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Paper:

A Hybrid Fuzzy System Dynamics Approach for Risk Analysis of AUV Operations

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The maturing of autonomous technology has fostered a rapid expansion in the use of Autonomous Underwater Vehicles (AUVs). To prevent the loss of AUVs during deployments, existing risk analysis approaches tend to focus on technicalities, historical data and experts' opinion for probability quantification. However, data may not always be available and the complex interrelationships between risk factors are often neglected due to uncertainties. To overcome these shortfalls, a hybrid fuzzy system dynamics risk analysis (*FuSDRA*) is proposed. The approach utilises the strengths while overcoming limitations of both system dynamics and fuzzy set theory. Presented as a three-step iterative framework, the approach was applied on a case study to examine the impact of crew operating experience on the risk of AUV loss. Results showed not only that initial experience of the team affects the risk of loss, but any loss of experience in earlier stages of the AUV program have a lesser impact as compared to later stages. A series of risk control policies were recommended based on the results. The case study demonstrated how the *FuSDRA* approach can be applied to inform human resource and risk management strategies, or broader application within the AUV domain and other complex technological systems.

Keywords: autonomous underwater vehicle, hybrid system dynamics, fuzzy set theory, risk analysis

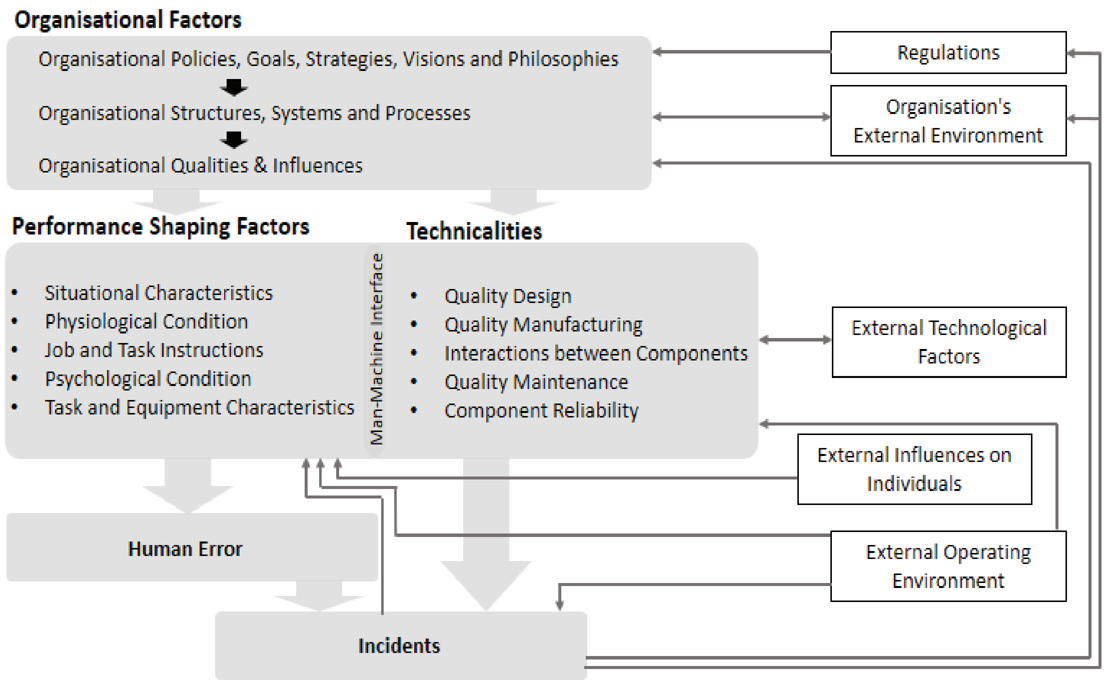
1. Introduction

1.1. Autonomous Underwater Vehicle

The autonomous underwater vehicle (AUV) is best described as self-powered robotic device that operates underwater. Commonly shaped like a torpedo, it is untethered and is 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 in scientific, commercial and military domains. The commercialization of AUVs in recent years has fostered a rapid expansion in AUV types, capabilities, and the use of multi-AUVs [1]. Consequently, analysing the risk of deployment becomes increasingly challenging, with the need for tailoring the analysis to both organisational requirements and specific AUV capabilities.

1.2. Risk Analysis of AUV Deployment

Since the first AUV was developed, there has been significant progress in risk analyses methods to better control the risk of AUV loss. Losing an AUV is not only financially costly, but it can also delay projects, damage reputation of the AUV community, cause the loss of valuable data and has a possibility of harming the environment. Therefore, many aspects of an AUV deployment had been examined in parts, both spatially and temporally, in an attempt to control the risk of loss. Most risk analysis approaches focused on technical aspects of AUVs to improve robustness and reliabilities in areas such as the mission management software, navigation system, collision avoidance system, emergency abort system, power system, homing system, and communication system [2–11]. As AUV technology gradually made the transition from research and development to operations, proactive and systematic risk analysis approaches based primarily on historical performance data of the AUV [12–14] emerge. Also with improvement in technical reliability, risk analysis of AUV operations gradually broadens to other operating uncertainties and phases of deployment [15–17]. This broadening scope of risk analysis meant that there



Arrow indicates certain degree of influence

Fig. 1. Generic risk structure influencing the risk of AUV loss with some taxonomies adapted from [25, 26].

is a need for reduced dependency on a vehicle's performance data, as relevant data may not always be available. Especially during the early phases of an AUV program or for an AUV which is relatively new in operation [18]. In addition, recent risk studies have also begun to recognise the importance of organisational and human factors in the risk analysis of AUV deployments [19–24]. However, existing analysis to predict the risk of AUV loss remains heavily dependent on historical performance data and expert's opinion.

1.3. Areas for Improvements

To develop a more comprehensive and effective risk analysis framework for AUV deployments, two areas for improvement were identified. First, the time-dependent nature of risks and the complex interrelationships between risk factors of an AUV program needs to be examined collectively as a whole. This includes the synergistic combination of technical system(s), people associated with the AUV program, operating environment, work activities, organisational factors as well as external influences (**Fig. 1**). Consider an analysis focusing solely on a single risk factor such as operating experience of the AUV team. With the availability of relevant data, it would be intuitive and statistically straightforward to investigate the inverse relationship between operating experience and the risk of loss (**Fig. 2A**). However, the inclusion of other risk factors complicates risk analysis (**Fig. 2B**). The uncertain inter-relationships between these risk factors, unclear degree of causality, difficulty in quantification and their dynamic behaviour resulted in an unknown combined effect on the risk of AUV loss. Consequently, these complex interrelationships between risk factors, although critical, are often neglected in existing risk analysis approaches. This leads to the second identified area for improvement, which is to reduce dependency on historical performance data by accounting for vagueness and ambiguity in the elicitation of expert's opinion. This paper presents the application of a hybrid fuzzy system-dynamics risk analysis approach to address these two identified areas of improvements.

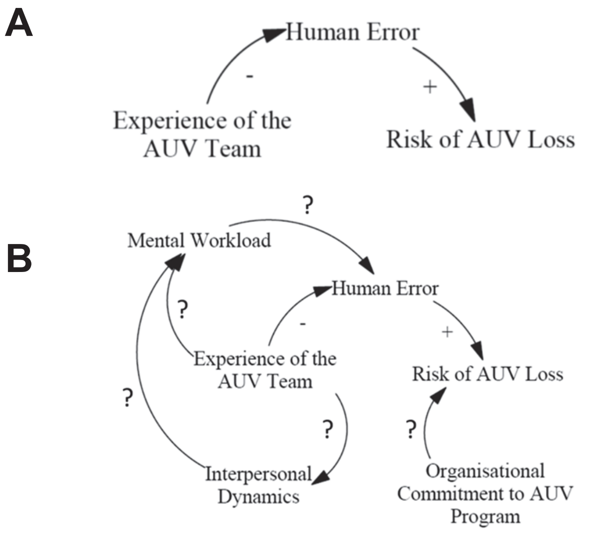


Fig. 2. **A**: An analysis focusing solely on experience of the AUV team. **B**: A more complex analysis involving additional risk factors with uncertain inter-relationships and unclear degree of causality.

1.4. Fuzzy System Dynamics

System dynamics is an objective-oriented deterministic approach used to study the behaviour of complex systems. The dynamic nature of risk and interrelationships between risk variables influencing the risk of AUV loss can be effectively modelled using system dynamics. However, uncertainties [27] may not be explicitly taken into account by deterministic system dynamic models (**Fig. 2B**). To overcome this limitation, fuzzy logic is integrated with system dynamics. The result is a hybrid *FuSDRA* approach which utilises the strengths while overcoming limitations of both system dynamics and fuzzy set theory. The *FuSDRA* approach, presented as a framework in this paper, provides a structured, robust, and effective solution for risk analysis of AUV deployment. Application of the approach can facilitate risk control policy recommendations which are expected to be more reliable and effective than those put forward by existing risk analysis approaches.

The hybrid *FuSDRA* approach was first proposed in the AUV domain with a simple application aimed at demonstrating its potential use [28]. In a more specific application, the *FuSDRA* approach was used to analyze how reducing government support and increasing technological obsolescence can impact the risk of AUV loss [29]. There is a paucity of literature on its application in other areas. Mostafa et al. [30] applied fuzzy system dynamics for the analysis of risks and uncertainties affecting build-operate-transfer infrastructure projects. Farnad et al. [31] used fuzzy system dynamics models to simulate different risk allocation strategies in construction projects. Michael and Charles [32] demonstrated how manpower recruitment and training strategies can be modelled using fuzzy system dynamics. Notably, the authors emphasised that the approach has the ability to solve real-world manpower planning problems and help organisations design more effective manpower management strategies.

The objective of this paper is to apply the *FuSDRA* approach for an in-depth analysis on the relationship between an AUV team's experience and the risk of loss. To our best knowledge, the *FuSDRA* approach has never been used in the analysis of human factors. Section 2 presents a brief overview of the *FuSDRA* approach. Section 3 presents the analysis. Section 4 discusses the benefits, limitations and scope for future work. Lastly, Section 5 concludes the paper.

2. Methodology

The proposed *FuSDRA* approach follows a three-stage iterative framework adapted from the generic risk analysis process widely used in international standards such as ISO31000 (Risk Management) [33] and ISO45001 (Occupational Health and Safety) [34]. An overview of the framework is presented in **Fig. 3**.

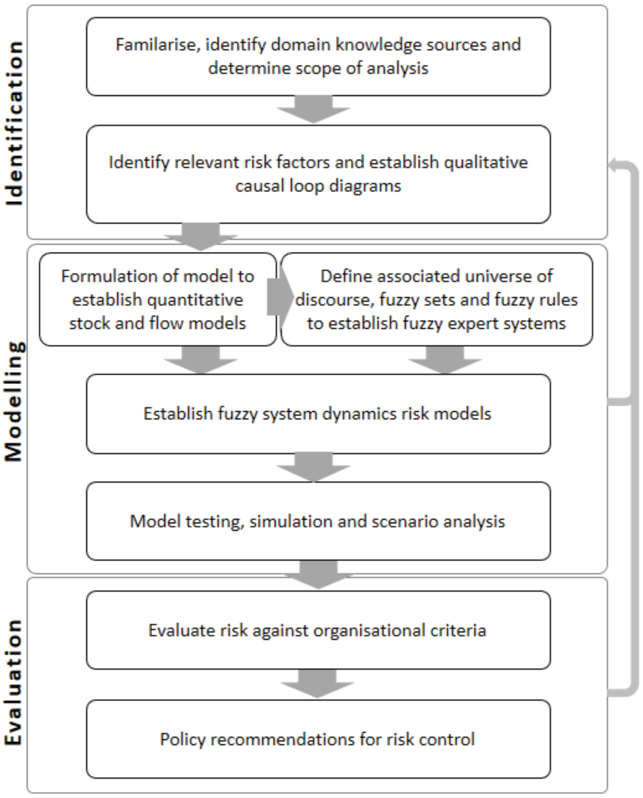


Fig. 3. An overview of the *FuSDRA* framework.

2.1. Identification

The identification stage aims to gain familiarity with the AUV program, determine domain knowledge sources, identify risk factors, and establish causal relationships. Domain knowledge sources can include both experts' opinion and documentation such as safe work procedures, technical specifications of the AUV, fault logs, and risk assessment records. Tapping into these domain knowledge sources, risk factors are identified. Causal relationships between the identified risk factors are then established and represented in a qualitative causal loop diagram (CLD), similar to the those presented in **Fig. 2**.

2.2. Modelling

The modelling phase aims to quantify the risk of loss through parameters' estimation, formulation of causal relationships and establishing initial conditions. Consider a system dynamics stock and flow diagram (**Fig. 4**), which is developed from a causal loop diagram.

The stock variable *'Average Experience of AUV Team'* (*Exp*) changes via flow variables *'Experience Gain'* and *'Experience Loss'* which are influenced by parameters *'Gain Rate'* (*GR*) and *'Loss Rate'* (*LR*). The corresponding integral equation of the model up to this point can be written as:

$$Exp(t) = Exp_0 + \int_0^t (GR - LR) \times Exp(t) \times dt. \qquad (1)$$

Experience is a function of time, where $Exp(t)$ stands

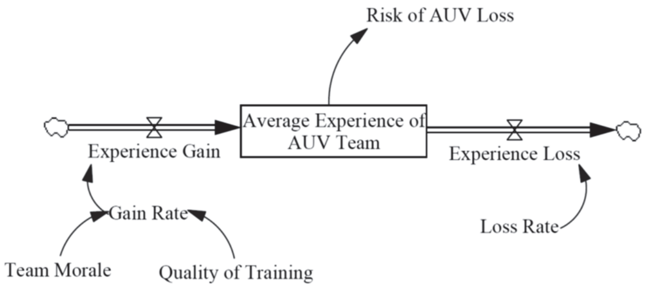


Fig. 4. An example of stock and flow diagram to be modelled with fuzzy system dynamics.

Table 1. An example of the universe of discourse, fuzzy sets and triangular membership function for the risk factor *'Average Experience of AUV Team.'*

Risk factor	**Universe of discourse (units)**	**Fuzzy sets**	**Membership function**		
			Min	**Most likely**	**Max**
Average experience of AUV Team	0–50, in practice usually ranges from 0–10 (years)	Low	0	0	5
		Average	0	5	10
		High	5	10	10

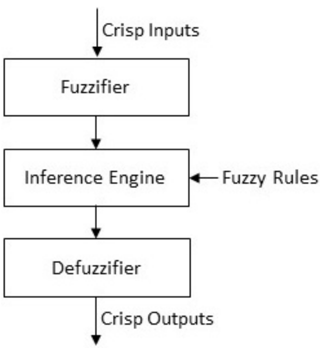


Fig. 5. The generic architecture of a fuzzy expert system adapted from Mendel [35].

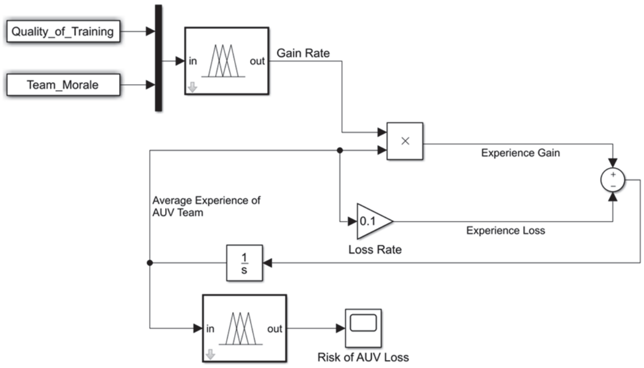


Fig. 6. Corresponding fuzzy system dynamics block diagram of **Fig. 4**.

for experience as function of time and Exp_0 stands for experience at the start of the process. It is calculated by taking into account the experience at the start of the program and the change due to loss and gain rates.

Hypothetically, the experience gain rate is further influenced by *'Quality of Training'* and *'Team Morale.'* The average experience of the team also impacts the *'Risk of AUV Loss.'* However, these causal relationships are harder to quantify deterministically due to uncertainty in the causal relationship. To overcome this, fuzzy logic is applied via a fuzzy expert system (**Fig. 5**), established through elicitation of expert's opinion. This involves determining the universe of discourse, defining fuzzy sets and membership functions, and constructing fuzzy rules [35]. To define these, experts' opinion can be elicited using matrices. An example of the universe of discourse, fuzzy sets and membership functions for *'Average Experience of AUV Team'* is shown in **Table 1**.

For intuitive elicitation of fuzzy rules, a hypercube matrix can be used. A hypercube is a geometric shape of *n*-dimensions, determined by the number of input risk factors [36]. 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.

The fuzzy rules are elicited in the form of IF-THEN rules such as:

IF Quality of Training is 'Poor'
AND Team Morale is 'Low'
THEN Experience Gain Rate is 'Low'

Defuzzification then translates 'Low' into a quantifiable level to be input back into the system dynamics model. There are several defuzzification methods [37, 38] 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 [39].

The fuzzy expert systems are integrated with the system dynamics models to construct the hybrid fuzzy system dynamics risk models using block diagrams. An example of the *FuSDRA* model based on **Fig. 4** is shown in **Fig. 6**. In the example, two fuzzy logic blocks represent the uncertain causal relationships in the stock and flow diagram. There is also an integrator block which outputs the integral of its input based on Eq. (2):

$$y(t) = \int_0^t u(t)\,dt + y_o, \quad \dots\dots\dots\dots \quad (2)$$

where y is the output at simulation time t with input u and initial condition y_o.

The *FuSDRA* models are subsequently tested, reviewed and calibrated before performing simulation and scenario analysis. The output is a set of systemic behaviour influencing the risk of AUV loss.

2.3. Evaluation

To evaluate the risk of loss, results from scenario analysis and simulation of the *FuSDRA* models are examined and compared against a pre-determined organisational evaluation criterion. For example, the acceptable probability of AUV loss based on the capital and operating cost of the AUV [12]. Insights gained through the risk analysis process and simulation of the risk models can be used for formulation of risk control policies. Lastly, regular review of the *FuSDRA* models is required to ensure relevancy and long-term sustainability.

2.4. Software

Two software was used for the construction of *FuSDRA* models presented in this paper. Vensim® [40] was chosen for system dynamics modelling due to its user-friendly interface, dimensional checks and visual clarity. MATLAB® fuzzy logic toolbox 2017 [41] was used to develop fuzzy expert systems. This tool provides a comprehensive and user-friendly environment to build and evaluate fuzzy systems. To construct the *FuSDRA* models, System dynamics models from Vensim® were converted into block diagrams with the MATLAB® Simulink toolbox 2018 [42]. This tool allows for the construction of mathematically complex systems involving many risk factors. More importantly, it enables the integration of fuzzy expert systems from MATLAB® fuzzy logic toolbox 2017 [41] in the system dynamics models with relative ease.

3. Case Study

3.1. Overview

To demonstrate application of the hybrid *FuSDRA* approach, a case study based on the *nupiri muka* AUV program is presented. Funded by the Antarctic Gateway Partnership and the University of Tasmania (UTAS), the primary objective of the *nupiri muka* AUV program is to acquire high-resolution data under sea ice and ice shelves in Antarctic regions for marine scientific research. Delivered in May 2017, the *nupiri muka* AUV is relatively new at the time of writing, with very limited historical performance data for meaningful probabilistic risk quantification. The high level of uncertainty makes the *FuSDRA* approach highly suitable to analyse the risk of AUV loss.

One of the main risk factors identified was the lack of operating experience. The following quote was taken from one of the interviews:

> *"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 evens the odds a little bit more."*

Therefore, the *FuSDRA* approach is applied to examine the impact of crew experience on the risk of AUV loss.

3.2. FuSDRA – Identification

The scope of analysis focuses on the operating experience of the AUV team. This includes factors associated with the performance of the AUV team, UTAS's policies, processes and *systems*, and relevant external influences. The time horizon for the analysis is set at 10 years, the pre-determined target service life of the AUV.

For the most part, the task of familiarization and establishing domain knowledge sources were conducted concurrently. Relevant information on the risk of AUV loss was found to be scattered throughout various organisational documents such as UTAS's risk management policy and framework, standard operating procedure, risk assessment records, fault log, insurance policy, business case for procurement of AUV, budget plans and meeting minutes. Additionally, documents provided by the AUV manufacturer (ISE Ltd.) also contained invaluable information for identifying risk factors and causal structures. These included 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, to calibrate the risk models and complement the interviews of domain experts. Additionally, several books and journal articles were used to identify possible risk factors and their causal structure. This included the recommended code of practice on the operation of AUVs [43], risk research articles, such as those from the *Autosub* AUV program [13, 15, 16, 44–47], as well as others which had been referenced in Section 1.2.

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

a. Implementing control measures based on the results of the 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

The interviews, carried out through both unstructured and semi-structured format, went through several iterations. Early interviews focused on identifying risk factors relating to operating experience and causal relationships while later sessions focused on establishing fuzzy rules used to define model behaviour. 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 those who are interviewed. In total, the interview sessions generated close to 100 pages of interview transcripts, minutes and observation notes. Additionally, a research journal was kept to document both verbal and non-verbal responses of interviewees to check for signs of bias or heuristics.

Through the domain knowledge sources, a causal loop diagram which consists of four main subsystems, directly and indirectly, influencing the risk of AUV loss was established. **Fig. 7** shows the overview of the subsystems and their interrelatedness, with the arrows indicating causation relationships.

Experience of the AUV team falls under the human reliability subsystem, which captures the contribution of human error to the risk of loss, including possible underlying causes of these errors. The interactions between the four subsystems, risk of AUV loss and external influences resulted in a causal loop diagram which is presented in **Fig. 8**. The dotted boxes broadly marked the four main subsystems and their associated risk factors.

3.3. FuSDRA – Modelling

3.3.1. Establishing FuSDRA Models

To construct the *FuSDRA* model, formulations, definitions and initial conditions must be set in the system dynamics model. Such information was sought primarily from interviews and supported by other identified domain knowledge sources. Example of some parameters used relating to operating experience are presented in **Table 2**. Uncertain causal relationships were represented through the application of fuzzy logic using fuzzy expert systems, with an example of fuzzy rule base consisting of crew experience presented in **Table 3**.

The fuzzy expert systems were subsequently incorporated into the system dynamics model with the resultant *FuSDRA* model shown in **Fig. 9**.

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

3.3.2. Model Testing

To build confidence in the developed *FuSDRA* model, three main approaches were taken. First, local knowledge and historical data were used to calibrate the model. Second, a series of tests mostly adapted from [48] were undertaken to uncover model errors and areas for improvement. Last, results from scenario analysis were discussed and compared with domain experts' opinion.

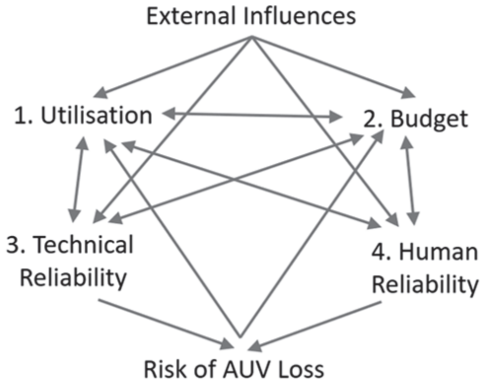


Fig. 7. Overview of the causal loop diagram for the *nupiri muka* AUV program.

With a focus on experience of the AUV team, a "one-at-a-time" [49] univariate analyses were performed on the risk factor 'initial average experience of AUV team.' Different input values ranging from 0.5 to 2 years were used for 'initial average experience of AUV team' to examine the effect on risk of AUV loss. The simulation results are presented in **Fig. 10** and **Table 4**.

The simulation results showed apparent differences in the 'risk of AUV loss' with varying '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. 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 years and 1 year is notably higher than that of 1.5 years and 2 years. There is also a significant difference in risk of loss right at the start of the AUV program between an AUV team of initial average experience of 0.5 years to 1.5 years and 2 years. Additionally, the simulations showed a surprising behaviour between 6.5 and 8.5 years into the program, with the plateauing of risk level. This is the period where both technical reliability of the AUV and human reliability remains relatively stable in the mature AUV program.

Simulation results from this analysis 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.

3.3.3. 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,

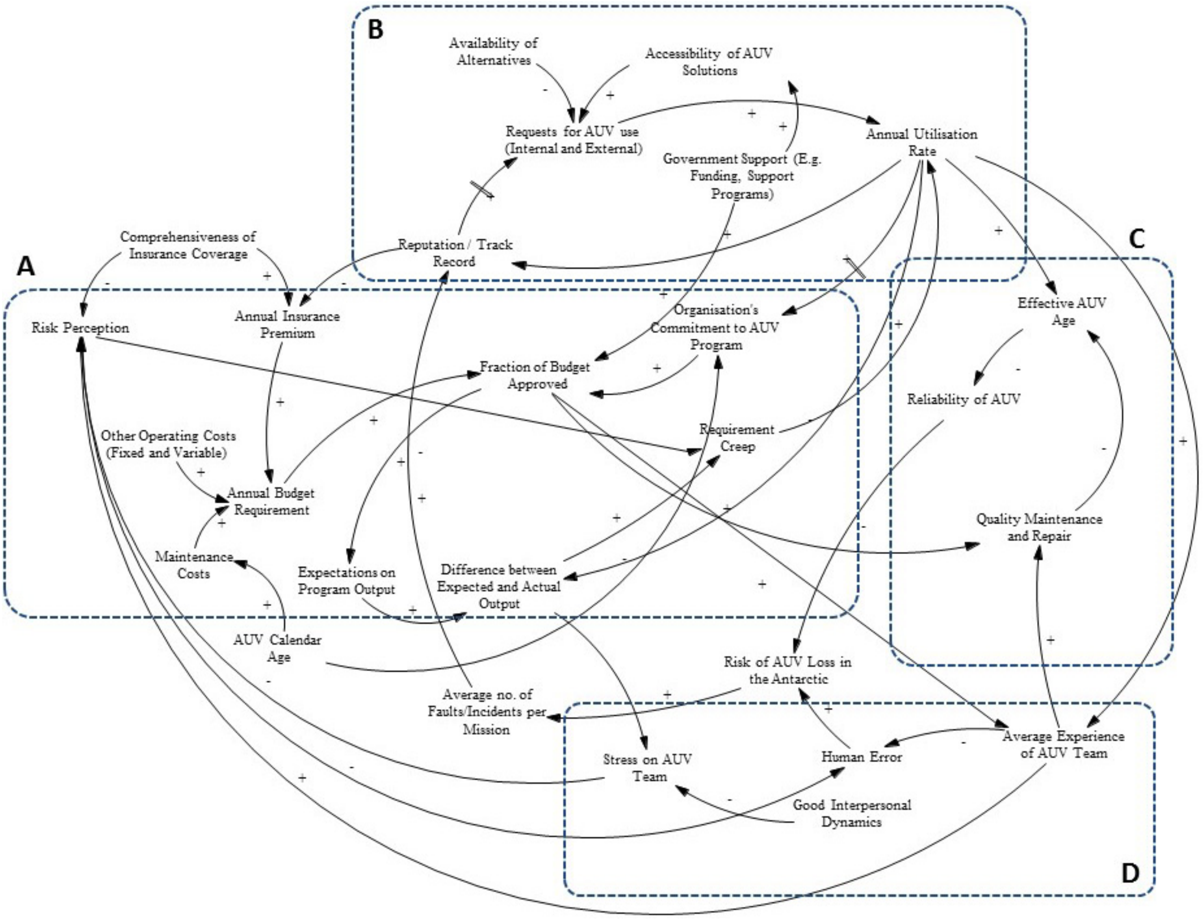


Fig. 8. Overview of the causal structure relating to risk of AUV loss for the *nupiri muka* AUV program, categorised broadly into four sub-models – **A**: Budget, **B**: Utilisation, **C**: Technical reliability, **D**: Human reliability.

Table 2. Example of some parameters used in the human reliability sub-model.

Risk factor	**Definition**	**Equation**
Change in average experience of AUV Team	The amount of experience gained or lost due to turnover, recruitment policies or hands-on experience.	*Function of* (Fraction of Budget Approved) and (Annual Utilisation Rate) Fuzzy Logic[1]
Average experience of AUV Team	Average experience of the primary AUV team in AUV operations.	INTEG (Change in Average Experience of AUV Team) Initial value = 1
Quality maintenance and repair	The level of quality maintenance and repair, including both reactive and preventive maintenance.	*Function of* (Average Experience of AUV Team) and (Fraction of Budget Approved) Fuzzy Logic[1]
Risk of AUV Loss	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]

[1] Represents the 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 inputs from domain experts in the form of fuzzy rule bases.

Table 3. An example of fuzzy rule base for the output 'Likelihood of Human Error.' The output variable "Likelihood of Human Error" is given against the input variables "Average Experience of the AUV Team" and "Risk Perception."

		Risk perception				
		Very poor	Poor	Ave	High	Very high
Average experience of AUV Team	Inexperience	Extreme	High	High	High	Ave
	Some experience	Very high	High	High	Ave	Low
	Average experience	High	Ave	Ave	Low	Low
	Very experienced	Ave	Ave	Low	Low	Very low
	Expert	Low	Low	Low	Very low	Very low

the choice of scenarios for analysis was based primarily on the operating experience of the AUV team. Here, the impact of experience loss due to turnover of the facility manager was examined. This concern was raised by several interviewees who highlighted strong reliance on the facility manager for the current *nupiri muka* AUV program. The following quote was taken from another one of the interviews:

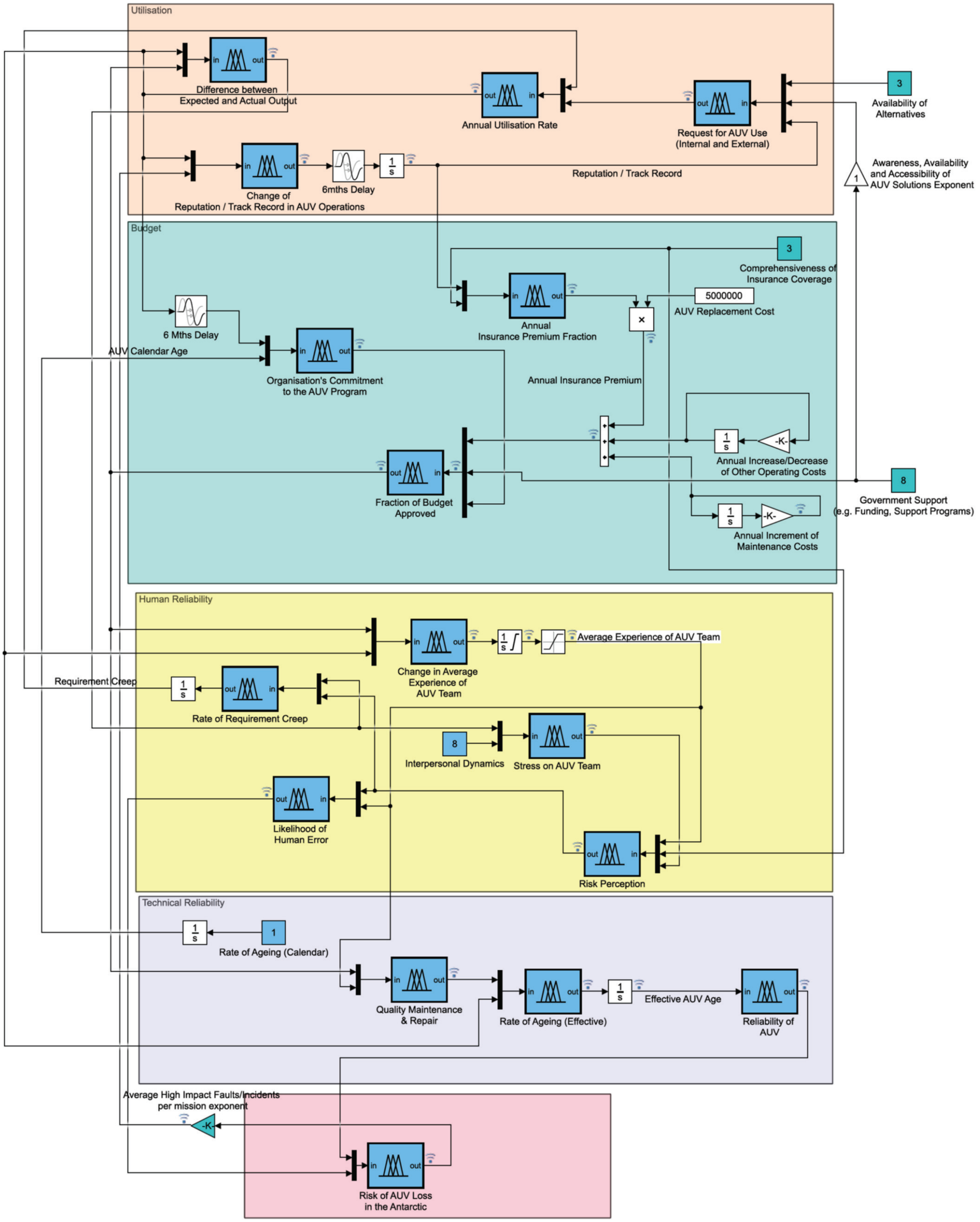


Fig. 9. The resultant *FuSDRA* model, categorised into four sub-models.

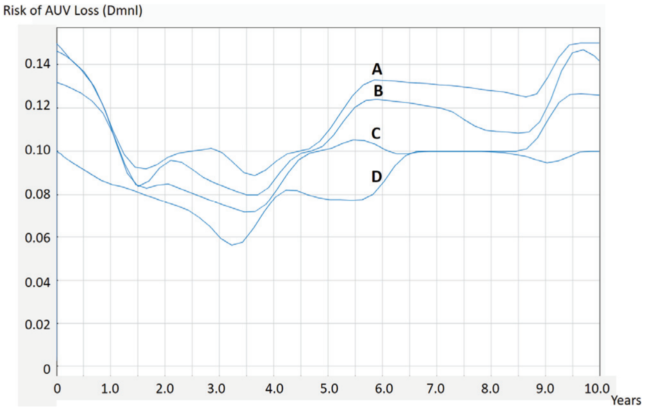


Fig. 10. Risk of AUV loss for different 'Initial average experience of AUV team.' **A**: 0.5 yrs, **B**: 1 yr, **C**: 1.5 yrs, **D**: 2 yrs.

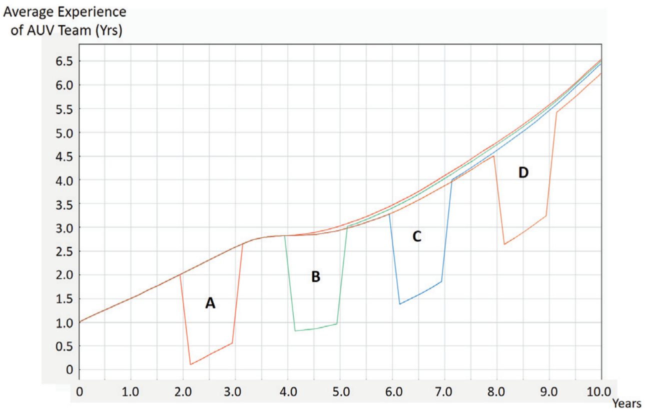


Fig. 11. The 'average experience of AUV team,' with an 1 yr replacement period for the departed facility manager at different time points of the AUV program. **A**: 2 yrs, **B**: 4 yrs, **C**: 6 yrs, **D**: 8 yrs.

Table 4. 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

> *"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?"*

To simulate the turnover 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. A hiring period of one year was subsequently applied in the model to simulate the recruitment of a replacement with similar experience level. The results are shown in **Figs. 11** and **12**.

Figure 11 shows the 'troughs' in 'average experience of AUV team' with the turnover of the facility manager at different point of the AUV program. **Fig. 12** 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). It is very conceivable 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 higher maintenance activities and budgetary constraints.

3.4. FuSDRA – Evaluation

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 (**Fig. 13**), 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 evaluated to be ⟨ Extreme ⟩, as circled in **Fig. 13**.

To reduce the risk of loss, a set of effective control measures are required. Simulation results from both the sensitivity analysis (**Fig. 10**) and scenario analysis suggested that 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 AUV program because of his relevant and extensive polar AUV experience. The following recommendations are therefore offered with the aim of retaining experienced employee, secure any replacement in a shorter period, and promote an effective knowledge transfer process.

With the program currently 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

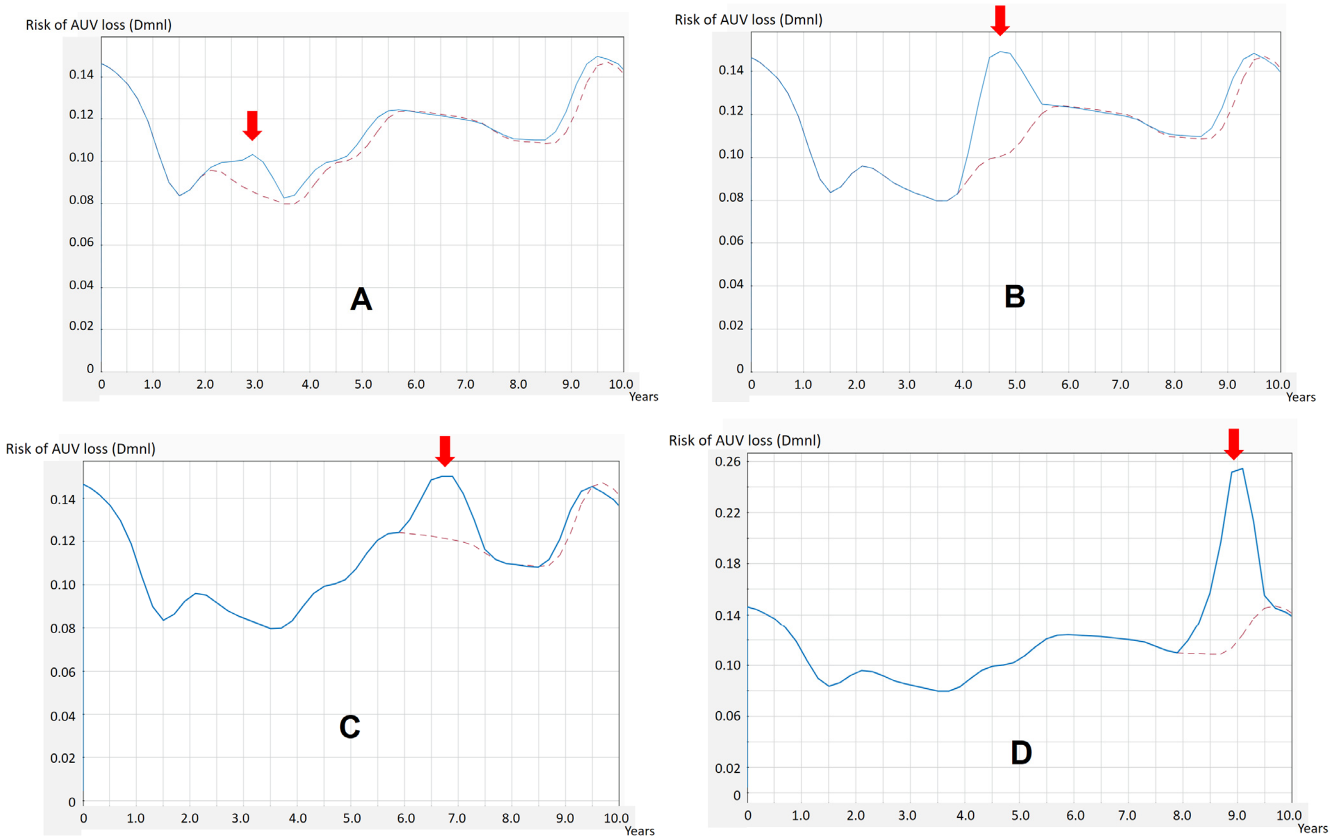
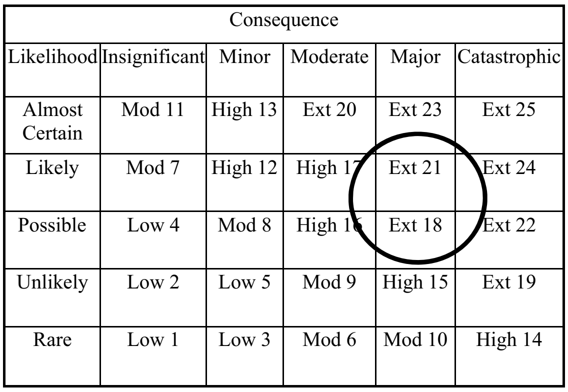


Fig. 12. Impact on 'risk of AUV loss' (arrow) as compared to the base scenario (dotted) with an 1 yr replacement period for the departed facility manager at different time points of the AUV program. **A**: 2 yrs, **B**: 4 yrs, **C**: 6 yrs, **D**: 8 yrs.



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

Fig. 13. Risk evaluation based on UTAS's semi-quantitative risk matrix.

contractual arrangement into a permanent role, under the condition that the facility manager is found to be suitable for the job. As the simulation results show, 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 the hiring time and achieve a lower risk of loss (**Fig. 11**), 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 (**Fig. 10**). 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, work shadowing, knowledge repository or rotational assignments. It is also critical to evaluate and measure the effectiveness of the knowledge transfer regularly to identify gaps and make improvements 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.

4. Discussion and Limitations

In the case study, the *FuSDRA* approach was applied to examine the impact of AUV team's experience on the risk of loss. When compared to common probabilistic risk analysis approaches, the *FuSDRA* approach showed more robust results by considering a wide range of risk factors. It can, therefore, enable the AUV owner to anticipate, respond and adapt human resource strategies to differing circumstances. 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 of the overall system of the AUV program. The 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.

Despite the advantages of the *FuSDRA* approach in analyzing risk of AUV loss, several challenges were encountered. First, the model building required the use of multiple software, namely Vensim® [40] for system dynamics modelling, MATLAB® fuzzy logic toolbox 2017 [41] for developing fuzzy expert systems, and MATLAB® Simulink toolbox 2018 [42] to construct the final *FuSDRA* risk model. The lack of an all-inclusive multifunctional software can impede the extensive use of *FuSDRA* in real-world systems. Therefore, commercial quality software should be developed to facilitate the three-stage iterative *FuSDRA* process. The second challenge encountered in application of the *FuSDRA* framework lies in the elicitation of fuzzy rules. Domain experts may have incomplete and episodic knowledge from their experience, causing incorrect or incomplete fuzzy rule bases. These experts may also hold different assumptions, resulting in inconsistent or conflicting opinions. Therefore, the elicitation of fuzzy rules can be improved by considering varying degrees of trust in the domain experts, such as using intuitionistic fuzzy logic. Lastly, the inability of the *FuSDRA* model to self-learn means that regular review of fuzzy rules is required to ensure relevance. This can be carried out through optimisation methods such as a genetic algorithm, neural networks or simulated annealing among others.

It is believed that the generic nature of the *FuSDRA* approach will be useful to different types of AUV operations. However, differing organisational needs and vehicle characteristics can result in a wide variety of risk factors. This implies that it is crucial to tailor the *FuSDRA* approach according to the identified problem and context, with potentially vastly differing results from the presented case study.

5. Conclusion

Effective management of the risk in AUV deployments is a challenge characterised with dynamic, fuzzy risk factors and their complex interrelationships. Existing risk analysis approaches tend to focus more on technicalities of the AUV and depended heavily on historical data for statistical analysis or experts' opinion for probability quantification. However, data may not always be available and the complex interrelationships between risk factors are often neglected due to uncertainties. It is under such dynamic, complex and fuzzy situations that the AUV owner often has to devise risk control measures and make difficult deployment decisions. Therefore, the formulation of effective risk control policies requires a new analysis tool which addresses these shortcomings. The *FuSDRA* approach is proposed here as a solution. Leveraging on the strengths of both fuzzy logic and system dynamics, *FuSDRA* enables the dynamic inter-relationships between risk factors from different dimensions to be modelled, furthermore account for vagueness and ambiguity. 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.

To demonstrate application of the proposed *FuSDRA* approach, a case study based on the *nupiri muka* AUV program, managed by UTAS was presented. A risk model was constructed and simulated to examine the impact of operating experience on the risk of AUV loss. Results showed that experience of the team plays a critical role in influencing the risk of AUV loss. It is, therefore, recommended that UTAS optimises 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. In particular, measures should be considered for the facility manager to improve his or her retention in later stages of the AUV program (>4 years), such as providing the option to convert contractual arrangement into a permanent role.

The *FuSDRA* methodological framework was created based on AUV operations. However, it is believed that the generic nature of the approach will be useful for managing risks of other complex technological systems similar to that of the AUV. For instances, in 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. Further advancement of this work to enhance the *FuSDRA* approach can focus on the development of an all-inclusive multifunctional software, improving the elicitation of fuzzy rules by considering varying degrees of trust in the domain experts and means of self-learning to ensure long-term relevancy of fuzzy rules.

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