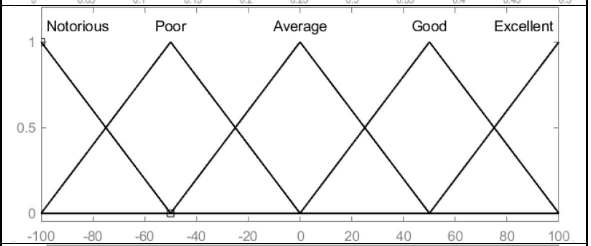
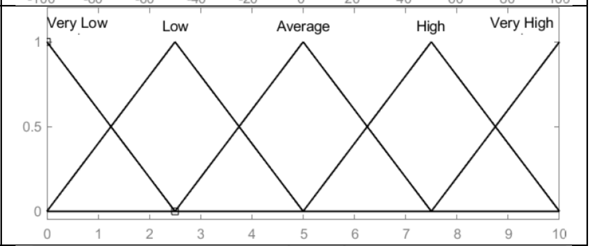
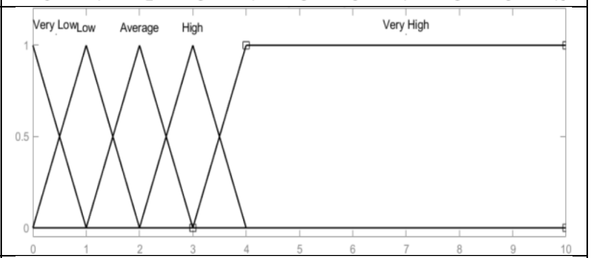
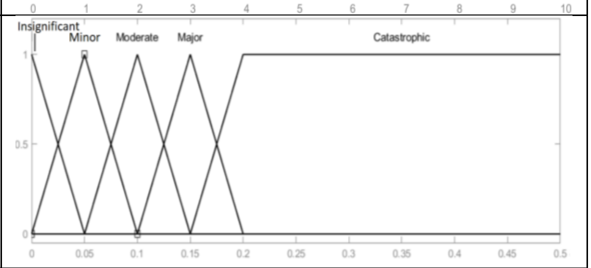
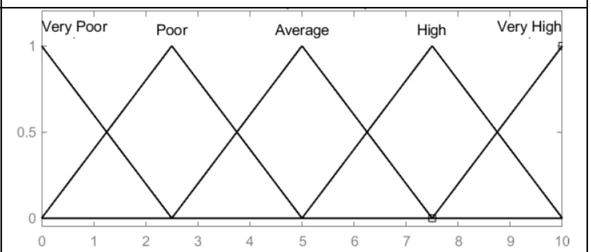
APPENDIX I: UNIVERSE OF DISCOURSE, FUZZY SETS, MEMBERSHIP FUNCTION AND FUZZY RULES (FIGURE 5.11)

Table IV-A. Risk factors and their associated universe of discourse, fuzzy sets and membership functions.

Risk factors (In alphabetical order)	Universe of Discourse (Units)	Fuzzy Sets and Membership Function
Annual Budget Requirement	0 to Positive Infinity, expected to range from \$200,000 to \$1,500,000 (AUD per Year)	
Annual Insurance Premium Fraction	0 to 1.0, expected to range from 0 to 0.5 (Fraction of replacement value per Year)	
Annual Utilisation Rate	0 to 1.0, expected to range from 0 to 0.5 (Fraction of available time per Year)	
Availability of Alternatives	0 to 10 (Dimensionless)	
Average Experience of AUV Team	0 to 50, expected to range from 0 to 20 (Years)	
Average Number of Faults/Incidents per Mission	0 to Positive Infinity, expected to range from 0 to 0.05 (Cases/Mission)	

Awareness, Availability and Accessibility of AUV Solutions	0 to 10 (Dimensionless)	
Calendar Age of AUV	0 to Positive Infinity, expected to range from 0 to 20 (Years)	
Change in Average Experience of AUV Team	Negative Infinity to Positive Infinity, expected to range from -2.0 to 2.0 (Years per year)	
Change in Reputation/Track Record in AUV Operations	-20 to 20 (Dimensionless per year)	
Comprehensiveness of Insurance Coverage	0 to 10 (Dimensionless)	
Difference Between Expected and Actual Output	0 to 10 (Dimensionless)	
Effective AUV Age	0 to Positive Infinity, expected to range from 0 to 20 (Years)	

Fraction of Budget Approved	0 to 1.0, (Fraction of Requested Budget)	
Government Support	0 to 10 (Dimensionless)	
Interpersonal Dynamics	0 to 10 (Dimensionless)	
Likelihood of Human Error	0 to 1.0, expected to range from 0 to 0.5 (Likelihood of human error)	
Organisation's Commitment to the AUV Program	0 to 10 (Dimensionless)	
Quality Maintenance and Repair	0 to 10 (Dimensionless)	
Rate of Effective Ageing	0 to Positive Infinity, expected to range from 0 to 2 (Years per year)	

Rate of Requirement Creep	0 to 1.0 (Dimensionless)	
Reliability of AUV	0 to 1.0, expected to range from 0 to 0.5 (Probability of hardware failure)	
Reputation/Track Record	-200 to 200, expected to range from -100 to 100 (Dimensionless)	
Request for AUV Use (Internal and External)	0 to 10 (Dimensionless)	
Requirement Creep	0 to 10 (Dimensionless)	
Risk of AUV Loss in the Antarctic	0 to 1.0, expected to range from 0 to 0.5 (Probability of loss)	
Risk Perception	0 to 10 (Dimensionless)	

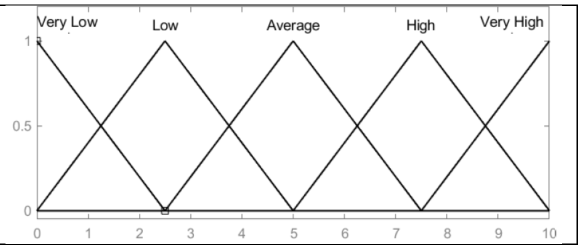
Stress on AUV Team	0 to 10 (Dimensionless)	

Table IV-B. Elicited fuzzy rules.

Table IV-B (a). Fuzzy rules for 'Risk Perception' depending on 'Average Experience of AUV Team', 'Comprehensiveness of Insurance Coverage' and 'Stress on AUV Team'.

Comprehensiveness of Insurance Coverage = Low		**Average Experience of AUV Team**				
		Inexperience	Some Experience	Experienced	Very Experienced	Expert
Stress on AUV Team	Very Low	Average	Average	High	Very High	Very High
	Low	Poor	Average	High	High	Very High
	Average	Poor	Poor	Average	High	Very High
	High	Poor	Poor	Average	High	Very High
	Very High	Very Poor	Very Poor	Poor	Average	High

Comprehensiveness of Insurance Coverage = Average		**Average Experience of AUV Team**				
		Inexperience	Some Experience	Experienced	Very Experienced	Expert
Stress on AUV Team	Very Low	Poor	Average	High	High	Very High
	Low	Poor	Poor	Average	High	Very High
	Average	Poor	Poor	Average	High	Very High
	High	Very Poor	Poor	Average	Average	Very High
	Very High	Very Poor	Very Poor	Poor	Average	High

Comprehensiveness of Insurance Coverage = High		**Average Experience of AUV Team**				
		Inexperience	Some Experience	Experienced	Very Experienced	Expert
Stress on AUV Team	Very Low	Poor	Poor	Average	High	Very High
	Low	Poor	Poor	Average	High	Very High
	Average	Very Poor	Poor	Poor	Average	Very High
	High	Very Poor	Very Poor	Poor	Average	High
	Very High	Very Poor	Very Poor	Very Poor	Poor	High

Table IV-B (b). Fuzzy rules for 'Annual Utilisation Rate' depending on 'Requirement Creep' and 'Requests for AUV use (Internal and External)'.

		Request for AUV Use (Internal and External)				
		Very Low	Low	Average	High	Very High
Requirement Creep	Very Low	Very Low	Low	Average	Average	Average
	Low	Very Low	Low	Average	Average	High
	Average	Very Low	Low	Average	High	High
	High	Very Low	Low	Average	High	Very High
	Very High	Very Low	Low	Average	High	Very High

Table IV-B (c). Fuzzy rules for 'Rate of Requirement Creep' depending on 'Risk Perception' and 'Difference Between Expected and Actual Output'.

		Risk Perception				
		Very Poor	Poor	Average	High	Very High
Difference Between Expected and Actual Output	Very Low	Average	Low	Low	Very Low	Very Low
	Low	Average	Average	Low	Low	Very Low
	Average	High	Average	Average	Low	Very Low
	High	Very High	High	High	Average	Low
	Very High	Very High	Very High	Very High	High	Average

Table IV-B (d). Fuzzy rules for ‘Request for AUV Use (Internal and External)’ depending on ‘Availability of Alternatives’, ‘Awareness, Availability and Accessibility of AUV Solutions’ and ‘Reputation/Track Record’.

Availability of Alternatives = Very Low		**Awareness, Availability and Accessibility of AUV Solutions**				
		Very Low	Low	Average	High	Very High
Reputation/ Track Record	Notorious	Low	Low	Average	Average	Average
	Poor	Low	Average	Average	High	High
	Average	Average	Average	High	High	Very High
	Good	Average	High	High	Very High	Very High
	Excellent	High	High	Very High	Very High	Very High

Availability of Alternatives = Low		**Awareness, Availability and Accessibility of AUV Solutions**				
		Very Low	Low	Average	High	Very High
Reputation/ Track Record	Notorious	Very Low	Very Low	Low	Low	Low
	Poor	Low	Low	Average	Average	Average
	Average	Low	Low	Average	High	High
	Good	Low	Average	High	High	Very High
	Excellent	Low	Average	High	Very High	Very High

Availability of Alternatives = Average		**Awareness, Availability and Accessibility of AUV Solutions**				
		Very Low	Low	Average	High	Very High
Reputation/ Track Record	Notorious	Very Low	Low	Low	Low	Low
	Poor	Very Low	Low	Low	Average	Average
	Average	Low	Low	Average	Average	High
	Good	Low	Average	Average	High	High
	Excellent	Low	Average	High	High	Very High

Availability of Alternatives = High		**Awareness, Availability and Accessibility of AUV Solutions**				
		Very Low	Low	Average	High	Very High
Reputation/ Track Record	Notorious	Very Low	Very Low	Very Low	Low	Low
	Poor	Very Low	Very Low	Low	Low	Average
	Average	Very Low	Low	Low	Average	Average
	Good	Low	Low	Low	Average	High
	Excellent	Low	Low	Average	High	High

Availability of Alternatives = Very High		**Awareness, Availability and Accessibility of AUV Solutions**				
		Very Low	Low	Average	High	Very High
Reputation/ Track Record	Notorious	Very Low	Very Low	Very Low	Very Low	Low
	Poor	Very Low	Very Low	Very Low	Low	Low
	Average	Very Low	Very Low	Low	Low	Average
	Good	Very Low	Low	Low	Low	Average
	Excellent	Low	Low	Low	Average	Average

Table IV-B (e). Fuzzy rules for 'Difference Between Expected and Actual Output' depending on 'Annual Utilisation Rate' and 'Fraction of Budget Approved'.

		Annual Utilisation Rate				
		Very Low	Low	Average	High	Very High
Fraction of Budget Approved	Very Low	Average	Low	Very Low	Very Low	Very Low
	Low	Average	Average	Low	Very Low	Very Low
	Average	High	Average	Low	Low	Very Low
	High	High	High	Average	Average	Low
	Very High	Very High	High	High	High	Average

Table IV-B (f). Fuzzy rules for 'Organisation's Commitment to the AUV Program' depending on 'Calendar Age of AUV' and 'Annual Utilisation Rate'.

		Annual Utilisation Rate				
		Very Low	Low	Average	High	Very High
Calendar Age of AUV	Infancy	Very High	Very High	Very High	Very High	Very High
	Early	Average	High	High	Very High	Very High
	Intermediate	Low	Average	Average	High	Very High
	Retiring	Very Low	Very Low	Low	Average	Average

Table IV-B (g). Fuzzy rules for 'Annual Insurance Premium Fraction' depending on 'Comprehensiveness of Insurance Coverage' and 'Reputation/Track Record in AUV Operation'.

		Reputation/Track Record				
		Notorious	Poor	Average	Good	Excellent
Comprehen-siveness of Insurance Coverage	Low	High	Reasonable	Reasonable	Low	Low
	Average	Very High	High	Reasonable	Reasonable	Low
	High	Very High	Very High	High	Reasonable	Reasonable

Table IV-B (h). Fuzzy rules for 'Change in Reputation/Track Record in AUV Operations' depending on 'Annual Utilisation Rate' and 'Average No. of High Impact Faults/Incidents per Mission'.

		Annual Utilisation Rate				
		Very Low	Low	Average	High	Very High
Average No. of High Impact Faults/Incidents per Mission	Very Low	Average	Good	Good	Excellent	Excellent
	Low	Poor	Average	Good	Good	Excellent
	Average	Poor	Poor	Average	Average	Good
	High	Notorious	Poor	Poor	Poor	Average
	Very High	Notorious	Notorious	Notorious	Poor	Poor

Table IV-B (i). Fuzzy rules for 'Fraction of Budget Approved' depending on 'Annual Budget Requirement', 'Organisation's Commitment to the AUV Program' and 'Government Support'.

Government Support = Very Low		**Annual Budget Requirement**				
		Very Low	Low	Average	High	Very High
Organisation's Commitment to the AUV Program	Very Low	Low	Very Low	Very Low	Very Low	Very Low
	Low	Low	Low	Low	Very Low	Very Low
	Average	Average	Average	Low	Low	Very Low
	High	Average	Average	Average	Average	Low
	Very High	High	High	High	High	Average

Government Support = Low		**Annual Budget Requirement**				
		Very Low	Low	Average	High	Very High
Organisation's Commitment to the AUV Program	Very Low	Low	Low	Very Low	Very Low	Very Low
	Low	Average	Low	Low	Very Low	Very Low
	Average	Average	Average	Average	Average	Low
	High	High	Average	Average	Average	Average
	Very High	High	High	High	High	Average

Government Support = Average		**Annual Budget Requirement**				
		Very Low	Low	Average	High	Very High
Organisation's Commitment to the AUV Program	Very Low	Average	Low	Very Low	Very Low	Very Low
	Low	Average	Low	Low	Low	Very Low
	Average	High	Average	Average	Average	Low
	High	High	High	High	Average	Average
	Very High	Very High	Very High	High	High	High

Government Support = High		**Annual Budget Requirement**				
		Very Low	Low	Average	High	Very High
Organisation's Commitment to the AUV Program	Very Low	High	Average	Low	Low	Very Low
	Low	High	Average	Average	Average	Low
	Average	High	High	High	Average	Average
	High	Very High	High	High	High	Average
	Very High	Very High	Very High	Very High	High	High

Government Support = Very High		**Annual Budget Requirement**				
		Very Low	Low	Average	High	Very High
Organisation's Commitment to the AUV Program	Very Low	High	High	Average	Average	Low
	Low	Very High	High	High	Average	Low
	Average	Very High	High	High	Average	Average
	High	Very High	Very High	Very High	High	Average
	Very High	Very High	Very High	Very High	High	High

Table IV-B (j). Fuzzy rules for 'Change in Average Experience of AUV Team' depending on 'Annual Utilisation Rate' and 'Fraction of Budget Approved'.

		Annual Utilisation Rate				
		Very Low	Low	Average	High	Very High
Fraction of Budget Approved	Very Low	High Loss	High Loss	Loss	Minimal Change	Gain
	Low	High Loss	Loss	Minimal Change	Gain	High Gain
	Average	Loss	Loss	Minimal Change	Gain	High Gain
	High	Minimal Change	Minimal Change	Gain	High Gain	High Gain
	Very High	Minimal Change	Gain	Gain	High Gain	High Gain

Table IV-B (k). Fuzzy rules for 'Stress on AUV Team' depending on 'Interpersonal Dynamics' and 'Difference Between Expected and Actual Output'.

		Difference Between Expected and Actual Output				
		Very Low	Low	Average	High	Very High
Interpersonal Dynamics	Very Poor	Low	Average	High	Very High	Very High
	Poor	Low	Average	Average	High	Very High
	Average	Very Low	Low	Average	High	High
	High	Very Low	Very Low	Low	Average	High
	Very High	Very Low	Very Low	Low	Average	Average

Table IV-B (l). Fuzzy rules for 'Likelihood of Human Error' depending on 'Average Experience of AUV Team' and 'Risk Perception'.

		Risk Perception				
		Very Poor	Poor	Average	High	Very High
Average Experience of AUV Team	Inexperience	Extreme	High	High	High	Average
	Some Experience	Very High	High	High	Average	Low
	Experienced	High	Average	Average	Low	Low
	Very Experienced	Average	Average	Low	Low	Very Low
	Expert	Low	Low	Low	Very Low	Very Low

Table IV-B (m). Fuzzy rules for ‘Quality Maintenance and Repair’ depending on ‘Average Experience of AUV Team’ and ‘Fraction of Budget Approved’.

		Fraction of Budget Approved				
		Very Low	Low	Average	High	Very High
Average Experience of AUV Team	Inexperience	Very Poor	Poor	Poor	Average	Average
	Some Experience	Very Poor	Poor	Average	Average	High
	Experienced	Poor	Average	Average	High	High
	Very Experienced	Average	Average	High	High	Very High
	Expert	Average	High	High	Very High	Very High

Table IV-B (n). Fuzzy rules for ‘Rate of Effective Ageing’ depending on ‘Quality Maintenance and Repair’ and ‘Annual Utilisation Rate’.

		Annual Utilisation Rate				
		Very Low	Low	Average	High	Very High
Quality Maintenance and Repair	Very Poor	Average	Average	Fast	Very Fast	Very Fast
	Poor	Average	Average	Fast	Fast	Very Fast
	Average	Slow	Slow	Average	Fast	Fast
	High	Very Slow	Slow	Average	Average	Fast
	Very High	Very Slow	Very Slow	Slow	Average	Average

Table IV-B (o). Fuzzy rules for ‘**Reliability of AUV’** depending on ‘**Effective AUV Age’**.

		Reliability of AUV
Effective AUV Age	Infancy	Average
	Early	Very High
	Intermediate	High
	Mature	Average
	Advanced	Low
	Retiring	Low
	Beyond Service Life	Very Low

Table IV-B (p). Fuzzy rules for ‘Risk of AUV Loss in the Antarctic’ depending on ‘Likelihood of Human Error’ and ‘Reliability of AUV’.

		Likelihood of Human Error					
		Very Low	Low	Average	High	Very High	Extreme
Reliability of AUV	Extreme	Moderate	Major	Major	Catastrophic	Catastrophic	Catastrophic
	Very Low	Moderate	Moderate	Major	Major	Catastrophic	Catastrophic
	Low	Minor	Moderate	Moderate	Major	Major	Catastrophic
	Average	Minor	Minor	Moderate	Moderate	Major	Major
	High	Insignificant	Minor	Minor	Moderate	Moderate	Major
	Very High	Insignificant	Insignificant	Minor	Minor	Moderate	Moderate

APPENDIX J: UTAS RISK MATRIX

UNIVERSITY OF TASMANIA RISK MATRIX

LIKELIHOOD SCALE:	
Descriptor	**Description**
Almost certain	The event is expected to occur in most circumstances /commonly repeating / occurs weekly
Likely	The event will probably occur in most circumstances / known to occur / occurs monthly
Possible	The event might occur, say yearly / has a 1 in 20 chance of occurring
Unlikely	The event could occur at some time, say once in every 10 years / say 1 in 100 chance of occurring
Rare	Event may only occur in only exceptional circumstances / less than a 1% chance of occurring

	Consequence				
Likelihood	**Insignificant**	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost Certain	Mod 11	High 13	Ext 20	Ext 23	Ext 25
Likely	Mod 7	High 12	High 17	Ext 21	Ext 24
Possible	Low 4	Mod 8	High 16	Ext 18	Ext 22
Unlikely	Low 2	Low 5	Mod 9	High 15	Ext 19
Rare	Low 1	Low 3	Mod 6	Mod 10	High 14

Risk Level	Authority to Accept Risk / Risk Delegation Level	Notification / Communication Requirements	Formal Recording / Reporting Requirements	Inherent Risk Review and Control Requirements
Extreme	SMT	Audit and Risk Committee of Council	Mandatory to Faculty Risk Register, Business Cases and Project Plans	Reviewed 6 monthly - Controls implemented to reduce residual risk to high or below within 12 months
High	Heads of School / Budget Centres (or Director level and above for a UTAS wide Corporate Governance type risk) or all staff on authorised Job Risk Analysis	Audit and Risk Committee of Council and SMT	Mandatory to Faculty Risk Register, Business Cases and Project Plans	Reviewed 12 mthly - Include consideration of this risk in strategic and capital planning and fiscal strategies
Moderate	Senior Lecturer / Senior Researcher / Manager level or all staff on authorised Job Risk Analysis	SMT Heads of School / Budget Centres (or Director level and above for a UTAS-wide Corporate Governance type risk)	Mandatory to Faculty Risk Register, Business Cases and Project Plans	Controls to be identified and actions to reduce residual risk opportunistically pursued
Low	All staff	Heads of School / Budget Centres (or Director level and above for a UTAS-wide Corporate Governance type risk)	Included in Risk Register	No

Incident / Event / Consequence Level	Authority to sign off incident report, accept investigation report and sign off both response and preventive action	Notification / Communication Requirements	Formal Recording / Reporting Requirements	Investigation Requirements
Catastrophic	Audit and Risk Committee of Council	Audit and Risk Committee of Council and SMT	Yes - mandatory	Formal - including detailed root cause analysis
Major	VC	Audit and Risk Committee of Council SMT	Yes - mandatory	Formal - including detailed root cause analysis
Moderate	SMT	Audit and Risk Committee of Council SMT	Yes - mandatory	Formal - include identification of preventive follow up actions
Minor	Heads of School / Budget Centres (or Director level and above for a UTAS-wide Corporate Governance type risk)	Faculty Dean / Executive Director	Yes - mandatory	Formal - include identification of preventive follow-up actions
Insignificant	All staff (or Manager level and above for a UTAS-wide Corporate Governance type risk)	Heads of School / Budget Centres (or Director level and above for a UTAS-wide Corporate Governance type risk)	Yes - mandatory	Informal

Consequence Scale							
Descriptor		Description					
		Financial, Legal, Commercial	HR, OHS	Service Quality, Operations, Business Interruption and	Political, Reputation and Image	Environmental and Community	Project
	Insignificant	Up to $5000 for Faculties, Institutes, Schools, Centres, Divisions & Sections (Up to $500K for a UTAS wide corporate governance risk) or 0.5% of budget Unlikely to result in adverse regulatory response or action.	Injury report and/or first aid only, and/ or may include substantial stress event reducing work effectiveness without lost time	An event the impact of which can easily be absorbed through normal activity. Repeat theme complaints at a school level and / or one or more registered formal complaints. Up to 10 recommendations from accreditation / licensing body. Loss of <1 days lectures or research or other operational activity or work from such activity. Negligible impact business interruption, brief loss of	Issue resolved promptly by day to day management processes/Little or no stakeholder interest	Brief pollution - no discernable impact or measurable impairment - for example, not exceeding published guideline values for "normal" or "background" levels. Internally reported. Environmental liability or remediation cost < $A5,000.	Small potential for cost impacts - 0.5% of budget, no time impact, no quality impact. There may issues that impact on the ability of the University to fully operate services or activities proposed for the building at time of delivery
	Minor	$5,001 to $50,000 for Faculties, Institutes, Schools, Centres, Divisions & Sections, ($.5m to $2.5m for a UTAS wide corporate governance risk) or 0.5-1% of budget Minor non - compliances & breaches of Acts, regulations or consent conditions. Not likely to result in regulatory action, may result in infringement notice. Incident reportable to regulatory authorities.	Medical Treatment Injury and/ or may include substantial stress event requiring professional clinical support	An event, the consequences of which can be absorbed but management effort is required to minimise impact. Minor delivery delays. Service issue causing / contributing to loss of up to 10 EFSLs or loss of research or consultancy project < $10,000 Up to 2 non-compliance recommendations but accreditation / license not immediately threatened. Loss of 1-5 days lectures or research or other	Issue raised by students and/or local press/ Minor, adverse local public or media attention & complaints. Reputation is adversely affected with a small number of affected people	Transient harm - Minor effects on biological or physical environment. Minor short- medium term damage to a localised area or that ceases once the event is over. Environmental liability or remediation cost $A5,000 - 50,000.	Small potential for cost impacts - 0.5- 1% of budget, no time impact, no quality impact. There may issues that impact on the ability of the University to fully operate services or activities proposed for the building at time of delivery
	Moderate	$50K-$0.5m for Faculties, Institutes, Schools, Centres, Divisions & Sections, ($2.5m to $10m for a UTAS wide corporate governance risk) or 1-5% of budget Serious breach of Act, regulation or consent conditions with potential for regulatory action such as issuance of a formal notice, a fine or prosecution.	Hospital treatment injury less than 3 days / lost time / serious temporary disability/ minor permanent disability	Significant event , which can be managed under special circumstances. Service issue causing / contributing to loss of 10-100 EFSLs,or loss of research or consultancy project ($10,000- $500,000). More than 2 non-compliance recommendations and /or ongoing accreditation & licensing under immediate threat Loss of 5 days - 6 weeks lectures or research or other operational activity or work	Student and or community concern, heavy local media coverage/ Criticism by NGOs. Reputation impacted with some stakeholders.	Moderate harm- Measurable impairment on biological or physical environment but not affecting ecosystem function. Short- medium term impacts, where the ecosystem will recover quickly & without intervention. Environmental liability or remediation cost $A50,000-500,000.	Medium potential for cost or time impact. 1-5% of budget, manageable impact on time, cost, resources and quality. Minimal impact on operation of services or activities proposed for the building
	Major	$0.5m to $5m for Faculties, Institutes, Schools, Centres, Divisions & Sections ($10m to $20m for a UTAS wide corporate governance risk) or 5-10% of budget Major breach of Act, regulations, or consent conditions that is expected to attract regulatory attention. Investigation prosecution and / or major fine possible.	Single death/ longer term hospitalisation/ permanent disabilities multiple persons	Major event that with prioritised and focused management will be endured. Service issue causing /contributing to loss of more than 100 EFSLs / subject viability threatened or loss of some research & consultancy clients. Limited accreditation of Faculty or School with conditions of accreditation & limitations applied. Loss of 6 -13 weeks lectures or research or other operational activity or work from such activity.	Embarrassment for the University, including adverse media coverage/ Significant adverse national media / public coverage/ reputation impacted with a significant number of stakeholders/ Breakdown in strategic & or business partnership	Significant harm - Serious environmental effects with some impairment of ecosystem function relatively widespread medium - long term impacts, requiring remediation, where ecosystem will recover over time once clean up has been completed. Environmental liability or remediation cost $A0.5m - $A5m	Major potential for cost or time impact. 5-10% of budget, will impact on time, cost, resources or quality. Potential impact on multiple work streams, projects or stakeholders. University will need to operate service or activity in another location for an extended period of time or delay commencement of service or activity for > 3months or Practical Completion Date increased by > 25%.

Catastrophic	Above $5m for Faculties, Institutes, Schools, Centres, Divisions & Sections (or Above $20m for a UTAS wide corporate governance type risk) or 10% of budget May be considered ' willful' or 'negligent' by regulator. Significant prosecution & fines likely. May result in significant litigation, including class actions. May jeopardise future approvals, registration, licensing & funding.	Multiple deaths/ permanent disability 5 plus persons	Extreme event with potential to lead to failure of most objectives or collapse of part of the business. School viability threatened by loss /lack of students or loss of a significant number of research or consultancy clients (more than 10% of budget or 5 clients). Non-accreditation of Faculty or School. Loss of 13+ weeks lectures or research or other operational activity or work from such activity Critical infrastructure service loss for > 1 month	Reputation and standing of the University affected nationally and internationally/ Serious public or media outcry (International coverage)/ Reputation impacted with majority of key stakeholders/ Significant breakdown in strategic & or business partnerships	Long term harm - Very serious environmental effects with significant impairment of ecosystem function. Long term, widespread effects. Remediation required. Environmental liability or remediation cost >$A5m	Major potential for cost or time impact - >10% of budget. Will have an unmanageable impact on time, cost, resources and quality. Potential impact on multiple work streams, projects or stakeholders. University cannot operate service or activity proposed in new/refurbished building. Potential showstopper.

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