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Highlights

- Mapping of Arctic and North Atlantic Maritime Safety and Security needs
- Classification of research and innovations needs by the PICK methodology
- Design of a goal programme to selected a balanced priority set of research needs
- Recommendations for a balanced research and innovation priority agenda are given

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Abstract

This paper details a methodology for the mapping and prioritization of needs for research and innovation across a multi-disciplinary topic area. The methodology is applied to needs arising from the field of Arctic maritime safety and security, in order to provide a roadmap for an ongoing multi-national European Union (EU) funded research project. A needs hierarchy containing topics, needs and sub-needs is first formed by utilization of multiple sources including facilitated stakeholder workshops, literature review and semi-structured questionnaires. A further round of stakeholder opinion is then sought in order to ascertain the importance and level of challenge involved in solving each identified sub-need. This information is utilized to form a PICK (Possible, Implement, Challenge, Keep Back) chart in order to visualize and categorize the sub-needs. A goal programming knapsack model is formulated to select a set of priority needs that satisfy goals relating to the maximization of overall importance, the balance between topics at the first level of the need hierarchy and the balance between more challenge (for longer term research) and implement (for shorter term implementation) needs. Sensitivity analysis is conducted around the number of chosen projects and the goal programming weights. Conclusions are hence drawn with respect to the methodology and the Arctic maritime safety and security field of application.

Keywords: OR in Maritime Sector, Multiple Criteria Analysis, Research Prioritization, Goal Programming, Arctic Security and Safety

1. Introduction

The Arctic and North Atlantic (ANA) region forms a complex geo-political zone in which to make safety and security decisions for two main reasons. Firstly, the number of stakeholders involved is significant and multi-national. In this work, the Arctic is defined as the region above the Arctic circle, including coastal regions of Norway, Iceland, Canada, Kingdom of Denmark (Greenland), Russia and the United States. The North Atlantic, for the purpose of this work, is broadly defined as the maritime zone bordered by the Arctic and the coastal regions of Norway, Iceland, Kingdom of Denmark (Greenland and Faroe Islands), Canada, Ireland and the United Kingdom (Northern Ireland and Scotland). Counting the additional Arctic council members of Finland and Sweden gives eleven direct ANA jurisdiction stakeholders, plus many other national and regional governments, industrial and third sector stakeholders with an interest in the ANA region, inclusive of indigenous peoples as defined by, and represented at, the Arctic Council (Arctic Council, 2021). Furthermore, the critical nature of the Arctic with respect to the ongoing climate change challenge makes the entire global population a stakeholder to decisions made regarding the Arctic. This should hence be seen as an essential domain for the usage of operational research techniques and methodologies to inform and optimise decisions taken regarding the Arctic.

Considering the specific issue of Arctic safety and security, there are numerous geographical and meteorological conditions to consider. The ANA region is mainly characterised by sparsity of population and vast distances between facilities. The geography can be challenging due to the presence of fjords and coastal mountains and scarcity of infrastructure, which make access difficult. The climate is inhospitable for large periods and involves polar night for some months of the year (Lauta *et* al., 2018), with the presence of drift and fast ice. However, the aforementioned climate change has led to an enhanced accessibility to the ANA region with a potential consequent increase in oil and gas drilling, fishing, tourism and maritime logistics activities (Flynn *et al.*, 2018; Marchenko *et al.*, 2018). This trend is predicted to increase for the rest of this century, with a number shorter and/or more fuel-efficient maritime shipping routes becoming available for greater portions of the year (Farré *et al.*, 2014) and potential exploitation of as yet large untapped volumes of oil and gas (Gautier *et al.,* 2009).

The above considerations give rise to the need for an increased safety and security infrastructure to be provided by the ANA governments, working through organisations such as the Arctic Council. There needs to be a collaborative, multi-national provision due to the nature of the ANA region. However, in order to achieve this goal, a common mapping of safety and security needs in the ANA region and a roadmap for their short and long term resolution is required.

The multi-disciplinary field of Arctic maritime safety and security has been the subject of previous research relating to risk management and strategic and operational decision support. Considering maritime shipping, this includes the mapping of risk factors associated with Arctic shipping and formulation of consequent stakeholder decision maker support (Christensen *et al*., 2019); the use of fuzzy fault tree analysis (Fu *et al*., 2018) and root cause analysis (Kum and Sahin, 2018) to assess the risk of major Arctic shipping incidents. In the field of ANA energy, including pollution and incident control, Necci *et al.*, (2019) offer a thorough statistical analysis of ANA oil and gas incidents and Hasle *et al.*, (2009) consider the handling of operational risk in ANA oil exploration including a mapping of stakeholder decision criteria. The risk management aspects of Arctic oil spills are considered by Johannsdottir and Cook, (2019). From a wider ANA perspective, Trump *et al,* (2012) utilise multi-criteria decision analysis to examine ANA sustainability, considering economic, environmental and social criteria and applying their methodology to an example from the field of mining. Whilst the above demonstrates some current and effective uses of risk management and operational research methodologies to support decision making in individual Arctic fields and circumstances, there is a subsequent need for methodologies to map, prioritise, balance, select and optimise overall ANA need for research and innovation across the wide field of ANA maritime safety and security.

Literature related to innovation mapping, in terms of the use of operational research techniques for prioritisation and selection, tends to be varied and multi-disciplinary in nature. Mavi and Mavi (2021) use goal programming guided DEA to find a common set of weights in order to assess national eco-innovation output at country level across the EU. In doing so, they were able to distinguish the drivers of, and the barriers to, eco-innovative operations. Chen *et al.* (2015) uses a binary goal programming approach to balance shorter-term existing capabilities (exploitative) and longer-term new capabilities (exploratory) business product innovation activities. In doing so, they propose a conceptual framework of a hybrid of OR techniques of the fuzzy Analytical Network Process (ANP) to assess criteria of project development, and goal programming to consider environmental and marketing constraints. Samanlioglu and Ayağ (2020) use hesitant fuzzy ANP to evaluate innovation projects in a group decision making environment. Song *et al.* (2019) use probabilistic hesitant fuzzy set (PHFS) as an improved method for group decision making, when different decision makers are not completely sure that one alternative is superior to another, and they applied the proposed method to the case of Arctic geopolitical risk evaluation.

There is a considerable body of literature on the usage of operational research methodologies to map, prioritise and select research need and projects in diverse fields of application. For instance, a priority list of non-communicable diseases for research funding evaluation support is found using MCDA by Babashahi *et al,* (2021). Mavrotas and Makryvelios, (2020) use a combination of MCDA, mathematical programming and Monte-Carlo simulation to rank and select research proposals under uncertainty. Similarly, Parreiras *et al.* (2019) use MCDA methods to support the assessment, evaluation, prioritisation and selection of research applications from a governmental perspective. Prioritization selection based on limited budget has been used for choices of cultural heritage projects by Huang *et al*., (2019). The work of Bakirli *et al*., (2014) selects a set of defence projects by a multi-objective goal programming knapsack method. Salo *et al*., (2003) use multi-criteria methods to assess research priority settings. The above works focus on the problem of selection or prioritisation from a well-defined list of projects, topics or proposals. In contrast, the methodology in this paper proposes a more holistic approach to mapping research and innovation need across a multi-disciplinary domain and selecting a priority set based on concepts of importance and balance between topics and short and long term needs.

This paper contributes to the ANA safety and security agenda by proposing and conducting a comprehensive mapping of ANA safety and security needs, achieved in the context of the European Union Horizon 2020 ARCSAR project (ARCSAR, 2021). A novel methodology is then proposed that adapts the concept of a PICK chart for classifying the identified needs with the technique of goal programming for identifying a balanced portfolio of priority sub-needs across the temporal (short versus long term research required) domain and fields of application. The methodological novelty lies in the combination of the PICK chart and goal programming techniques in order to classify and prioritise a set of research and innovation gaps, whilst maintaining multiple, different types of balance across the field of application. The knapsack based weighted goal programme with included multiple balance goals is a further point of novelty in itself. The proposed methodology hence has wider significance as a contribution to the field of research and innovation topic and project mapping, prioritisation and selection across a multi-disciplinary field of application with multiple stakeholders.

The remainder of this paper is divided into 4 Sections. Section 2 presents the mapping methodology for ANA safety and security mapping and the subsequent need hierarchy. Section 3 details the methodology for selection a priority set of ANA safety and security sub-needs based on an adapted PICK chart and goal programming, with weight sensitivity analysis conducted. Section 4 discusses the results from methodological and application perspectives. Finally, Section 5 draws conclusions.

2. **Mapping of Arctic and North Atlantic Safety and Security Needs**

This work develops a methodology for classification prioritising needs and innovation requirements based on security issues raised from initial stages of the ARCSAR project (ARCSAR, 2021), an EU funded research and innovation project, to create the Arctic and North Atlantic Security and Emergency Preparedness Network. This network consists of partners from industry, academia, governmental and non-governmental organisations and encompasses practitioners. The practitioners include coast guards, marine rescue and coordination centres, third sector rescue organisations, satellite technology providers, and Arctic cruise operators.

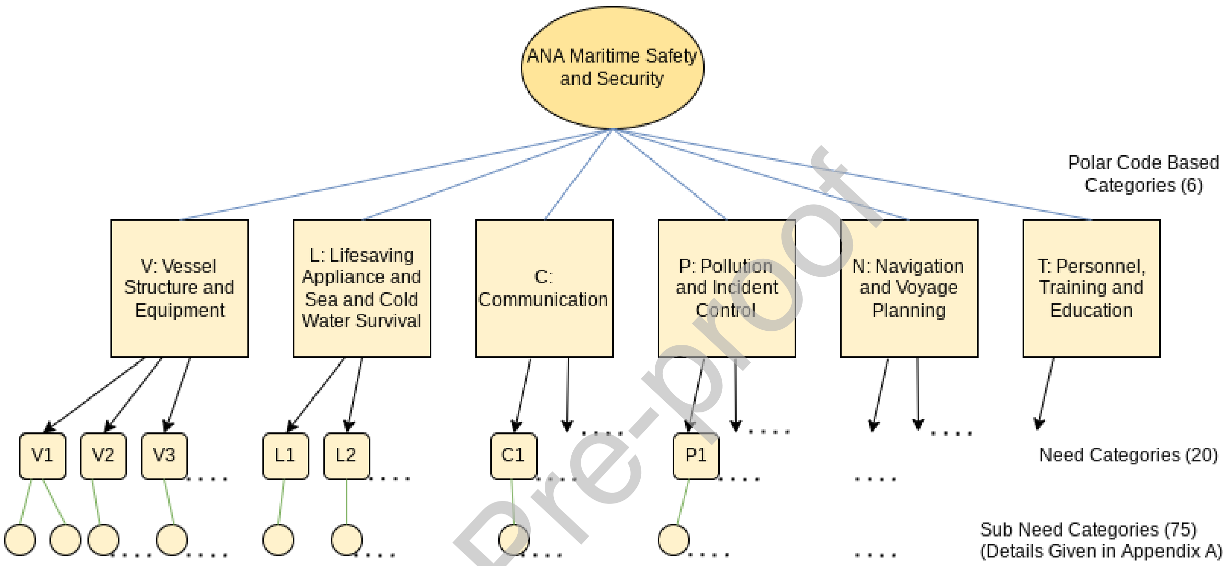

Figure 1: Hierarchy of ANA Maritime Safety and Security Needs

Due to the multi-disciplinary nature of the ANA security and safety field, it was anticipated that a relatively large number of diverse needs would arise and subsequently need an effective means of classification. This classification is intended to be used to provide a road map for the ARCSAR project, the current wider ANA research and innovation agenda, and future ANA research strategy development at organisational, national and trans-national levels. The development of the network is dynamic, with the higher levels set *a priori* to the collection and analysis of data and the lower levels formed as the data was analysed and sub-need categories and patterns emerged.

Considering the higher level, the internationally agreed and accepted document for maritime regulations is the International Code for Ships Operating in Polar Waters (the Polar Code: IMO, 2014). It is therefore the logical choice to adapt classification of issues presented in the polar code to form the highest level of the need network. This led to the development of the following six classes, each of which is given a letter label in order to categorise the lower network levels, as shown in Figure 1:

- Vessel structural and equipment issues (V),
- Lifesaving appliance and sea and cold survival issues (L),
- Communication Issues (C),

- Pollution and incident control issues (P),
- Navigational and voyage planning issues (N)
- Personnel, training and education issues (T).

Multiple secondary and primary sources and methods were utilised to collect the ANA maritime safety and security need data. For secondary sources, a thorough review of scientific literature and results of past and current ANA related projects was undertaken, searching for identified needs across the six polar code categories. The primary data was collected by multiple interactions with the practitioners and experts in the ARCSAR network, and their wider contacts. The primary data collection mechanisms were:

- A series of three interactive workshops that explored needs in one or more of the polar code categories. Attendees were drawn from multiple countries, disciplines and job role, and divide into groups to explore and identify need. As appropriate, formal techniques such as root cause analysis to learn from failures (Labib, 2014) were used to identify issues, and in other occasions a moderator facilitated group discussion working through pre-defined questions. The results were recorded and analysed.
- A series of six semi-structured questionnaires designed to identify topic needs. These questionnaires were widely distributed amongst the ARCSAR network and their contacts. The results were also recorded and analysed.

In total, the three workshops were attended by 131 (40, 23 and 68 respectively) attendees, and 29 responses to the semi-structured responses were received. The set of primary and secondary data was then analysed in order to identify arising sub-needs and the need network shown by Figure 1 dynamically evolved. This resulted in two further levels, which are termed need and sub-need categories. As shown by Figure 1, the classification contains 20 need and 75 sub-need categories, a full list of which is given in Appendix A. Either, or both, of these levels can be utilised in further categorisation, analysis and/or policy support, dependent on the level of need fidelity required. The categorisation given by Figure 1 and the subsequent analysis in this paper should hence be viewed as the synthesised expertise of the 131 workshop attendees, 29 interview responders and of the wider Arctic and North Atlantic search and rescue stakeholder community, who have inputted their views through a varied means included a dedicated online ARCSAR innovation Arena for the discussion of Arctic Search and Rescue needs, challenges and innovations. A list of synopses of the priority sub-needs given by the methodology developed in this paper is given in Appendix B. For the interested reader, a description of Arctic Search and Rescue innovations to fill the sub-needs detailed in this paper, together with the classification of potential barriers to their uptake is given by (Willis *et al.*, 2022).

3. Selection of a Balanced Priority List of Arctic and North Atlantic Safety and Security Sub-Needs

Due to the relatively large number of needs (20) and sub-needs (75), it is necessary to develop a priority set of sub-needs in order to guide the ARCSAR project in its fast-tracking of research and innovations. A priority list is also essential in informing wider ANA research and innovation agendas that have a finite available budgets and hence require a prioritisation mechanism. An overall Pareto-based logic was used to determine the approximate size of the priority sub-need set, that is it should be approximately 20% of the size of the total sub-need set. There was also the need to ensure that the priority set contained a balance of sub-needs across the six polar categories in order to ensure a balanced portfolio of prioritised sub-needs. Furthermore, the sub-need priority list should also contain a balance between less challenging needs that can be met in the shorter term and those more challenging needs that require further research before a longer-term resolution. The remainder of this Section describes a combined bi-objective priority grid and weighted goal programming methodology with subsequent sensitivity analysis in order to derive priority sub-need list(s).

3.1. Bi-Objective Priority Grid

The ARCSAR project is focused on maritime safety and security in the Arctic and North Atlantic, hence safety, risk, reliability and maintenance are crucial general disciplines that underpin the scope of the project. The methodology for prioritisation of sub-needs presented here is based on operational research methods for decision analysis guided by the mentioned disciplines.

In both safety and security disciplines it can be observed that the evolution of subsequent generations of research and development can be summarised comprising four generations in terms of their increasing value. The First Generation is characterised as being 'descriptive' in nature and aims to answer the question of 'What happened?'. The Second Generation is characterised as 'diagnostic' and aims to answer the question of 'Why did it happen?'. The Third Generation is characterised as 'prognostic' and aims to answer the question of 'When will it happen?'. Finally, the Fourth Generation is characterised as 'prescriptive' and aims to answer the question of 'What must be done?' (Mobley, 2004). Hence the highest value in this classification is the prescriptive nature of models in order to strategically, and dynamically, inform the decision maker on what policies, strategies, or actions should be carried out. The basic idea of decision grids is that they aim to provide a visual representation based on two or more criteria, and hence the term 'multiple criteria', and they therefore directly address the prescriptive requirement in strategic decision-making. Examples of such grids are the Decision Making Grid (DMG) (Labib, 2004), Jack-Knife Diagram (JKD) (Knights, 2001), and PICK (Badiru, and Thomas, 2013).

This work utilises a revised structure of the two-by-two PICK diagram as shown in Figure 2, and employs a variation of the JKD to determine the position of the thresholds between categories in the grid. The grid is based on the data collected from a survey carried out among experts in terms of the two dimensions of importance and difficulty. The main limitation of our approach is that we rely on one source of data (limited number of experts). A proposed extension to this work is to consider other types of sources, such as for example evidence from causal factors of major incidents. Another further work can relate to construction of a three by three diagram such as the DMG, and utilisation of a resource allocation model such as knap-sack method for planning optimisation of effort.

The quantification of sub-needs by importance and level of difficulty (challenge) is used to produce a classification. An adapted version of the PICK chart process (George, 2003) is used for this purpose. The classic PICK (Possible, Implement, Challenge, Kill) chart is a bi-objective classification process (Badiru, and Thomas, 2013). Therefore, a further consultation with experts within the ARCSAR network was undertaken in order to quantify the level of difficulty and importance of each of the 75 sub-needs. Questionnaires were thus distributed amongst the six sets of practitioner and academic experts of the ARCSAR network, elucidating a total of 28 expert responses. Each questionnaire requested the following information from the respondent, both values on a 1-10 scale:

1. A quantification of the level of importance of the sub-need
2. A quantification of the challenge of resolving the sub-need

The 1-10 scale was chosen as it provides a balance between ease of use by the experts and the granularity of the scale. The geometric mean is used in order to adapt the process to the multi expert situation of the questionnaire responses, as it is a well-established measure used to aggregate the opinions of experts. Therefore, assuming that a given sub-need s is quantified by $e_s = 1, \ldots, E_s$ experts where $s = 1, \ldots, 75,$ the importance and difficulty scores can thus be defined as:

- i_{es}: level of importance assigned to sub-need s by the e_sth expert, $s = 1, \ldots, 75, e_s = 1, \ldots, E_s$
- d_{es}: level of difficulty assigned to sub-need s by the e_sth expert, $s = 1, \ldots, 75, e_s = 1, \ldots, E_s$

The overall level of importance for sub-need s, denoted I_s, is calculated as the geometric mean of the experts' assigned importance values:

$$I_s = \left(\prod_{e_s=1}^{E_s} i_{e_s} \right)^{\frac{1}{E_s}}, \quad s = 1, \ldots, 75 \qquad (1)$$

Similarly, the overall level of difficulty for sub-need s, denoted D_s is calculated as the geometric mean of the experts' assigned difficulty values:

$$D_s = \left(\prod_{e_s=1}^{E_s} d_{e_s} \right)^{\frac{1}{E_s}}, \quad s = 1, \ldots, 75 \qquad (2)$$

The set of 75 (I_s, D_s) co-ordinates are then plotted on a 2-dimensional graph, which forms the basis of the PICK chart given by Figure 2.

In order to classify the sub-needs into the four groups of the PICK process, horizontal (D^*) and vertical (I^*) lines represented the classification boundaries for difficulty and importance respectively are calculated and plotted on the graph. As the values are comprised of expert opinions, the method is refined to use the geometric rather than arithmetic mean of all expert responses across all sub-needs (E). The usage of the PICK results to select a ratio (proportion of a fifth – detailed in Section 3.2.2) of the sub-needs as a priority set is the reason behind the usage of the geometric mean. This is because geometric mean works better with ratio scales as explained in review of scales in ratio comparisons. See Ishizaka and Labib (2011), and Aguarón, and Moreno-Jiménez (2003), where geometric mean rather than the arithmetic mean has been suggested by other authors for usage in similar circumstances. The geometric mean can give importance to lower scores by a particular expert, but this is not an issue in the context of this paper, as the aim to produce a priority set of sub-needs that will be acceptable, and hence actionable, across a range of multi-national, multi-disciplinary stakeholders. Hence, a low score by a particular expert could indicate the non-acceptance of the sub-need by a subset of stakeholders as a priority or as difficult to solve. This is turn could indicate difficultly in acceptance and resolution, and hence should result in a lower overall score.

This gives the threshold value calculations:

$$I^* = \left(\prod_{s=1}^{75} \prod_{e_s=1}^{E_s} i_{e_s} \right)^{\frac{1}{E}} \tag{3}$$

$$D^* = \left(\prod_{s=1}^{75} \prod_{e_s=1}^{E_s} d_{e_s} \right)^{\frac{1}{E}} \tag{4}$$

Where,

$$E = \sum_{s=1}^{75} E_s \tag{5}$$

The plotting of the (dotted) horizontal line at level of difficulty (D^*) and (dotted) vertical line at importance level (I^*) on Figure 2 allows for the sub-needs to be divided into four classes:

- Possible (low difficulty, low importance). These sub-needs are possible to meet in the sense that they are judged to have a relatively low level of challenge in meeting them. However, they are not classed as a high priority due to their relatively low level of importance.
- Implement (low difficulty, high importance). These sub-needs are classified as candidates for immediate action as they are judged both as important and relatively easy to resolve.
- Challenge (high difficulty, high importance). These sub-needs are classified as candidates for further research and innovation effort as they are judged to be both important and difficult to resolve.
- Keep Back (high difficulty, low importance). The sub-needs are not prioritised as they are judged to be both difficult to resolve and of low importance. Note that the Badiru, and Thomas, (2013) terminology has been changed from “kill” as these sub-needs were still identified as valid and hence should not necessarily be discarded, but rather kept in reserve whilst other sub-needs are resolved. Additionally, the word “kill” is not deemed appropriate for an application arising from the field of safety and security.

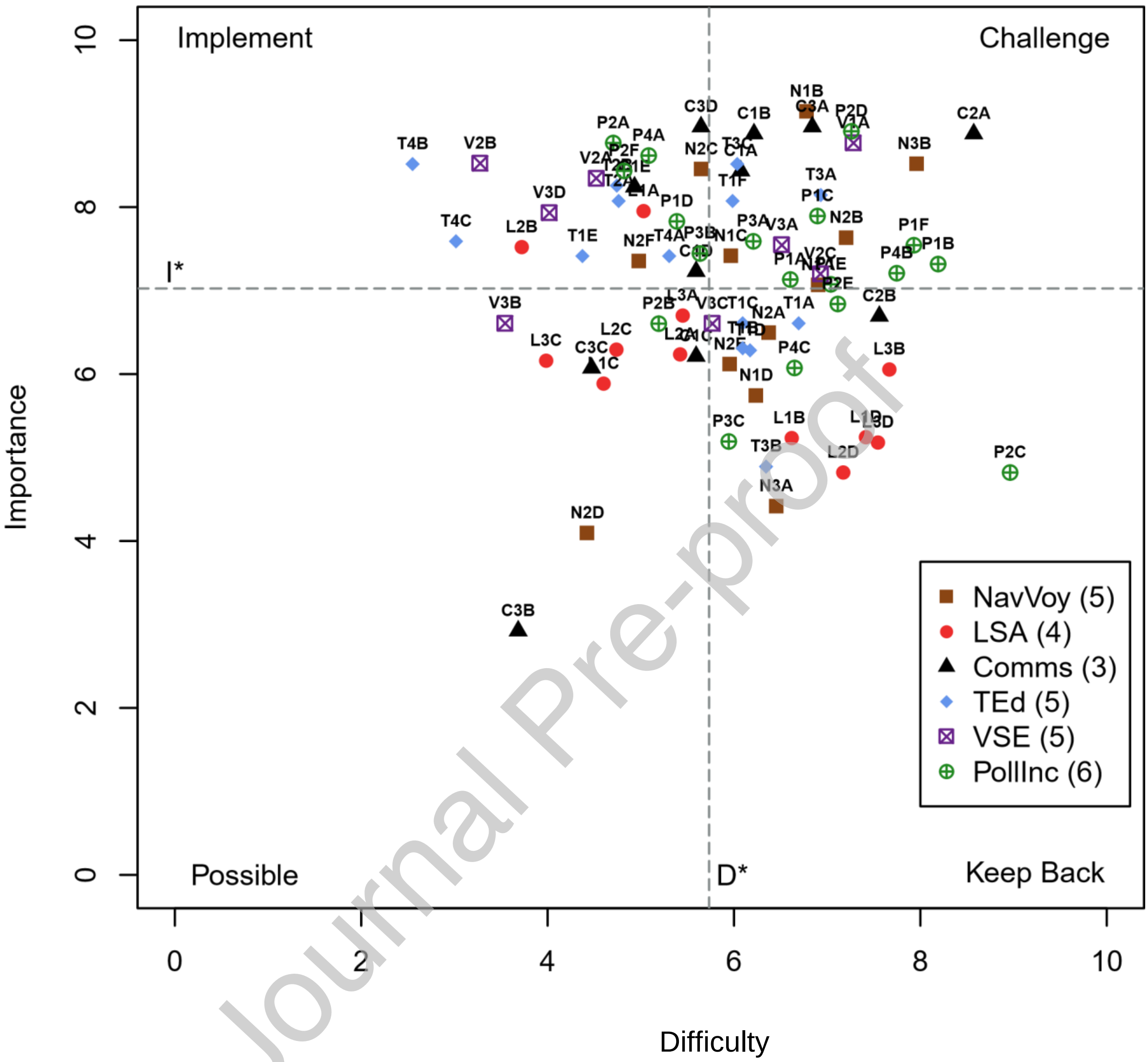

Figure 2: PICK Chart of ANA Sub-Needs (codes given in Appendix A, the number of experts giving scores in each category is given in brackets after the category key).

3.2. Goal Programming Balanced Knapsack Model

The above methodology uses expert knowledge to assign values to the list of Arctic safety and security sub-needs based on the level of challenge and importance. Further analysis of these results would be useful as an aid to decision-makers' selection amongst the sub-needs.

A weighted goal programming model (Jones and Tamiz, 2010, Jones *et al.*, 2021) of a multi-objective knapsack problem is formulated that selects tasks for prioritisation up to a maximal level of total difficulty whilst attempting to achieve the following goals as closely as possible:

G1: Achieve the maximal level of importance within the total allowable difficulty limit

G2: Achieve a balance between the less challenging (possible, implement) and more challenging (challenge) topics chosen. This is needed in order to mix short and long term choices, otherwise the knapsack will fill with less challenging, high importance sub-needs. Note that the "keep back" topics are not eligible to be chosen, as the PICK methodology has identified them as having relatively low importance compared to their difficulty.

G3: Achieve a balance between the sub-needs chosen from the six topics. This is needed to ensure a balanced portfolio of chosen topics.

The weighted goal programming variant is chosen as it provides trade-off information between the multiple conflicting goals in cases where there is no pre-emptive ordering of the goals. Variants that consider or incorporate the balance between goals, such as Chebyshev or extended goal programming have not been chosen as goals G2 and G3 already include a measure of balance, and previous goal programming applications (Jones *et al.,* 2021) show that double consideration of balance can be unhelpful in terms of the results produced.

3.2.1. Model Indices

Two principal indices are defined, corresponding to the topic and sub-need levels of the need hierarchy given in Figure 1:

Topics(t): $1, \ldots, 6$
Sub-needs for topic t: $1, \ldots, N_t$

3.2.2. Model Data

The data and parameters required for the model are:

D : Maximum total difficulty level of chosen projects (size of knapsack – set at 15 times the average sub-need difficulty, in order to generate a priority list of approximately 20% of the total sub-needs)

i_{ts} : Importance level of sub-need s from topic t
d_{ts} : Difficulty level of sub-need s from topic t

$$\alpha_{ts} = \begin{cases} 1 & if\ sub-need\ s\ from\ topic\ t\ in\ implement\ category \\ 0 & otherwise \end{cases} \quad t = 1, \dots, 6; s = 1, \dots, N_t$$

$$\beta_{ts} = \begin{cases} 1 & if\ sub-need\ s\ from\ topic\ t\ in\ possible\ category \\ 0 & otherwise \end{cases} \quad t = 1, \dots, 6; s = 1, \dots, N_t$$

$$\gamma_{ts} = \begin{cases} 1 & if\ sub-need\ s\ from\ topic\ t\ in\ challenge\ category \\ 0 & otherwise \end{cases} \quad t = 1, \dots, 6; s = 1, \dots, N_t$$

I^*= Target level of total importance (calculated in Section 3.2.4)
B^*=Highest level of imbalance between challenge and possible/implementation sub-needs (calculated in Section 3.2.4)
C^*=Highest level of imbalance over the set of topics (calculated in Section 3.2.4)
w_1 = Weight associated with the minimization of unwanted deviations from the first (importance level) goal
w_2 = Weight associated with the minimization of unwanted deviations from the second (balance between categories) goal
w_3 = Weight associated with the minimization of unwanted deviations from the third (balance between topics) goal

3.2.3 Decision and Deviational Variables

$$x_{ts} = \begin{cases} 1 & if\ sub-need\ s\ from\ topic\ t\ chosen\ in\ priority\ set \\ 0 & otherwise \end{cases} \quad t = 1, \dots, 6; s = 1, \dots, N_t$$

n_1 : Negative deviation from the first goal target
p_1 : Positive deviation from the first goal target
n_2 : Negative deviation from the second goal target
p_2 : Positive deviation from the second goal target
n_{ij} : Negative deviation from goal target concerning the difference between topics i and j $(i > j)$
p_{ij} : Positive deviation from goal target concerning the difference between topics i and j $(i > j)$

3.2.4. Goal Programming Model

$$Min\ a = \frac{w_1 n_1}{I^*} + \frac{w_2(n_2 + p_2)}{B^*} + \frac{w_3 \sum_{i=1}^{6} \sum_{j=1, j>i}^{6} (n_{ij} + p_{ij})}{C^*} \quad (6)$$

Subject to,

$$\sum_{t=1}^{6} i_{ts}x_{ts} + n_1 - p_1 = I^* \tag{7}$$

$$\sum_{t=1}^{6}\sum_{s=1}^{N_t} (\alpha_{ts} + \beta_{ts} - \gamma_{ts})\, x_{ts} + n_2 - p_2 = 0 \tag{8}$$

$$\sum_{s=1}^{N_i} x_{is} - \sum_{s=1}^{N_j} x_{js} + n_{ij} - p_{ij} = 0 \quad i,j = 1,\dots,6, j > i \tag{9}$$

$$\sum_{t=1}^{6}\sum_{s=1}^{N_t} d_{ts}x_{ts} \leq D \tag{10}$$

$$x_{ts}\ binary\ t = 1,\dots,6; s = 1,\dots,N_t;\ n_1,p_1,n_2,p_2 \geq 0; \quad n_{ij},p_{ij} \geq 0\ \ i,j = 1,\dots,6, j > i \tag{11}$$

Where (6) is the weighted goal programming achievement function, that minimises the sum of unwanted, weighted, normalised deviations from the three goal targets. The calculation of the normalisation constants is given in Section 3.2.4. Equation (7) measures the deviation from the importance (G1) goal. Equation (8) measures the imbalance (G2) between short term ($\alpha_{ts} = 1\ or\ \beta_{ts} = 1$) and long term sub-needs ($\gamma_{ts} = 1$). Equation set (9) measures the pairwise imbalances between the number of projects in pairs of topics. As there are six topics, there will be 15 pairwise imbalances, represented by the unwanted deviation variables $n_{ij}\ or\ p_{ij},\ i,j = 1,\dots,6, j > i$. Equation (10) ensures that the total difficulty level of the chosen sub-needs is no more than the maximal permitted level of D. Sign restriction set (11) imposes binary restrictions on the decision variables and non-negativity restrictions on the deviational variables.

3.2.5. Calculation of Normalization Constants

In order to solve weighted goal programming model (6)-(11), the normalization constants $I^*, B^*, and\ C^*$ must first be calculated. This is required in order to ensure commensurability of the goals. The commonly used percentage normalization method of dividing be the goal target level cannot be used because the second and third goals have a zero goal target level. Therefore, a measure of range of unwanted deviations is used instead (Jones and Tamiz, 2010). As the least unwanted deviation from each goal is zero (i.e. all goals can be met when considered separately) then the worst unwanted deviation from each goal can be used as the normalization constant. First considering the importance goal (G1), the lowest importance can be found at the null case of not selecting any sub-needs (i.e $x_{ts} = 0, \forall\, t,s$). In this case the unwanted deviation n_1 takes the value of I^*, the maximal importance possible within the difficulty knapsack of size D. I^* can be found through a single objective knapsack optimization:

$$Max\ I = \sum_{t=1}^{6}\sum_{s=1}^{N_t} i_{ts}x_{ts} \tag{12}$$

Subject to:

(10) and (11),

Considering the second goal (8), the maximum imbalance, B^*, between short and long term sub-needs can be found by filling the difficulty knapsack with as many short-term projects as possible and no long term projects. Formally B^* is given by the solution of the single objective knapsack model

$$Max\ B = \sum_{t=1}^{6}\sum_{s=1}^{N_t} (\alpha_{ts} + \beta_{ts})x_{ts} \tag{13}$$

Subject to:

(10) and (11),

Considering the third goal (9), C^* is found when the total imbalance between topics is at its greatest. As this is difficult to express in terms of decision variables, a direct maximization of the unwanted deviations representing imbalance between topics is used instead. Thus, C^* is given by the solution of the single objective knapsack model

$$Max\ C = \sum_{i=1}^{6}\sum_{j=1, j>i}^{6} \left(n_{ij} + p_{ij}\right) \tag{14}$$

Subject to:

(9), (10) and (11), $n_{ij} \times p_{ij} = 0 \quad i = 1, \dots, 6, j = 1, \dots, 6, j > i$

The above methodology yielded the values of $B^* = 20$ and $C^* = 69$

3.3. Weight Sensitivity Analysis

In order to generate solutions in decision and objective space, and to investigate the trade-offs between goals the weight sensitivity analysis algorithm of (Jones, 2011) is used. This algorithm is chosen as it is pragmatic, contains relatively few parameters to set, and is compatible with the weighted goal programming technique. The algorithm investigates raising one or more weights from an initial solution within preferential limits set by the decision maker's. As the key trade-off of interest is between overall level of importance (G1) and balance (G2 and G3), an initial solution than allocates 50% of weight to importance (G1), and the remaining weight equally split between the short-long term project balance (i.e. 25% to G2) and topic balance (i.e. 25% to G3). This gives the initial solution of $w_1 = 0.5, w_2 = 0.25, w_3 = 0.25$, whose corresponding solution can be found in the first row of Table 1. As this solution already contains a high level of balance, a choice is made to constraint the region of weight space solutions with at least 50% of weight assigned to importance (G1), that is $w_1 \geq 0.5$. The parameters of MAXLEVEL=2 (i.e. raise up to two weights simultaneously) and TMAX=2 (i.e. perform at most two bisections for each raised weight direction) are chosen, in order to produce an appropriate number of points in weight space to investigate. As three of the six potential weight raise directions are trivial because the initial solution lies on the $w_1 = 0.5$ boundary of the weight space to be investigated, the three remaining directions yield thirteen points, which are graphically demonstrated by Figure 3. Note that the directions of raising (w_1, w_2) and (w_1, w_3) are set so that the original intended balances of $w_1 = 2w_2$ and $w_1 = 2w_3$ are maintained respectively. The resulting weight sets are given in Table 1. The thirteen corresponding instances of the goal programming model (6)-(11) are solved using LINGO version 18 (LINGO, 2021) on a standard PC to optimality. This resulted in nine distinct solutions, whose values in corresponding weight space points and values in decision and objective space are given in Table 1. The first Column gives each solution an alphabetical label for ease of analysis. Columns 2-4 of Table 1 give the point(s) in weight space generated by the weight sensitivity analysis with the corresponding distinct solution given by the remaining columns. The 5th column gives the solution in decision space, in the form of the set of prioritised sub-needs, with the description of the sub-need code given in Appendix A. Columns 6-8 give the solution in objective space, in the form of the percentage importance gap from optimal $(\frac{n_1}{I^*})$, the level of imbalance between categories $(n_2 + p_2)$ and the level of imbalance between topics$(\sum_{i=1}^{6} \sum_{j=1,j>i}^{6} (n_{ij} + p_{ij}))$respectively.

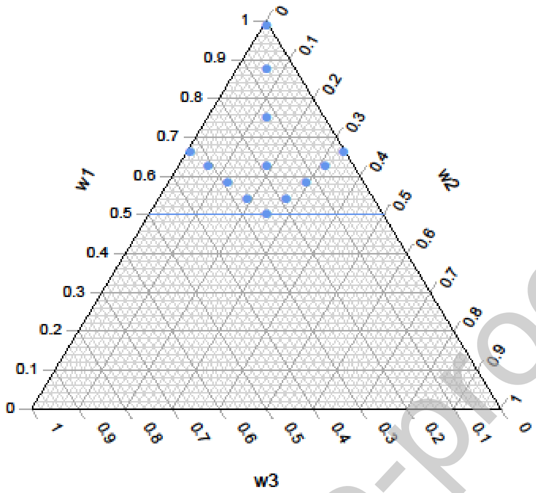

Figure 3: Weight Sensitivity Algorithms Points in Weight Space.

Solution	w_1	w_2	w_3	Selected Sub-Needs	Importance Gap: $100\frac{n_1}{I^*}$	Short Long term Imbalance: $n_2 + p_2$	Topic Imbalance: $\sum_{i=1}^{6}\sum_{j=1,j>i}^{6}(n_{ij} + p_{ij})$
A	0.500 0.625 0.583 0.542 0.542	0.250 0.188 0.292 0.271 0.188	0.250 0.188 0.125 0.188 0.271	N1B,N1C,N2B,L2B,L3C,C1A,C1B,C3A,T3C,T4B,T4C,V2A,V2B,V3D,P2A, P2F,P3A	10.477	1	5
B	0.990	0.005	0.005	N2F,L1A,L2B,C1B,C1E,C3D,T1E,T2A,T2B,T3C,T4B,T4C,V2A,V2B,V3B,V3D,P2A,P2F,P4A	0.033	15	31
C	0.750	0.125	0.125	N1B,N1C,N2F,L1A,L2B,L3C,C1A,C1B,C1E,T3C,T4B,T4C,V2A,V2B,V3D,P2A,P2F,P4A	5.314	8	0
D	0.875	0.063	0.063	N1B,N2F,L1A,L2B,L3C,C1B,C1E,C3D,T1E,T2B,T4B,T4C,V2A,V2B,V3B,V3D,P2A,P2F,P4A	0.864	15	13
E	0.663	0.332	0.005	N1B,N1C,L2B,C1A,C1B,C3A,T1F,T3C,T4B,T4C,V2A,V2B,V3D,P2A,P2F, P3A,P4A	8.602	1	21
F	0.625	0.313	0.063	N1B,N1C,L1A,L2B,C1A,C1B,C3A,T1F,T3C,T4B,T4C,V2A,V2B,V3D,P2A, P2F,P3A	9.032	1	13
G	0.663	0.005	0.332	N1B,N2C,N2F,L1A,L2B,L3C,C1B,C3A,C3D,T2B,T4B,T4C,V2A,V2B,V3D, P2A,P2F,P4A	4.000	12	0
H	0.583	0.125	0.292	N1B,N1C,N2F,L1A,L2B,L3C,C1A,C1B,C1E,T3C,T4B,T4C,V2B,V3B,V3D, P2A,P2F,P3A	7.103	6	0
I	0.625	0.063	0.313	N1B,N1C,N2C,L1A,L2B,L3C,C1B,C1E,C3D,T3C,T4B,T4C,V2A,V2B,V3D, P2A,P2F,P4A	4.260	10	0

Table 1: Solutions of weight sensitivity analysis

3.4. Sensitivity Analysis with Respect to Knapsack difficulty level (D).

As detailed in Section 3.2.2, the knapsack size in terms of difficulty (D) has been set at a level whereby approximately 20% of the total number of 75 projects would be selected to belong to the priority sub-need set. In order to test the sensitivity of this assumption, a sensitivity analysis is thus conducted with respect to D. The baseline value of D was calculated as 15 (a fifth of the 75 sub-needs) times the average level of difficulty, giving a baseline value of $D = 154.56$. The baseline model uses the most commonly found solution from Table 1: solution A, and the hence the initial weights that generated solution A, $w_1 = 0.5, w_2 = 0.25, w_3 = 0.25$. Maintaining this weight scheme, the methodology of Section 3.2 is reapplied varying D by -10%, -5%, 0% (baseline), 5% and 10%. This is a reasonable range as the initial baseline estimate for the priority set had a good rationale in the context of the project. All models were solved to optimality using LINGO 18.0, except for the calculation of the C^* normalization constant, where the best-found value after an hour of execution time was used. The results of the difficulty level sensitivity analysis are given in Table 2.

Percentage Change D	Priority Set Size	Selected Sub-Needs	Normalised Hamming Distance from Baseline	Importance Gap:	Short-Long term Imbalance	Topic Imbalance:
-10%	15	N1B,N1C, L1A, L2B, C1A, C1B, C3A, T3C, T4B, T4C, V2A, V2B, P2A, P2D, P4A	0.854	11.19	1	9
-5%	16	N1B,N1C, L1A, L2B, C1A, C1B, C3A, T3C, T4B, T4C, V2B, V3B,V3D, P2A, P2D, P3A	0.873	11.10	0	8
0% (Baseline)	17	N1B,N1C,N2B,L2B,L3C,C1A ,C1B,C3A,T3C,T4B,T4C,V2A ,V2B,V3D,P2A, P2F,P3A	0	10.48	1	5
+5%	18	N1B,N1C,N2F, L1A, L2B, L3C, C1A, C1B, C3A, T3C, T4B, T4C, V2B, V3B,V3D, P2A, P2D, P3A	0.873	10.12	2	0
+10%	18	N1B,N1C,N3B, L1A, L2B, L3C, C1A, C1B, C3A, T3C, T4B, T4C, V2A, V2B,V3D, P2A, P2D, P3A	0.909	11.65	0	0

Table 2: Results of sensitivity analysis with respect to knapsack difficulty level (D).

The first column gives the percentage change of D from the baseline case. Columns 2-4 describe the solutions in decision space. The second column gives the number of sub-needs in the chosen priority set, which can be seen to increase in a regular manner as the size of the difficulty knapsack enlarges. Column 3 gives the set of sub-needs in the priority set. The fourth column gives the normalised Hamming distance from the baseline solution, as a measure of similarity. That is, the proportion of the 57 eligible sub-needs that have the same binary value (i.e chosen or not chosen) as the baseline solution. This column shows a relatively high level of similarity throughout the range, with all solutions having at least 85.4% of the chosen/not chosen decisions in common, which in turn indicates the relatively stability of the baseline solution to changes in the knapsack size. Columns 4-6 describe the solutions in objective space, with the same definitions as found in the first row of Table 1. Considering the importance gaps given by the fourth column, these again point to the relative stability of the baseline solution, with a range of 10.12%-11.65% seen, and little observable pattern over the range. The fifth and sixth columns give the level of balance in the solutions, with an observable improvement in topic balance as the knapsack size increases, however this trend, along the balance values in general, are most likely explained by the numerical properties of the priority set size (e.g. an odd size priority set cannot have a short-long term imbalance of zero and some topic imbalance must occur if the priority set is not divisible by six). When comparing with other weight solutions found in Table 1, it can be seen that a relative level of balance of the baseline solution is maintained when varying the knapsack difficultly size.

4. **Discussion of Results**

Figure 2 shows the results of the priority grid process and Table 1 provides the solutions from the goal programming knapsack model. The details of the sub-needs and the codes used in figure found in appendix A. Table 1 provides the list of sub-needs selected (five of the weight sets provide the same solution) together with three measures; the importance gap (difference between importance of solution from the maximum possible importance level), the Short-long term imbalance (sum of difference from the second model goal on categories in the PICK grid), and topic imbalance (which measures the difference in balance of selection among the six ARCSAR topic areas).

The results of the initial weight set (0.50, 0.25, 0.25) demonstrate that an initially equal weighting on balance and methodology generates a solution with a high level of both types of balance, with a consequence of a 10.477% “importance gap”, defined as the proportion gap between the maximal feasible level of importance (I^*) and the level of achieved importance. The importance gap is thus given by $\frac{n_1}{I^*}$ *100%. The weight sensitivity analysis described in Section 3.3 therefore explores the trade-off between loss of balance and lowering of the importance gap by examination of the weight points shown in Figure 3, leading to the solutions in Table 1. The three-dimensional nature of the trade-off is demonstrated by the solutions in Table 1. These demonstrate that the conflict between topic balance and importance is stronger than the conflict between short-long term balance and importance. For instance, comparing solutions A and G shows that the importance gap can be reduced from 10.477% to 4.000% whilst maintaining an optimal short-long term balance, but at the cost of an increase in topic imbalance from 1 to 12 (on a scale of 1-15 amongst solutions found). A comparable result between importance and topic imbalance is harder to find; but comparing solutions A and E shows that the importance gap can be reduced from 10.477% to 8.602% whilst maintaining topic balance, but at the cost of increasing short-long term imbalance from 5 to 21 (on a scale of 0-31 amongst solutions found). Solution B demonstrates that to reduce the importance gap to a very low level (0.033%) requires substantive trades in both balance measures.

The considering of balance versus trade-off can be achieved by aggregating the topic and long-short term imbalance measures, each normalized onto a 0-1 scale. Thus a combined imbalance measure, β can be defined as:

$$\beta = \frac{n_2 + p_2}{15} + \frac{\sum_{i=1}^{6} \sum_{j=1,j>i}^{6} \left(n_{ij} + p_{ij}\right)}{31} \tag{15}$$

Where Figure 4 thus demonstrates the trade-off curve between worst of the two imbalance measures β and importance gap $\frac{n_1}{I^*}$ *100%.

Considering the implications of the results for the field of maritime ANA safety and security, the core set of sub-needs that appear under every weight combination in Table 1 has a cardinality of eight (L2B, C1B, T4B, T4C, V2A, V2B, P2A, P2F). The extended set of sub-needs appearing in one or more weight combinations has a cardinality of 25. The sub-needs in the core set demonstrate some technological (L2B, C1B are requests for technologies to combat heat loss, improve accessibility and timeliness of satellite data respectively) priority needs. However, there are also core priority needs in the areas of collaboration and coordination (T4B and T4C are requests for enhanced sharing amongst SAR practitioners and hospitals dealing with emergency incidents respectively) and of standardization and regulation throughout the ANA zone (V2B, P2A and P2F pertain to the standardization of life saving equipment requirements and maintenance schedules, standardized oil spill regulations and the coverage of all ANA vessels by the IMO polar code regulations respectively). Finally, priority sub-need V2B concerns the practical logistics need of ensuring that lifeboats are accessible at all times. Solution A is taken as the baseline, due to its good level of balance and the fact that it is the only solution found by multiple (five) weight sets, thus indicating its appeal to a wider range of potential stakeholders. This adds a further nine sub-needs to the priority set (N1B, N1C, N2B, L3C, C1A, C3A, T3C, V3D, P3A). Adding these sub-needs ensure that a good level of balance is achieved in the priority list. Similar to the core sub-needs, they also contain a mix of technological (N1B, N1C, L3C, C1A, C3A), collaborative (N2B, V3D) and standardization (T3B), as well as an element of training needs assessment (P3A).

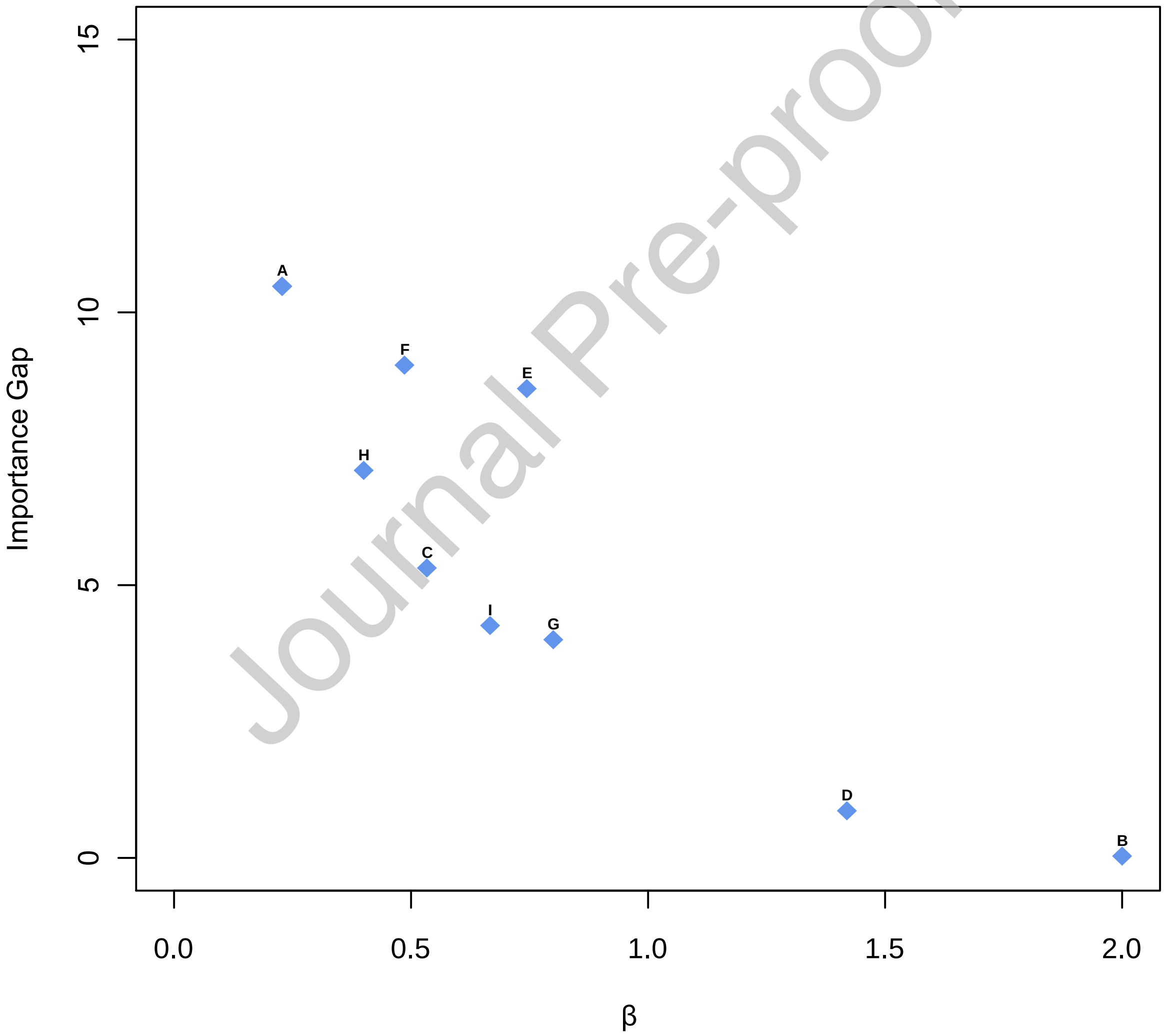

Figure 4: Overall Imbalance versus Importance Gap Trade Off

5. Conclusions

This paper has proposed and utilised a methodology for the mapping and prioritisation of a complex and multi-disciplinary hierarchy of needs for research and innovation across a multi-disciplinary field of application. The specific field of application that inspired the development of the methodology is that of ANA maritime safety and security, where the effects of global climate change have made the necessity of the mapping and prioritisation necessary (ARCSAR, 2021). The novel mapping and prioritisation methodology has allowed the construction of a need hierarchy and a priority list that is balanced with respect to both short-long term research timescales and topics of application. Furthermore, the baseline priority list (A) contained sub-needs relating to technological development, collaboration, standardisation and regulation, logistical and training considerations. This further demonstrates the multi-dimensional nature of research needs in the ANA maritime safety and security field. The weight sensitivity analysis of section 3.3 aids stakeholders in understanding the trade-off between importance and balance when selecting priority sub-needs. The methodology is sufficiently general to be applied to any such field of application. The specific results from the case presented in the paper are essential in the context of guiding the ongoing ARCSAR (ARCSAR, 2021) project and future research and innovation activities in the ANA region. They are also intended to guide future ANA research and innovation agendas on the national and uber-national level. Similar guidance can be expected if the proposed methodology is applied to other multi-disciplinary fields of application.

A limitation of this work is that the expert selected initial sub-needs groupings are limited to the current world-view of the experts consulted at the time, with the mitigating factor that a significant number of experts across different domains were consulted. However, it should be noted future surprise incidents in the Arctic can have a potential for including either additional needs or giving more weights to existing needs. According to Iglesias-Mendoza *et al.,* 2021, a study by Taleb, 2010 provided a simplified but comprehensive means of differentiating Black Swan and Black Elephant events. Black Swan is a term used to describe an event that occurs as a surprise, which is often associated with characteristics such as rarity, extreme impact and retrospective predictability. Conversely, Black Elephant signifies a known event that was ignored. Nevertheless, our proposed methodology provides a mechanism for prioritisation based on current knowledge but is sufficiently adaptive to cope with developments and new knowledge within this, and other, regions based on future experiences.

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Appendix A – Arctic Maritime Safety and Security Sub-Needs

This Appendix gives the List of Arctic Maritime Safety and Security Sub-Needs and their associated codes, which form the lower layer of the classification scheme in Figure 1. The codes are used in Table 1 and Figure 2. Concerning the codes, the first digit is a capital letter that indicates the category according to the Polar Code as detailed in Section 2 (e.g. P= Pollution and Incident Control), the second digit indicates a need level category. The third letter indicates a sub-need within a need category. A full description of need and sub-need categories, together will cross-need connections is given in (Jones *et al.*, 2020).
.

Code	Vessel Structural and Equipment – Sub Need	Code	Life Saving Appliance and Cold and Sea Survival – Sub Need
V1A	Pro-active vessel design and construction to minimise likelihood and impact of emergency incidents	L1A	Research into mapping of actual realistic survival times by category (age, vulnerability, location, conditions)
V2A	Ensuring accessibility of lifeboats/rafts at all times	L1B	More nuanced survival planning with respect to type of vessel and incident
V2B	Standardisation of requirements (including maintenance schedules) for life saving equipment	L1C	Research into human behaviour and decision making when cold
V2C	Enhanced vessel based mass or individual marine rescue equipment	L1D	Research into gap between lab/mannequin tests and ANA realities
V3A	Formation of a “buddy” rescue system for vessels	L2A	Enhanced lifeboat / raft technology and design
V3B	Learning and transference from other sectors (e.g offshore energy)	L2B	Technologies to combat heat loss
V3C	Clarification on points of regulation for vessels	L2C	Technologies to provide water and combat dehydration
V3D	Enhanced collaboration between vessel owners and SAR and industrial stakeholders	L2D	Enhanced flotation suits suitable for ANA conditions
		L3A	Enhanced liaison between industrial developers and SAR practitioners
	Pollution and Incident Control – Sub Need	L3B	Increased numbers of sharing of helicopters to provide adequate coverage
P1A	Autonomous technology capable of operation in dangerous and harsh conditions.	L3C	Collaboration on how to meet “5 day” requirement of polar code
P1B	Technology for detecting oil under ice	L3D	Common training of all crews/workers in ANA in lifesaving/survival issues
P1C	Development of user-friendly “Arctic tool box” for oil spill management		
P1D	Satellite data analysis tools for oil spill management		**Communication – Sub Need**
P1E	Need for enhanced pollution monitoring sensors	C1A	Ensuring sufficient satellite coverage of ANA region
P1F	Enhanced technology for oil recovery under ANA conditions	C1B	Communication Technology to ensure satellite data is accessible within required

			timescale
P2A	Standardised regulations for prevention of oil spill	C1C	AI and data analytics for processing of satellite data
P2B	Enhanced international agreements treatments and commitments relating to nuclear facilities and vessels in the ANA region	C1D	Collaboration between satellite stakeholders to ensure maximal coverage and emergency preparedness and protection against cyber-threats
P2C	Demilitarisation strategies in the Arctic region	C1E	Systems and Training to allow effective satellite data usage by SAR and indigenous communities
P2D	Regulations on heavy oils in the Arctic region	C2A	Broadband coverage of the ANA region
P2E	Further development of international decontamination strategies and technologies	C2B	Technology to allow Improved broadband speed in the ANA region
P2F	Ensuring all vessels covered by Polar Code or similar regulations	C3A	Need for enhanced batteries with longer life for usage in ANA region
P3A	Skills assessment of new competences needed to deal with Arctic pollution incidents	C3B	Technology to allow enhanced communications through water in ANA conditions
P3B	Classification of Arctic pollutants and their consequences	C3C	Multi-national isotope detection system and response protocols
P3C	Research into the effects of a nuclear incident in the Arctic	C3D	Enhanced radio communications coverage
P4A	Pollution risk and incident data sharing and analysis		
P4B	Further definition of acceptable response times		**Personnel, Training and Education Sub-Need**
P4C	Need for prevention measures and protocol for dealing with fire on a nuclear vessel	T1A	Advanced, age appropriate training for crews of vessels (including small vessels)
		T1B	Development of advanced, ANA training materials for SAR teams
	Navigation and Voyage Control Sub-Need	T1C	Training and technology to fill the language gap
N1A	Automated system to avoid and investigate alarms	T1D	Specific training to deal with nuclear incidents
N1B	AI and data analytic tools and apps for advanced ice and route condition forecasting	T1E	Enhanced development of Arctic simulators
N1C	Technology to ensure systems are not weather affected	T1F	Further live exercises to train for different types of incidents
N1D	Emergency port identification system and associated logistics planning	T2A	Age appropriate multi-media technology for emergency situations
N2A	Creation of Navigational ship areas of corridors	T2B	Collection of information from crew and passengers involved in ship abandonments
N2B	Creation of (electronic) platform for sharing past and current ship and route	T3A	Formal certified courses for Arctic crew vessels

	information		
N2C	Resilience plans for navigation in case of Arctic incident	T3B	Regulations to ensure compulsory medical care insurance for all ANA passengers
N2D	Maps that incorporate indigenous community names	T3C	Standardised protocol for incident investigation and implementation of lessons learned
N2E	Dissemination of available technology to all ANA stakeholders	T4A	Enhanced involvement of indigenous partners in SAR activities
N2F	Liaison between product developers and ANA end-users to ensure correctly developed and used technologies	T4B	Enhanced sharing of results of ongoing SAR projects within ANA SAR community
N3A	Assistive drone technology	T4C	Enhanced liaison with hospitals for emergency incident planning
N3B	Enhanced ANA vessel traffic management systems		

Appendix B – Descriptions of Priority Sub-Needs

Sub-Need	Sub-Need Title	Category	Description of Sub-Need
V2A	Ensuring accessibility of lifeboats/rafts at all times	**Implement**	Although the cruise ship will often be the safest place to stay during a serious incident, it is sometimes necessary to evacuate the ship. Proper rescue equipment on board a cruise ship can be crucial in reducing the risk of loss of life. This may be a problem in some situations i.e. if the vessel grounds and starts listing, so that lifeboats are not possible to lower/be used for evacuation. There is a need to look at optimal strategies in this type of situation.
V2B	Standardisation of requirements (including maintenance schedules) for life saving equipment	**Implement**	There are some existing standards for life saving equipment abroad vessels, defined by the IMO Maritime Safety Committee. These would benefit from further analysis and of there functionality in Arctic waters and potentially the development of enhanced or modified standards. Optimisation modelling can suggest necessary and optimal maintenance schedules for life saving equipment on polar vessels.
V3D	Enhanced collaboration between vessel owners and SAR and industrial stakeholders	**Implement**	It can be challenging to establish a joint understanding of a situation during major actions, especially if the SAR agencies and the home offices/vessel owners have not been liaising before. The SAR agencies may also not be aware what kind of capacities the vessels

			have on board and what kind of help could they possibly offer during an incident. There is a need to increase cooperation between the vessel owners, home officer and SAR agencies including visits briefing, and smaller joint exercises, in order to better understand each other's operations and capacities better. Additionally, In the Arctic organisations such as AECO who is a consortium that represents cruise ships operators and owners as well as organise events for table top exercises of simulation (TTXs) help to enhance collaboration and communication among stakeholders. There is a need to sustain and further develop such exercises, and develop other means to enhance collaboration.
L2B	Technologies to combat heat loss	**Implement**	A plethora of innovative personal protective clothing and equipment is available for use in cold environments. However, whether this clothing and equipment can combat heat loss, and meet the minimum 5-day requirement in ANA regions, in both young and older individuals is unknown. Today's requirements for standard rescue equipment are not sufficiently adapted to the conditions that may arise during voyages. In addition, most deaths in older individuals are caused by thrombotic events post cold exposure, possibly linked to skin cooling and dehydration, rather than cold *per se* and this should also to be considered within this need.
L3C	Collaboration on how to meet "5 day" requirement of polar code	**Possible**	The International Maritime Organization (IMO) based regulation, the International Code for Ships Operating in Polar Waters, also known as the Polar Code, was implemented in January 2017. The code enforces various requirements in respect of search and rescue equipment including 'those evacuating from a vessel in distress in polar waters should be able to survive a minimum of five days in the rescue equipment, be it in a lifeboat, a life raft or in equipment arranged on the ice'. In cooperation with several universities and institutions, the Norwegian Coast Guard conducted a search and rescue exercise in 2016 in Svalbard, in order to evaluate this requirement and the usability of the standard survival equipment. The exercise report (Solberg et al. 2016) concluded that, if the expected five-day rescue

			period utilizing the standard SOLAR approved equipment required by the Polar Code is to be fulfilled, the related technology must be developed in order for the equipment to be realistically functional. As the Polar Code is open to interpretation by each vessel operator performing their own assessments, the assessment on is suitable and required may differ across the industries. (Solberg et al. 2016; Ikonen, 2017) There is a need for collaboration between Arctic SAR stakeholders to collaborate and develop protocols to ensure this requirement is fulfilled in all circumstances and territories, and map what the barriers are for why it could not be fulfilled (Kruke and Auestad, 2021).
C1A	Ensuring sufficient satellite coverage of ANA region	**Challenge**	The Arctic satellite connections, broadband, radio coverage and other means of communication are limited due to remoteness and the lack of relevant infrastructure, however satellite coverage around the Arctic areas is increasing rapidly, as more satellites are sent to cover the whole Arctic during the next few years. There is a need to map which satellite services are currently available to Arctic operations and what is still needed, especially from the viewpoint of a smaller operator that is still lacking needed coverage for High North operations.
C1B	Communication Technology to ensure satellite data is accessible within required timescale	**Challenge**	Due to the satellite passings and lack of 24/4 coverage of satellite in the Arctic, there are latencies in receiving satellite data for i.e. navigation, situational awareness, up-to-date ice charts, and ice drift and wind data. Some private operators may be able to provide real-time satellite data however the cost may be a barrier.
C3A	Need for enhanced batteries with longer life for usage in ANA region	**Challenge**	Due to the conditions in the Arctic, which may especially during winter time be very harsh, freezing temperatures affect battery life in various applications i.e. radio communications equipment, phones, drones and other equipment that may be necessary in an emergency situation or for navigation.
P2A	Standardised regulations for prevention of oil spill	**Implement**	More experience is needed to fully understand the limitations in current MER procedures and what plans exist for future standardised procedures in the High Arctic. The Arctic

			Council also already has the MOSPA agreement, with preventative measures. As part of MOSPA, Arctic States have agreed to (i) maintain a national system to promptly and effectively respond to oil pollution incidents, including a minimum level of available oil spill response equipment, training procedures, and communication capabilities; (ii) share information about national authorities to facilitate effective communication across borders in case of an emergency and (iii) assess oil pollution incidents in the Arctic and immediately inform all Parties to the agreement whose interests could be affected.
P2F	Ensuring all vessels covered by Polar Code or similar regulations	**Implement**	The IMO polar code has clear guidelines on the requirements for vessels operating in polar waters in order to ensure their safety. This need concerns regulatory and collaborative advances that are needed to close any loopholes allowing vessels not covered by the polar code to operate unsafely in polar waters.
P3A	Skills assessment of new competences needed to deal with Arctic pollution incidents	**Challenge**	New types of fuel for shipping are constantly being developed and this poses challenges to the oil spill authorities, as they need to be aware of the behaviour and consistence of these new fuels. Some also behave very differently in cold conditions. There is a need to know what kind of skills, competence and knowledge the responders and operational coordinators need in order to respond to the challenges of oil spills in the ANA region. Additionally, R&D on the field is needed to keep up the pace with these changes to respond to MER (Marine Environmental Response) incidents efficiently. In addition, knowledge on the topic combined with contextual knowledge is necessary to conduct operations without exposing SRUs (SAR responding units) to unnecessary hazards and guarantee the continuity of the SAR system.
N1B	AI and data analytic tools and apps for advanced ice and route condition forecasting	**Challenge**	A principal challenge for vessels in the Arctic is the existence of, and hence navigation through, different forms of ice. Advances in artificial intelligence and data analytics have allowed for the better prediction of meteorological conditions, and of ice flows and formations. However, this information needs to be brought to a sufficient technology readiness level and availability whereby it can be effectively used to inform vessel future Arctic routes with greater accuracy and hence safety as well as to swiftly direct SAR responding units towards operation areas and avoiding unwanted

			situations while operations are ongoing.
N1C	Technology to ensure systems are not weather affected	**Challenge**	Due to the cold conditions, especially in the Arctic region, icing often occurs on board vessels and communications infrastructure on land. This may affect the navigational systems. There is a need to ensure that i.e. ice accumulation prevention on antennas are in place.
N2B	Creation of (electronic) platform for sharing past and current ship and route information	**Challenge**	With the current and projected increase of vessel traffic in the polar region due to climatic change, there is a need for an enhanced system of recording and sharing ship and route movements through and between Arctic territories. Advances in artificial intelligence also allow for the measurement of risk and the detection of anomalies indicating potentially dangerous and/or unsafe vessel behaviours to be built into a future electronic platform.
T3C	Standardised protocol for incident investigation and implementation of lessons learned	**Challenge**	Most ANA emergency preparedness and response organizations have their own systems and procedures for logging after action reports from incidents and exercises and identifying follow-up actions however as of yet, there are no ANA-wide standards available for emergency response agencies on exercise/incident reports, as well as SOPs for implementing lessons learned from major cases in the region. There is a demand for a systemised effort for pulling out key lessons learned from a common system. A significant problem in terms of lessons learned as outcome of an incident investigation is that at an individual level, the motive of learning is sometime not clear, especially when the main aim of being involved in such investigation is to avoid blame. There are also external influences such as budgetary and time constraints that may hinder implementations of lessons learned.
T4B	Enhanced sharing of results of ongoing SAR projects within ANA SAR community	**Implement**	There are a variety of SAR related projects in the ANA region and each producing reports or results. There is a need to establish a systematic approach as to how will the results from SAR projects reach the wider ANA SAR community, and how will the SAR organizations actually learn from the results. This involves existing fora and should use terminology common to the SAR community. This will offer opportunities to share best practices, develop

			advanced technologies for SAR and situation awareness, and enhance existing skills capabilities through organisation of TTX and LivEX simulation exercises.
T4C	Enhanced liaison with hospitals for emergency incident planning	**Implement**	In case of an Arctic mass-casualty incident, there needs to be a pre-planned clear line of communication and logistics planning between healthcare providers, the local communities and the SAR responders. This plan should consider the need to remoteness and limited capacity of healthcare facilities in some Arctic territories, and hence the potential need to utilise facilities across multiple territories.