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AN ARCTIC ENVIRONMENT READINESS MODEL FOR QUANTIFYING THE IMPACT OF EXTREME ARCTIC WEATHER ON SYSTEM READINESS

by

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December 2021

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13. ABSTRACT (maximum 200 words)

The Arctic region offers significant opportunities for the U.S. military to expand its footprint, but the geographical location and harsh climate pose challenges to operational expansion in this region. To aid decision makers in assessing the impact of these conditions on readiness of equipment and the feasibility of operational expansion in the Arctic, this thesis develops an Arctic Environment Readiness (AER) model.

A case study of a flotilla of ships is used to illustrate how the AER model can estimate readiness and to what degree various factors (such as logistic delay time, temperature, and the addition of a port) impact fleet readiness. The developed model is not only shown capable of quantifying and plotting fleet readiness along a specific route but also scalable and flexible. It can accommodate multiple variables to assess their impact on fleet readiness and allows investigation of requisite maintenance capabilities at a port, which can aid in optimizing port effectiveness and available resources.

Although the developed AER model successfully uses a Design Structure Matrices approach to quantify readiness in the design and planning phases, it was limited by a lack of available operational data. With such data in follow-on work, a corresponding model could be developed for different weather conditions and operating environments.

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AN ARCTIC ENVIRONMENT READINESS MODEL FOR QUANTIFYING THE IMPACT OF EXTREME ARCTIC WEATHER ON SYSTEM READINESS

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ABSTRACT

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LIST OF ACRONYMS AND ABBREVIATIONS

A_o	Operational availability
ADT	Administrative delay time
AER	Arctic Environment Readiness
CTE	Coefficients of thermal expansion
DOD	Department of Defense
DSM	Design Structure Matrix
FMEA	Failure Modes & Effects Analysis
FMECA	Failure Modes, Effects & Criticality Analysis
IRL	Integration Readiness Level
LDT	Logistics delay time
MDT	Maintenance downtime
MTBF	Mean time between failure
MTBM	Mean time before maintenance
PoF	Physics of Failure
RAM	Reliability, availability and maintainability
SR	System readiness
SRL	System readiness level
TRL	Technology Readiness Level

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EXECUTIVE SUMMARY

The Arctic region offers significant opportunities to expand the military's operational footprint. Yet, despite operating in the Arctic region for about 100 years, the military continues to confront climate challenges posed by the Arctic, slowing the expansion of operations within the region. Exposure to the Arctic's harsh environment causes failures (e.g., fuel and oil freeze), poor communication, and limited movement of the systems. From a military standpoint, the Arctic region offers a tactical advantage by providing a power projection platform, which is critical to both economic and national security. In addition, depending on the destination, setting up an operational port in the Arctic region may reduce the distance traveled, saving resources such as fuel and time to travel, as well as provide access to previously untapped resources such as energy and food.

In this thesis, we propose the development of an Arctic Environment Readiness (AER) model that quantifies and plots fleet readiness along the route to enhance decision making. The AER model utilizes Design Structure Matrices (DSM) and reliability, availability, and maintainability (RAM) factors such as failure rate, mean corrective and preventative maintenance, mean time between maintenance (MTBM), operational availability, etc. The model provides insights for (1) managing a fleet readiness, (2) examining the impact of infrastructure development, and (3) investigating requisite capabilities at the port. In addition, the model is expandable to examine other factors to derive a more accurate estimate.

The methodology consists of three main steps: (1) Develop the AER model to calculate the respective ships' operational availability, which would then be translated into the fleet readiness. (2) Apply the DSM to represent the route map of the flotilla of ships in the form of a square matrix. This would also facilitate the assessment of the impact to readiness due to environmental factors and infrastructure development. (3) Analyze the DSM result in terms of the daily readiness shown in the route taken by the fleet.

In this study, the AER model is made up of multiple layers of DSMs, namely the geographical, system, environmental, and reliability DSMs. Within each DSM, the related factors are stored in their respective DSM databases, and they are interconnected to one another through equations. For example, the geographical DSM would consist of the location and distance factors, while the RAM Factors DSM would consist of the RAM factors, such as maintenance downtime (MDT), MTBM, logistics delay time (LDT), administrative delay time (ADT), etc. Setting up the AER model this way allows the model to be scaled and facilitates the study of individual factors within the DSMs and helps to understand their impact on readiness.

Next, maintenance-related data are collected and input into their respective DSMs to facilitate the calculation of operational availability [1]. This would then translate to readiness, which is defined as the average operational availability of the fleet.

A case study of a flotilla of ships is used to illustrate how the AER model estimates readiness and examine the impact of different factors (LDT, temperature, and the addition of another port). The case study demonstrated that the AER model can successfully estimate fleet readiness and the effect on readiness when the variables change. The AER model identified that the LDT variable has a more significant influence on fleet readiness as compared to the temperature variable.

Additionally, increasing the number of ports would improve fleet readiness due to the increased flexibility for the fleet to dock for maintenance and resupply purposes. The model also explored how equipping different ports with different levels of maintenance capabilities would impact fleet readiness.

While the AER model presents a DSM approach to quantify readiness during the design and planning phases, it is limited by the lack of readily available operational data to develop a corresponding AER model for different conditions, such as weather and system operating environment. There are many factors that can influence fleet readiness, but not all factors affect fleet readiness equally. To account for this inequality, a weighted approach can be implemented for different variations of the AER model.

In conclusion, the paper presents a model that quantifies and plots fleet readiness along the route to enhance decision making. The AER model is scalable and flexible to include and examine multiple variables as well as their impact to readiness. The model is also able to investigate the requisite maintenance capabilities at the port to increase the effectiveness of the port and optimize the available resources.

References

[1] B. S. Blanchard and W. J. Fabrycky, *Systems engineering and analysis* (5th Edition), Upper Saddle River, NJ: Pearson Prentice Hall, 2011.

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I. INTRODUCTION

The Arctic region offers significant opportunities to expand the military's operational footprint. Yet, despite operating in the Arctic region for about 100 years, the military continues to confront climate challenges posed by the Arctic, slowing the expansion of operations within the region. Exposure to the Arctic's harsh environment causes failures (e.g., fuel and oil freeze), poor communication, and limited movement of the systems. While these climate challenges will need to be addressed, the immediate challenge of limited maintenance capability has to be explored first. The spectrum of maintenance tasks performed on a system often requires specialized equipment currently unavailable in the Arctic regions, stunting any sustained expansion into that area.

The Arctic region offers a tactical advantage by providing a power projection platform for the United States from a military standpoint, which is critical to both economic and national security. In addition, depending on the destination, setting up an operational port in the Arctic region may reduce the distance traveled, saving resources such as fuel and time to travel, as well as provide access to previously untapped resources such as energy and food. This would also prevent other nations from asserting or expanding control in the Arctic region to support their claims of the area for their benefit. By maintaining a substantial presence in the Arctic region, the U.S. military would mitigate the risk of conflict and ensure peace in the region, which is beneficial to all nations on a global scale.

While the Arctic region offers significant opportunities and strategic benefits, currently there is a lack of methodology for the identification and assessment on the feasibility of building a port in the Arctic. In addition, there is also limited research with regard to the environmental and geographical impact on the readiness of military equipment. The lack of substantial research meant that we are unable to fully exploit the operational benefits of the Artic region in a timely manner. To address the limited research on this area, this project aims to develop an Arctic Environment Readiness (AER) model that includes the standard factors used in the Department of Defense (DOD) for reliability, availability, and maintainability (RAM). Example of the factors considered include failure rate, reliability, mean corrective and preventative maintenance, number and type of spares, mean time between maintenance (MTBM), maintenance downtime (MDT), operational availability, etc. Once the model is developed, it can be utilized to examine the impact of infrastructure development. The impact is shown relative to the improvement on readiness and on the potential posed by the increased range available to the systems operating in the Arctic.

In this thesis, we propose a model that quantifies and plots the fleet readiness along the route to enhance decision making. The AER model is based on Design Structure Matrix (DSM) and RAM factors. The model provides insights into (1) managing a fleet's readiness, (2) examining the impact of infrastructure development, and (3) investigating requisite capabilities at the port.

To demonstrate the feasibility of the proposed AER model, a case study of a flotilla of ships is used to illustrate how the AER model can estimate readiness and to what degree various factors (such as logistic delay time, temperature, and the addition of a port) impact fleet readiness. The developed model is not only shown capable of quantifying and plotting fleet readiness along a specific route, but also scalable and flexible. It can accommodate multiple variables to assess their impact on fleet readiness and allows investigation of requisite maintenance capabilities at a port, which can aid in optimizing port effectiveness and available resources.

The subsequent chapters of this thesis are structured as follows: Chapter II reviews the concept of readiness, and past researches on system failure modes. Chapter III describes the methodology and the development of the AER model. The chapter also explains the application of the model. Chapter IV presents a case study to illustrate how the AER model is used to predict fleet readiness and determine the effectiveness of building an additional port. In addition, the chapter explains the results and analysis with the use of five different test cases. Chapter V discusses some of the limitations of the methodology and recommendations for future works. Finally, Chapter VI summarizes the findings of the thesis and presents the conclusion.

II. LITERATURE REVIEW

Readiness is a word commonly used in the military context in reference to highly operational units, such as ambulance services and emergency response teams. The Oxford Dictionary defines readiness as “the state of being ready or prepared for something” [1]. With this definition in mind, it is worth noting that there is a difference between having an asset and being able to utilize it. While having or owning an asset will provide some form of deterrence, it is the readiness to deploy it at a split second that will determine the outcome of the battle. Therefore, it is of great importance to ensure assets are maintained at a high readiness state continuously and that they are ready to respond within a short time frame.

A. READINESS

Despite the prevalence of articles related to readiness, research conducted specifically on readiness in the Arctic region is limited. This is due to the fact that readiness has to be context specific and deployments to the Arctic are often hindered by the climate that impede the collection of data. One of the most closely related studies that addresses operational readiness centered on the System Readiness Level (SRL), which was proposed by Sauser et al. [2]. Sauser et al. developed the SRL index that associates Technology Readiness Level (TRL) [3] and Integration Readiness Level (IRL) [4] to map readiness across different maturity states of the system, which is accomplished by converting qualitative narrative into quantitative metrics. Additionally, McConkie et al. [5] formulated a mathematical model to facilitate decision making by calculating the SRL developed by Sauser et al. Their study illustrated that for the SRL model to be valid, additional mathematical properties are recommended, and further research is required as the current model could achieve misleading results.

In Edouard Kujawski’s analysis and critique of the SRL article, he argued that SRL is fundamentally flawed as the calculated SRL may not truly represent the actual SRL of the system, especially when the system comprises multiple subsystems at different TRL and IRL [6].The article cautioned against using the SRL to make decisions due to the misleading metrics, which may possibly lead to negative outcomes.

In another study, Tetlay and John defined

> System Readiness (SR) [as] the validation and Boolean (either the system is “ready” for use or not) aspect of the system development and overall life cycle and occurs after System Maturity, i.e., the system must first be fully “mature” before it can be made “ready” for use. The process starts from User Requirements and finishes at System Validation. System Readiness determines whether or not the system is now “ready” for use in its intended operational environment. Therefore, System readiness is context dependent. To achieve System Readiness the System must be validated against the User Requirements, i.e., you will achieve SR by building the right system for a given context. [7].

It should be noted that SR is highly context dependent and multidimensional, as well as closely related to defining system maturity in the operational system level context. The SR refers to the complete design process and how well the design process was executed. In contrast, the readiness in this work focuses on the system during its operation phase and the required resources to keep it operating. Thus, it is not useful to utilize the SRL as the basis for the AER model in this study.

Availability, the second RAM factor, is defined as “suitable or ready for use” [8], which is utilized here to derive readiness as the context of being ready, which is similar to readiness. According to Blanchard Fabrycky’s 2014 *Systems Engineering and Analysis*, availability can be expressed in three different forms, namely inherent availability, achieved availability, and operational availability [9].

Inherent availability is derived from the design of the equipment. It is “the probability that a system or equipment, when used under stated conditions in an ideal support environment (i.e., readily available tools, spares, maintenance personnel, etc.), will operate satisfactorily at any point in time as required” [9]. It includes corrective maintenance and excludes preventive maintenance, logistics delay time (LDT), and administrative delay time (ADT).

Achieved availability is similar to inherent availability and is the achieved level of performance that the equipment is ready for use. It is also “the probability that a system or equipment, when used under stated conditions in an ideal support environment (i.e., readily available tools, spares, maintenance personnel, etc.), will operate satisfactorily at any point in time as required" [9]. Nevertheless, although it includes both corrective and preventive maintenance, it ignores LDT and ADT.

Operational availability is the actual availability of the equipment working in its intended operating environment over a period of time. It is "the probability that a system or equipment, when used under stated conditions in an actual operational environment (i.e., readily available tools, spares, maintenance personnel, etc.), will operate satisfactorily at any point in time as required" [9]. It takes into consideration corrective maintenance, preventive maintenance, LDT, and ADT. The operational availability is selected as the definition of readiness as the study examines operational data to estimate the fleet readiness and accounts for corrective maintenance, preventive maintenance, LDT, and ADT.

Additionally, the fleet readiness is expressed in terms of probability, and it changes as the fleet travels along its route. This is a representation of the Markov model for systems that exhibit probabilistic movement over a period of time and change from one state to another. It is utilized to examine the probabilities of future events by analyzing the current known probabilities [10], [11].

In order to address readiness in the Arctic region and enable the model to be expandable to handle the multidimensional aspects and complexity of the Arctic environment, an AER model using the Design Structure Matrix (DSM) is proposed in this study. The AER model defines readiness based on the average operational availability of the fleet, taking into consideration RAM factors that include failure rate, reliability, mean corrective and preventative maintenance, and so forth, as well as environmental factors such as temperature, wind, and fog conditions and many more. For illustration purposes, the study focuses on the three selected variables (1) temperature, (2) LDT, and (3) number of ports, as well as various RAM factors to demonstrate their impact on readiness.

B. FAILURE MODES

Mean time between failure (MTBF) plays a major role in the calculation of availability, which affects readiness, and MTBF can be influenced by the failure mode due to a change in the operational environment. Every component, equipment, or device has its own share of failure modes and probability of failure, due to their manufacturing process, functionality, materials used, etc. By studying and predicting the type and probability of failure modes that are likely to occur for various types of equipment in the Arctic, it is possible to produce a more accurate AER model and improve decision making.

Various methods and tools have been developed to predict and analyze the failure modes of a system and its associated components. Failure Modes & Effects Analysis (FMEA) and Failure Modes, Effects & Criticality Analysis (FMECA) are common techniques used during reliability evaluation to assess risk [12], [13], [14]. In addition, research has investigated how to model failure propagation during conceptual design with the goal to predict failure propagation pathways and their likelihood of occurrence [15], identify failure modes, predict system reliability [16], [17], and common cause failures that propagate through the environment [18], and determine the impact of failures on the system's operation [19]. This work is focused on the design process where the results are used to improve the system itself. In contrast to the work in this manuscript, the focus is on assessing the system and improving the resources related to its readiness.

Studies were also conducted to assess the correlation between temperature and the reliability of both mechanical and electrical components [14]. Temperature induces stress on an item and propels it towards failure. While some items are impacted less, those that are affected by extreme temperatures often deteriorate at the material level. The mismatch between two coefficients of thermal expansion (CTE) is a major known cause of failure. Imagine two materials attached together, shrinking and expanding as the diurnal temperature rises and drops. The attachment between the two materials is a boundary condition, which requires that both expand equally at that point. If CTEs are different and the same temperature fluctuation is experienced by both materials, the two will stress one another at that boundary point. This stress will eventually lead to failure of the material. According to Dobržinskij, the reliability of internal combustion engines can be influenced by the climate and operating conditions [20]. Similarly, other articles supported that the reliability of electronics and electrical components is affected by temperature [21], [22], [23].

Each factor is complicated and challenging by itself, and when they combine, it increases the complexity of the problem. Hence it is recommended to include a scaling factor with regard to failure modes and factors affecting the MTBF, as there are different approaches to refine and improve the model. There are many potential models that can be used to refine the AER model, depending on the factors considered and the model’s intended application [24]. In this study, we include the temperature factor to explore the impact on availability using the Arrhenius model, while assuming other failure modes to be equal and constant [22], [25]. Beside simplifying the AER model for illustration purposes, it also demonstrates that the model is expandable and other variables can be added to solve a complex problem.

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III. METHODOLOGY

This chapter explains the methodology utilized in this research. To achieve this, a case study of a flotilla of ships is used to demonstrate the ability of the methodology to predict the readiness of the fleet. The method involves three main steps: (1) Develop the AER model to calculate the respective ships' operational availability, which can then be translated into the fleet readiness. (2) Apply the AER model for different weather and operating conditions. This can also facilitate the assessment of the impact due to environmental factors and infrastructure development. (3) Analyze the result, which is a DSM that reflects the daily readiness as shown in the route taken by the fleet.

A. DEVELOPMENT OF THE AER MODEL

The AER model can be identified by its two main functions, create the datum and assess the impact of additional factors. As summarized in Figure 1, development of the AER consists of (1) defining the DSMs, (2) building the sublayer matrices, and (3) connecting the interactions between the different layers.

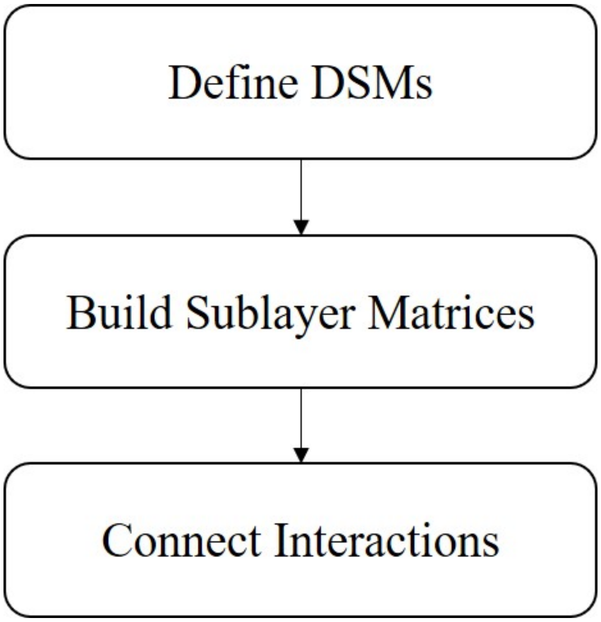


Figure 1. AER Model Development

1. Define the DSMs

a. Design Structure Matrix (DSM)

According to *Design Structure Matrix Methods and Applications*, the DSM is a modeling tool that is useful “to represent the elements comprising a system and their interactions, thereby highlighting the system’s architecture (or designed structure)” [26]. The book mentioned that while there is exponential information growth in today’s world context, there are limited processing capabilities within each individual. Even with a team effort and a group’s shared knowledge, the probability of error continues to rise with the increasing amount of information requires processing. The DSM was developed to handle large amounts of information and manage complexity, and it is suitable in applications of engineered systems and engineering management. The DSM is a highly flexible tool that showcases the interactions between different elements within a system, as well as scalability to combine different system architectures to show how they are interconnected in the larger system [26].

In this study, the AER model is made up of four main layers of DSMs, namely the geographical, system, environmental, and reliability DSMs, as shown in Figure 2. The related factors are stored within the main matrices, and if they require calculation, they are stored in the forms of sublayer matrices or in databases if they are numeric data. They are interconnected to one another through equations. For example, the geographical DSM would consist of the location and distance factors, while the RAM factors DSM would consist of MDT, MTBM, LDT, ADT, etc. The result of the AER model is the fleet readiness matrix, which is output for interpretation and analysis to assess the impact of the factors input into the model on readiness.

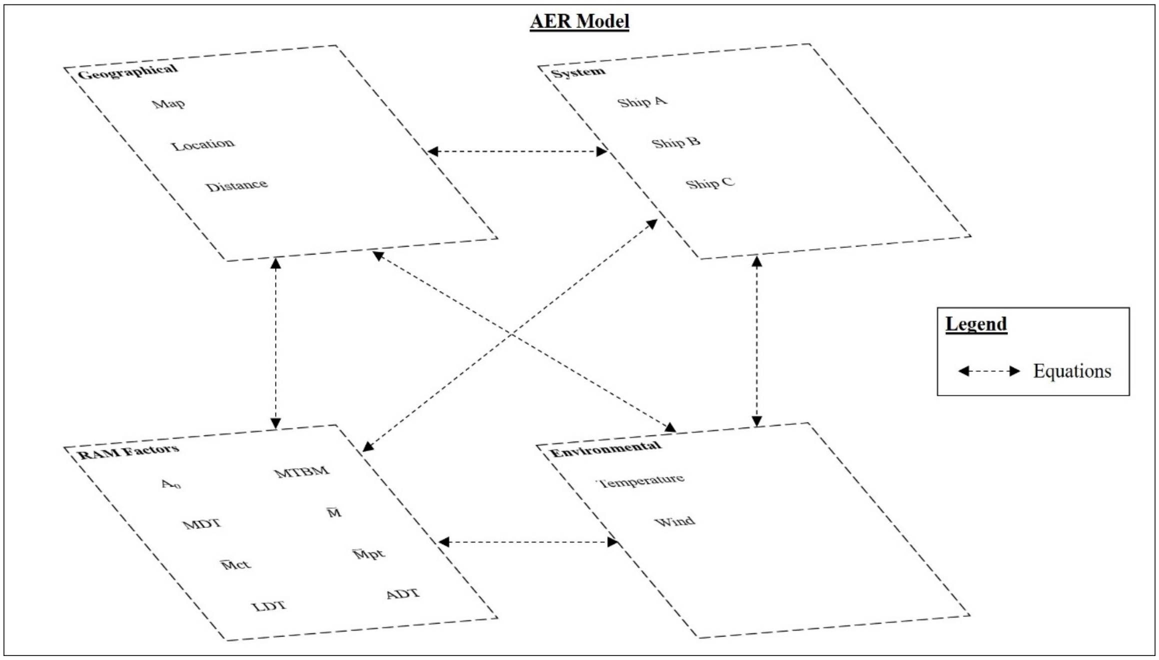


Figure 2. Overall AER Model Architecture Diagram

2. Build Sublayer Matrices

a. Geographical DSM

The foundation of the AER model is determined by the geographical DSM, which consists of a map and the port locations that are input to derive the distance of the fleet from the ports and stored in its matrix. The distance can also be translated into LDT, which is a function of distance. These integrate with other factors and matrices to form the AER model.

A 10 by 10 square matrix is used to represent a 100-cell mini map for the purpose of illustration, and the x-axis and y-axis of the map are labeled from 0 to 9 as shown in Figure 3. Next, the ports are identified and stored in the location matrix. For this case, the starting port and destination port are represented by cell coordinates (0, 7) and (9, 2), respectively. The fleet is simulated to travel from the start point to the end point, and the distance traveled is measured from the midpoint of the cell to the midpoint of the destination cell (time taken to travel from one cell to another is 24 hours measured in the horizontal or vertical direction). The fleet will always take the shortest route, and the distance traveled is measured using Pythagoras's theorem [27].

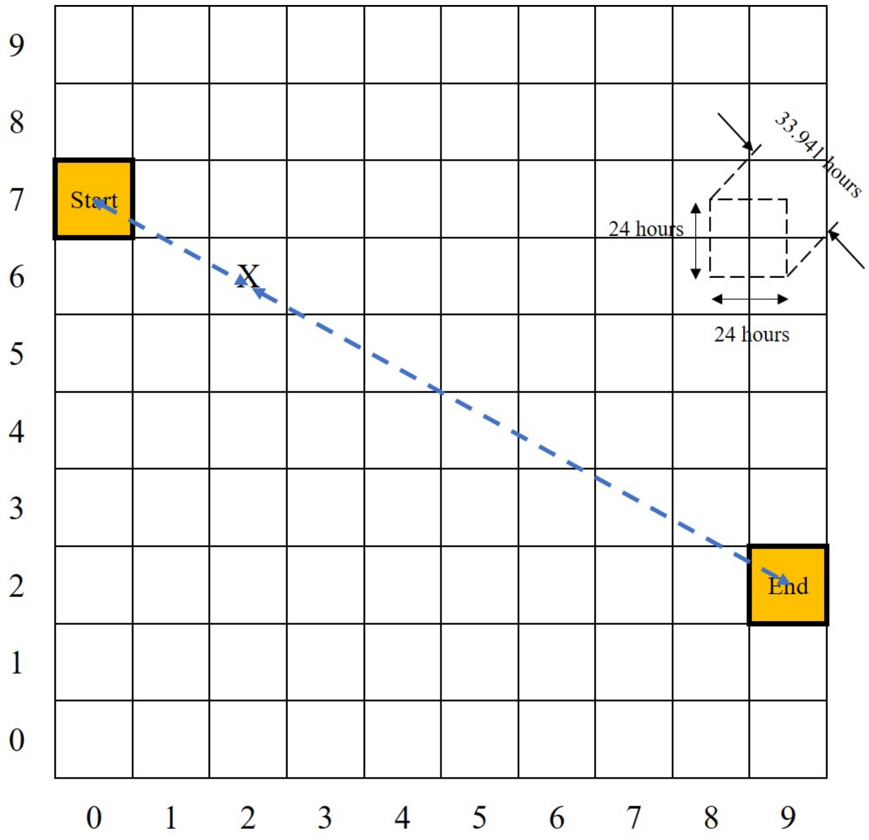


Figure 3. DSM Mini Map

In this case, the ports are situated at the points of interest, which are the start and end points, and the ports are where the fleet can dock for resupply and maintenance activities. There are different actions a fleet can take when a ship needs repairs: (1) travel to the next closest port for repair, (2) request the delivery of a replacement part from the closest port to the fleet, or (3) wait for a tow and get towed to the closest port for maintenance activities. The distances for (1) and (2) are equal, while the distance for (3) is double. Taking into consideration the worst-case scenario that a tow is required, the longer distance is selected as it is a more conservative approach. LDT is calculated from the closest port to the current location and multiplied by two, due to the distance required by the tugboat to travel from the nearest port to the ship location and back to the port. As shown in Figure 3, assuming that one of the components on the ship broke down at coordinates (2, 6), the LDT is the time taken from current location to the start point as it is the closest port as compared to the end point and is multiplied by two.

b. RAM Factors DSM

The RAM factors are stored in the sublayer matrices. They are made up of basic RAM factors, such as failure rate, frequency of preventive maintenance, mean corrective maintenance time, and mean preventive maintenance time, to derive the higher order RAM factors that include operational availability, mean time before maintenance, and maintenance downtime. The higher order RAM factors can be derived from the following equations:

(1) Readiness

Readiness is defined as the average operational availability of the fleet. The readiness of the fleet is expressed as:

$$Readiness = \frac{\sum_{i}^{n} A_{oi}}{n} \tag{1}$$

It is practical to set a figure for readiness as this will act as the baseline requirement for decision making. For example, 0.8 would mean the fleet needs to maintain a readiness of 80% throughout the journey from start to end. In addition, while the average operational availability of the fleet has just been defined as readiness, another possible way to express readiness is based on the lowest operational availability of the fleet. However, this method can over-constrain the whole system design and sub-optimize the solution, resulting in inefficient use of resources as more ports than necessary would be built. Nonetheless, even if the readiness met the baseline requirement, it is important to compare respective ships' operational availability to ensure they do not differ by too much and result in an unbalanced fleet.

(2) Operational Availability (A_o)

Operational availability is expressed as [9]:

$$A_0 = \frac{MTBM}{MTBM + MDT} \tag{2}$$

(3) Mean Time Before Maintenance (MTBM)

MTBM is the average time between all maintenance actions, consisting of both scheduled and unscheduled maintenance activities and can be expressed as [9]:

$$MTBM = \frac{1}{\lambda_{sys} + fpt_{sys}} \tag{3}$$

(4) Failure Rate (λ_{sys})

Failure rate is defined as “the rate at which failures occur in a specified time interval” [9]. The failure rate per hour is expressed as:

$$\lambda_{sys} = \frac{1}{MTBM_u} \tag{4}$$

where $MTBM_u$ is the mean time between all unscheduled (corrective) maintenance and it should be estimated to be equal to MTBF, taking into consideration of all failure modes and defects [9].

(5) Frequency of Preventive Maintenance (fpt_{sys})

The frequency of preventive maintenance is defined as the “rate at which preventive actions are taken per system operating hour” and can be expressed as [9]:

$$fpt_{sys} = \frac{1}{MTBM_s} \tag{5}$$

where $MTBM_s$ is the mean time between all scheduled (preventive) maintenance [9].

(6) Maintenance Downtime (MDT)

As described in *Systems Engineering and Analysis*, MDT is the total time taken to repair and recover a non-functional system to its full operational state, as well as to maintain an operational system at its specified state of performance [9]. It includes LDT and ADT, and is expressed as:

$$MDT = \bar{M} + LDT + ADT \tag{6}$$

(7) Mean Active Maintenance Time ($\bar{\text{M}}$)

Mean Active Maintenance Time is the mean time taken to perform maintenance activities, both scheduled and unscheduled maintenance [9]. It does not include LDT and ADT, and is expressed as:

$$\bar{M} = \frac{\lambda_{sys}(\bar{M}ct) + fpt_{sys}(\bar{M}pt)}{\lambda_{sys} + fpt_{sys}} \tag{7}$$

(8) Mean Corrective Maintenance Time ($\bar{\text{M}}$ct)

Corrective maintenance comprises of all maintenance activities needed to repair or recover a non-functional system to full operational state and is expressed as [9]:

$$\bar{M}ct = \frac{\sum(\lambda_i)(Mct_i)}{\sum(\lambda_i)} \tag{8}$$

(9) Mean Preventive Maintenance Time ($\bar{\text{M}}$pt)

Preventive maintenance comprises of all maintenance activities needed to maintain an operational system at its specified state of performance, and is expressed as [9]:

$$\bar{M}pt = \frac{\sum(fpt_i)(Mpt_i)}{\sum(fpt_i)} \tag{9}$$

(10) Logistics Delay Time (LDT)

Logistics delay time is the time taken for replacement parts to be delivered for maintenance activities, and includes the waiting time for facilities and equipment to be available for use, and it plays a major role in MDT [9]. It is expressed as:

$$LDT = \frac{\lambda(LDT_u) + fpt(LDT_s)}{\lambda + fpt} \tag{10}$$

where LDT_u and LDT_s are the logistics delay time for unscheduled and scheduled maintenance, respectively.

(11) Administrative Delay Time (ADT)

Administrative delay time is the time taken to perform administrative work (such as assigning of personnel, ordering of replacement parts, etc.) to facilitate maintenance activities [9]. It is expressed as:

$$ADT = \frac{\lambda(ADT_u) + fpt(ADT_s)}{\lambda + fpt} \tag{11}$$

where ADT_u and ADT_s are the administrative delay time for unscheduled and scheduled maintenance, respectively.

c. System DSM

The system DSM consists of the hierarchy of the fleet and the respective components within each ship. It also documents whether the components are placed in series or in parallel as this will affect the availability of the ship. The system DSM facilitates the calculation of an individual ship's operational availability to derive the final outcome, which is the fleet readiness.

d. Environmental DSM

The model utilizes the environmental matrix to include components' failure rates that are dependent on other factors, such as temperature and wind conditions, and feeds the results back to the model. This would facilitate the study of the impact of individual factors and allow scalability of the AER model. The following paragraphs explain some of the environmental factors that can affect the fleet readiness.

(1) Harsh Arctic Environment

Besides the RAM factors that have a significant impact on fleet readiness, readiness is also dependent on the weather and operating conditions. The operating environment in the Arctic is heavily influenced by the climate, especially temperature, wind, fog, and darkness:

- Temperature: The geographical location of the Arctic region prevents it from receiving much direct sunlight and results in low temperatures throughout the year. The daily average temperature varies from -40°C to 10°C and the temperature fluctuates across the months [28]. Additionally, the ocean temperature can drop as low as -1.7°C [29]. These low temperatures add stress on the equipment and can impact reliability.

- Wind Conditions: High intensity winds are another feature of the Arctic region. In the event of a Polar Low, sudden strong winds can occur and change direction at will [30].

- Fog Conditions: Fog is formed under different conditions; for example, advection fog appears mainly in the summer when warm air travels across the cold water [31]. In addition, fog conditions are common and can appear up to 25 times in a month, which may hinder work getting done due to low visibility [31].

- Darkness: Another factor that impacts visibility is the lack of sunlight in the Arctic. The Arctic is characterized by the minimal amount of sunlight it receives due to the low angle of the sun. Depending on the latitude, the Arctic region can experience darkness for extended periods of up to six months [32].

Besides the climate, the ocean itself also poses challenges in the form of waves and icebergs.

- Waves: Due to the strong winds and ocean currents, waves are formed and can reach a height of 4 to 5 meters. The open sea provides the stage and opportunity for the waves to build up momentum to create huge waves, which are potential hazards to floating bodies [33].

- Icebergs: Global warming expedites the formation of icebergs as they break away from the glacier fronts [34]. While icebergs vary in size, the larger icebergs pose a threat to floating bodies due to their volume and strength.

Icing is another factor that contributes to maintenance challenges, and in the worst-case scenario, a vessel may capsize due to instability caused by the buildup of ice [35]. Icing is triggered by both environmental factors and vessel characteristics, and the effect is particularly prominent during periods of low air and water temperatures and when high wind speeds are present [36].

Furthermore, the lack of infrastructure in the Arctic region heavily impacts the rate and quality of maintenance activities. Homlong et al. explained that the lack of well-developed infrastructure such as well-equipped ports limits the ability to repair and perform maintenance activities, and skilled workers are less likely to work in harsh environments [37]. The article also noted that without well-developed infrastructures, it takes more time to replenish supplies, and personnel are unable to react promptly to the fast-changing climate.

In addition to environmental factors, human factors play a vital role in operational safety and system performance. According to Homlong, to observe in detail and identify how people perform and accomplish a certain task, task analysis is carried out to breakdown and analyze both physical and mental activities [38]. Specifically, he analyzed the impact that the Arctic environment has on personnel, and those effects include reduction in cognitive abilities, as well as a decrease in sensitivity, agility, and psychomotor skills. Homlong's article also examined other scientific studies that show effects of poor decision-making skills, as well as the inability to maintain the presence of mind and attentiveness in this environment. This can increase not only the probability of accidents occurring, but also damage to muscles and tissues due to the personnel's reduced ability to perceive pain [39]. Prolonged exposure to harsh weather also increases the risk of hypothermia and frostbite injuries, resulting in loss of manhours. Homlong's research identified the additional strain on maintenance personnel due to the harsh environment. This results in the consumption of more resources, such as longer preparation and maintenance time, as well as the need for special training, personal protective equipment, and tools.

Meanwhile, the demands for ship maintenance, towing and salvage services, as well as deepwater ports are growing, but there are not enough facilities and ports to keep up with these demands [40]. Building and establishing an Arctic port has its own set of challenges as compared to building ports in other parts of the world. According to Panahi et al. despite the fact of increasing movement and activities in the Arctic, there has been limited research conducted on ports and related infrastructures [41], [42], [43]. Panahi et al. stated that there is a knowledge gap in understanding the full aspect of what the Arctic can provide, as well as a lack of expertise in building ports and infrastructures in the Arctic because so few studies have been conducted on this topic [44].

Another obstacle to port building is the ever-changing geographic features of the Arctic due to global warming and melting ice caps [34]. Furthermore, inaccessibility is another problem caused by the remote location and harsh climate of the Arctic, which greatly reduces the likelihood of attracting human resources and expertise to manage, build, and work at the ports [41], [45], [46].

To add complexity to these environmental and human factors, countries situated in the Arctic circles have their own considerations and objectives; some emphasize conserving the environment, while others are focusing on mining natural resources and developing defense capabilities and bases [41]. Panahi et al. also highlighted the possibilities of political challenges when it comes to building ports and infrastructures as such projects involve joint or multi-national collaboration. Nevertheless, the Arctic is of great strategic value in terms of resources, tourism, and defense and security [47], [48], [49]. In summary, the weather and environmental factors can impact fleet readiness, while the different aspects of port building contribute to the challenge of infrastructure and capabilities development.

Table 1 summarizes the inputs and outputs of the sublayer matrices to obtain the final output of the AER model, which is the fleet readiness and readiness plot.

Table 1. Inputs and Outputs of AER Model

DSM Description	Input	Sublayer Output	AER Output
Geographical	Map	Distance & LDT	Fleet Readiness & Readiness Plot
	Port coordinates		
RAM	$\bar{M}$ct	MTBM, MDT, $\bar{M}$	
	$\bar{M}$pt		
	$MTBM_u$		
	$MTBM_s$		
	ADT		
	LDT		
System	Fleet Hierarchy	Respective Ship A_0	
	Component Hierarchy		
Environmental	Temperature	Modified $MTBM_u$	
	Wind Conditions		

3. Connect Interactions

Respective elements within the DSMs are identified by the x-coordinates and y-coordinates and are connected to other elements in separate matrices by referencing the same x-coordinates and y-coordinates. Using the geographical DSM as the foundation, the distance and LDT are calculated and stored in the sublayer matrices.

The failure modes are identified, and the influencing factors are input into the environmental DSM. The affected MTBF is calculated from the environmental DSM, using relevant models and equations.

Next, using the RAM factors and system DSM, we can derive the respective ship A_0, using Equations 2 to 11. As shown in the example in Figure 4, to derive the first element of A_o, the AER model will retrieve the information of the first element from the MTBM and MDT matrices and then will perform the calculation accordingly using Equation 2. The model will continue to populate the values for the rest of the data and store the derived A_o values in the A_o matrices. The AER model provides the final output, which is fleet readiness, based on the system DSM. This forms the datum of the AER model once the interactions are connected in the model.

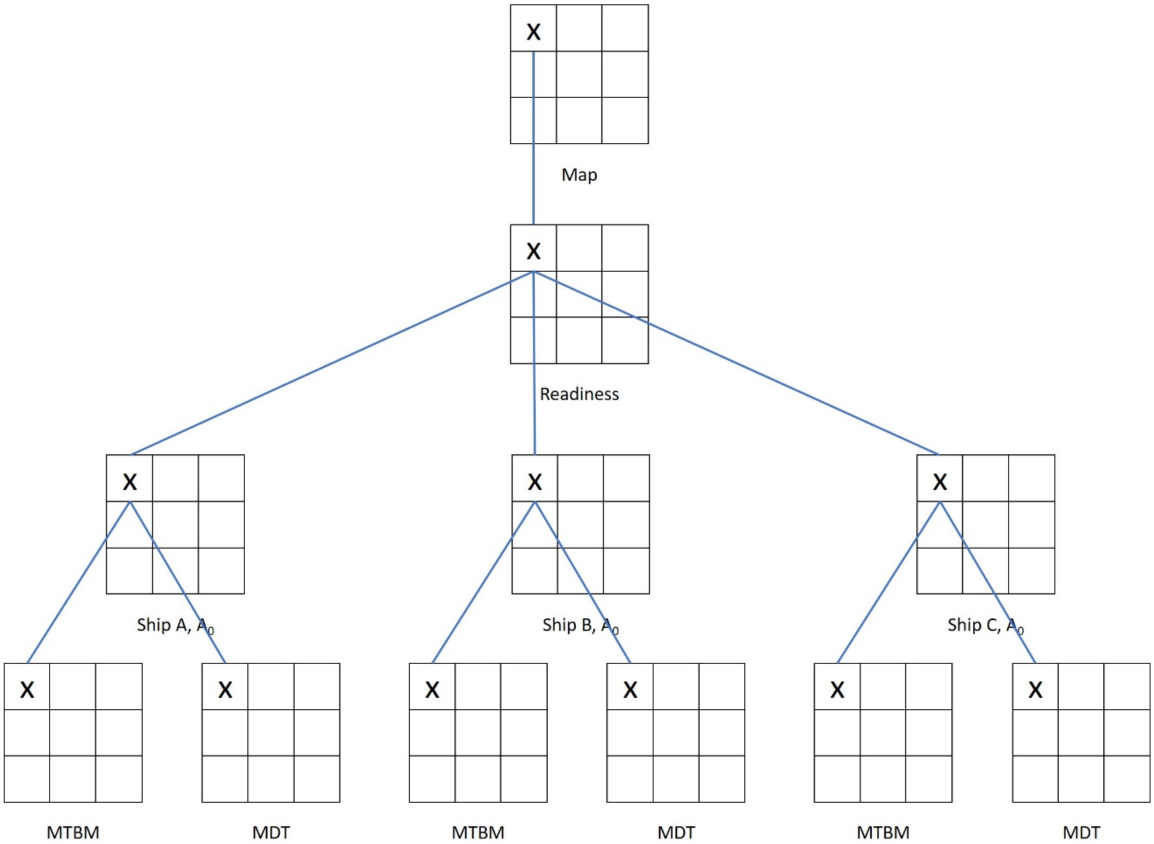


Figure 4. Interaction between DSMs

B. APPLICATION OF AER MODEL

1. Collect Data

To apply the AER model, the first step is to define the fleet size and decompose the fleet into its respective ships and components to facilitate the collection of maintenance related data ($MTBM_u$, $MTBM_s$, $\bar{M}ct$, $\bar{M}pt$, LDT and ADT). The raw data are required to form the database and store in separate DSMs to enable the eventual calculation of readiness. Certain data are required more than once by different metrics, and storing them in different matrices enables easy retrieval during the calculation process. As shown in Figure 5, the data are interconnected to one another (via their respective Equations 1 to 11) to form a complex architecture.

One way to collect $MTBM_u$, $MTBM_s$, $\bar{M}ct$ and $\bar{M}pt$ is by using the design RAM factors provided by the original equipment manufacturer, while the other method is through the collection of operational data and the regular update of that data.

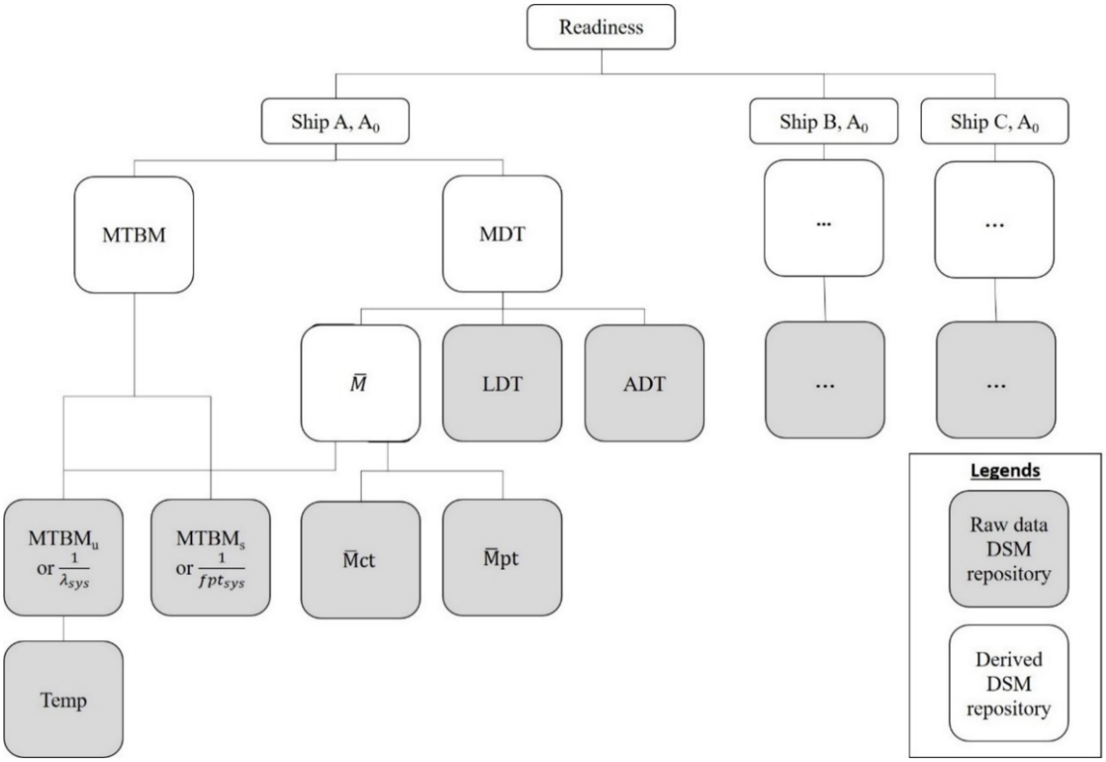


Figure 5. AER DSMs and Interactions

2. Examine Additional Factor(s)

To examine additional factor(s), we can expand the datum by adding new DSMs to the original AER model. As fleet readiness is influenced by different factors under different weather and operating conditions, the inclusion of independent variables would provide a detailed analysis of infrastructure development.

There are many potential models that can be integrated into the AER model, depending on the factors and application under consideration. For example, there are various Physics of Failure (PoF) models that exist for specific applications. Additionally, new PoF models can be developed from accelerated test data and a statistical model relating system life to stress. The accuracy of these models depends on the accuracy of the data and the correct application of parametric estimation techniques such as the maximum likelihood estimate, Bayesian approaches, etc.

3. Perform DSM Result Analysis and Optimization

The output of the methodology is the mini map with the derived readiness mapped on the proposed route from the start point to the end point. A sample result is shown in Figure 6, where it can be seen that readiness decreases as the fleet moves away from the starting point and increases as the fleet moves closer to the destination port. This is due to the changes in the LDT, as the LDT is reduced when the fleet is closer to a port.

To achieve a more comprehensive result, the RAM factors such as $MTBM_s$, LDT, and ADT can be adjusted to obtain a more realistic simulation depending on the size of the map and data collected, and other factors can be added to examine the impact to fleet readiness. In addition, adding and changing the location of a new port allows us to optimize the solution based on the terrain. Thus, Figure 6 demonstrates the addition of a port to the original scenario and allows us to analyze how the addition of a port impacts fleet readiness. It examines the improvement to readiness and explores the possibility of increasing operating range for the systems operating in the Arctic. Other factors such as cost benefit analysis or the feasibility of building a port at the location can be considered to optimize the solution.

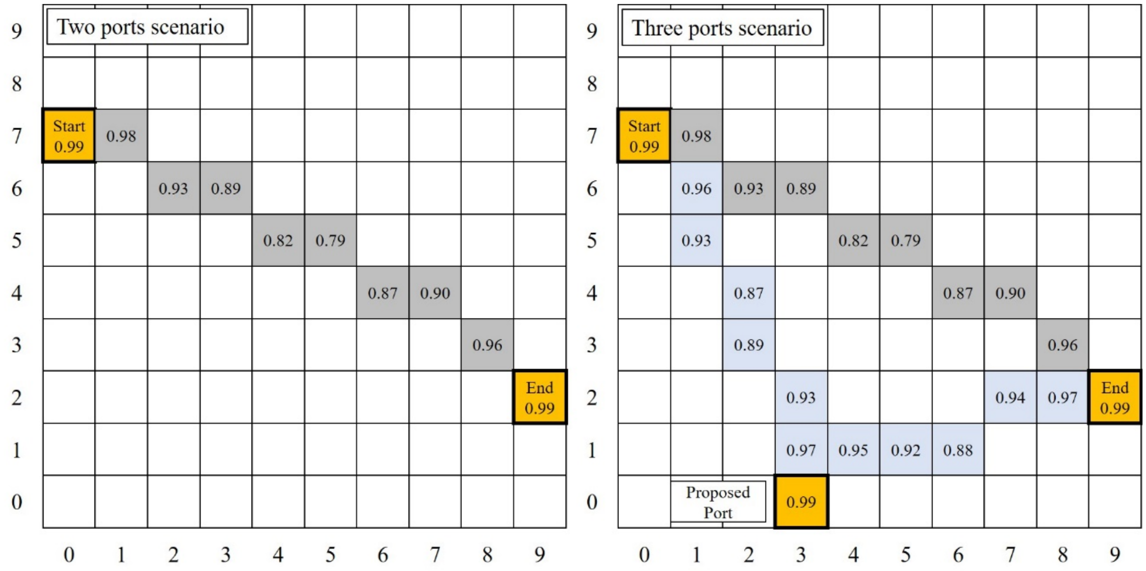


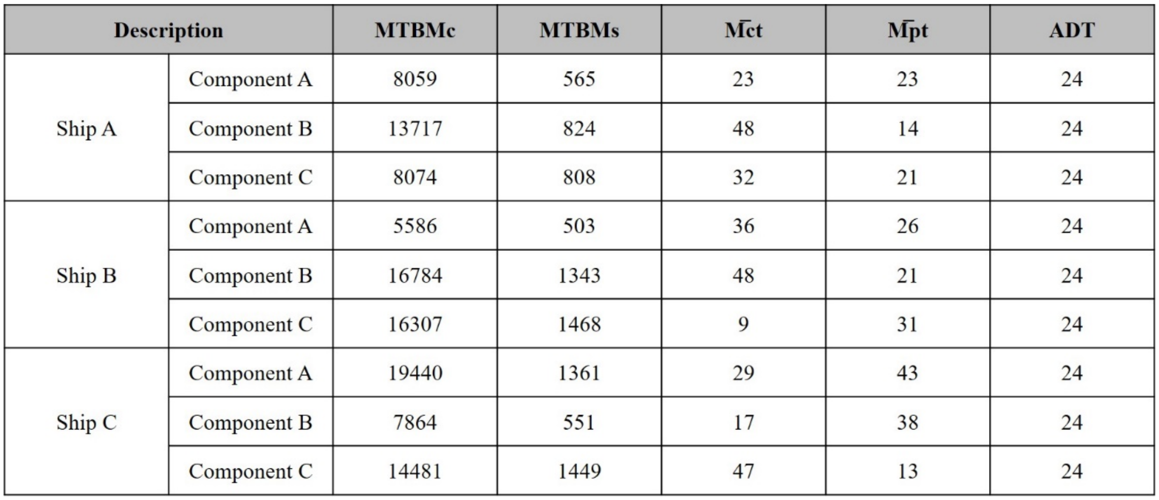
Figure 6. Comparison of AER Model Results

IV. RESULTS AND ANALYSIS

The following case study is presented to illustrate how the AER model is used to predict fleet readiness and determine the effectiveness of building an additional port. Table 2 summarizes the values of the RAM factors utilized in this work. The RAM factors data are randomly generated based on an open-source database as operational data are limited [50], [51]. Nonetheless, users may be able to implement the model with operational data for detailed analysis on a specific operational environment of interest. A_o, MTBM, MDT and $\overline{M}$ are derived using the AER model.

LDT is the time taken to travel to repair the defective component or the time taken for the delivery of the replacement part, and is measured from the current location to the next closest port. ADT is assumed to be constant regardless of the types of defects and given a value of 24 hours for this case study. This forms the datum for the AER model.

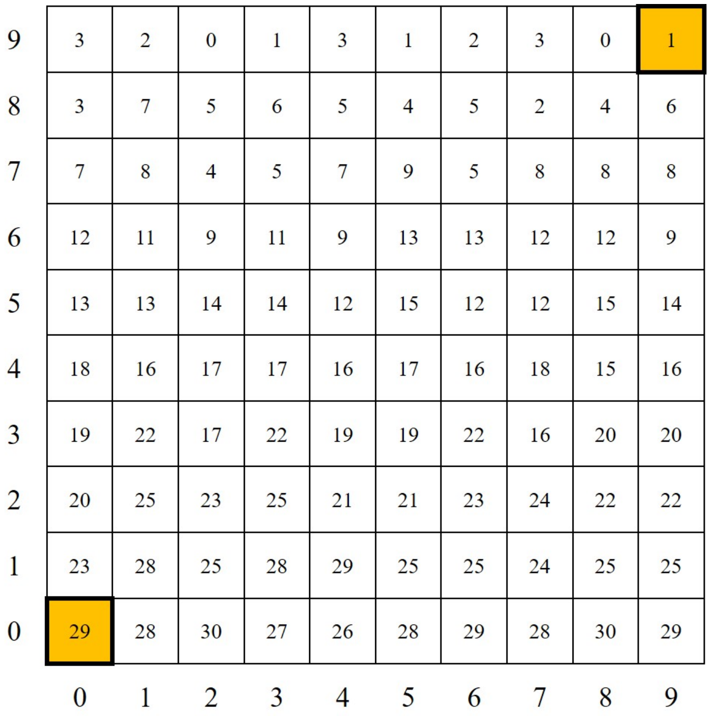
Table 2. RAM Factors Utilized in the AER model



Description		MTBMc	MTBMs	$\overline{M}ct$	$\overline{M}pt$	ADT
Ship A	Component A	8059	565	23	23	24
	Component B	13717	824	48	14	24
	Component C	8074	808	32	21	24
Ship B	Component A	5586	503	36	26	24
	Component B	16784	1343	48	21	24
	Component C	16307	1468	9	31	24
Ship C	Component A	19440	1361	29	43	24
	Component B	7864	551	17	38	24
	Component C	14481	1449	47	13	24

In addition, the Arrhenius model is utilized to establish the correlation between temperature and $MTBM_s$ [52]. It should be noted that the Arrhenius model is a PoF model that was derived based on the rate of chemical reaction in materials, and there are other PoF models for different applications.

While most of the ships have sufficient waste heat aboard to keep critical systems warm, smaller vessels' hull structures and deck equipment are often impacted by temperature [53]. As shown previously in Figure 5, the temperature factor is added to the AER model, and since temperature affects the $MTBM_s$, the temperature matrix is connected to the $MTBM_s$ matrix. A randomly generated temperature matrix is created between the range of 0°C and 30°C to observe the impact on readiness when the temperature changes. The temperature at the bottom of the mini map is higher as compared to the top of the mini map to simulate the change of temperature from a temperate climate to an Artic climate, as shown in Figure 7.



9	3	2	0	1	3	1	2	3	0	1
8	3	7	5	6	5	4	5	2	4	6
7	7	8	4	5	7	9	5	8	8	8
6	12	11	9	11	9	13	13	12	12	9
5	13	13	14	14	12	15	12	12	15	14
4	18	16	17	17	16	17	16	18	15	16
3	19	22	17	22	19	19	22	16	20	20
2	20	25	23	25	21	21	23	24	22	22
1	23	28	25	28	29	25	25	24	25	25
0	29	28	30	27	26	28	29	28	30	29
	0	1	2	3	4	5	6	7	8	9

Figure 7. Temperature DSM in Degree Celsius (°C)

For the case study, a 10 by 10 square matrix is used to represent a 100-cell mini map and the ports are highlighted in orange, with the starting port and destination port being represented by cell coordinates (0, 0), and (9, 9), respectively. The fleet was simulated to travel from the start point to the end point as shown in Figure 7.

A. VARY TEMPERATURE AND VARY LDT

In the first instance, the temperature and LDT change according to the cell to simulate the changing environment of the Arctic. As shown in Figure 8, the readiness of the fleet decreases as it moves away from the starting point and increases again as it gets closer to the destination port.

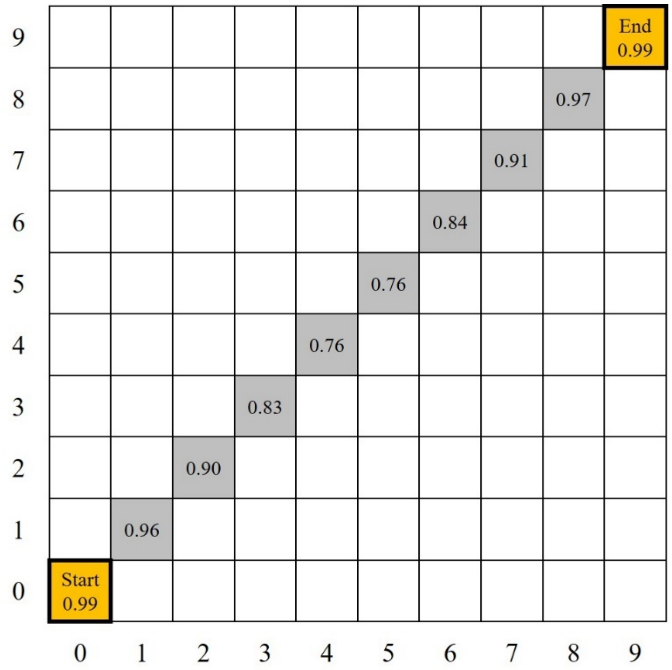
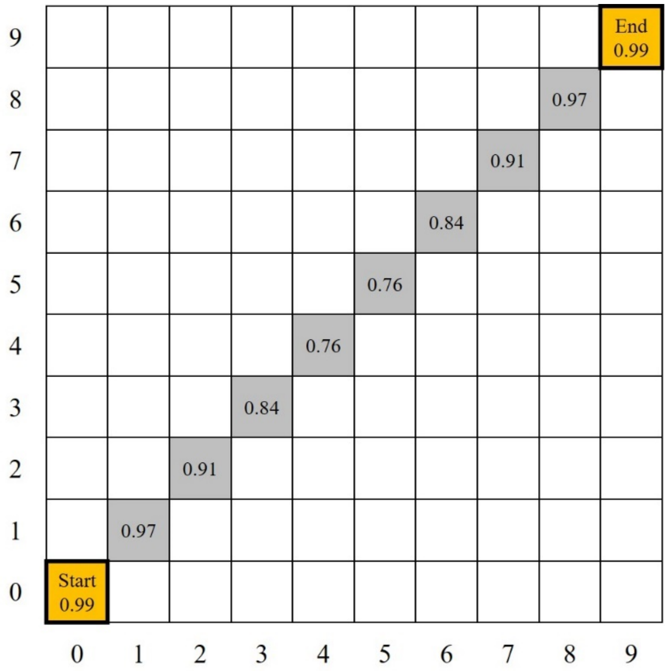


Figure 8. AER Result for Varying Temperature and LDT

This will form the datum of the case study for comparison against other test results when variables are modified or added.

B. CONSTANT TEMPERATURE AND VARYING LDT

To observe the effect of temperature on readiness, the temperature variable is kept constant while the LDT continues to vary across the map. From Figure 9, it is possible to a slight adjustment in the readiness of the fleet as the temperature is kept constant, but the level of readiness maintains the same trend of decreasing as the fleet travels away from the ports and increasing when it travels closer. It is observed that the temperature variable has a slight effect on the readiness, as there was minimal fluctuation in the fleet's readiness with a maximum difference of 1% as compared to the original values.



	0	1	2	3	4	5	6	7	8	9
9										End 0.99
8									0.97	
7								0.91		
6							0.84			
5						0.76				
4					0.76					
3				0.84						
2			0.91							
1		0.97								
0	Start 0.99									

Figure 9. AER Result for Constant Temperature and Varying LDT

C. VARY TEMPERATURE AND KEEP LDT CONSTANT

For illustration purposes and to observe the effect of LDT on readiness, the LDT variable is kept constant by assuming that spares were provisioned from the starting port and carried onboard, while the temperature varies across the map. The author is aware that a constant LDT may not be realistic; however, the simulation would emphasize the relationship between temperature and readiness of the fleet. As shown in Figure 10, the readiness is consistent across the route with minimal fluctuation. It is also observed that the effect of LDT is significantly larger as compared to the temperature variable, as there is more fluctuation between Figure 8 and Figure 10.

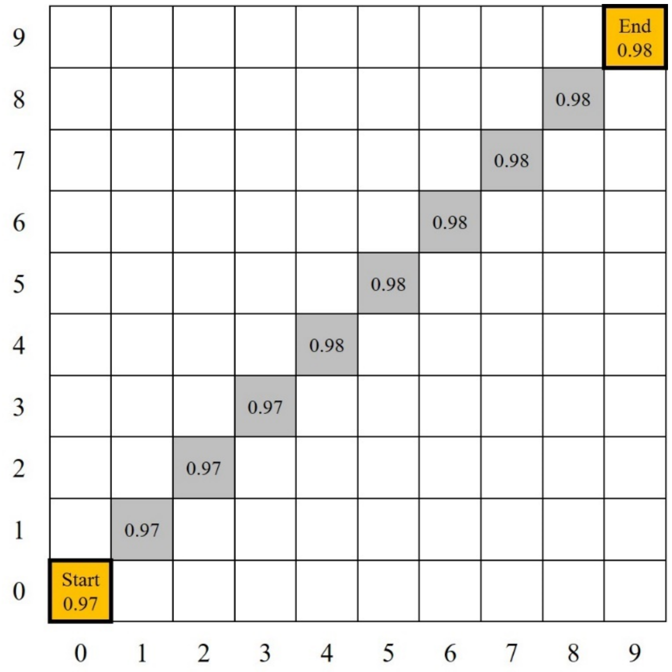


Figure 10. AER Result for Varying Temperature and Constant LDT

Here, the results from the three configurations demonstrate that the AER model can estimate the fleet's readiness as well as the effect on readiness when the values of the variables change. The AER model has identified that the LDT variable has a more significant influence on fleet readiness as compared to the temperature variable, but as this is a simplified case study, more failure modes and data should be included to achieve a more comprehensive result.

D. INCREASE NUMBER OF PORTS

To enhance the AER model and examine the impact of infrastructure development, a port is added at coordinates (5, 9). As shown in Figure 11, by adding a port, the fleet is able to dock for maintenance and resupply, which slightly improves the fleet's readiness denoted in blue, as compared to the original route in grey. Moreover, the additional port also improves the fleet readiness of the original route as shown in Figure 12. This is due to the fleet being closer to the added port as compared to the destination port, which reduces the LDT.

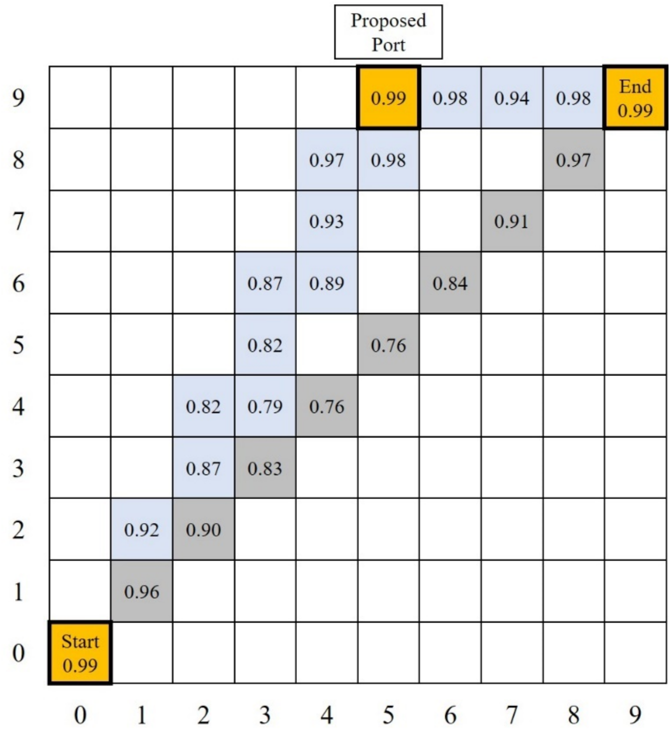


Figure 11. AER Result with Additional Port

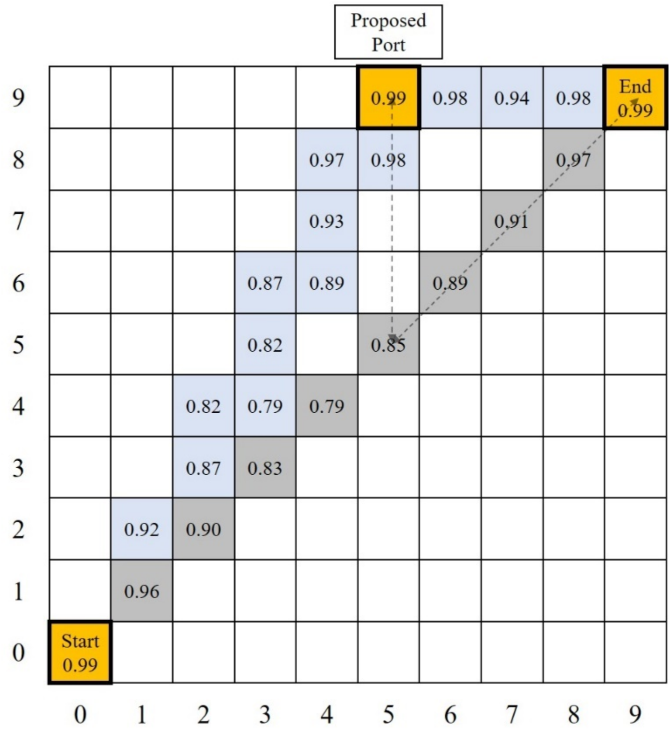
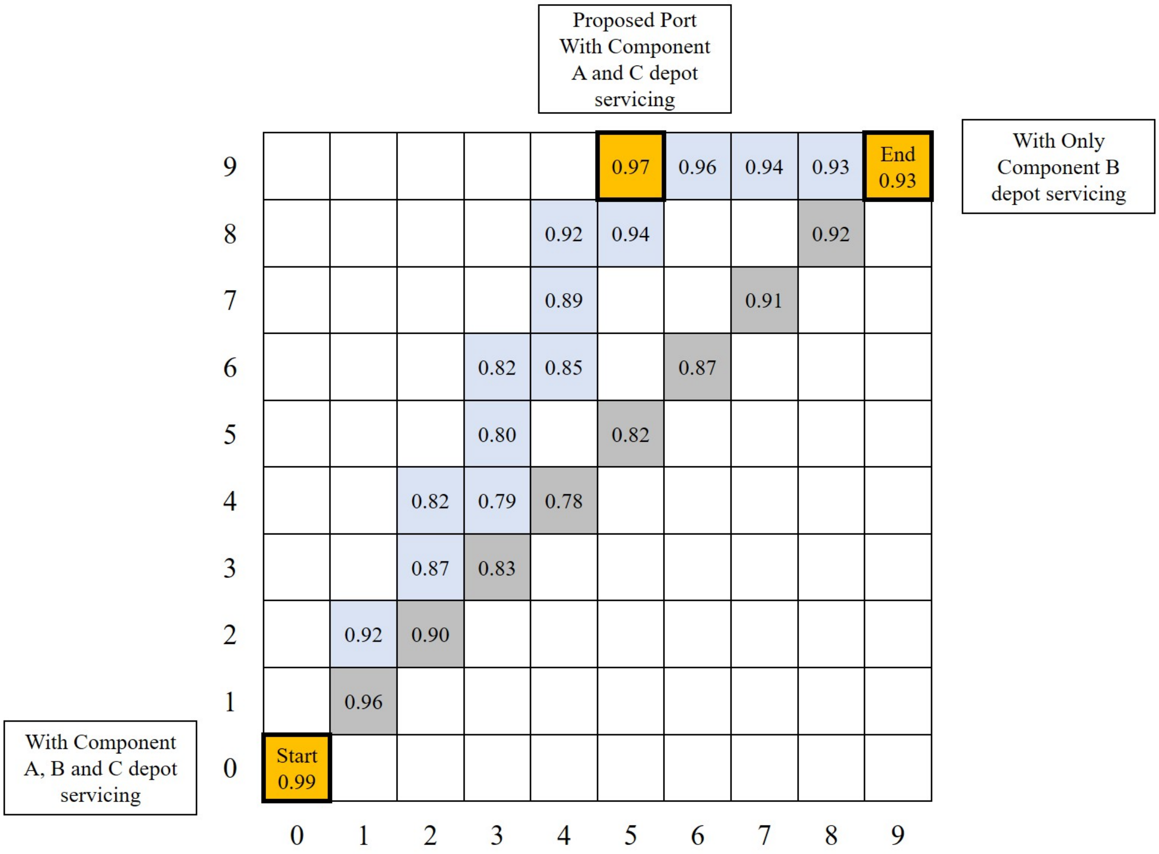


Figure 12. Updated AER Result with Additional Port

The increased number of ports allows greater flexibility for the fleet to dock for maintenance and resupply purposes, which improves the fleet's readiness. This demonstrates the scalability of the AER model to include not only more variables for analysis, but also a change in the location of the added port to analyze the impact of infrastructure development.

E. INCLUDE DEPOT SERVICING

During the design phase of port infrastructure, the type and level of servicing that will be provided at the port should be determined to maximize efficiency while reducing cost. As shown in Figure 13, the new port is equipped with components A and C depot servicing, while the destination port is equipped with component B depot servicing. It is possible to achieve a relatively high level of readiness by splitting the components' depot servicing between the new port and the destination port.



	0	1	2	3	4	5	6	7	8	9
9						0.97	0.96	0.94	0.93	End 0.93
8					0.92	0.94			0.92	
7					0.89			0.91		
6				0.82	0.85		0.87			
5				0.80		0.82				
4			0.82	0.79	0.78					
3			0.87	0.83						
2		0.92	0.90							
1		0.96								
0	Start 0.99									

Figure 13. AER Result with Depot Servicing Options

The model developed can be used to explore the feasibility of potential ports and determine the maintenance capabilities required at each port. As demonstrated in Figure 14, the AER model facilitates the comparison between two potential ports and the respective maintenance capabilities. This can maximize the readiness while optimizing resources.

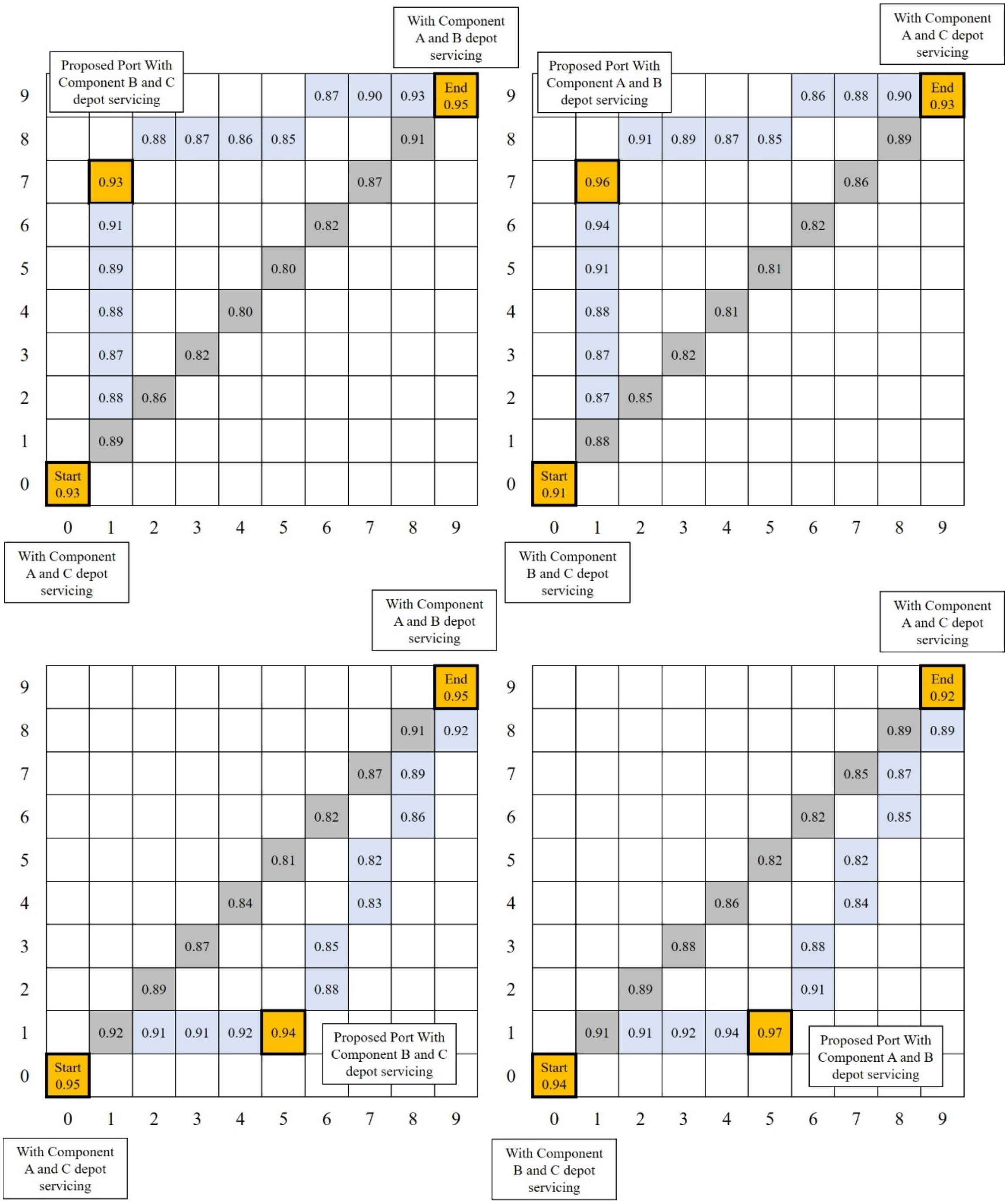


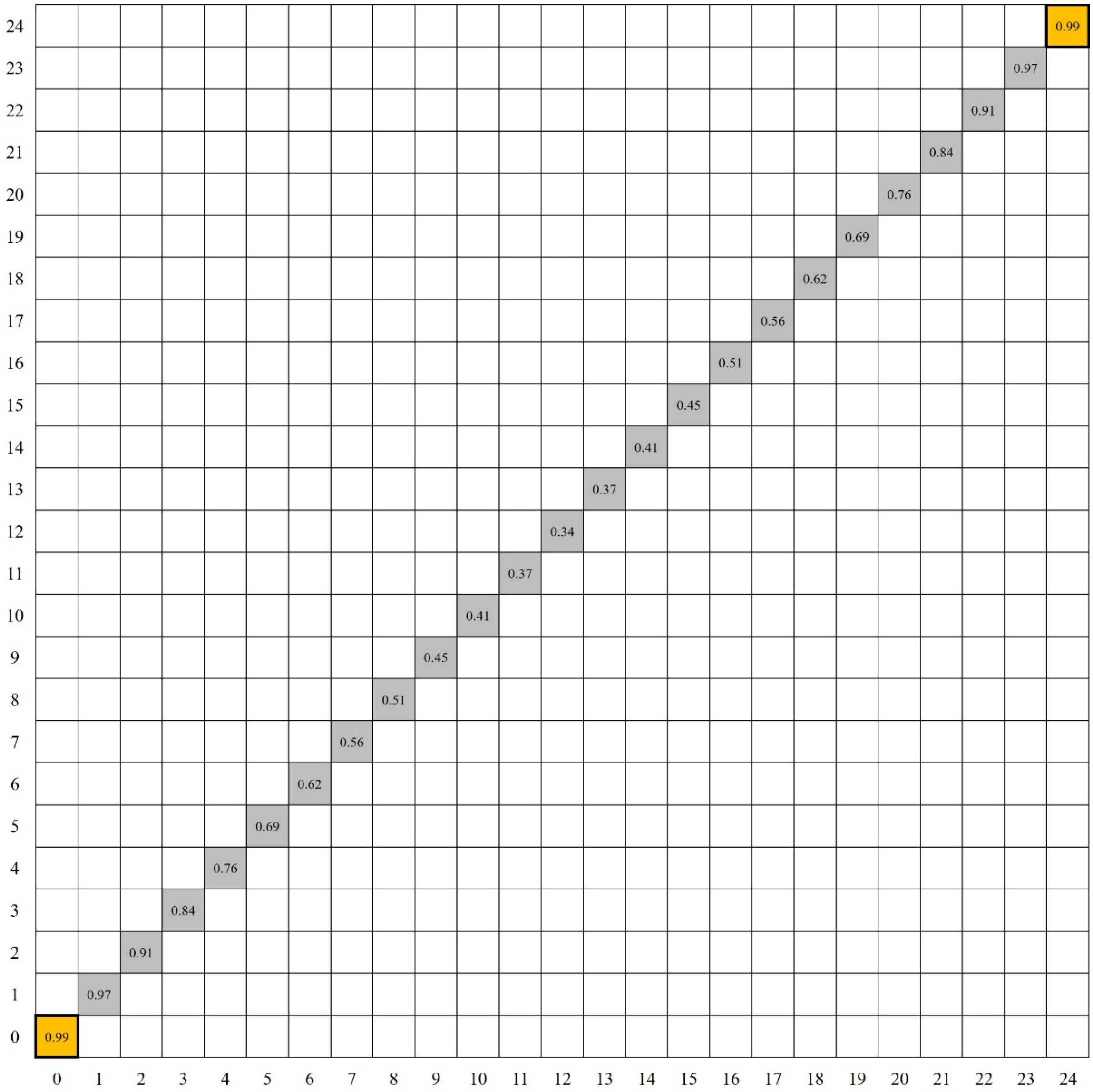
Figure 14. Comparison of Different Ports and Requisite Capabilities

Table 3 summarizes the results of the AER model. The initial result set the datum for comparison, which demonstrated that LDT has a more significant impact on readiness as compared to temperature. Additional runs also established that the AER model is flexible and scalable to examine more factors and investigate the impact to readiness. By changing the variables and finetuning the requisite capabilities at the port, the accuracy of the model can be improved and an optimized solution for the problem can be achieved.

Table 3. Summary of AER Results

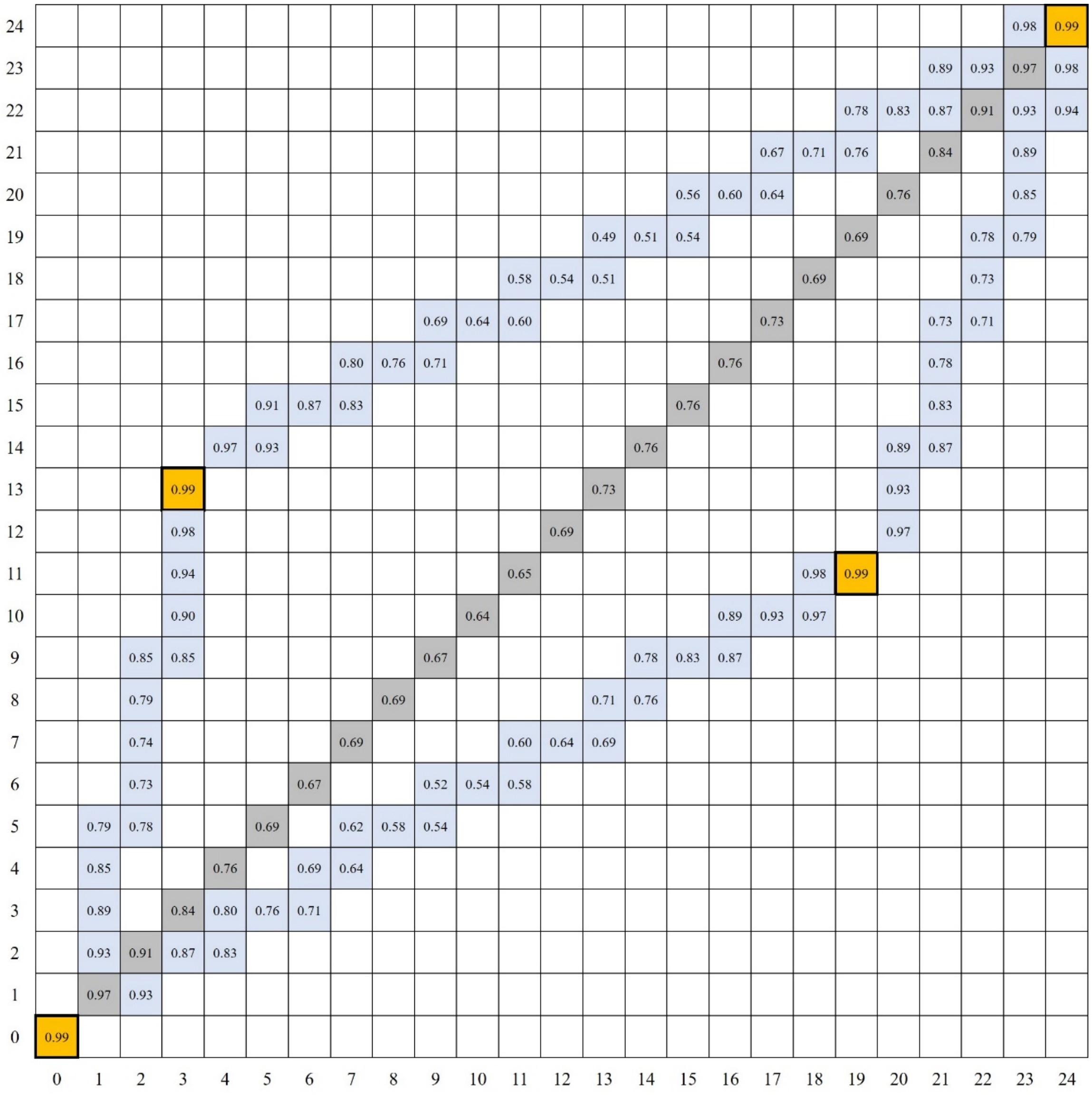
Temperature	LDT	Number of Ports	Types of Depot Servicing	Results
Vary	Vary	2	×	Datum
Vary	Constant	2	×	Temperature has a slight effect on readiness
Constant	Vary	2	×	LDT has a significant effect on readiness
Vary	Vary	3	×	Greater flexibility and improve readiness
Vary	Vary	3	✓	Increase flexibility and scalability, optimize resources

The true potential of the AER model can be achieved through a larger map, which examines different port options and maintenance capabilities. As shown in Figure 15, which contains a 25 by 25 square matrix with the ports highlighted in orange, fleet readiness decreases drastically as the fleet travels away from the ports. As the map and travel distance increase, the number of ports required to sustain the fleet's readiness increases as well. To analyze the impact on readiness using different port options and maintenance capabilities, a larger map is required as shown in Figure 16. Figure 16 demonstrates the flexibility of the AER model to place the port at a different location to examine the impact to readiness, and it demonstrates the combined outcome of having two or more ports along the envisaged route. To further showcase the scalability of the model, it can be superimposed onto a real geographical map to examine the impact of infrastructure development. This will greatly enhance the planning for infrastructure development while optimizing resources.



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24																									0.99
23																								0.97	
22																							0.91		
21																						0.84			
20																					0.76				
19																				0.69					
18																			0.62						
17																		0.56							
16																	0.51								
15																0.45									
14															0.41										
13														0.37											
12													0.34												
11												0.37													
10											0.41														
9										0.45															
8									0.51																
7								0.56																	
6							0.62																		
5						0.69																			
4					0.76																				
3				0.84																					
2			0.91																						
1		0.97																							
0	0.99																								

Figure 15. 25 by 25 AER Result



	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24																								0.98	0.99
23																						0.89	0.93	0.97	0.98
22																				0.78	0.83	0.87	0.91	0.93	0.94
21																		0.67	0.71	0.76		0.84		0.89	
20																0.56	0.60	0.64			0.76			0.85	
19														0.49	0.51	0.54				0.69			0.78	0.79	
18												0.58	0.54	0.51					0.69				0.73		
17										0.69	0.64	0.60						0.73				0.73	0.71		
16								0.80	0.76	0.71							0.76					0.78			
15						0.91	0.87	0.83								0.76						0.83			
14					0.97	0.93									0.76						0.89	0.87			
13				0.99										0.73							0.93				
12				0.98									0.69								0.97				
11				0.94								0.65							0.98	0.99					
10				0.90							0.64						0.89	0.93	0.97						
9			0.85	0.85						0.67					0.78	0.83	0.87								
8			0.79						0.69					0.71	0.76										
7			0.74					0.69				0.60	0.64	0.69											
6			0.73				0.67			0.52	0.54	0.58													
5		0.79	0.78			0.69		0.62	0.58	0.54															
4		0.85			0.76		0.69	0.64																	
3		0.89		0.84	0.80	0.76	0.71																		
2		0.93	0.91	0.87	0.83																				
1		0.97	0.93																						
0	0.99																								

Figure 16. 25 by 25 Optimized AER Result

The result of this study shows that the LDT has a significant impact on fleet readiness and that the location and requisite capabilities at the port should be considered carefully during the design and planning phases. The AER model is not only effective in estimating fleet readiness, but it is also scalable and flexible to include and examine multiple variables while optimizing resource management.

V. FUTURE WORK/DISCUSSION

In this research, the AER model presents a DSM approach to quantify fleet readiness during the design and planning of operational expansion in the Arctic region. The limitation is the lack of readily available operational data to develop a corresponding AER model for different conditions. There are many factors that can influence fleet readiness, but not all factors affect fleet readiness equally. To account for this inequality, a weighted approach can be implemented to the AER model. There could be a set of weighted conventions for different conditions to represent the effect of some variables that may be more prominent in certain conditions, but their impact may decrease in other conditions.

One factor that was not analyzed in this study is the human factor. Under harsh Arctic conditions, it is not possible for humans to work continuously without any rest, and delays are to be expected. However, for the purpose of this study, the human factor was normalized and assumed to be constant across all weather conditions. To improve the accuracy of the AER model, the LDT and ADT should be adjusted according to the Arctic climate and working conditions.

Besides travelling to the next closest port for repair, requesting the delivery of a replacement part from the closest port, or waiting for a tow and getting towed to the closest port for maintenance activities, the fleet can perform alternative recovery actions when a ship is in need of repair. Depending on the failure, alternative recovery actions could include preparing multiple spare parts onboard and having maintenance crew to carry out rectification of minor defects. Different failures and recovery actions would result in different outcomes and LDT. To expand the depth of the model in this research, the failure and recovery action taken by the fleet can be considered in follow-on work.

As the AER model was illustrated using a 10 by 10 square matrix, the scalability of this model can be further explored. To accomplish this, the model can be expanded and superimposed on a world map, along with a larger fleet size and more components. To extend this work further, obstacles, future researchers can include the human factor, and more varied weather conditions, which will make the model more comprehensive and improve its robustness.

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VI. CONCLUSION

To enhance decision making, this paper has presented a model to quantify and plot fleet readiness as a fleet moves along its route in the Arctic. Taking into consideration the RAM factors and the Arctic geographical and weather conditions, the model utilized the DSM method to estimate fleet readiness. Based on the case study in this paper, it is assessed that the model is scalable and has the flexibility to examine more variables and their impact on readiness. It also illustrates how to improve the accuracy of the results.

Furthermore, the model is capable of examining the impact of infrastructure development to determine the optimal location for port building. Related to this, the model is also used to investigate the requisite maintenance capabilities at the port to increase the effectiveness of the port and optimize the available resources.

The implementation of this model is heavily dependent on the availability of data, such as RAM factors data, weather data, and geographical data. When operational data is not readily available, the next best alternative is to utilize historical data of similar systems or the OEM design specification.

To obtain a more detailed analysis, more factors need to be collected and added to the model. However, as the factors present a numeric estimation for different variables, it is important to determine the relationship among the different factors and to observe if there is any significant effect on readiness. As mentioned earlier, a weighted approach can be considered, as the impact of the variables varies over different weather and operating conditions.

The operational expansion into the Arctic region could provide the U.S. military a strategic advantage. Given the time and resource constraints posed by the harsh Arctic conditions in terms of maintenance and logistics activities, the AER model is useful for addressing the impact of those conditions on fleet readiness with an operational expansion into the Arctic regions. Furthermore, the designed model can help determine whether potential operational expansion into the Arctic region is a feasible pursuit in the long run.

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