Fall 2020

Integrating resilience into military infrastructure mission assurance assessments and decision making

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INTEGRATING RESILIENCE INTO MILITARY INFRASTRUCTURE MISSION

ASSURANCE ASSESSMENTS AND DECISION MAKING

by

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A DISSERTATION

Presented to the Graduate Faculty of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

ENGINEERING MANAGEMENT

2020

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PUBLICATION DISSERTATION OPTION

This dissertation consists of the following four peer reviewed publications that have been published, submitted, or that will be submitted, formatted in the style used by the Missouri University of Science and Technology:

Paper I, found on pages 20–40, has been published in the proceedings of the American Society for Engineering Management International Annual Conference, in Philadelphia, PA, in October 2019.

Paper II, found on pages 41–77, has been submitted to Natural Hazards Review.

Paper III, found on pages 78–112, is intended for submission to Military Operations Research Journal.

Paper IV, found on pages 113-142, is intended for submission to Omega. The International Journal of Management Science.

ABSTRACT

This research created the Mission Assurance Resilience Matrix, a decision framework that integrates existing infrastructure assessment methods with emerging resilience research to model resilience under uncertainty as part of a detailed infrastructure management system. This framework enables military decision makers to easily visualize deficiencies in infrastructure resilience and assess where to most efficiently allocate resources. This research further extends results by including modules on training and education as a component of the scope of work.

There are three significant contributions of this research. The first identifies the gaps of how and where modeling under uncertainty, infrastructure systems management, and resilient systems are integrated into the standard undergraduate and graduate engineering management curriculum. The second is the development of the Mission Assurance Resilience Matrix (MARM), a quantitative visual tool to communicate the impact of project selection decisions to enhance resilience of military infrastructure systems and assist decision makers in understanding how a singular project may influence the resilience of multiple systems using the tradespace analysis. The third is the verification of the MARM model as a computer-based, decision-support tool.

While the implementation of this research is specific to military installations, the framework developed is broadly applicable and can be expanded to incorporate the entire MAA framework as well as extended to support assessment of the resilience of public and private non-military infrastructure systems.

ACKNOWLEDGMENTS

Special gratitude and appreciation go to my advisor, Dr. Suzanna Long for her patience, guidance, and encouragement to take on this challenge and stay on track. I also appreciate the insights, guidance, and instruction of my committee, Dr. Joel Burken, Dr. Steve Corns, Dr. Ruwen Qin, Dr. Casey Canfield, and LTC Jim Schreiner, PhD, that improved the research so it would have the most significant impact possible.

I would like to thank LTC Jakob Bruhl, P.E., PhD and LTC James Richards, P.E. for their assistance and reviews of the early stages of development of this research. Additional gratitude goes to the various military and government employees working within the Department of Defense's Mission Assurance Assessment community for their insights and feedback on the various tools developed through this research. Special contributions were made by the US Army Africa's Deputy Chief of Staff Engineer section: Ms. Annie Savage, Mr. Eric Doro, and Sergeant First Class Ryan Swanson.

I thank the faculty, staff, and fellow students in the Department of Engineering Management and Systems Engineering for their instruction, support, and comradery. I also thank the Departments of Systems Engineering and Civil and Mechanical Engineering at the United States Military Academy for their outstanding encouragement.

Finally, I dedicate this dissertation to my wife Katie and our kids Emme, Jax, and Karlee. Your love, support, encouragement, and frequent study breaks kept me sane and moving forward to complete this. Katie, I especially appreciate all the time you spent reviewing and proofreading my manuscripts. You are all amazing and I love you all so much!

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NOMENCLATURE

Symbol	Description
MARM	Mission Assurance Resilience Matrix
DoD	Department of Defense
MAA	Mission Assurance Assessment
DCIP	Defense Critical Infrastructure Program
FOUO	For Official Use Only
AFRICOM	United States Africa Command
USARAF	United States Army Africa Command
RM	Resilience Matrix
ERS	Engineered Resilience Systems
SME	Subject Matter Expert
ASEM	American Society for Engineering Management
ABET	Accreditation Board for Engineering and Technology
DHS	Department of Homeland Security
ASEE	American Society for Engineering Education

1. INTRODUCTION

With the increasing frequency and severity of natural and man-made disasters around the world, the challenge of building tools that assess, quantify, and clearly articulate the resilience of an infrastructure system is a growing topic of discussion amongst infrastructure system managers and researchers. Multiple efforts have been made to develop indices to quantify resilience using metrics (Cardoso et al. 2015; Kerner and Thomas 2014; Wood et al. 2019). An evaluation of several different metrics concluded that one of the challenges is to validate measures of performance for these metrics when the events considered are infrequent and where specific community and disaster conditions are never exactly the same and highlight that there is little utility in these metrics unless they can be confidently used to inform decisionmakers (Bakkensen et al. 2017).

While much effort has been put into the collection and reporting of various infrastructure assessment data, there is a significant gap in the ability to translate the existing Department of Defense's (DoD) Mission Assurance Assessment (MAA) into a framework that uses resilience to drive infrastructure investment decisions. It is critical to improve the resilience of military installations and their complex infrastructure systems to strengthen response to the uncertainty and threat driven by the increasing frequency and severity of natural and man-made disasters.

This research contributes to closing the gap in several unique and novel aspects. This research created a decision framework, the Mission Assurance Resilience Matrix (MARM), that can model resilience under uncertainty as part of a detailed infrastructure management system. The framework models military installations as complex infrastructure systems and directly addresses the DoD's mandate to incorporate resilience along with risk and life cycle cost into assessment, planning, and resourcing of its critical infrastructure (Department of Defense 2019; NAVFAC 2017). This research further extends results by including modules for the training and education of engineering managers, who are uniquely postured to lead the management of complex and multi-disciplinary infrastructure systems.

1.1. RESILIENCE AND INFRASTRUCTURE TERMINOLOGY

Resilience is a term widely used in various industries and settings with different connotations depending on how the term is defined. Prior to undertaking the integration of resilience into military decision-making frameworks, a clear definition of resilience to be used in this research must be established.

1.1.1. Definition of Resilience. An integrative literature review of resilience definitions in recent technical literature concluded that, "resilience is an ability to prepare for, withstand, and/or recover from adversity, emergencies or failures in a timely manner and still be able to function at least nominally while minimizing potential losses in the system" (Wilt et al. 2016). Furthermore, the National Academy of Sciences (NAS) defines disaster resilience as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events" (Committee on Increasing National Resilience to Hazards and Disasters 2012). This definition not only connotates the system's capacity to return to previous levels of operation, but also the ability to adapt and improve to offer even better levels of service and operation.

Additionally, military infrastructure resilience as a property should be viewed in terms of interconnected functions and systems, not simply individual features (Aven and Thekdi 2018; Linkov et al. 2018) which necessitates that an installation's resilience be considered broader than simply its ability to resume combat related operations following a shock. Thus, the framework for restoration of operations needs to scale across the interconnected functions and various types of disasters with minimal modification (Ramachandran et al. 2015).

Resilience is defined within the DoD MAA framework as the ability to support the functions necessary for mission success with high probability, short periods of reduced capability, and across a wide range of scenarios, conditions, and threats, despite hostile action or adverse conditions and may leverage cross-domain or alternative government, commercial, or international capabilities (Department of Defense 2016a).

1.1.2. Military Infrastructure. Military infrastructure comprises a broad portfolio covering a wide range of facilities and systems that vary from "home station" installations based in the United States to permanent and expeditionary installations forward based around the world (Lostumbo et al. 2013). The formal definition of a military installation is "a base, camp, post, station, yard, center, or other activity under the jurisdiction of the Secretary of a military department or, in the case of an activity in a foreign country, under the operational control of the Secretary of a military department or the Secretary of Defense, without regard to the duration of operations control" (Congressional Research Service 2019).

Military infrastructure systems possess several characteristics that make them unique compared to infrastructure systems in the civilian sector. They require consideration of operational vulnerability to an intelligent adversary, not just nature or a targeted act of violence, as the enemy can have an impact in a powerful and sustained way (Hagen et al. 2017). The requirements they must fulfill are impacted by changes to unit structures, deployable systems, command and control focus/emphasis, and politics. Additionally, the design, construction, and approval of projects to improve military infrastructure is impacted by the availability and limitations of different "pots" of money that can be appropriated by Congress for these projects such as Operations and Maintenance, Facilities Sustainment, Restoration and Modernization, Civil Works, and Military Construction. The rules for each type of appropriation prohibit the mixing or combination of funds from various sources, often limiting efficient use of resources and minimizing impact of the projects (Congressional Research Service 2019). The combination of these unique characteristics makes it imperative that infrastructure resilience decision support tools are tailored for utilization within military applications.

1.2. ENGINEERING MANAGEMENT RESILIENCE EDUCATION

The shortfalls in the DoD's approach to resilience highlights a greater gap in engineering management education and instruction that does not substantially address or incorporate infrastructure resilience. Findings from a review of current literature are that there is a significant gap in addressing infrastructure resilience in both the formal engineering management body of knowledge and engineering management educational research perspectives. A search of the discipline's foundational documents, the Engineering Management Body of Knowledge and associated Engineering Management Handbook, yields no results for infrastructure resilience. In Domain 3, Strategic Planning, sustainability is listed, but not resilience (Farr et al. 2016; Shah and Nowocin 2015), which is significant given recent emphasis on resilience.

This infrastructure resilience education gap has been identified in additional literature. Ramirez and Rioux conducted a survey of select Department of Homeland Security (DHS) personnel to identify potential courses and topics to be included in Homeland Security programs to help inform those involved in curriculum development, and their assessment indicates that there is a significant gap and a strong need to include courses into curricula that address response to and mitigation of disasters (Ramirez 2012). The White House Educators Commitment on Resilient Design, signed in 2016, calls for a focus on resilient design across all disciplines. The intent of this commitment is for institutions to commit to teach students who can lead the various activities (such as planning, design, engineering, and construction) to build resilient infrastructure (Pope 2016). This commitment is in line with the goals of this research to identify where and how infrastructure resilience is being taught at institutions of higher education.

Due to the complexity of these infrastructure systems and the various engineering and other disciplines involved with the design and operation of a complex infrastructure system, solutions to improve infrastructure resilience require a multidisciplinary approach, which involves several disciplines that each provide a different perspective on a problem or issues. The student is required to integrate the often-diverse ideas (Stember 1991). It has been argued that engineering management programs provide the leaders needed to manage these complex and interdisciplinary efforts (Perry et al. 2017).

Evaluation of engineering management programs for infrastructure resilience topics and multidisciplinary approaches follow a mixed method research approach following previous methodology used to assess how engineering leadership programs bin together along various dimensions – end goal, application of leadership learning, scale of leadership action, leadership emphasis, participant selection, compulsoriness, and integration (Klassen et al. 2016). Qualitative evaluation of educational programs to identify key dimensions and develop a conceptual framework from which to categorize programs can employ a modified version of analytical induction (Patton 2014).

1.3. MISSION ASSURANCE ASSESSMENT FRAMEWORK AND SHORTFALLS

Prior to incorporating techniques to improve resilience in military decision-making tools the current infrastructure assessment framework and its shortfalls must be understood.

1.3.1. Mission Assurance Assessment Framework. The DoD made infrastructure resilience a focal point of its installation management strategy implemented in the Defense Critical Infrastructure Program (DCIP) due to the increasing frequency and severity of disasters, both natural and manmade, as well as a mandate from Congress to integrate installation resilience in master plans that incorporate disaster-related and environmental conditions and the measures to mitigate these risks (116th Congress 2019). This risk management program confirms the availability of resources deemed essential to successful completion of DoD missions and includes assets that are essential to planning, mobilizing, deploying, executing, and sustaining U.S. military operations worldwide. The goal of the DCIP is to reduce or eliminate unacceptable risk to Defense Critical Assets, thus enabling the successful execution of DoD missions, regardless of the threat or hazard (Department of Defense 2018a). The DoD also highlighted infrastructure resilience as a key component of its National Defense Strategy by specifying that there will be a priority to transition to smaller, dispersed, resilient, and adaptive basing (Department of Defense 2018b).

To establish a comprehensive and integrative infrastructure assessment framework, the DoD implemented the Mission Assurance Strategy and defined mission assurance as a process to protect or ensure the continued function and resilience of capabilities and assets critical to the performance of DoD Mission-Essential Functions in any operating environment or condition (Department of Defense 2017). The intent is for implementation of this framework to assist the DoD to prioritize infrastructure investments and provide input into the DoD's existing planning, budgeting, requirements, and acquisition process as decisions are made on increasing resilience capacity.

The Department of Defense (DoD) uses the Mission Assurance Assessment (MAA) benchmarks for the basis of assessing its installations to meet its mandate to incorporate resilience measurement and quantification into its existing and decision-making framework (Department of Defense 2018c). The MAA framework divides the assessment into twenty-three distinct functions, such as antiterrorism, physical security, and emergency management, with each area containing multiple categories to be assessed, for a total of over 200 benchmark categories. Responsibilities for assessing the functions are assigned to members of the assessment team depending on their expertise. The specific benchmark metrics from the DoD Mission Assurance Benchmarks dated 28 March 2018 are unclassified but designated as For Official Use Only (FOUO) (Department of Defense 2018c). Therefore, they cannot be published in this dissertation in full, but the broad categories and representative identification numbers are summarized and identified in this research to allow for easier connection back to the base document.

Assessment teams submit completed MAA reports to the Office of the Secretary of Defense to apprise Combatant Commanders and other military leaders of the status of military installation infrastructure. These reports are an important input for these leaders to understand risk, inform the development of specific requirements for future infrastructure projects, and assist in making decisions about which ones to fund.

1.3.2. Mission Assurance Assessment Framework Shortfalls. Several shortfalls have been identified in the MAA framework. It stipulates that resilience be incorporated along with risk and life cycle cost (Department of Defense 2018a), but the current framework lacks integration of all these aspects (Department of Defense 2019; NAVFAC 2017). There is also a shortfall in the ability to identify strategic protection and resilience risks or critical interdependencies within its infrastructure systems and, therefore, the ability to make sound policy and investment decisions. Additionally, the visibility on emerging protection and resilience best practices and performance metrics is limited and the connection between the data collection process conducted by installation infrastructure assessment teams and installation risk management decision making procedures is broken. Mission assurance seeks to address these shortfalls and support DoD's existing resource allocation and Defense Acquisition System processes (Department of Defense 2017).

The military places the responsibility and provides the resources to execute resilience assessment and improvement at the Geographic Combatant Commands, such as the United States Africa Command (AFRICOM), which is further delegated to the subordinate Service components, such as the United States Army Africa Command (USARAF) (Department of Defense 2019). This presents a challenge in that each service approaches the MAA through its own lens, which results in an inefficient and ineffective single-service approach to resilience. This issue was highlighted in the DoD report to Congress in 2019 on the vulnerabilities of 79 of its most important bases. The results reported "fell short of congressional intent by omitting most overseas bases, and it did not include any attempt at an infrastructure risk mitigation plan or calculating associated funding for such a plan" (Berger 2019).

A final shortfall is that the DoD's current concept of resiliency is not comprehensive. The current guidance connects resilience solely to climate change and neglects the impacts of other hazards (Department of Defense 2016b). Additionally, the DoD's current infrastructure decision-making framework stipulates the incorporation of risk and life cycle cost and includes a mandate to incorporate resiliency, but there is a lack of integration of all these aspects into the current assessment framework (Department of Defense 2019; NAVFAC 2017) and does not incorporate uncertainty to these critical military infrastructure systems.

1.4. RESILIENCE MATRIX METHODOLOGY

Labaka et al. developed a matrix to relate resilience policies to three stages of resilience (prevention, absorption, and recovery) (Labaka et al. 2015), but this matrix was developed at the strategic level and does not translate well down to the individual installation assessment level. It also does not address adapting to improve resilience based on what was learned from a shock to the system. Subsequent research developed a

Resilience Matrix (RM) that supports a transparent connection between resilience policies and potential outcomes and provides a framework for cross-compatibility of metrics from different disciplines for cyber resilience. This RM methodology was based on the National Academy of Sciences definition of resilience as a framework to assess the performance of integrated complex systems (Linkov et al. 2013a) and extended to assess the performance of integrated complex systems (Fox-Lent et al. 2015; Wood et al. 2019). The RM integrates assessment of resilience at the functional and system levels, so that the evaluation is not just based on the features of the infrastructure. This is highly applicable to military infrastructure assessments, due to the unique, complex, and highly integrated nature of military infrastructure as a system of systems.

The RM is a 4x4 matrix such that the four columns describe the four stages of disaster management (plan/prepare, absorb/withstand, recover, adapt). The rows describe the four general management domains of a complex system, (physical, information, cognitive, and social), as described in the US Army's Network-Centric Warfare doctrine (Alberts and Hayes 2005). The RM integrates assessment of resilience at the functional and system levels, so that the evaluation is not just based on the features of the infrastructure and helps decision makers answer the question " How is the system's ability to [plan/prepare for, absorb, recover from, adapt to] a cyber disruption implemented in the [physical, information, cognitive, social] domain? " (Linkov et al. 2013b).

Finally, this RM methodology defines a system's overall resilience as the aggregate of the sixteen metrics that could result from multi-criteria decision analysis methods (Heinimann and Hatfield 2017). A system with robust safeguards where all elements of the resultant matrix have been addressed can be considered to be highly resilient. In contrast, a lack of attention to one or more elements in the RM would indicate a point of vulnerability, which may be used to direct attention to improve the security of the system as a whole (Zussblatt et al. 2017).

The RM has been applied to assess many types of infrastructure systems such as cyber (Linkov et al. 2013b), energy (Roege et al. 2014), coastal communities (Fox-Lent et al. 2015), urban planning and assessment (Fox-lent and Linkov 2018), and reservoirs (Mustajoki and Marttunen 2019). This dissertation is the first work to apply the RM framework to the DoD Mission Assurance Assessment construct by developing the Mission Assurance Assessment Resilience Matrix (MARM). The RM framework is highly applicable to the assessment of resilience in the DoD MAA due to three characteristics. It is flexible and does not define specific metrics, but provides a framework to identify the relevant metrics to assess performance from a wider system perspective, which also lend to its ability to be generalizable to many types of infrastructure systems. It provides a baseline performance score on which the resilience improvement potential of proposed system changes can be evaluated (Fox-Lent et al. 2015).

1.5. TRADESPACE ANALYSIS

The Department of Defense (DoD) Engineered Resilience Systems (ERS) tradespace analysis methodology is used to incorporate resilience into deployable military systems, such as helicopters and tanks. ERS tradespace analysis is currently used to create an integrated capability for systems engineers, engineer managers, and acquisition personnel to increase the quality of acquisition decision-making for deployable systems. ERS improves informed decision-making early in the DoD Acquisition process, prior to the Milestone A decision point, when there is both significant uncertainty in the project, but also substantial impact on overall project costs based on these early decisions (Sitterle et al. 2015). This allows engineers to efficiently allocate resources through tradespace analysis, which identifies which projects to pursue to improve resilience by relating the cost of the projects to the potential resilience improvement (Bostick et al. 2018).

There are important shared resilience attributes between deployable military systems and the installation infrastructure which enables them, making the extension of ERS methods desirable (Ewing et al. 2006). An analogy can be drawn between deployable weapon systems and fixed site infrastructure, which project combat power from power projection platforms (military installations) to assist design engineers, facility operators and managers, and infrastructure decision makers to see the impacts of project selection on resilience.

1.6. MODEL VERIFICATION AND VALIDATION METHODOLOGY

A decision support tool is most useful when the impact of underlying uncertainty inherent in the model is understood and the tool has been verified and validated for its utility and appropriateness. Verification is the process of determining if you are building the model right and validation is answering the question are you building the right model (Andradhttir et al. 1997; Kleijnen 1997; Sargent 2013). Ling and Mahadevan elaborate on this concept by decsribing model validation as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended use of the model and that statistics-based quantitative methods are needed to supplement subjective judgments and to systematically account for errors and uncertainty in both model prediction and experimental observation (Ling and Mahadevan 2013).

The incorporation of uncertainty has not been applied to the assessment framework for critical military infrastructure systems but is a goal of the DoD Mission Assurance Strategy to improve allocation of constrained resources during selection of projects that improve resilience of military projection platforms (Department of Defense 2018a).

1.6.1. Sources of Uncertainty. Uncertainty in the model due to measurement error, imprecise and/or insufficient data, natural variability, and model uncertainty (Ling and Mahadevan 2013) must be investigated to complete the model verification and validation process. This is especially important since the MAA framework relies on the aggregation of the judgements from subject matter experts with varying levels of experience with the assessment framework and familiarity with the infrastructure systems, which can introduce uncertainty due to conflicting opinions and judgments or judgments are expressed with a measure of uncertainty (Yaniv 1997).

One potential source of uncertainty is due to differences in how individual assessors assess the condition of infrastructure based on benchmark category metrics and weight the importance of a benchmark based on its description. Yaniv suggests that decisionmakers will need to reconcile inconsistencies among judgmental estimates and determine their influence on the overall aggregate judgement by weighting input judgements by the confidence expressed by the judges and/or trimming of outlying (extreme relative to the other opinions in the sample) judgements to increase accuracy

(Yaniv 1997). Particular attention needs to be paid to uncertainty in the starting conditions in order to improve the decision making process by identifying the critical criteria and then reevaluating more accurately the weights of these criteria due to subjectivity causing difficulty in accurately representing the importance of these criteria (Triantaphyllou and Sánchez 1997). This information will be useful in decision making since it explains synthetically how much the assessment is biased by the assessor judgements (Zavadskas et al. 2007)

1.6.2. Modified Delphi Method. The Delphi Method was developed by the Research and Development (RAND) Corporation in the 1960's in Santa Monica California for the "systemic solicitation and collation of judgements on a particular topic through a set of sequential questionnaires interspersed with summarized information and feedback of opinions derived from earlier responses". The Delphi method is based on structural surveys and makes use of the information provided by experts (Balasubramanian and Agarwal 2012). The Delphi method is useful when evidence is lacking or limited: it relies on "collective intelligence" of group members to jointly produce better results than anyone in the group could produce on his or her own, resulting in increased content validity (Miller et al. 2020).

The Delphi Method is appropriate for this research for several reasons. The first is that the information available for this research was limited due to DoD MAA security and information classification concerns. Second, it works well with a group of subject matter experts (SME), which was appropriate given the limited number of subject matter experts available to provide input on the MARM. The DoD Mission Assurance Assessment community is quite small and the assessments process can be both functionally and installation specific. To ensure that the subject matter experts used in this study would have the requisite familiarity with the MAA in general and the specific benchmarks and metrics from the case study data set, the set of experts was limited to the US Army Africa Deputy Chief of Staff Engineer (DCSENG) staff.

The evaluation of the objectives identified in each round of the Modified Delphi Method were used to verify the MARM as a decision support tool and provide insight as to potential sources of uncertainty in the model that may have an impact on the overall assessment of the resilience of the infrastructure systems for an installation.

1.6.3. Sensitivity Analysis. The benefits of sensitivity analysis on the MARM are to gain basic insight on the system, to indicate whether the model operates as intended, to identify the key components of the model that require further calibration and/or study, and to assess the relative importance of input variables for guidance in data collection and model calibration (Manache and Melching 2008). To achieve this, a global, all-at-a-time sensitivity analysis for decision-making (Pianosi et al. 2016) was used to analyze the impact of uncertainty arising from an assessment team's selection of the benchmark category weights and criteria within the model to verify the consistency of the MARM with expected real-world behavior. Sensitivity analysis explores the relationships between the output and the inputs of a modeling application and is crucial to the validation and calibration of numerical models. It can be used to check the robustness of the final outcome against slight changes in the input data and can help reduce uncertainty in multi-criteria decision-making and the stability of its outputs by illustrating the impact of introducing small changes to specific input parameters on evaluation outcomes (Chen et al. 2010). The MARM, constructed as a quantitative conversion of the qualitative assessment priority and ratings into a singular score, is a good candidate for sensitivity analysis to determine relations between parameters and outputs of a simulation model (Norton 2015).

In typical optimization applications, uncertainty is considered a potentially harmful factor and the aim of analysis is to explore and discover the degree of sensitivity of the optimal solution to changes in key factors. An insensitive solution is considered advantageous (Muñoz et al. 2016). Since the MARM is not an optimization tool, but rather an assessment tool, it is intended to be sensitive to allow the initial conditions to determine which cell in the matrix is the furthest from ideal and needs the most attention to conduct projects to bring it to the ideal state. Sensitivity analysis was utilized to determine how the model as originally constructed responds to the uncertainty in assessment of benchmark category priority weights and ratings as well as assess the difference between the summation versus average of benchmark category cells in each resilience matrix cell.

1.6.4. Monte Carlo Simulation. Based on the construction of the MARM and its design to be a decision-support tool, the exploration of the sensitivity of the cells within the MARM due to uncertainty of the assessments is very suitable for Monte Carlo simulation (Van Hoey et al. 2014). This is similar to the approach that Nguyen et. al took with development of resilience indices for Multi Echelon Assembly Supply Chains (MEASC), though that research sought to optimize the supply chain network. Both the supply chain resilience indices and the MARM can help decision makers make the trade-off between resilience and cost (Nguyen et al. 2020).

1.6.5. System Usability Scale. A final aspect of model verification regards the usability of a tool as an information collection and processing system through the use of the System Usability Scale (SUS) developed by John Brooke at Digital Equipment Corporation. The SUS is used to take a quick measurement of how people perceived the usability of computer systems on which they are working. Raw scores ranging from 0 (poorest rating) to 4 (best rating) are converted to get the standard SUS score, which is on a scale of 0 to 100 (Lewis 2018). The score can then be given a grade based on the overall usability of the system identified as it compares to other computer based systems (Lewis and Sauro 2018).

1.7. RESEARCH OBJECTIVES AND CONTRIBUTIONS

The goal of this research was to close the gap between the existing DoD Mission Assurance Assessment processes and the mandate the DoD has to incorporate resilience into their assessment process. There is a significant lack of ability to take qualitative assessment information and convert it to actionable information that can be used to support military decision making on project selection to improve installation resilience.

1.7.1. Publication 1. Proper training and education are key components to addressing this issue, but it is unclear how and where modeling under uncertainty, infrastructure systems management, and resilient systems are integrated into the standard undergraduate and graduate engineering management curriculum. This research used a mixed method to determine whether and at what level engineering managers receive instruction regarding the implementation of tools and techniques to improve infrastructure resilience. The results of the study extend academic literature on infrastructure resilience education by identifying five dimensions to quantitatively assess engineering management programs to detect gaps, trends, and best practices in current infrastructure resilience education.

1.7.2. Publication 2. This research addressed a considerable gap in the existing Department of Defense (DoD) Mission Assurance Framework between the infrastructure assessment process and resilience considerations through the integration of a resilience matrix to develop the Mission Assurance Resilience Matrix (MARM). The MARM converts qualitative assessment data into a quantifiable and interactive resilience decision support tool. The integration of the resilience matrix was used to develop a quantitative visual tool to communicate the impact of decisions made using the tradespace analysis. This methodology provided a framework to improve the selection of projects that enhance resilience of military infrastructure systems and assist decision makers in understanding how a singular project may influence the resilience of multiple systems.

1.7.3. Publication 3. The goal of this study was to verify the MARM as an infrastructure resilience decision support tool. This was accomplished by utilizing the Modified Delphi Method to examine the amount of potential uncertainty in the MARM due to subject matter expert assessment of benchmark category priority weights and ratings as well as validating the hypothesis that the MARM does perform differently from the SME project selection heuristics, though more research needs to be conducted to quantify the amount of that impact. The study also incorporated a System Usability Scale to establish the level of usability of the MARM as an information technology tool. The results of this study verify the MARM's potential as a beneficial decision support tool.

1.7.4. Publication 4. The goal of this study was to investigate the behavior of the MARM due to uncertainty by using a Monte Carlo simulation to conduct a sensitivity analysis of the prioritization and ratings of the benchmark categories imbedded into the cells of the matrix. The results of this analysis demonstrated the ability to use sensitivity analysis to investigate uncertainty in the MARM, highlight the challenges of incorporating the MARM into the existing DoD Mission Assurance Construct to assess infrastructure resilience, and identify opportunities to improve the integration and use of the MARM for extension and expansion to the broader infrastructure resilience community.

The results of this dissertation, which are built for a specific installation, are broadly applicable and can support engineers in the design and/or management of infrastructure systems to improve resilience in an efficient manner.

PAPER

I. A MIXED METHOD STUDY OF INFRASTRUCTURE RESILIENCE EDUCATION AND INSTRUCTION

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ABSTRACT

As the frequency and severity of natural and man-made disasters increases, the importance of improving the resilience of complex infrastructure systems in an uncertain environment is increasingly critical. Proper training and education are key components to addressing this issue, but it is unclear how and where modeling under uncertainty, infrastructure systems management, and resilient systems are integrated into the standard undergraduate and graduate engineering management curriculum. This research uses a mixed method to determine whether and at what level engineering managers receive instruction regarding the implementation of tools and techniques to improve infrastructure resilience. A review of current courses and content informs a systems-thinking approach to resilience and investigates how the topic of infrastructure resilience is being taught. The results of the study identify gaps in existing engineering management curriculum with respect to the topic of resilience. The findings from these results can be used to by the engineering management educator to provide coursework and training that can be used to lead teams that design, build, analyze the resiliency of current infrastructure systems, or restore damaged infrastructure systems to their original state.

Keywords: Infrastructure, resilience, education

1. INTRODUCTION

Critical infrastructure systems such as hospitals, transportation networks, and utility systems, are becoming increasing more complex and interdependent while at the same time there has been a significant increase in operational uncertainty of these systems due to either natural or man-made disasters. Infrastructure resilience is the concept that addresses this uncertainty though it has been defined in many ways by a host of experts across a vast cross-section of disciplines. This research utilized its previous work on an integrative literature review to define resiliency as “an ability to prepare for, withstand, and/or recover from adversity, emergencies or failures in a timely manner and still be able to function at least nominally while minimizing potential losses in the system” (Wilt, Long, & Shoberg, 2016).

Due to the complexity of these infrastructure systems and the various engineering and other disciplines involved with the design and operation of a complex infrastructure system, solutions to improve infrastructure resilience require a multidisciplinary approach and makes the application of operational concepts of engineering management towards understanding and improving infrastructure resilience more important to maintaining, restoring, and adapting critical infrastructure to deal with disasters. It has been argued that engineering management programs provide the leaders needed to manage these complex and interdisciplinary efforts (Perry, Hunter, Currall, & Frauenheim, 2017), so proper training and education of engineering managers in infrastructure resilience is critical to enable them to successfully lead infrastructure resilience programs and projects. However, at this time, it is unclear how and where modeling under uncertainty, infrastructure systems management, and resilient systems are integrated into the standard engineering curriculum.

This research uses a mixed method approach to determine whether and at what level engineering managers receive instruction regarding the implementation of tools and techniques to improve infrastructure resilience. The mixed methods research utilized a qualitative search of current courses in select schools with accredited engineering management programs, either by the American Society for Engineering Management (ASEM) or the Accreditation Board for Engineering and Technology (ABET), for terms related to infrastructure resilience in addition to content across engineering disciplines and their connection to current studies on engineering pedagogy to inform a systems-thinking approach to resilience and how the topic of infrastructure resilience is being taught. The results of the search were then quantitively investigated to identify trends and gaps in existing engineering management curriculum with respect to the topic of resilience. The findings from these results can be used to by the engineering management educator to provide coursework and training that can be used to lead teams that design, build, analyze the resiliency of current infrastructure systems, or restore damaged infrastructure systems to their original state.

2. LITERATURE REVIEW

This study began with seeking to identify a working definition for resilience that could be applied to infrastructure systems. The search began with the two cornerstone documents published by the American Society for Engineering Management; A Guide to the Engineering Management Body of Knowledge and the Engineering Management Handbook (ASEM, 2019). It turns out that neither of these documents have any mention of infrastructure resilience, which indicates there is a gap and opportunity to incorporate concepts of and methods for addressing infrastructure resilience in the Engineering Management Body of Knowledge.

Previous work to determine a working definition for infrastructure resilience through a State-of-the-Art Matrix (SAM) analysis of resilience literature found that resilience is defined somewhat loosely and varies across disciplines and concluded that an appropriate working definition of resilience is "the is an ability to prepare for, withstand, and/or recover from adversity, emergencies or failures in a timely manner and still be able to function at least nominally while minimizing potential losses in the system". (Wilt, Long, & Shoberg, 2016). This definition informed the research of courses in the targeted programs that included related themes or topics.

Since the Department of Homeland Security (DHS) is the agency given the responsibility for infrastructure planning and projection at the Federal level, it is instructive to investigate what efforts they have put forth towards educational initiatives in infrastructure resilience. Ramirez and Rioux conducted a survey of select DHS personnel to identify potential courses and topics to be included in Homeland Security programs to help inform those involved in curriculum development, and their assessment indicates that there is a significant gap and a strong need to include courses into curricula that address response to and mitigation of disasters (Ramirez & Rioux, 2012).

This infrastructure resilience gap was also identified at the highest levels of our national government and addressed with the White House Educators Commitment on Resilient Design, signed in 2016 that calls for a focus on resilient design across all disciplines. Eighty-three schools and fourteen research centers, institutes and associations signed the commitment, to include several of these schools were studied in this research based on their accreditation with either ABET or ASEM. The intent of this commitment is for institutions to commit to teach students who can lead the various activities (such as planning, design, engineering, and construction) to build resilient infrastructure (White House, 2016). This commitment is in line with the goals of this research to identify where and how infrastructure resilience is being taught at institutions of higher education.

Though not an exhaustive search, another avenue pursued was to conduct a search for infrastructure resilience related articles in the American Society for Engineering Education (ASEE) annual conference proceedings over the past 10 years. ASEE is the largest annual gathering of engineering educators in the country and an investigation of the types of articles and divisions in which they appear were used to identify the closest to “real time” state-of-the-art educational research as well as trends in infrastructure resilience education. The search, which incorporated the keywords of either infrastructure, resilience or both, yielded a total of 244 results.

Table 1. Infrastructure and/or Resilience Articles in ASEE Conference Proceedings 1998-2018.

Results by Year			**Results by Division**	
2018	34		Civil Engineering	44
2017	51		Multidisciplinary Engineering	12
2016	41		Community Engagement Division	11
2015	19		Environmental Engineering	9
2014	17		Liberal Education/Engineering & Society	8
2013	17		Minorities in Engineering	8
2012	16		Electrical and Computer	6
2011	12		Construction	5
2010	10		Cooperative & Experiential Education	5
2009	2		Energy Conversion and Conservation	5
2008	3		Entrepreneurship & Engineering Innovation	5
2007	7		International	5
2005	5		K-12 & Pre-College Engineering	5
2004	4		Design in Engineering Education	4
2003	2		First-Year Programs	4
2002	2		Mechanics	4
2001	1		College Industry Partnerships	3
1998	1		Computing & Information Technology	3
			Educational Research and Methods	3
			Engineering Management	3
			Systems Engineering	3
			Architectural	2
			Computing and Information Technology	2
			Graduate Studies	2
			Information Systems	2
			Military and Veterans	2
			Military and Veterans Constituent Committee	2
			Technological and Engineering Literacy/Philosophy of Engineering	2
			Women in Engineering	2
			Aerospace	1
			Architectural Engineering	1
			Division Experimentation & Lab-Oriented Studies	1
			Engineering Economy	1
			Engineering Ethics	1
			Engineering Leadership Development	1
			Engineering Leadership Development Division	1
			Industrial Engineering	1
			Instrumentation	1
			Liberal Education	1
			Manufacturing	1
			National Science Foundation	1
			Pre-College Engineering Education	1
			Pre-College Engineering Education Division	1
			Two Year College Division	1

There was a significant jump from 19 articles in the 2015 proceedings to over 30 each of the past three years. The division with the largest number of articles was the Civil Engineering Division followed by the Multidisciplinary Engineering Division. The Engineering Management had three articles over the period covered by the search. The search results are shown in Table 1.

Findings from the review of current literature are that there is a significant gap in addressing infrastructure resilience in both the formal engineering management body of knowledge and engineering management educational research perspectives. This study aims to address overall trends in infrastructure resilience to help close that gap.

3. MULTIDISCIPLINARY PEDAGOGY

Due to the wide range of systems and disciplines involved in infrastructure resilience, effective educational efforts should be multi- or inter-disciplinary. Stember provides a good elaboration of the distinctions between the two approaches. Multidisciplinary involves several disciplines who each provide a different perspective on a problem or issues. The student is required to integrate the often-diverse ideas. Interdisciplinary: integration of the contributions of several disciplines to a problem or issue is required. Interdisciplinary integration brings interdependent parts of knowledge into harmonious relations through strategies such as relating part and whole or the particular and the general. A genuinely interdisciplinary enterprise is one that requires more or less integration and even modification of the disciplinary contributions while the inquiry or teaching is proceeding and is a complex endeavor to explicate relationships, processes, values, and context using the diversity and unity possible only through collaborative approaches. (Stember, 1991). This study incorporated a multidisciplinary approach to its search for infrastructure resilience courses and research areas.

4. METHODOLOGY

The research started with an online search conducted for infrastructure resilience education that yielded over 39 million website hits. The search was refined by searching only for “infrastructure resilience education”, but still yielded about 575 website hits, many of which were not related to this investigation. This is due to the various ways that resilience, infrastructure, and education are defined and used in practice. To narrow the study down and make it more pertinent to undergraduate and graduate level education, this study focused on two groups of universities. The first group of institutions considered were the seven institutions with graduate Engineering Management programs certified by the American Society for Engineering Management (ASEM, 2019). This initial group was expanded to include the sixteen schools with Accreditation Board of Engineering and Technology (ABET) accredited Engineering Management programs (ABET, 2019). One school, the Missouri University of Science and Technology, fit both criteria.

This sample was selected to filter out the various types of engineering management programs since engineering management can be loosely interpreted and housed in various departments or programs (such as a business school, industrial engineering department, etc.). This list was not designed to be all inclusive, but rather a cross section of schools that have been accredited in order to provide a look at a broad range of programs and institutions that are well regarded in the field and have met common criteria. This also narrowed down the programs to an appropriate number from which to build the framework of this study which can be utilized as the scope is increased in future work.

Additionally, information on infrastructure resilience related courses was not found for all schools, so the final list of schools studied was reduced to fifteen, as shown in Table 2.

Table 2. List of ASEM and ABET Accredited Engineering Management Programs.

Institution		Category
1	Missouri University of Science and Technology	ASEM Accredited & ABET EM Accredited
2	Drexel University	ASEM Accredited
3	Old Dominion	ASEM Accredited
4	University of Idaho	ASEM Accredited
5	Western Michigan University	ASEM Accredited
6	Air Force Institute of Technology	ABET EM Accredited
7	Arizona State University *	ABET EM Accredited
8	Clarkson University *	ABET EM Accredited
9	Gonzaga University	ABET EM Accredited
10	Montana State University	ABET EM Accredited
11	North Dakota State University	ABET EM Accredited
12	Rensalear Polytechnic Institute *	ABET EM Accredited
13	Stevens Institute of Technology *	ABET EM Accredited
14	United States Military Academy	ABET EM Accredited
15	University of Connecticut	ABET EM Accredited

Not included due to lack of data		Category
1	The British University in Dubai	ASEM Accredited
2	St. Cloud State	ASEM Accredited
3	California State University, Northridge	ABET EM Accredited
4	South Dakota School of Mines and Technology	ABET EM Accredited
5	Universidad Ana G. Mendez - Gurabo Campus	ABET EM Accredited
6	University of Arizona	ABET EM Accredited
7	University of the Pacific	ABET EM Accredited

* Signatory Institution to the White House Educators Commitment on Resilient Design

The evaluation of each program followed the methodology of Klassen, Reeve, Rottmann, Sacks, Simpson, and Huyuh who assessed how engineering leadership programs bin together along various dimensions – end goal, application of leadership learning, scale of leadership action, leadership emphasis, participant selection, compulsoriness, and integration (Klassen, Reeve, Rottmann, Sacks, Simpson, & Huyuah, 2016). The qualitative evaluation of these Engineering Management programs sought to identify key dimensions and develop a conceptual framework based on the pedagogical research that applied to the institutions studied. This strategy employed a modified version of analytical induction (Patton, 2014).

The search began in the course catalog for each institution’s engineering management program for the keywords “infrastructure” and “resilience” other related terms. Then the search was expanded for any course in the institution’s catalog with these keywords. Finally, the search expanded to research centers and faculty. The results from the search from each institution were captured and cataloged according to institution, program, individual course number and description, graduate or undergraduate, course focus, and whether the courses were cross listed or included other departments to indicate multidisciplinary.

From the search of each school’s website and course catalog for courses and reach related to infrastructure resilience, five dimensions emerged to assess the programs emerged. The schools were assessed on: Program Structure, Academic Focus, Research Center/Focus Area, Multidisciplinary, and Disciplinary Programs. By conducting a qualitative analysis of the program and course descriptions focused on keywords linked to infrastructure resilience, a quantitative assessment of the types and numbers of programs reveals the state-of-the art of current infrastructure resilience education at these selected schools. An in-depth discussion on each dimension follows.

4.1. DIMENSION 1: PROGRAM STRUCTURE

The structure of each program fell into one of the following categories: undergraduate courses only, graduate courses only, or a mix of undergraduate and graduate courses. Some programs also afforded the opportunity to earn either an infrastructure resilience related minor/focus area or graduate certificate. No programs offered a purely infrastructure resilience related graduate degree (Master or PhD). The breakdown across these categories are shown in Figure 1.

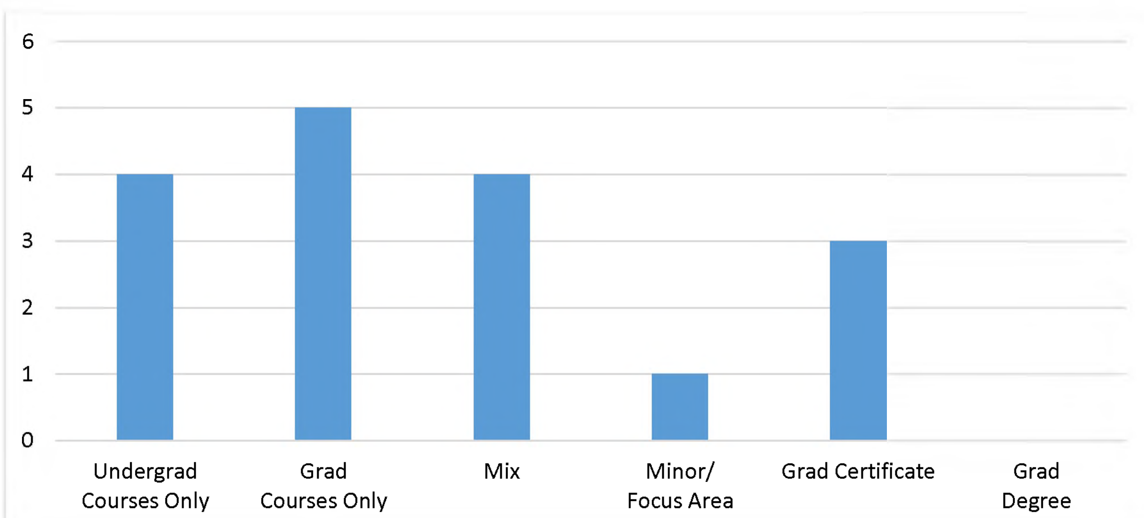

Figure 1. Dimension 1: Program Structure.

4.2. DIMENSION 2: ACADEMIC FOCUS

Assessing the program and course descriptions for each institution identified whether the program/courses focused more on design for resilience, assessment of as-built environment, or disaster response. The determination the breakdown of the courses focused on if the course descriptions described designing infrastructure to be resilience, how to assess current infrastructure for resiliency, how to restore infrastructure/disaster response. Several of the programs incorporated a mix of these three focus areas. The breakdown across these categories are shown in Figure 2. The majority of programs focus on assessment of the as-built environment for resilience with a slightly smaller number of programs focused on incorporating resilience into design. Only two programs taught response concepts. About a third of the programs incorporated a mix of the three areas, with two those programs incorporating all three areas.

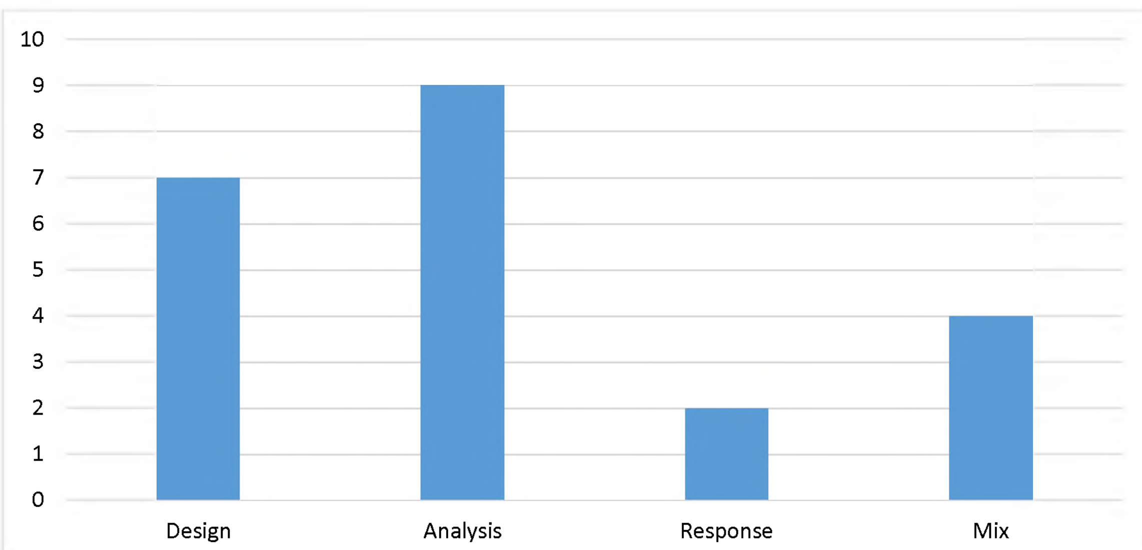

Figure 2. Dimension 2: Academic Focus.

4.3. DIMENSION 3: RESEARCH CENTER/FOCUS AREA

The program descriptions and instructor biographies identified if the institution had a specific center that conducted research into infrastructure resilience or if it is a faculty area of research. Housing of a research center or the indication that infrastructure resilience is a research topic of the faculty typically provides opportunities for this research to enter into the classroom or student research opportunities, thereby enhancing educational engagement with infrastructure resilience topics. The breakdown in shown in Figure 3.

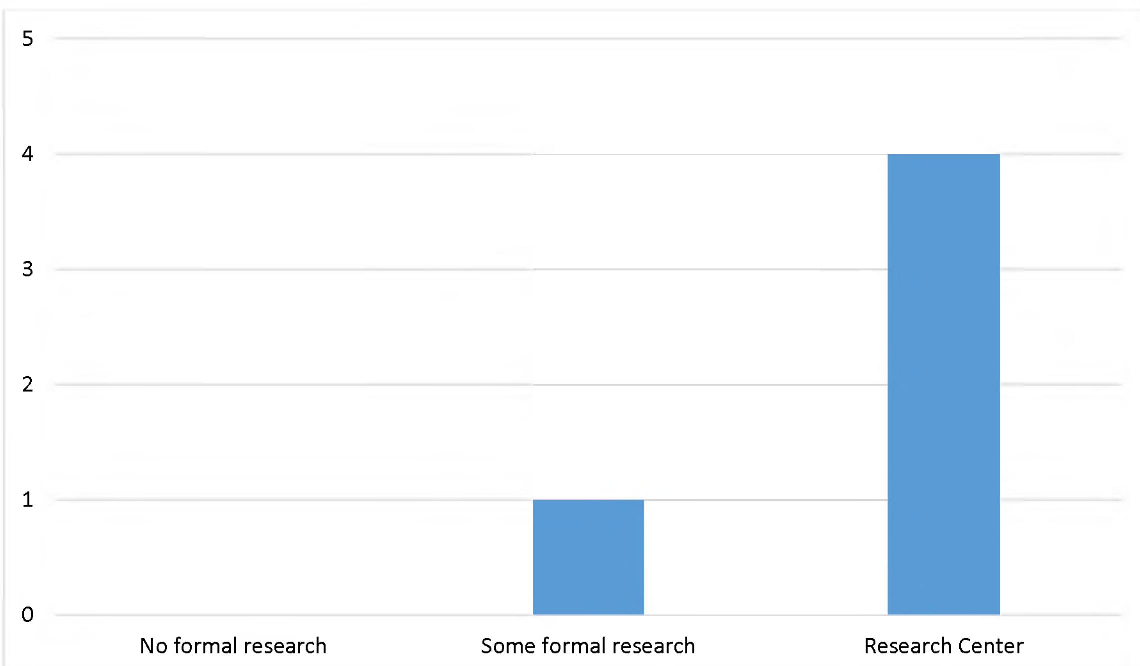

Figure 3. Dimension 3: Research Center or Research Focus Area.

4.4. DIMENSION 4: MULTIDISCIPLINARY

The level of multidisciplinary work was assessed for each program by looking at several elements to include if the course was cross-listed with multiple departments, the number and types of departments listed in the program or course descriptions, and the number and types of departments included in research descriptions. A slight majority of programs are multidisciplinary, but a large number do not appear to incorporate multidisciplinary education into their teaching of infrastructure resilience topics. The rankings were based on the following rubric:

Not multidisciplinary: only one department listed in program, course, or research material

Somewhat multidisciplinary: only one additional department listed in program, course, or research material

Very multidisciplinary: more than one additional department listed in program, course, or research material

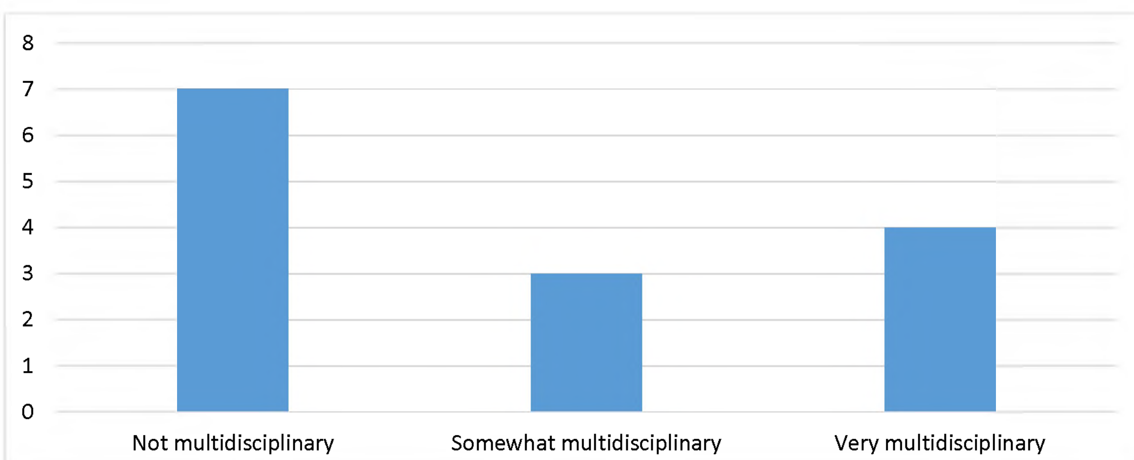

Figure 4. Dimension 4: Multidisciplinary.

4.5. DIMENSION 5: DISCIPLINARY DEPARTMENTS

Related to the investigation of the programs relative level of multidisciplinary connectedness, the types of disciplinary departments involved in infrastructure resilience was captured. As shown in Figure 5, the majority of programs house their infrastructure resilience education capacity in their civil engineering program, with environmental engineering and engineering management. Departments in the other category include architectural engineering, construction management, industrial and systems engineering, and homeland security.

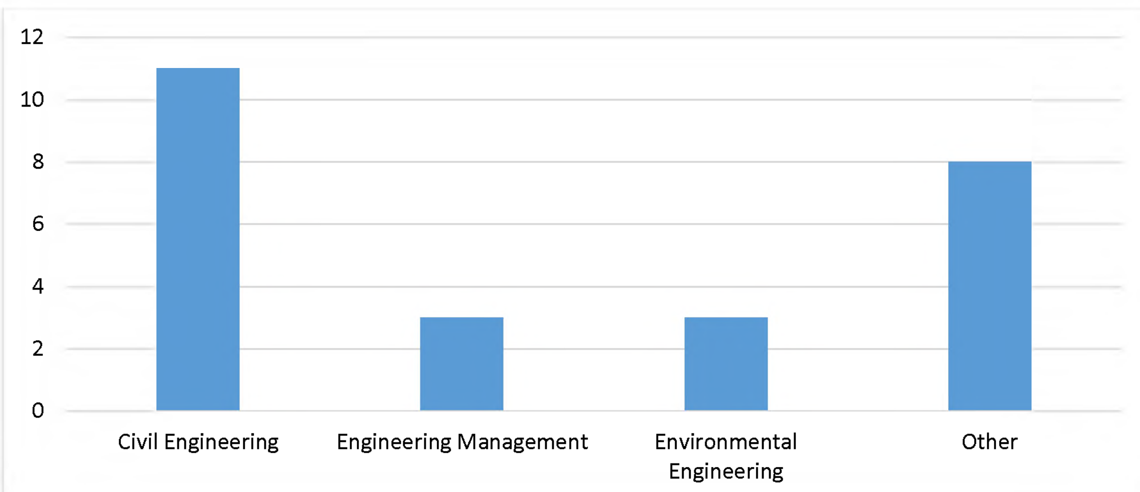

Figure 5. Dimension 5: Disciplinary Departments.

5. DISCUSSION

The significant weather events of the Spring of 2019 (unprecedented numbers of tornados and historic flooding along some of our nation's major waterways), demonstrate the need and timeliness of this research into where and how infrastructure resilience is being incorporated into engineering management education. Engineering managers are uniquely postured, based on the nature of the discipline, to lead the design, analysis and response to improving the resilience of complex and multidisciplinary infrastructure systems. But the study of where and how infrastructure resilience is being incorporated within these fifteen institutions with engineering management programs is very instructive as to the gaps in the current state of infrastructure resilience education.

Through the qualitative investigation of the 15 programs selected for this study, five dimensions emerged from which to quantify the number of programs in each portion of the spectrum under each specific dimension. This quantitative assessment helps identify the trends and gaps in current infrastructure resilience education.

There is a significant lack of discussion on the instruction of infrastructure resilience education within the engineering management education discipline. Less than 2% (3 of 244) papers presented at the ASEE Annual Conference over the past ten years tied to infrastructure resilience education were tied to the Engineering Management Division.

The breakdown across programs teaching at the undergraduate, graduate, or a mix of both is evenly distributed. This is greatly impacted by whether the school has an undergraduate or graduate program. More enlightening though is where the institution has a research center or research focus from their faculty on infrastructure resilience. Only one third of the institutions in the study incorporate infrastructure resilience research, whether in the form of a research center or a faculty research focus area.

Finally, the most significant gap is in the incorporation of a multidisciplinary approach to infrastructure resilience education. Almost half (7 of 15) of the institutions did not describe a multidisciplinary approach to infrastructure education. And the clear majority (11 of 15) of the programs connected infrastructure education to the civil engineering program. While the largest component of an infrastructure system is typically the structural, and hence, civil engineering component, infrastructure systems are increasingly complex and multidisciplined when the electrical, mechanical, information technology, environmental, and safety/security components are incorporated. Only 20% (3 of 15) programs had a connection to engineering management courses displays the gap due to the lack of connection to engineering management programs. Due to the nature of the engineering management discipline as teaching engineers how to design, build, analyze, and restore across a multitude of disciplines, there is great opportunity to demonstrate the value and applicability of engineering management programs as multidisciplinary.

In summary, the teaching of infrastructure resilience tends to be siloed into graduate civil engineering programs and not strongly linked to faculty and/or research centers. The academic focus of the programs is relatively evenly split between design of new infrastructure systems and analysis of the as-built or to be built environment. There are a few institutions that are focused on the mix of design, analysis, and disaster response for infrastructure resilience, incorporating a multidisciplinary approach, and integrating research into classroom instruction. There appears to be a large gap, and therefore a great opportunity, for engineering management programs to expand their instruction in infrastructure resilience topics. The lessons learned from this study can inform institutions that are looking to broaden their incorporation of infrastructure resilience into their academic program as to best practices linked to pedagogy.

6. RECOMMENDATIONS AND POTENTIAL AREAS FOR FUTURE RESEARCH

The major recommendation is that academic institutions with engineering management programs at either the undergraduate and/or graduate level use this framework with which to evaluate how their program addresses the instruction of infrastructure resilience. Specifically, they can assess if they have coursework in these topic areas, if there is multidisciplinary approach, and if faculty research is being connected to classroom instruction. They can then look to the best practices from other institutions identified in this study to fill in the gaps in their programs.

The most robust programs studied incorporated a research center and/or faculty research with an online certificate or graduate program that included several classes in infrastructure resilience that incorporated all three focus areas: design for resilience, assessment of the as-built environment, and disaster response. This can serve as a model for programs seeking to be at the leading edge of meeting the increasing demand for engineer managers that can lead and solve these complex infrastructure resilience issues.

A second recommendation is to expand this study to non-ASEM and non-ABET accredited institutions. There are many more engineering management programs across the country that can be investigated to determine what other best practices are available to incorporate across the field to improve the overall instruction of infrastructure resilience topics.

Additionally, academic institutions are not the only entities operating in the infrastructure resilience education realm. Several societies, Federal agencies, cooperative programs, and conferences are offering professional education courses or programs in infrastructure resilience. These include the American Society for Civil Engineering (ASCE) (American Society of Civil Engineers, 2019), the Center for Infrastructure Transformation and Education (CIT-E), a community of practice comprised of faculty members who share a passion for infrastructure education and intends to transform the way that civil and environmental engineering topics are taught, (Center for Infrastructure Transformation and Education, 2019) the George Mason University Center for Infrastructure Protection & Homeland Security which is currently completing a multi-year Higher Education Initiative with DHS to develop and evaluate curriculum for graduate and professional workforce training and education in topics vital to the critical infrastructure community (Center for Infrastructure Protection and Homeland Security, 2019), and the Critical Infrastructure Resilience Institute, which conducts research and education that enhances the resiliency of the nation's critical infrastructures and the businesses and public entities that own and operate those assets and systems (Critical Infrastructure Resilience Institute, 2019).

Finally, the investigation can be further expanded to survey practicing engineering managers in the field of infrastructure resilience to identify the education gaps they feel should be filled to assist them in their work. Expanding the research in these areas will not only provide a larger menu of best practices from which programs can incorporate infrastructure resilience, but also provide a more holistic look at infrastructure education as a whole to identify system gaps and opportunities for improvement across the spectrum of engineering education; undergraduate, graduate, and professional.

REFERENCES

Accreditation Board for Engineering and Technology. (2019). *ABET-Accredited Programs*. Retrieved from Accreditation Board for Engineering and Technology: http://main.abet.org/aps/Accreditedprogramsearch.aspx

American Society for Engineering Management. (2019). *Graduate Program Certification*. Retrieved from American Society for Engineering Management: https://asem.org/Graduate-Program-Cert

American Society of Civil Engineers. (2019). *Infrastructure*. Retrieved from American Society of Civil Engineers https://www.asce.org/infrastructure/

Center for Infrastructure Protection and Homeland Security. (2019). Retrieved from Center for Infrastructure Protection and Homeland Security: https://cip.gmu.edu/

Center for Infrastructure Transformation and Education. (2019). Retrieved from Center for Infrastructure Protection and Homeland Security: http://www.cit-e.org/

Critical Infrastructure Resilience Institute. (2019). Retrieved from Critical Infrastructure Resilience Institute: http://ciri.illinois.edu/

Department of Homeland Security. (2013). *NIPP 2013: Partnering for Critical Infrastructure and Resilience*. Retrieved from Department of Homeland Security: https://www.dhs.gov/sites/default/files/publications/NIPP%202013_Partnering%20for%20Critical%20Infrastructure%20Security%20and%20Resilience_508_0.pdf

Klassen, M., Reeve, D., Rottmann, C., Sacks, R., Simpson, A., & Huyuh, A. (2016). Charting the Landscape of Engineering Leadership Education in North American Universities. *Proceedings of the 123rd American Society for Engineering Education Annual Conference,* (CD-ROM).

Patton, M. (2014). *Qualitative Research & Evaluation Methods, Fourth Edition*. SAGE Publications.

Perry, S., Hunter, E., Currall, S., & Frauenheim, E. (2017). Developing Engineering Leaders: An Organized Innovation Approach to Engineering Education, *Engineering Management Journal, 29(2)*, 99-107.

Ramirez, C., & Rioux, G. (2012). Advancing Curricula Development for Homeland Security Education through a Survey of DHS Personnel. *Journal of Homeland Security, 1(1),* 6 – 25.

Stember, M. (1991). Advancing the Social Sciences Through the Interdisciplinary Enterprise. *The Social Science Journal, 28(1)*. 1-14.

White House. (2016). *Designing for a Resilient Future*. Retrieved from The White House: https://obamawhitehouse.archives.gov/blog/2016/10/31/designing-resilient-future

Wilt, B., Long, S., & Shoberg, T. (2016). Defining Resilience: A Preliminary Integrative Literature Review. *Proceedings of the American Society for Engineering Management 2016 International Annual Conference, S. Long, E-H. Ng, C. Downing, & B. Nepal eds.*, (CD-ROM).

II. IMPROVING MISSION ASSURANCE ASSESSMENTS FOR RESILIENCE OF MILITARY INSTALLATIONS

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ABSTRACT

It is critical to improve the resilience of military installations and their complex infrastructure systems to strengthen response to the uncertainty and threat driven by the increasing frequency and severity of natural and man-made disasters. This research addresses a considerable gap in the existing Department of Defense (DoD) Mission Assurance Framework between the infrastructure assessment process and resilience considerations and integrates a resilience matrix that converts qualitative assessment data into a quantifiable and interactive resilience decision support tool. The integration of the resilience matrix provides a quantitative visual tool to communicate the impact of decisions made using the tradespace analysis. This methodology provides a framework to improve the selection of projects that enhance resilience of military infrastructure systems and assist decision makers in understanding how a singular project may influence the resilience of multiple systems. The results of this research, which are built

for a specific installation, are broadly applicable and can support engineers in the design and/or management of infrastructure systems to improve resilience in an efficient manner.

Keywords: Infrastructure resilience, infrastructure assessment, resilience matrix, decision-making tool, tradespace

1. INTRODUCTION

Military installations and their complex infrastructure systems are operating in a progressively more uncertain environment due to the increasing frequency and severity of natural and man-made disasters. Similar to civilian infrastructure systems, assessment and decision-making regarding improvement to the resilience of military infrastructure systems are extremely challenging. Each installation is a unique system of systems due to the interconnectedness of structural, electrical, cyber/information technology, security, mechanical, and environmental systems. The resilience of the installation is determined by how quickly the multiple integrated subsystems can return to acceptable levels of operation in the event of a major disruption due to a disaster. Military infrastructure systems possess several unique characteristics that increase the complexity of assessing and decision-making regarding resilience. Additionally, the constraints on military infrastructure systems under the current operating and fiscal climate makes it imperative that military decision makers have a well thought out and readily applicable methodology for incorporating resilience into infrastructure system decision making.

This research integrates a resilience matrix into the existing Department of Defense (DoD) Mission Assurance Assessment (MAA) framework for infrastructure assessment, resulting in the Mission Assurance Resilience Matrix (MARM). It also applies concepts from the Department of Defense (DoD) Engineered Resilience Systems (ERS) tradespace analysis methodology used to incorporate resilience into deployable military systems, such as helicopters and tanks, to create a decision support tool. This integration of resilience matrix methodology with tradespace analysis to infrastructure systems has potential benefits for military infrastructure decision-making regarding design of new infrastructure systems for resilience, the improvement of resilience within the already built environment, or improvements to disaster response. This methodology can aid engineers, so they make better informed decisions early in the process for the design and/or management of infrastructure systems to improve resilience in an efficient manner.

1.1. MILITARY INFRASTRUCTURE

Military infrastructure comprises a broad portfolio covering a wide range of facilities and systems. The formal definition of a military installation is "a base, camp, post, station, yard, center, or other activity under the jurisdiction of the Secretary of a military department or, in the case of an activity in a foreign country, under the operational control of the Secretary of a military department or the Secretary of Defense, without regard to the duration of operations control" (Congressional Research Service 2019). These facilities vary from "home station" installations based in the continental United States, to forward based installations such as those in Germany and Korea, to expeditionary base camps and operating bases that support operations in Iraq, Afghanistan, and Syria (Lostumbo et al. 2013).

Military infrastructure systems possess several characteristics that make them unique compared to infrastructure systems in the civilian sector. They require consideration of operational vulnerability to an intelligent adversary, not just nature or a targeted act of violence, as the enemy can have an impact in a powerful and sustained way (Hagen et al. 2017). The requirements they must fulfill are impacted by changes to unit structures, deployable systems, command and control focus/emphasis, and politics. Additionally, the design, construction, and approval of projects to improve military infrastructure is impacted by the availability and limitations of different “pots” of money that can be appropriated by Congress for these projects such as Operations and Maintenance (O&M), Facilities Sustainment, Restoration and Modernization (SRM), Civil Works, and Military Construction. The rules for each type of appropriation prohibit the mixing or combination of funds from various sources, often limiting efficient use of resources and minimizing impact of the projects (Congressional Research Service 2019). The combination of these unique characteristics makes it imperative that infrastructure resilience decision support tools are tailored for utilization within military applications.

1.2. STRATEGIC EMPHASIS ON RESILIENCE AND MISSION ASSURANCE STRATEGY

Congress reinforced previous mandates that the DoD address the resilience of its infrastructure in the Military Installation Resilience Assuredness Act enacted by the House of Representatives in May 2019. This act specifically requires commanders of military installations to integrate installation resilience in master plans that incorporate disaster-related and environmental conditions and the measures to mitigate these risks (116th Congress 2019). Towards this end, the DoD made infrastructure resilience a focal point of its installation management strategy implemented in the Defense Critical Infrastructure Program (DCIP). This risk management program confirms the availability of resources deemed essential to successful completion of DoD missions and includes assets that are essential to planning, mobilizing, deploying, executing, and sustaining U.S. military operations worldwide. The goal of the DCIP is to reduce or eliminate unacceptable risk to Defense Critical Assets, thus enabling the successful execution of DoD missions, regardless of the threat or hazard (Department of Defense 2018a). The DoD also highlighted infrastructure resilience as a key component of its National Defense Strategy by specifying that there will be a priority to transition to smaller, dispersed, resilient and adaptive basing (Department of Defense 2018b).

To establish a comprehensive and integrative assessment framework, the DoD implemented the Mission Assurance Strategy and defined mission assurance as a process to protect or ensure the continued function and resilience of capabilities and assets – including personnel, equipment, facilities, networks, information and information systems, infrastructure, and supply chains – critical to the performance of DoD Mission-Essential Functions (MEF) in any operating environment or condition (Department of Defense 2017). The intent is for implementation of this framework to assist the DoD prioritize infrastructure investments and provide input into the DoD's existing planning, budgeting, requirements, and acquisition process as decisions are made on increasing resilience capacity. The DoD Mission Assurance Strategy identified a shortfall in the ability to identify strategic protection and resilience risks or critical interdependencies within its infrastructure systems and, therefore, the ability to make sound policy and investment decisions. Additionally, it indicated that the visibility on emerging protection and resilience best practices and performance metrics is limited and the connection between the data collection process conducted by installation infrastructure assessment teams and installation risk management decision making procedures is broken. Mission assurance seeks to address these shortfalls and support DoD's existing resource allocation and Defense Acquisition System processes (Department of Defense 2017).

1.3. DEFINITION OF RESILIENCE

Resilience is a term widely used in various industries and settings with different connotations depending on how the term is defined. The preponderance of literature focuses on returning the system to its original operating level after the impact of an instantaneous event, i.e. some exogenous "shock", whether a natural or man-made disaster. Wilt, Long, and Shoberg conducted an integrative literature review of resilience definitions in recent technical literature and concluded that, "resilience is an ability to prepare for, withstand, and/or recover from adversity, emergencies or failures in a timely manner and still be able to function at least nominally while minimizing potential losses in the system" (Wilt et al. 2016). Furthermore, the National Academy of Sciences (NAS) defines disaster resilience as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events" (Committee on Increasing National Resilience to Hazards and Disasters 2012). This definition not only connotates the system's capacity to return to previous levels of operation, but also the ability to adapt and improve to offer even better levels of service and operation.

For military infrastructure decisions, which must be made under constrained resources but a long operational horizon of at least 50 years, it is appropriate to broaden the context of the "shock" to the system beyond a natural or man-made disaster to include any change in the system's environment that degrades value delivery and ensure adaptation is incorporated such that the return of system "value delivery" would be the recovery. A simple example is a new shopping mall that initially attracts attention and is busy with shoppers but is not resilient to a "shock" such as changing shopping trends and/or local demographics, will endure a slow fade, rather than a stoppage after a singular event, until it becomes obsolete. Similarly, military infrastructure must be resilient to not only instantaneous events, but also able to adapt to changing purposes or capacities due to variations (i.e. "shocks") in the environmental, political, social, or strategic environments.

Additionally, military infrastructure resilience as a property should be viewed in terms of interconnected functions and systems, not simply individual features (Aven and Thekdi 2018; Linkov et al. 2018) which necessitates that an installation's resilience be considered broader than simply its ability to resume combat related operations following a shock. Thus, the framework for restoration of operations needs to scale across the interconnected functions and various types of disasters with minimal modification (Ramachandran et al. 2015). The recovery of Tyndall Air Force Base in the Florida Panhandle from Hurricane Michael in October 2018 is an illustrative example of the interconnectedness of functions on a military installation. Though the base could quickly remove debris and reopen the airfield, the myriad of support facilities that need to be rebuilt to return the base to fully operational status shows the broader contextualization of resilience needed for military infrastructure. The Base Commander, Colonel Laidlaw stated, “I can't bring lots of people back until I rebuild my child development center. I can't bring in new and additional airmen in until I rebuild some of the dorms” (Shapiro 2019). These facilities do not directly influence airfield operations but are necessary for the restoration of the base to pre- “shock” operations. This connects the importance of this research as the DoD Mission Assurance Construct considers military installations as functions and systems rather than a set of features.

1.4. PURPOSE OF STUDY

This study integrates infrastructure resilience into the existing military installation mission assurance assessment (MAA) process. This integration of resilience into the MAA uses a resilience matrix and tradespace analysis. This not only fills a gap in the literature, but also provides military decision makers with a visual and interactive decision support tool when assessing infrastructure resilience and impacts of individual infrastructure improvement projects on system resilience. It also connects the infrastructure assessment data collection and decision-making processes.

2. METHODOLOGY

This research applies a resilience matrix methodology to construct a Mission Assurance Resilience Matrix (MARM) utilizing a subset of the DoD Mission Assurance Assessment framework to convert current assessment collection methods to resilience metrics and analysis. The MARM is then employed to conduct a tradespace analysis to investigate the impacts of project selection on installation infrastructure resilience.

2.1. MATRIX APPROACH TO RESILIENCE ASSESSMENT

Previous research proposed the use of a resilience matrix as a framework to assess the performance of integrated complex systems (Fox-Lent et al. 2015). The resilience matrix integrates assessment of resilience at the functional and system levels, so that the evaluation is not just based on the features of the infrastructure. This is highly applicable to military infrastructure assessments, due to the unique, complex, and highly integrated nature of military infrastructure as a system of systems. This resilience matrix framework consists of a 4x4 matrix. The rows describe the four general management domains of a complex system (physical: sensors, systems, platforms, and facilities; information: the information collected, posted, pulled, displayed, processed, and stored; cognitive: the perceptions and understanding of what this information states and means and the mental models, preconceptions, biases, and values that serve to influence how information is interpreted and understood, as well as the nature of the responses that may be considered; and social: command and control processes and the interactions between and among individuals and entities that fundamentally define organization and doctrine) described in the United States Army's Network-Centric Warfare doctrine defined by Alberts and Hayes (Alberts and Hayes 2005). The four columns of the resilience matrix describe the four stages of disaster management (plan/prepare, absorb/withstand, recover, adapt) described previously.

2.2. MISSION ASSURANCE ASSESSMENT FRAMEWORK

The United States Army uses the DoD MAA Benchmarks for the basis of assessing its installations. The guidance states that throughout the process, assessment teams will apply the benchmark for each category with paramount consideration toward the impact to mission accomplishment, sustainment, and resilience (Department of Defense 2018c). Resilience is defined within this framework as the ability to support the functions necessary for mission success with high probability, short periods of reduced capability, and across a wide range of scenarios, conditions, and threats, despite hostile action or adverse conditions and may leverage cross-domain or alternative government, commercial, or international capabilities (Department of Defense 2016a). Assessment teams submit completed MAA reports to the Office of the Secretary of Defense to apprise Combatant Commanders and other military leaders of the status of military installation infrastructure. These reports are an important input for these leaders to understand risk, inform the development of specific requirements for future infrastructure projects, and assist in making decisions about which ones to fund.

The MAA framework divides the assessment into divided into sixteen distinct functions, such as antiterrorism, physical security, and emergency management, with each area containing multiple categories to be assessed. Responsibilities for assessing the functions are assigned to members of the assessment team depending on their expertise. Assessment teams are composed of various specialties such as engineer, logistics, and cyber/information technology to conduct MAAs of military installations utilizing a checklist to assess each benchmark. For example, the engineer typically assesses around 50 benchmark categories within four specific areas of the MAA. The specific benchmarks utilized for this study are taken from the DoD Mission Assurance Benchmarks dated 28 March 2018, which are unclassified but designated as For Official Use Only (FOUO) (Department of Defense 2018c). Therefore, they cannot be published in this article in full, but the broad categories and representative identification numbers are summarized and implemented in this research to allow for easier connection back to the base document.

The implementation of the resilience matrix into the MAA process employed a general case based on data provided by the assessment team from the US Army Africa (USARAF) Deputy Chief of Staff Engineer (DCSENG) section. As one of the US Army's Component Commands, USARAF has responsibility of conducting MAAs for several contingency site locations. Members of the Engineer section assess physical infrastructure systems at these locations as part of the MAA team. To complete the checklist, the assessor assigns a qualitative rating of "Black", "Red", "Amber", or "Green" to each category based on their subject matter expertise and evaluation of the benchmark descriptions. The development of the rating is based on various Department of Defense guides but is largely subjective based on the experience and professional judgment of the assessment team. Details from the DCSENG assessment are integrated with assessors evaluating the other functions into a comprehensive report summarizing the results from the MAA team as required by the DoD Mission Assurance Construct.

2.3. MISSION ASSURANCE RESILIENCE MATRIX CONSTRUCTION

Despite Congressional guidance, the MAA framework does not specifically or directly assess the resiliency of a military installation as a system nor identify which improvements would impact resilience the most. To close this gap, this research utilizes the resilience matrix method to map a subset of the MAA benchmark categories that an engineer assessment team evaluates as part of an installation assessment and improve the ability to visualize the cost-benefits of potential infrastructure improvement projects to allow leaders to understand the influence that one project may have on multiple functions or systems. The construction of the Mission Assurance Resilience Matrix (MARM) and associated data visualization and decision analysis tools was completed using Microsoft Excel since this is a common and familiar platform for military assessment teams to collect data and implement the framework. The MARM and visualization tools were added as an additional tab linked to the category assessments to enable data input through the current process by the assessment team to directly feed into the MARM and the associated decision tools avoids requiring the assessment team to create a separate document.

The first step of construction of the MARM was to select the benchmark categories most pertinent to military installation infrastructure resilience based on input from subject matter experts from the USARAF DCSENG section. Since the benchmarks as they are written do not specifically address resilience, the input from subject matter experts was critical and identified that several of the MAA benchmark categories make an indirect connection to the definition of resilience to include adaptation to avoid becoming obsolete. For example, the requirement that the ammunition and explosive infrastructure should meet future and emerging mission requirements assesses how the installation can be resilient to a potential future "shock" to the system that would necessitate an expansion of ammunition and explosive storage capacity. Some benchmarks are written to where they may fit into multiple cells of the resilience matrix. Finally, to streamline this study, benchmarks specific to expeditionary installations were removed to further narrow the focus to more permanent installations (expeditionary installations can be added into the framework at a later time). This screening reduced the list to 41 benchmark categories.

The model converts the qualitative rating (B/R/A/G for Black, Red, Amber, and Green) for each category by the assessment team into a quantitative value using a qualitative conversion factor (Table 1). Additionally, decision makers do not prioritize all MAA benchmark categories equally, so to account for this, a priority weight factor, similar to the priority matrix developed to model resilience time (Ramachandran et al. 2015), was incorporated (Table 2).

Table 1. Qualitative Assessment Conversion.

Qualitative Rating	Score
Green	1
Amber	2
Red	3
Black	4

Table 2. Priority Weight Factor.

Qualitative Weight	Score
Highest	5
	4
Neutral	3
	2
Lowest	1

This framework permits the calculation of a quantitative Benchmark Score for each category using Equation (1):

$$Benchmark\ Score = Quantitative\ Assessment\ Conversion\ x\ Priority\ Weight\ Factor \quad (1)$$

A larger Benchmark Score indicates a category with a higher importance in poor condition. The following is an example calculation for the Antiterrorism category, ID: AT-19, which, in this example, was assessed at "Black" with a priority weight of "Highest": "Black" Assessment Conversion = 4, Weight = 5, Benchmark Score = 4 x 5 = 20.

To illustrate the operation of the model, an example data set for the engineer function MAA benchmark categories was generated to create a test case. Ratings (B/R/A/G) were randomly assigned for each of the categories (Table 3). These subjective assessments were then turned into a numerical Benchmark Score for each category using Table 1 and Table 2 and Equation (1).

To identify the role that each benchmark plays in resilience, each benchmark category was categorized according to the 16 cells within a resilience matrix (Table 4). For example, the Antiterrorism benchmark, AT-19, was deemed to best relate to the cognitive domain within the prepare phase. Some categories are written broadly enough that they could fit into multiple categories, so based on subject matter expert input, they were placed into only the most appropriate category. Also, this categorization process ensured that each cell in the resilience matrix contained at least one benchmark category.

A visual tool was developed to help an assessment team quickly see the results of the categorization and assessment and of the benchmark categories in terms of resilience. Using a "lookup" function, the Excel file automatically looks up where the category ID is placed into the resilience matrix and pulls in the qualitative assessment and matches the shade of the cell with the rating color code in an Initial Resilience Matrix Categorization Dashboard (Figure. 1).

Table 3. Engineer Initial MAA Benchmark Example Data Set.

Category	ID	Weight	B/R/A/G	Score
Antiterrorism	AT-19	5	B	20
Antiterrorism	AT-20	3	R	9
Electromagnetic Environment	EMP-01	3	A	6
Electrical Power (EP) Supply	EP-01	5	A	10
Electrical Power (EP) Supply	EP-02	2	G	2
Electrical Power (EP) Supply	EP-03	4	B	16
Electrical Power (EP) Supply	EP-04	4	R	12
Electrical Power (EP) Supply	EP-05	3	A	6
Fire Protection Infrastructure	FP-01	1	B	4
Fire Protection Infrastructure	FP-02	4	R	12
Fire Protection Infrastructure	FP-03	3	A	6
Fire Protection Infrastructure	FP-04	4	G	4
Fire Protection Infrastructure	FP-05	1	B	4
Fire Protection Infrastructure	FP-06	4	R	12
HVAC	HVAC-01	3	B	12
HVAC	HVAC-02	1	R	3
HVAC	HVAC-03	4	A	8
HVAC	HVAC-04	4	G	4
HVAC	HVAC-05	1	B	4
Munition Operations	MO-02	5	G	5
Munition Operations	MO-03	2	G	2
Munition Operations	MO-06	5	R	15
Munition Operations	MO-07	3	A	6
Munition Operations	MO-08	1	G	1
Natural Gas Supply	NG-01	2	A	4
Natural Gas Maintenance	NG-02	1	G	1
Physical Security	PS-04	2	A	4
Physical Security	PS-06	1	G	1
Physical Security	PS-11	5	B	20
Physical Security	PS-12	4	R	12
Physical Security	PS-13	4	A	8
Physical Security	PS-14	4	G	4
Physical Security	PS-15	5	B	20
Utilities	UT-01	5	R	15
Utilities	UT-02	5	A	10
Utilities	UT-03	3	G	3
Utilities	UT-04	2	B	8
Utilities	UT-05	4	R	12
Water Systems	WTR-01	5	R	15
Water Systems	WTR-02	4	A	8
Water Systems	WTR-03	5	G	5

Table 4. Mission Assurance Categories to Resilience Matrix Categorization.

	Prepare	Absorb	Recover	Adapt
Physical	EP-02 MO-07	EP-05 FP-02 FP-03 HVAC-04 HVAC-05 MO-03 PS-04 PS-12	EP-04 WTR-03	EP-01 WTR-01
Information	AT-20 HVAC-03 WTR-02	HVAC-02 NG-02	FP-01 FP-04 UT-02	HVAC-01 NG-01
Cognitive	PS-11 AT-19 EMP-01 FP-05 MO-02 PS-06	PS-14 UT-01	UT-03	PS-15 MO-06
Social	FP-06 PS-13	UT-04	UT-05 EP-03	MO-08

Any changes made by the assessment team on either the location of the category in the matrix or its rating would automatically be updated in the dashboard. This provides immediate feedback as to how the installation is assessed in a manner that is very familiar to military decision makers as the Black, Red, Amber, and Green construct is widely used across the DoD.

In an ideal installation assessment, every benchmark category, no matter its priority, would be assessed as “Green” and its Benchmark Score would equal its priority weight as per Equation (2). This scoring convention was developed so that the highest priority category that was assessed to be the worst condition, (i.e. “Black”), would get the highest score. Using this convention, the difference from the ideal score (Delta from Ideal) for each benchmark category is calculated using Equation (3) and shown in Table 5. A Delta from Ideal equal to zero means that the benchmark category is assessed as

“Green” and cannot be improved. A larger Delta from Ideal indicates that category is further from ideal and may have a large negative impact on resilience if not improved.

$$\textit{Benchmark Ideal Score} = \textit{Weight} \times 1\ (\text{“Green”}) \tag{2}$$

$$\textit{Delta from Ideal} = \textit{Benchmark Score} - \textit{Benchmark Ideal Score} \tag{3}$$

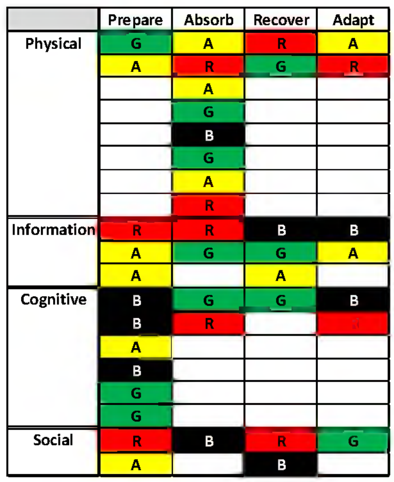

Figure 1. Initial Resilience Matrix Categorization Dashboard.

Table 5. Initial MAA Delta from Ideal.

	Prepare	Absorb	Recover	Adapt
Physical	0	3	8	5
	3	8	0	10
		3		
		0		
		3		
		0		
		2		
		8		
Information	6	2	3	9
	4	0	0	2
	4		5	
Cognitive	15	0	0	15
	15	10		10
	3			
	3			
	0			
	0			
Social	8	6	8	0
	4		12	

Most cells in the MARM contained multiple benchmark categories, so the Delta from Ideal for all categories in the cell were summed to calculate a MARM Cell Score using Equation (4). The categories with the highest priority that were furthest from ideal would have the greatest impact on the Cell Score. Also, this accounts for some MARM cells having multiple categories providing a cumulative effect of their scores. The summation of the benchmark Delta from Ideal scores was selected rather than the average to maintain the impact of categories that are both highly weighted and a significant difference between their assessed score and ideal score. For example, if a category was deemed to be a priority "5" and assessed "Black" but was averaged with several categories that have a lower priority and assessed "Green", the impact of the high priority category would be lost.

$$Cell\ Score = \sum_{i=1}^{n} Benchmark\ Delta\ from\ Ideal \tag{4}$$

The cell scores were aggregated to create the Initial Mission Assurance Resilience Matrix and formatted by applying a conditional formatting in Excel where each cell in the MARM is coded with the highest scores colored red to show that these were the highest risk cells and dark green indicates all the categories in the cell meet their benchmarks. This creates a dashboard to better visualize closeness to ideal for each cell in the Initial MARM (Figure. 2). In this example, the Cognitive-Prepare is the furthest from ideal and this decision tool visually indicates this to decision makers for their consideration. The Cognitive-Absorb and Social-Adapt are already at ideal, so they do not warrant further attention. The other cells are color coded as per their cell scores as distributed between the highest and lowest scores.

	Prepare	Absorb	Recover	Adapt
Physical	3	27	8	15
Information	14	2	8	11
Cognitive	36	10	0	25
Social	12	6	20	0

Figure 2. Initial MARM Dashboard.

2.4. IMPROVED STATE MISSION ASSURANCE ASSESSMENT EXAMPLE

One purpose of the MARM is to assist decision makers in determining what projects to fund, but at this point, the Initial MARM (Figure. 2) only serves to assist decision makers in identifying areas of concern. Based on the assessment details, members of the MAA team or other staff, as required, nominate specific projects to address shortfalls. Each of these projects have an estimated cost and an assessment of the improvement it would provide; that is, how much it would change the qualitative B/R/A/G assessment for the category. An Improved State MAA example data set was generated by randomly selecting categories to improve one or more levels in the qualitative assessment (i.e. from “Black” to “Red” “Amber” or “Green”, from “Red” to “Amber” or “Green”, and from “Amber” to “Green”) and a cost randomly assigned for the notional project that would contribute to the increased score (Table 6) in order to extend the analysis and quantify the impact of specific projects on infrastructure resilience. To illustrate, a project with an estimated cost of $32,601 is expected to change the assessment of benchmark category AT-19 to “Green” from its original “Black” assessment (from Table 3).

Table 6. Engineer Improved State MAA Benchmark Example Data Set.

ID	Weight	B/R/A/G	Score	Cost
AT-19	5	G	5	$ 32,601
AT-20	3	A	6	$ 99,423
EMP-01	3	G	3	$ 88,530
EP-01	5	G	5	$ 88,694
EP-02	2	G	2	$ 70,269
EP-03	4	A	8	$ 67,219
EP-04	4	A	8	$ 48,611
EP-05	3	G	3	$ 58,969
FP-01	1	R	3	$ 40,798
FP-02	4	A	8	$ 57,938
FP-03	3	G	3	$ 1,214
FP-04	4	G	4	$ 82,379
FP-05	1	G	1	$ 84,887
FP-06	4	A	8	$ 80,862
HVAC-01	3	A	6	$ 4,383
HVAC-02	1	G	1	$ 58,018
HVAC-03	4	G	4	$ 24,381
HVAC-04	4	G	4	$ 26,317
HVAC-05	1	A	2	$ 97,110
MO-02	5	G	5	$ 28,563
MO-03	2	G	2	$ 75,880
MO-06	5	G	5	$ 88,779
MO-07	3	G	3	$ 66,845
MO-08	1	G	1	$ 22,430
NG-01	2	G	2	$ 47,680
NG-02	1	G	1	$ 47,475
PS-04	2	G	2	$ 42,392
PS-06	1	G	1	$ 56,335
PS-11	5	A	10	$ 74,194
PS-12	4	G	4	$ 29,689
PS-13	4	G	4	$ 6,552
PS-14	4	G	4	$ 85,045
PS-15	5	A	10	$ 47,119
UT-01	5	A	10	$ 64,623
UT-02	5	G	5	$ 40,840
UT-03	3	G	3	$ 22,357
UT-04	2	A	4	$ 1,984
UT-05	4	G	4	$ 23,252
WTR-01	5	A	10	$ 52,161
WTR-02	4	G	4	$ 84,541
WTR-03	5	G	5	$ 82,731

Equation (1) was applied to calculate a benchmark score for the improvement in each category, and Equations (2) and (3) used to calculated an Improved State Delta from Ideal for each benchmark category (Table 7) and an updated visualization tool (Figure.

3). Cell Scores for the improved state example were calculated using Equation (4) and visualized using the Improved State MARM Dashboard (Figure. 4).

Table 7. Improved State MAA Delta from Ideal.

	Prepare	Absorb	Recover	Adapt
Physical	0	0	4	0
	0	4	0	5
		0		
		0		
		1		
		0		
		0		
		0		
Information	3	0	2	3
	0	0	0	0
	0		0	
Cognitive	5	0	0	5
	0	5		0
	0			
	0			
	0			
	0			
Social	4	2	0	0
	0		4	

	Prepare	Absorb	Recover	Adapt
Physical	G	G	A	G
	G	A	G	A
		G		
		G		
		A		
		G		
		G		
		G		
Information	A	G	R	A
	G	G	G	G
	G		G	
Cognitive	A	G	G	A
	G	A		G
	G			
	G			
	G			
	G			
Social	A	A	G	G
	G		A	

Figure 3. Improved State Resilience Matrix Categorization Dashboard.

	Prepare	Absorb	Recover	Adapt
Physical	0	5	4	5
Information	3	0	2	3
Cognitive	5	5	0	5
Social	4	2	4	0

Figure 4. Improved State MARM Dashboard.

The Resilience Cell Score Improvement is calculated to determine the combined improvements derived by completing all the possible projects in each cell in the MARM by subtracting the Improved State Resilience Cell Score from the Initial Resilience Cell Score, (Equation (5)).

$$\begin{gathered}\textit{Resilience Cell Score Improvement} = \\ \textit{Initial Resilience Cell Score (Table 3)} - \textit{Improved State Resilience Cell Score (Table 6)}\end{gathered} \quad (5)$$

A larger Resilience Cell Score Improvement is better because the combined effect of all projects associated with each resilience cell more significantly lowered the total Delta from Ideal for the cell. The Difference in Delta from Ideal MARM Dashboard (Figure. 5) provides a visualization of which cell in the MARM has the combination of projects that would have the greatest impact on improving resilience towards ideal. In this example case, the total combination of all the projects in the Cognitive-Prepare will have the most impact on improving resilience, while the total combination of all the projects in the Cognitive-Recover and Social-Adapt will not have any impact on improving resilience.

	Prepare	Absorb	Recover	Adapt
Physical	3	22	4	10
Information	11	2	6	8
Cognitive	31	5	0	20
Social	8	4	16	0

Figure 5. Difference in Delta from Ideal MARM Dashboard.

2.5. INFRASTRUCTURE IMPROVEMENT PROJECT COST ANALYSIS

While the combination of all the projects in a specific cell in the MARM allows the visualization of the impact of completing all the projects assigned to those categories, the reality of a constrained resource environment is that it is not likely that all the projects in a particular MARM cell could be completed, or that it would be efficient to only focus on projects in one cell at the expense of all the projects in another cell. Decision makers need to visualize the impact of individual projects across the entire MARM. To demonstrate impact, the final component incorporates cost analysis for each benchmark category into the overall MARM.

A Cost Impact Score was calculated for each category to better understand and visualize the return on investment of the projects. The Cost Impact Score was calculated by taking the difference between the Initial (Table 3) and Improved (Table 6) Benchmark Scores and dividing it by the associated project cost (Table 6) and scaled by a factor of 100,000 for readability (Equation 6).

$$Cost\ Impact\ Score =$$

$$\frac{Initial\ Benchmark\ Score\ (Table\ 3) - Improved\ State\ Benchmark\ Score (Table\ 6)}{Benchmark\ Project\ Cost\ (Table\ 6)} * 100{,}000 \qquad (6)$$

The following is an example for AT-19:

$$\text{Cost Impact Score} = \frac{20 - 5}{\$32{,}601} * 100{,}000 = 46.01$$

The results for the example data set (initial and improved states) were summarized into a Project Cost Impact Summary (Table 8). Projects that were initially assessed as ideal ("Green") will result in a Cost Impact Score of zero, so these projects would not contribute at all to improving resilience of the installation and can be screened out from this analysis. This is not to suggest that there is no value to these projects, just that they do not contribute to improve resilience.

The Cost Impact Scores were mapped back into the MARM to create the Cost Impact MARM Dashboard (Figure. 6) to show which specific projects had the biggest impact ("bang for the buck") on improving the resilience scores. In this example, the Fire Protection project for ID FP-03 in the Physical-Absorb cell (Impact of 247.02) and the Utility project in the Social-Absorb cell (Impact of 201.59) have the greatest returns on investment. The same conditional formatting was applied where "Green" indicates the largest impact on the overall cell in the MARM (high improvement for low cost) and "Red" indicates zero impact. This decision tool allows decision makers to get a clear and concise picture of the cost impact, or return on their investment, of their potential resilience improvement projects on the overall resilience of the installation.

Table 8. Project Cost Impact Summary.

ID	Weight	Initial B/R/A/G	Score	Improvement B/R/A/G	Score	Project Cost	Cost Impact
AT-19	5	B	20	G	5	$ 32,601	46.01
AT-20	3	R	9	A	6	$ 99,423	3.02
EMP-01	3	A	6	G	3	$ 88,530	3.39
EP-01	5	A	10	G	5	$ 88,694	5.64
EP-02	2	G	2	G	2	$ 70,269	0.00
EP-03	4	B	16	A	8	$ 67,219	11.90
EP-04	4	R	12	A	8	$ 48,611	8.23
EP-05	3	A	6	G	3	$ 58,969	5.09
FP-01	1	B	4	R	3	$ 40,798	2.45
FP-02	4	R	12	A	8	$ 57,938	6.90
FP-03	3	A	6	G	3	$ 1,214	247.02
FP-04	4	G	4	G	4	$ 82,379	0.00
FP-05	1	B	4	G	1	$ 84,887	3.53
FP-06	4	R	12	A	8	$ 80,862	4.95
HVAC-01	3	B	12	A	6	$ 4,383	136.88
HVAC-02	1	R	3	G	1	$ 58,018	3.45
HVAC-03	4	A	8	G	4	$ 24,381	16.41
HVAC-04	4	G	4	G	4	$ 26,317	0.00
HVAC-05	1	B	4	A	2	$ 97,110	2.06
MO-02	5	G	5	G	5	$ 28,563	0.00
MO-03	2	G	2	G	2	$ 75,880	0.00
MO-06	5	R	15	G	5	$ 88,779	11.26
MO-07	3	A	6	G	3	$ 66,845	4.49
MO-08	1	G	1	G	1	$ 22,430	0.00
NG-01	2	A	4	G	2	$ 47,680	4.19
NG-02	1	G	1	G	1	$ 47,475	0.00
PS-04	2	A	4	G	2	$ 42,392	4.72
PS-06	1	G	1	G	1	$ 56,335	0.00
PS-11	5	B	20	A	10	$ 74,194	13.48
PS-12	4	R	12	G	4	$ 29,689	26.95
PS-13	4	A	8	G	4	$ 6,552	61.05
PS-14	4	G	4	G	4	$ 85,045	0.00
PS-15	5	B	20	A	10	$ 47,119	21.22
UT-01	5	R	15	A	10	$ 64,623	7.74
UT-02	5	A	10	G	5	$ 40,840	12.24
UT-03	3	G	3	G	3	$ 22,357	0.00
UT-04	2	B	8	A	4	$ 1,984	201.59
UT-05	4	R	12	G	4	$ 23,252	34.41
WTR-01	5	R	15	A	10	$ 52,161	9.59
WTR-02	4	A	8	G	4	$ 84,541	4.73
WTR-03	5	G	5	G	5	$ 82,731	0.00

3. DISCUSSION OF RESULTS

This section describes the applicability of the MARM to mission assurance assessment practitioners and conducts a tradespace analysis utilizing the example data set.

3.1. APPLICATION TO MISSION ASSURANCE ASSESSMENT TEAMS

The most immediate result is that the engineer MAA now has a direct connection and contribution to assessing resilience as defined by the installation's ability to prepare for, absorb, recover from, and adapt to disasters and is visually depicted by the MARM. The results inform the decision-making tools used to analyze tradeoffs between various infrastructure improvement projects competing for limited resources.

The feedback from the subject matter experts from the USARAF DCSENG staff is that this will certainly assist them. The model was built in Excel and linked directly to the Excel file that they use to record assessment data so that it will automatically feed into the MARM analysis. It is also easily updated to account for changes in the prioritization of the benchmarks. Using the data summarized for this test case (Figure. 6), the assessment team could inform decision makers that the project that impacts the Physical-Absorb cell will provide the greatest improvement to resilience for the cost associated with it and that there are additional high payoff projects (one in Social-Absorb and another in Information-Adapt).

	Prepare	Absorb	Recover	Adapt
Physical	0.00	5.09	8.23	5.64
	4.49	6.90	0.00	9.59
		247.02		
		0.00		
		2.06		
		0.00		
		4.72		
		26.95		
Information	3.02	3.45	2.45	136.88
	16.41	0.00	0.00	4.19
	4.73		12.24	
Cognitive	13.48	0.00	0.00	21.22
	46.01	7.74		11.26
	3.39			
	3.53			
	0.00			
	0.00			
Social	4.95	201.59	34.41	0.00
	61.05		11.90	

Figure 6. Project Cost Impact MARM Dashboard.

3.2. APPLICATION OF RESILIENCE OF DEPLOYABLE SYSTEMS FOR TRADESPACE ANALYSIS

The next step of the research was to determine how far budgeted resources can go to improving resilience. For this example, could they fund these three high impact projects form the Physical-Absorb cell? Could additional projects be funded and in what order should they prioritized should additional funding become available? To answer these questions, ERS tradespace analysis was implemented, which is currently used to create an integrated capability for systems engineers, engineer managers, and acquisition personnel to increase the quality of acquisition decision-making for deployable systems, such as tanks and helicopters. ERS improves informed decision-making early in the DoD Acquisition process, prior to the Milestone A decision point, when there is both significant uncertainty in the project, but also substantial impact on overall project costs based on these early decisions (Sitterle et al. 2015). There are important shared resilience attributes between deployable military systems and the installation infrastructure which enables them, making the extension of ERS methods desirable (Ewing et al. 2006). This study applies the analogy between these deployable weapon systems and fixed site infrastructure, which project combat power from power projection platforms (military installations) around the world and assists design engineers, facility operators and managers, and infrastructure decision makers to see the impacts of project selection on resilience.

The ERS methodology for tradespace analysis was applied to the MARM to conduct tradeoff analysis between individual projects and their impact on infrastructure resilience to assist decision makers in developing answers to questions about which projects to fund. To facilitate the tradespace analysis, the data in Table 8 were sorted by Cost Impact and an additional column, Project Selection, was added to track if the project has been selected to include in the tradespace to produce the Tradespace Project Selection Dashboard (Figure. 7). The data in the dashboard was connected using “lookup” functions in Excel to automatically update the Improved State Delta from Ideal table, MARM, and Difference in Delta from Ideal dashboards to enable the impact of the decisions made in the tradespace analysis to be readily seen.

			Initial		Improvement				
Category	ID	Weight	B/R/A/G	Score	B/R/A/G	Score	Cost	Cost Impact	Project Selection
Fire Protection Infrastructure	FP-03	3	A	6	G	3	$ 1,214	247.02	Y
Utilities	UT-04	2	B	8	A	4	$ 1,984	201.59	Y
HVAC	HVAC-01	3	B	12	A	6	$ 4,383	136.88	Y
Physical Security	PS-13	4	A	8	G	4	$ 6,552	61.05	Y
Antiterrorism	AT-19	5	B	20	G	5	$ 32,601	46.01	Y
Utilities	UT-05	4	R	12	G	4	$ 23,252	34.41	Y
Physical Security	PS-12	4	R	12	G	4	$ 29,689	26.95	Y
Physical Security	PS-15	5	B	20	A	10	$ 47,119	21.22	Y
HVAC	HVAC-03	4	A	8	G	4	$ 24,381	16.41	Y
Physical Security	PS-11	5	B	20	A	10	$ 74,194	13.48	Y
Utilities	UT-02	5	A	10	G	5	$ 40,840	12.24	Y
Electrical Power (EP) Supply	EP-03	4	B	16	A	8	$ 67,219	11.90	Y
Munition Operations	MO-06	5	R	15	G	5	$ 88,779	11.26	Y
Water Systems	WTR-01	5	R	15	A	10	$ 52,161	9.59	Y
Electrical Power (EP) Supply	EP-04	4	R	12	A	8	$ 48,611	8.23	Y
Utilities	UT-01	5	R	15	A	10	$ 64,623	7.74	Y
Fire Protection Infrastructure	FP-02	4	R	12	A	8	$ 57,938	6.90	Y
Electrical Power (EP) Supply	EP-01	5	A	10	G	5	$ 88,694	5.64	N
Electrical Power (EP) Supply	EP-05	3	A	6	G	3	$ 58,969	5.09	Y
Fire Protection Infrastructure	FP-06	4	R	12	A	8	$ 80,862	4.95	
Water Systems	WTR-02	4	A	8	G	4	$ 84,541	4.73	
Physical Security	PS-04	2	A	4	G	2	$ 42,392	4.72	
Munition Operations	MO-07	3	A	6	G	3	$ 66,845	4.49	
Natural Gas Supply	NG-01	2	A	4	G	2	$ 47,680	4.19	
Fire Protection Infrastructure	FP-05	1	B	4	G	1	$ 84,887	3.53	
HVAC	HVAC-02	1	R	3	G	1	$ 58,018	3.45	
Electromagnetic Environment	EMP-01	3	A	6	G	3	$ 88,530	3.39	
Antiterrorism	AT-20	3	R	9	A	6	$ 99,423	3.02	
Fire Protection Infrastructure	FP-01	1	B	4	R	3	$ 40,798	2.45	
HVAC	HVAC-05	1	B	4	A	2	$ 97,110	2.06	
Electrical Power (EP) Supply	EP-02	2	G	2	G	2	$ 70,269	0.00	N
Fire Protection Infrastructure	FP-04	4	G	4	G	4	$ 82,379	0.00	N
HVAC	HVAC-04	4	G	4	G	4	$ 26,317	0.00	N
Munition Operations	MO-02	5	G	5	G	5	$ 28,563	0.00	N
Munition Operations	MO-03	2	G	2	G	2	$ 75,880	0.00	N
Munition Operations	MO-08	1	G	1	G	1	$ 22,430	0.00	N
Natural Gas Maintenance	NG-02	1	G	1	G	1	$ 47,475	0.00	N
Physical Security	PS-06	1	G	1	G	1	$ 56,335	0.00	N
Physical Security	PS-14	4	G	4	G	4	$ 85,045	0.00	N
Utilities	UT-03	3	G	3	G	3	$ 22,357	0.00	N
Water Systems	WTR-03	5	G	5	G	5	$ 82,731	0.00	N
						Total	$ 2,204,072	Total	$ 724,509

Figure 7. Tradespace Analysis Project Selection Dashboard.

To illustrate the tradespace analysis and the utility of the various aspects of the dashboard as a decision analysis tool, an example tradespace analysis was conducted using the example data sets and an assumed maximum budget for projects to improve the installation's resilience of $750,000. The determination of which projects to pursue while remaining within the prescribed budget utilizing the following steps and the Trade Space Tracking Table (Figure. 7).

1. Eliminated from consideration any projects that do not improve the category benchmark score (for example, in this case projects for benchmark EP-02, FP-04, HVAC-04, etc.) that are highlighted in red and note elimination by selecting "N" for each of these projects in the Project Selection column. For these projects not selected, their Initial Benchmark Assessment and Score were transferred over to the dashboard matrices.
2. Selected desired projects by choosing "Y" in the Project Selection column. In this example, selection started with the highest impact project from the Tradespace Project Selection Dashboard (Figure. 7). Once "Y" was selected in the Project Selection column for a project, the cost is automatically added to the total shown at the bottom the dashboard. This facilitated the tracking of the total cost of the projects selected for the analysis. Also, the improvements to the resilience assessment and benchmark scores were automatically updated into the dashboard matrices.
3. This project selection process continued until the total cost of the selected projects reached the budget limit.

For this example, the total cost of the projects reached $724,509, which was still under the total available budget of $750,000. There were no projects remaining to select that would improve resilience while remaining within the budget constraints. The corresponding improvements were consolidated and visualized through the Tradespace Analysis MARM Dashboard (Figure. 8).

Initial MARM				
	Prepare	Absorb	Recover	Adapt
Physical	3.00	27.00	8.00	15.00
Information	14.00	2.00	8.00	11.00
Cognitive	36.00	10.00	0.00	25.00
Social	12.00	6.00	20.00	0.00

Improved State MARM

Improved	Prepare	Absorb	Recover	Adapt
Physical	3.00	9.00	4.00	10.00
Information	10.00	2.00	3.00	5.00
Cognitive	11.00	5.00	0.00	5.00
Social	8.00	2.00	4.00	0.00

Difference in Delta from Ideal MARM

Difference	Prepare	Absorb	Recover	Adapt
Physical	0.00	18.00	4.00	5.00
Information	4.00	0.00	5.00	6.00
Cognitive	25.00	5.00	0.00	20.00
Social	4.00	4.00	16.00	0.00

Green indicates larger improvement

Project Cost Impact by MARM Cell

Cost	Prepare	Absorb	Recover	Adapt
Physical	$ -	$ 147,810	$ 48,611	$ 52,161
Information	$ 24,381	$ -	$ 40,840	$ 4,383
Cognitive	$ 106,795	$ 64,623	$ -	$ 135,897
Social	$ 6,552	$ 1,984	$ 90,471	$ -

Figure 8. Tradespace Analysis MARM Dashboard.

This tradespace analysis assists decision making in three significant ways.

1. A project with a lower cost impact may still be selected over a project with a higher cost impact if that higher cost impact project is too expensive to fit within the budgetary constraints and the lower cost impact project would fit in the budgetary constraint. For example, using this process, selection of all the highest cost impact projects down through FP-02 increases the total project cost to $665,540. Selecting the next highest cost impact project, EP-01, would add $88,694 to the total project cost,

increasing it to $754,234, which is over the allocated budget of $750,000. The ability to visualize this allows the decision makers to decide whether to select a lower cost impact project that fits within the overall budget.

2. The impact on the resilience matrix due to tradeoff between projects can be seen using the MARMs produced. As shown in Tradespace Analysis Dashboard (Figure. 8), within the Initial MARM, the cells Cognitive-Recover, and Social-Adapt were already at ideal, so it would be expected that no projects would be selected to improve these cells. The impact of the project selection process on the other cells in the MARM can easily be seen. No projects were selected to improve the Physical-Prepare or Information -Absorb cells. Significant improvement was in the Cognitive-Prepare and Cognitive-Adapt cells. Results from this analysis technique would highlight this to decision makers and allow them to provide guidance on the tradeoff analysis to ensure that this cell would be addressed, if desired.

3. The final utility of this tradespace analysis, as seen in this example, is that it highlights that there are no other projects available from this portfolio that will fit within the remaining $25,491 of the budget and still have an impact on resilience. The selection of either project that improves MN-08 or UT-03 would fit in the budget but would not improve the resilience of the installation. Therefore, neither project would be an efficient use of resources from a resilience standpoint. An important value of this decision analysis tool is to see the impact of changing the project mix to use resources efficiently.

4. CONCLUSIONS AND FUTURE WORK

4.1. APPLICABILITY FOR PRACTITIONERS

This research developed and demonstrated the use of a visual and interactive Mission Assurance Resilience Matrix that converts the qualitative infrastructure assessments completed as required by the DoD Mission Assurance Strategy into a quantitative decision support tool. The methodology and results from the example data set were shared with the subject matter experts within the US Army Africa DCSENG staff. Their feedback as practitioners in the field is that this approach will be very useful in several areas.

First, this study and the interactive tools it produced connect the assessments that are conducted by the assessment team to the intent of the Mission Assurance Construct of improving the resilience of military infrastructure. Assessment teams conduct a very detailed assessments, but this information did not effectively inform or feed the installation project selection and approval process as it was not easily consolidated, evaluated, assessed, understood, and communicated.

The matrices described in this research assist decision makers visualize where the installation infrastructure is deficient in terms of resiliency and then assess where to most efficiently allocate resources to improve the infrastructure resiliency. Conducting tradespace analysis informs decision makers about which projects to pursue to improve resilience by relating the cost of the projects to the potential improvement within the resilience matrix.

While the implementation in the example in this research is specific to military installations, the framework developed is broadly applicable. This allows it to be widely utilized by non-military practitioners such as facility managers, departments of public works, or state and national infrastructure leaders.

4.2. FUTURE WORK

The next phase of this research is to analyze a case study utilizing data from actual military infrastructure assessments completed by the USARAF DCSENG staff to identify uncertainty within and impact to the MARM. This will confirm the usefulness and relevance of these tools to forward based military infrastructure decision makers. It may also identify additional criteria to consider within the framework.

Finally, the implementation of this resilience matrix methodology to a specific portion of the Mission Assurance Framework can extend to other functions beyond the engineer assessment. Additionally, it may be applied to other types of military infrastructure such as civil works projects that are constructed and operated by the US Army Corps of Engineers but fall into a separate decision-making process and under differing policy and funding approvals and appropriations. These extensions will demonstrate the generalizability of applying the resilience matrix methodology to various military decision-making processes.

4.3. DATA AVAILABILITY STATEMENT

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGMENTS

We thank Ms. Annie Savage, Mr. Eric Doro, and Sergeant First Class Ryan Swanson from the US Army Africa Deputy Chief of Staff Engineer (DCSENG) division for providing important information and insights into the DoD Mission Assurance Assessment process and for their reviews of the MARM model and manuscript.

REFERENCES

116th Congress, U. S. (2019). H.R. 3041 Military Installation Resilience Assuredness Act. Washington DC: 116th Congress.

Alberts, D. S., and Hayes, R. E. (2005). Power to the Edge: Command and Control in the Information Age. Washington DC: Department of Defense Command and Control Research Program.

Aven, T., and Thekdi, S. (2018). “The importance of resilience-based strategies in risk analysis, and vice versa.” IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems, B. D. Trump, M.-V. Florin, and I. Linkov, eds., EPFL International Risk Governance Center (IRGC), Lausanne, CH.

Committee on Increasing National Resilience to Hazards and Disasters. (2012). Disaster resilience: A national imperative. Disaster Resilience: A National Imperative, Washington, D.C.: The National Academies Press.

Congressional Research Service. (2019). Military Construction: Authorities, Process, and Frequently Asked Questions. Washington, D.C.: Congressional Research Service.

Department of Defense. (2016). Directive 3100.10 Space Policy. Washington, D.C.: DoD.

Department of Defense. (2017). DoD Manual 3020.45, Defense Critical Infrastructure Program (DCIP): DoD Mission-Based Critical Asset Identification Process (CAIP). Washington, D.C.: DoD.

Department of Defense. (2018a). Mission Assurance (MA) Construct. Washington, D.C.: DoD.

Department of Defense. (2018b). 2018 National Defense Strategy Summary. Washington, D.C.: DoD.

Department of Defense. (2018c). DoD Mission Assurance Assessment Benchmarks. Washington, D.C.: DoD.

Ewing, P. L., Tarantino, W., and Parnell, G. S. (2006). “Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis.” Decision Analysis, 3(1), 33–49.

Fox-Lent, C., Bates, M. E., and Linkov, I. (2015). “A matrix approach to community resilience assessment: an illustrative case at Rockaway Peninsula.” Environment Systems and Decisions, Kluwer Academic Publishers, 35(2), 209–218.

Hagen, J., Morgan, F., Heim, J., and Carroll, M. (2017). The Foundations of Operational Resilience -- Assessing the Ability to Operate in an Anti-Access/Area Denial (A2/AD) Environment: The Analytical Framework, Lexicon, and Characteristics of the Operational Resilience Analysis Model (ORAM). The RAND Corporation, Santa Monica, CA.

Linkov, I., Fox-Lent, C., Read, L., Allen, C. R., Arnott, J. C., Bellini, E., Coaffee, J., Florin, M. V., Hatfield, K., Hyde, I., Hynes, W., Jovanovic, A., Kasperson, R., Katzenberger, J., Keys, P. W., Lambert, J. H., Moss, R., Murdoch, P. S., Palma-Oliveira, J., Pulwarty, R. S., Sands, D., Thomas, E. A., Tye, M. R., and Woods, D. (2018). “Tiered approach to resilience assessment.” Risk Analysis, Blackwell Publishing Inc., 38(9), 1772–1780.

Lostumbo, M. J., McNerney, M. J., Peltz, E., Eaton, D., Frelinger, D. R., Greenfield, V. A., Halliday, J., Mills, P., Nardulli, B. R., Pettyjohn, S. L., Sollinger, J. M., and Worman, S. M. (2013). Overseas Basing of U.S. Military Forces: An Assessment of Relative Costs and Strategic Benefits. The RAND Corporation, Santa Monica, CA.

Ramachandran, V., Long, S. K., Shoberg, T., Corns, S., and Carlo, H. J. (2015). “Framework for modeling urban restoration resilience time in the aftermath of an extreme event.” ASCE Natural Hazards Review, 16(4).

Shapiro, A. (2019). “Tyndall Air Force Base Still Faces Challenges in Recovering from Hurricane Michael.” National Public Radio All Things Considered, Accessed April 12, 2020. https://www.npr.org/2019/05/31/728754872/tyndall-air-force-base-still-faces-challenges-in-recovering-from-hurricane-michael.

Sitterle, V. B., Freeman, D. F., Goerger, S. R., and Ender, T. R. (2015). “Systems engineering resiliency: Guiding tradespace exploration within an engineered resilient systems context.” Procedia Computer Science, Elsevier Masson SAS, 44(C), 649–658.

Wilt, B., Long, S., and Shoberg, T. (2016). “Defining resilience: A preliminary integrative literature review.” 2016 International Annual Conference of the American Society for Engineering Management, Concord, NC, 1–11.

III. VERIFYING THE MISSION ASSURANCE RESILIENCE MATRIX THROUGH THE MODIFIED DELPHI METHOD AND SYSTEM USABILITY SCALE

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ABSTRACT

The ability to quantitatively evaluate the resilience of infrastructure systems within an assessment framework and communicate the impact of potential infrastructure improvement projects is a growing topic of research. Several metrics and assessment techniques have been developed and verified or validated to one degree or another. The Mission Assurance Resilience Matrix (MARM) was developed based on previous resilience matrix research to address the gap in the Department of Defense's incorporation of resilience into its Mission Assurance Assessment framework.

This research conducts initial verification and validation of the effectiveness and usability of the MARM as an acceptable and applicable computer-based resilience assessment and decision support tool through the use of a Modified Delphi Method to collect and evaluate the amount and impact of subject matter expert uncertainty and bias within the framework.

Keywords: Infrastructure resilience, resilience matrix, Delphi Method, System Usability Scale, uncertainty

1. INTRODUCTION

1.1. BACKGROUND

With the increasing frequency and severity of natural and man-made disasters around the world, the challenge of creating tools that assess, quantify, and clearly articulate the resilience of infrastructure systems is a growing topic of discussion amongst infrastructure system managers and researchers. Multiple efforts have been made to develop indices to quantify resilience using metrics (Cardoso et al. 2015; Kerner and Thomas 2014; Wood et al. 2019). Bakkensen et. al evaluate several different metrics and conclude that one of the challenges is to validate measures of performance for these metrics and that there is little utility unless they can be confidently used to inform decisionmakers. One recommendation was that indices should be much clearer in what they aim to explain and follow up with explicit testing to see if the indices perform well (Bakkensen et al. 2017).

A Mission Assurance Resilience Matrix (MARM) was previously developed by Richards et. al based on the resilience matrix research conducted by Linkov et. al to close the gap between the mandate for the Army to address resilience in its assessment process and its current infrastructure assessment framework. The MARM is the first application of the resilience matrix methodology to the Department of Defense's (DoD) Mission Assurance Assessment (MAA) framework, therefore the model needs to be tested, verified, and validated. This study is the initial step in that process.

1.2. RESILIENCE MATRIX FRAMEWORK

The Resilience Matrix (RM), developed by Linkov et. al (Linkov et al. 2013b; a), provides a framework to identify the relevant metrics to assess performance from a wider system perspective, is generalizable, and provides a baseline performance score on which the resilience improvement potential of proposed system changes can be evaluated (Fox-Lent et al. 2015). The columns of the matrix are based on the stages identified in the National Academy of Sciences definition of resilience (plan/prepare, absorb/withstand, recover adapt), and the rows describe the four general management domains of a complex system, (physical, information, cognitive, and social) (Fox-Lent et al. 2015). The RM framework has been applied to assess many types of infrastructure systems such as cyber (Linkov et al. 2013b), energy (Roege et al. 2014), coastal communities (Fox-Lent et al. 2015), urban planning and assessment (Fox-lent and Linkov 2018), and reservoirs (Mustajoki and Marttunen 2019).

1.3. MISSION ASSURANCE RESILIENCE MATRIX

The RM methodology was selected to incorporate resilience into the MAA framework since it is generalizable and assesses performance at a system level that can handle the uniqueness, complexity, and integrated nature of military infrastructure systems. The MAA framework consists of over 200 benchmark categories assessed by a cross-functional team which produces a report that provides important input for leaders to understand risk, inform the development of specific requirements for future infrastructure projects, and assist in making decisions about which ones to fund. The MARM was constructed from a subset of the MAA benchmark categories assessed by the engineer function and its novel incorporation of project cost estimates with the quantification of qualitative assessment data into unitless and similarly scored cells within the matrix, enable its use as a decision support tool. The MARM is designed to improve visualization of the cost-benefit analysis of potential infrastructure improvement projects to allow leaders to understand the influence that one project may have on multiple functions or systems. For a full treatment of the development of the MARM see Richards et. al (Richards et al. n.d.).

Since the MARM is the first application of the resilience matrix methodology to the DoD Mission Assurance Assessment framework, verification and validation of the MARM as a resilience assessment and decision-support tool must be completed prior to expanding it to the broader DoD MAA framework. This study implements several model verification and validation techniques through the Modified Delphi Method to confirm that the MARM is an acceptable and applicable computer-based resilience assessment and decision support tool.

1.4. MODEL VERIFICATION AND VALIDATION

Model verification and validation are critical steps in the system development process. Verification is generally defined as the process of determining if you are building the model right and validation is generally defined as determining if you are building the right model (Andradhttir et al. 1997; Kleijnen 1997; Sargent 2013). Uncertainty in the model due to measurement error, imprecise and/or insufficient data, natural variability, and model uncertainty must be investigated to complete the model verification and validation process (Ling and Mahadevan 2013). This is especially important since the MAA process relies on the aggregation of the judgements from subject matter experts (SME) with varying amounts of experience with the assessment framework and familiarity with the infrastructure systems. The varying levels of expertise can introduce uncertainty due to conflicting opinions and judgments or judgments are expressed with a measure of uncertainty (Yaniv 1997).

2. MODIFIED DELPHI METHOD

This study utilized a Modified Delphi Method to solicit subject matter experts, collect and process the data from each round of input, and frame the next round of information to be requested, collected, and processed in order to implement the various techniques to meet each of the model verification objectives of the study. The Delphi Method was developed by the Research and Development (RAND) Corporation in the 1960's in Santa Monica California for the "systemic solicitation and collation of judgements on a particular topic through a set of sequential questionnaires interspersed with summarized information and feedback of opinions derived from earlier responses". The Delphi method is based on structural surveys and makes use of the information provided by experts (Balasubramanian and Agarwal 2012).

The Delphi Method was selected for this study for several reasons. The first is that it is useful when evidence is lacking or limited: it relies on "collective intelligence" of group members to jointly produce better results than anyone in the group could produce on his or her own, resulting in increased content validity (Miller et al. 2020). It works well with a group of subject matter experts (SMEs), which was appropriate given the limited number of subject matter experts available to provide input on the MARM. The DoD Mission Assurance Assessment community is quite small and the assessments process can be both functionally and installation specific. To ensure that the subject matter experts used in this study would have the requisite familiarity with the MAA in general and the specific benchmarks and metrics from the case study data set, the set of experts was limited to the US Army Africa Deputy Chief of Staff Engineer (DCSENG) staff.

To provide the requisite details on the benchmark category metrics and conditions for the participants to provide detailed and accurate input throughout the rounds of the Delphi Method, an infrastructure assessment previously completed by one of the subject matter experts was utilized as a case study data set. Using the case study data set allows for the evaluation of the consistency of the responses across the participants. The specific benchmarks utilized in the case study data are taken from the DoD Mission Assurance Benchmarks dated 28 March 2018, which are unclassified but designated as For Official Use Only (FOUO) (Department of Defense 2018c). Therefore, they cannot be published in this article in full, but the broad categories and representative identification numbers are summarized and implemented in this paper to allow for easier identification.

The Delphi Method typically consists of three to six rounds with qualitative and quantitative assessment from the previous round used to prepare the subsequent round. This study modified the first round of data collection from the typical Delphi Method. The evaluation of the objectives identified in each round of the Modified Delphi Method were used to verify the MARM as a decision support tool and provide insight as to potential sources of uncertainty in the model that may have an impact on the overall assessment of the resilience of the infrastructure systems for an installation.

2.1. ROUND 1

This first round was modified from the standard Delphi Method by grouping some of the SMEs together to eliminate potential gaps in their expertise to assess the benchmark categories. Three SMEs (SME Team) collaborated to assess the benchmark category ratings and priority weights. The fourth SME completed the actual infrastructure assessment used for the case study and was very familiar with the condition statements and metrics. This SME, referred to as the Case Study Assessor (CSA), provided an individual assessment of the category ratings and priority weights.

The first objective of Round 1 was to assess the consistency between the teams and determine the average of their assessment of the 32 benchmark categories. The teams rated each category condition from Black = Worst, Red = Poor, Amber = Fair, or Green = Good/Ideal based on the descriptions of the conditions of the category from the case study assessment. Each team also assigned a priority (1 = Low through 5 = High) for each category based on its metric description. From this data, the resulting scores throughout the MARM methodology were calculated and used for comparison between the SMEs.

To meet the second objective, the SME Team, based on their experience with infrastructure improvement projects in the region, was asked to provide a three-point cost estimate (Low, Middle, and High) for a hypothetical improvement project to improve the resilience assessment to “Green” for a subset of eight categories. The data collected and processed from this round framed the subsequent rounds of the Modified Delphi Method.

2.2. ROUND 2

Round 2 of this study had two objectives, 1) to assess the amount of agreement of each SME and consensus across the SMEs of the Round 1 results, and 2) to evaluate consensus between the SMEs as to their categorization of each benchmark category into the MARM. An instructional email was sent to each of the SMEs with an attached Excel file that contained the formatted results of Round 1: benchmark category metric, condition description, average rating, and average priority weight. Each SME was asked to individually assess their level of agreement with the average category rating and priority weight as well as to categorize each of the 32 benchmark categories for the domain and resilience stage under which it most appropriately fit (Table 1).

Table 1. Management Domains and Resilience Stages for Resilience Matrix Categorization.

Domains	Resilience Stages
Physical: sensors, systems, platforms, and facilities	Prepare: all the preparation (plans, training, projects) conducted prior to a disaster event
Information: collected, posted, pulled, displayed, processed, and stored	Absorb: how the infrastructure withstands the disaster and minimizes impacts to operations
Cognitive: perceptions and understanding of what this information states and means and the mental models, preconceptions, biases, and values influence how information is interpreted and understood	Respond: the restoration of operations that were impacted by a disaster
Social: command and control processes and the interactions between and among individuals and entities that fundamentally define organization and doctrine	Adapt: actions taken to learn from/improve resilience based on the previous disaster

There is no standard across the literature as to what defines consensus when conducting the Delphi Method, though most studies settle in the 70-80% range with a mean score determined by the type of scale used (Bentley et al. 2016). This study defines consensus as at least three or four of the SMEs assigning the same level of agreement and a quantitative mean of the level of agreement of 3.75 or greater using the 5-point Likert scale (“Strongly Agree” = 5 and “Strongly Disagree” = 1).

2.3. ROUND 3

The objectives of Round 3 were threefold, 1) assess the amount of agreement between the SMEs with regard to the average Cost Impact Scores calculated in Round 1 to determine if the MARM would perform differently from the SME heuristic project selection methods, 2) conduct a cumulative assessment of SME responses to investigate the potential of bias in responses, and 3) verify the usability of the MARM as a computer-based decision-support tool through the System Usability Scale methodology.

To meet the first objective, an email, with guidance and an Excel file attached containing the Cost Impact Score results from Round 1 for the subset of eight benchmark categories, asked each SME to individually assess their level of agreement of the prioritization of the project based on its condition description and Cost Impact Score. These results were used to conduct a hypothesis test to validate if the MARM performs differently from project selection heuristics that the experts may currently use.

Evaluation of the cumulative responses of the level of agreement for each SME across all the rounds was used to meet the second objective to investigate the potential for SME bias. Tversky and Kahneman describe three heuristics that SMEs use in making their judgements that can lead to bias in their judgements and highlight that the impact of these biases in the evaluation of compound events are particularly significant in the context of planning and in risk (Tversky and Kahneman 1974). Though this study did not collect the specific data to determine which type of heuristic (representativeness, availability, adjustment, and anchoring) subject matter experts may be using to bias their assessments, the analysis of the cumulative SME levels of agreement provides an indication of the presence of these heuristics and their accompanying biases.

2.4. SYSTEM USABILITY SCALE

The final objective of Round 3 was to verify the usability of the MARM as a computer-based decision-support tool through the use of the System Usability Scale (SUS). The SUS was developed by John Brooke at Digital Equipment Corporation and is used to take a quick measurement of how people perceived the usability of computer systems on which they are working (Brooke, 1986). Each user is asked to provide their level of agreement (strongly agree, agree, neutral, disagree, and strongly disagree) on ten statements, which were slightly modified from the original SUS to specify the MARM as the system for evaluation and included in the Excel file sent out to collect Round 3 input (Table 2).

Raw scores ranging from 0 (poorest rating) to 4 (best rating) are used to calculate a standard SUS score, which is on a scale of 0 to 100, that can then be graded in comparison to other computer systems using the Curved Grading Scale (Table 3) (Lewis 2018).

Table 2. System Usability Scale Modified Statements (Brooke, 1986).

1. I think that I would like to use this system frequently in conjunction with MAA assessments.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

Table 3. Curved Grading Scale for the SUS (Lewis and Sauro 2018).

Grade	SUS	Percentile Range
A+	84.1 – 100	96 – 100
A	80.8 – 84.0	90 – 95
A-	78.9 – 80.7	85 – 89
B+	77.2 – 78.8	80 – 84
B	74.1 – 77.1	70 – 79
B-	72.6 – 74.0	65 – 69
C+	71.1 – 72.5	60 – 64
C	65.0 – 71.0	41 – 59
C-	62.7 – 64.9	35 – 40
D	51.7 – 62.6	15 – 34
F	0 – 51.6	0 -14

3. RESULTS AND DISCUSSION

3.1. MODIFIED DELPHI METHOD ROUND 1

The two teams of SMEs assigned a condition rating of Black, Red, Amber, or Green for each category based on its condition description from the case study assessment. For 22 of the 32 (68.75%) categories, the two teams rated the benchmark categories exactly the same. Of the ten categories that were not rated the same, eight ratings were within one rating of each other (i.e. assessed as Black and Red, Red and

Amber, or Amber and Green), one category had a two rating difference (Amber and Black), and the final category had a three rating difference (Black and Green).

Both teams also assigned a priority weight ("5" = Highest priority to "1" = Lowest priority) for each category based on its metric description. The teams assigned the exact same priority weight to 17 of the 32 categories (53.13%). For the other 15 categories, six categories each had a priority weight difference of one or two, with the remaining three categories having a spread of three or four.

To quantify the ratings and assess how the differences between the SME teams would propagate through the MARM, a Benchmark Score was calculated for each category based on the conversion of the rating and priority weight using conversion factors (Table 4) and Equation (1) to calculate the Benchmark Category Score (Table 4). A larger Benchmark Score indicates a category with a worse condition given a higher priority.

$$Benchmark\ Score = Quantitative\ Assessment\ Conversion\ x\ Priority\ Weight\ Score \qquad (1)$$

Table 4. Benchmark Category Score Conversion.

	High		Neutral		Low
Priority Weight Score	5	4	3	2	1
Green = 1	5	4	3	2	1
Amber = 2	10	8	6	4	2
Red = 3	15	12	9	6	3
Black = 4	20	16	12	8	4

The cumulative impact of the uncertainty in both rating and priority weight was emphasized by the reduction in consistency in Benchmark Scores. Of the 32 categories, less than half (46.88%) yielded the same exact score between the SME teams, though

71.88% of the categories had scores within two of each other. The mean difference between the 17 non-concurrent benchmark scores was 4.24, with a standard deviation of 3.17. The impact of uncertainty on the remaining nine categories is significant as their mean difference between the teams was 7.00, with a maximum difference of 11, which is significant when comparing scores from Table 4.

Table 5. Modified Delphi Method Round 1: Consistency Results.

	Priority Weight Delta	Category Rank Delta	Category Score Delta
Consistency (delta = 0)	17	22	15
Consistency %	53.13%	68.75%	46.88%
Total Delta Count	15	10	17
Total Delta Percent	46.88%	31.25%	53.13%
Delta = 1 Count	6	8	4
Percent of Total Delta	40.00%	80.00%	12.50%
Delta = 2 Count	6	1	4
Percent of Total Delta	40.00%	10.00%	12.50%
Delta > 2 Count	3	1	9
Percent of Total Delta	20.00%	10.00%	28.13%

The MARM methodology was developed to quantitatively compare a category's current condition to its ideal by comparing its Benchmark Score to its Ideal Score. Since a "Green" rating has a Score Conversion equal to one (Table 4), an ideal rating would yield a Benchmark Ideal Score solely based on its priority weight using Equation (2).

$$\textit{Benchmark Ideal Score} = \textit{Weight} \times 1\ (\text{"Green"}) \tag{2}$$

For each benchmark category, the difference between the current Benchmark Score and its Ideal Benchmark Score was calculated to determine its Delta from Ideal using Equation (3).

$$\textit{Delta from Ideal} = \textit{Benchmark Score} - \textit{Benchmark Ideal Score} \tag{3}$$

The next step in the MARM methodology was to determine where each category fits into the MARM based on the resilience stage and domain definitions (Table 1). An example was created by the authors to map the 32 categories used in this study to enable an initial comparison of the results of Round 1 (Table 6). SME input was utilized to create mapping specific to their input in this study in Round 3 of the Delphi Method.

Table 6. Case Study Mission Assurance Categories to Resilience Matrix Categorization.

	Prepare	Absorb	Recover	Adapt
Physical	EP-02 MO	EP-05 FP-02 FP-03 HVAC-04 HVAC-05 PS-04 PS-12	EP-04 WTR-03	EP-01 WTR-01
Information	AT-20 HVAC-03 WTR-02	HVAC-02	FP-01 FP-04 UT-02	HVAC-01
Cognitive	PS-11 AT-19 FP-05 PS-06	PS-14 UT-01	UT-03	
Social	PS-13	UT-04	UT-05 EP-03	

Note: The MARM as originally constructed consisted of 41 benchmark categories filling all 16 cells of the matrix. The case study data only utilized 32 categories, with all of the categories assigned to the Cognitive-Adapt and Social-Adapt cells removed.

Antiterrorism (AT)
Electromagnetic Environment (EMP)
Electrical Power (EP)
Fire Protection Infrastructure (FP)
Heating, Ventilation, Air Conditioning (HVAC)
Munition Operations (MO)
Natural Gas Supply/Maintenance (NG)
Physical Security (PS)
Utilities (UT)
Water Systems (WTR)

The Delta from Ideal score for each benchmark was plugged into the example MARM (Table 6) and combined with any other benchmark category Delta from Ideal scores in the cell to calculate the Cell Score using Equation (4) since all Delta from Ideal scores are unitless and are similarly scaled.

$$Cell\ Score = \sum_{i=1}^{n} Benchmark\ Delta\ from\ Ideal \tag{4}$$

A larger Cell Score indicates that the cumulative impact of the individual category differences from ideal are large and therefore the resilience of that cell low. The cells scores were plugged into the MARM and a color scale applied to allow a decisionmaker to have a snapshot of the infrastructure system's resiliency (Figures 1 and 2). The impact of consensus (or lack thereof) is displayed in the two MARMs created from the Round 1 results. The MARM created from the SME Team results shows that the Physical-Absorb has the highest Cell Score and is significantly the least resilient based on their assessment with the Cognitive-Prepare cell as the second-worst, still by a significant amount over the other cells. The CSA MARM indicates that the Physical-Prepare is the cell that assessed as furthest from its ideal resilience condition with the Absorb-Physical the second worst, just slightly worse than Cognitive-Prepare and Cognitive-Absorb.

	Prepare	Absorb	Recover	Adapt
Physical	10.00	23.00	4.00	0.00
Information	0.00	0.00	6.00	0.00
Cognitive	8.00	18.00	0.00	0.00
Social	0.00	0.00	0.00	0.00

Figure 1. SME Team Round 1 MARM.

	Prepare	Absorb	Recover	Adapt
Physical	15.00	11.00	0.00	0.00
Information	0.00	0.00	6.00	0.00
Cognitive	9.00	9.00	0.00	0.00
Social	5.00	0.00	0.00	0.00

Figure 2. CSA Round 1 MARM.

The final component of the MARM methodology is to integrate the Cell Scores with cost estimates for infrastructure improvement projects to calculate a Cost Impact Score. This quantifies the improvement that you get for the resources expended and allows decisionmakers to compare potential infrastructure improvement projects and consider their impact on resilience improvement to ensure they are spending their limited resources in an effective manner.

As part of Round 1, the SME team provided a three-point cost estimate (Low, Middle, and High) for a hypothetical improvement project for eight selected categories. The other 24 categories were eliminated from this analysis since they were administrative or had been assessed by SME Team as "Green" in Round 1 and would not be a candidate for an improvement project. The most likely cost was calculated assuming a Beta distribution of the cost estimates using Equation (5) (Prakash n.d.).

$$Most\ Likely\ Cost = \frac{(Low\ Cost + 4 * Middle\ Cost + High\ Cost)}{6} \tag{5}$$

The Cost Impact Score was calculated by taking the difference between the Initial and Improved Benchmark Scores and dividing it by the associated project cost and scaled by a factor of 100,000 for readability (Equation 6) for each of the categories using both the SME Team Benchmark scores and the CSA Benchmark scores to facilitate comparison. Additionally, an Average Cost Impact Score was calculated using the average rating and average priority weight for each category (Table 7).

$$Cost\ Impact\ Score = \frac{Initial\ Benchmark\ Score - Improved\ State\ Benchmark\ Score}{Benchmark\ Project\ Cost} * 100{,}000 \quad (6)$$

The SME Team had one and the CSA two categories with a calculated Cost Impact Score of zero, which would be an inefficient use of resources if the project was completed. This is significant as it shows the difference in how a SME rates and prioritizes a category will impact how much impact that project will have on the resilience assessment and decision-making process. Four categories had a difference between the SME Team and CSA Cost Impact Factors of less than five, and one category (PS-06) had a difference in the Cost Impact Score just under six.

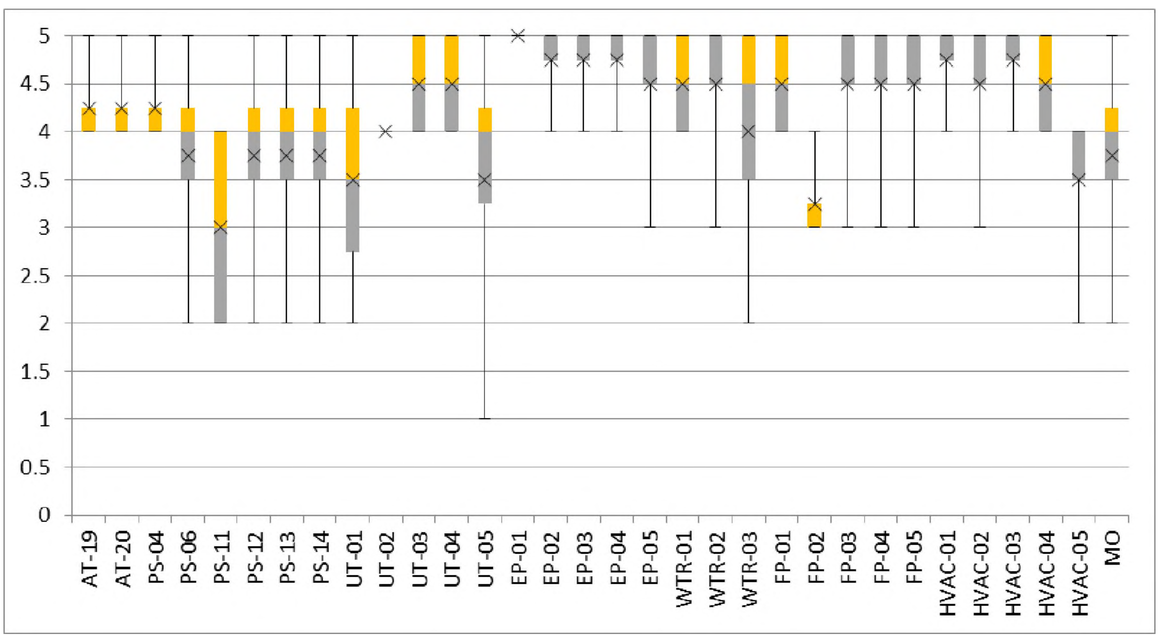
Table 7. Modified Delphi Method Round 1: Cost Impact Score Results.

Benchmark Category	Low Cost Estimate	Middle Cost Estimate	High Cost Estimate	Most Likely Cost	Cost Impact SME Team Score	Cost Impact CSA Score	Cost Impact Average Score
PS-04	$75,000	$187,500	$275,000	$183,333	2.73	0.00	1.36
PS-06	$5,310	$18,000	$30,000	$17,885	22.37	16.77	20.97
PS-12	$200,000	$480,000	$750,000	$478,333	3.14	1.25	2.09
PS-14	$200,000	$480,000	$750,000	$478,333	3.14	1.67	2.35
UT-01	$5,000	$42,000	$75,000	$41,333	7.26	2.42	4.84
WTR-03	$6,000	$18,000	$48,000	$21,000	19.05	0.00	8.33
HVAC-05	$3,000	$30,000	$112,000	$39,167	0.00	12.77	3.83
MO	$135,000	$280,000	$350,000	$267,500	3.74	5.61	4.67

3.2. MODIFIED DELPHI METHOD ROUND 2

The results of Round 2 were evaluated from two perspectives: 1) the amount of agreement and consistency between SMEs for each benchmark category, and 2) cumulative amount of agreement and consistency between SMEs. Mean Likert scores and response rates were used to evaluate agreement and consensus.

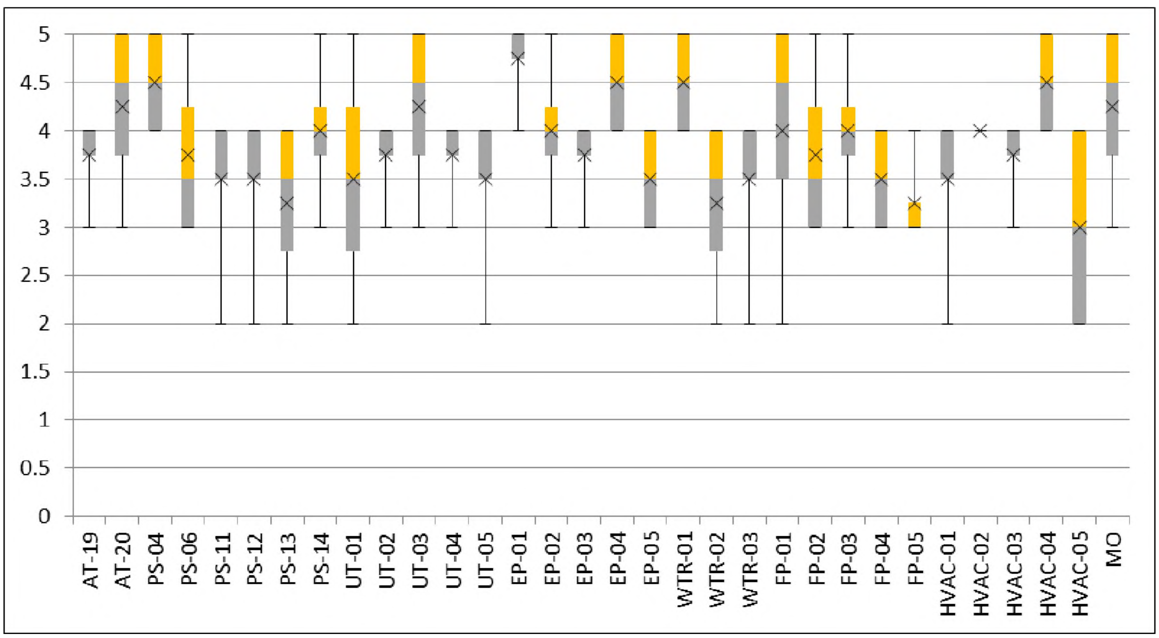
There was a high amount of SME agreement regarding the average benchmark category ratings with at least three of the four SMEs indicating agreement with the benchmark category rating in 29 of the 32 categories (90.63%) (Figure 3). Only one category, UT-05, showed a low amount of agreement, with ratings spread from Strongly Disagree to Strongly Agree. There was also a high amount of consistency amongst the SMEs as demonstrated by 27 of the 32 (84.38%) categories having a mean Likert score of 3.75 or greater, with 22 of the 32 (68.75%) categories having a mean Likert score of 4 or greater (Figure 3).



Note: X = Mean Likert score with the spread of the responses indicated by the "whiskers, and quartiles indicated by the shaded boxes. The smaller the shaded box, the greater the level of consensus.

Figure 3. Category Rating Level of Agreement Responses.

For the priority weight, the amount of agreement was slightly lower, but still relatively high, with at least three SMEs indicating agreement with the priority weight for 23 of the 32 categories (71.88%). In only one case did a category have more than one SME indicate disagreement. This amount of agreement was further shown with 20 of the 32 (62.5%) categories having a mean Likert score of 3.75 or greater and of these, 13 of the 32 (43.63%) categories had a mean Likert score of 4 or greater (Figure 4).



Note: X = Mean Likert score with the spread of the responses indicated by the "whiskers, and quartiles indicated by the shaded boxes. The smaller the shaded box, the greater the level of consensus.

Figure 4. Priority Weight Level of Agreement Responses.

For the category ratings, there was a high amount of cumulative agreement as 83.59% of the responses were either Strongly Agree or Agree. The responses for the priority weights showed a slightly lower, but still a relatively high amount of cumulative agreement with 71.88% of the responses either Strongly Agree or Agree. The difference between the two is due to the number of neutral (“Neither agree or disagree”) responses. There were only 10 of these responses for the category rating, but that jumped to 25 for the priority weight. Both had a similar number of disagreement (“Strongly disagree” or “Disagree”) responses (11 total responses for each) (Table 8).

Table 8. Modified Delphi Method Round 2: Amount of Benchmark Category Agreement.

	Category Rating Count	Category Rating Percent	Priority Weight Count	Priority Weight Percent
Strongly Agree	59	46.09%	25	19.53%
Agree	48	37.50%	67	52.34%
Neither Agree or Disagree	10	7.81%	25	19.53%
Disagree	10	7.81%	11	8.59%
Strongly Disagree	1	0.78%	0	0.00%

For the SME categorization of the benchmark categories, the cumulative results show a strong preference to place the categories into the Physical domain and the Prepare stage (Table 9). Several cells in the MARM did not have any categories placed into them by the SMEs. This is problematic and indicates that without clear guidance, assessment teams will likely create a highly unbalanced matrix that may have many cells that look “Green” since they have no categories placed in them. This would indicate that the cell is at its ideal condition and provide a false sense that the infrastructure system has a high amount of resilience. This result may also be an indication of the impact of the lack of formal resilience education and training for engineering managers (Richards and Long 2019).

Table 9. Modified Delphi Method Round 2: Occurrences of Cell Categorization.

	Prepare	Absorb	Recover	Adapt
Physical	50.00%	17.19%	3.91%	3.13%
Information	14.06%	2.34%	0.00%	0.78%
Cognitive	0.78%	1.56%	0.00%	0.00%
Social	3.13%	3.13%	0.00%	0.00%

Categorization of the benchmark categories by the SMEs showed less consistency than for the benchmark ratings or priority weights in terms of resilience stage. In 18 of the 32 categories (56.25%) there was consensus between at least three of the four SMEs with which stage the benchmark category should be placed, while in 14 of the categories (43.75%) there was consensus between only two of the SMEs. Of those 14 categories, eight were split across two stages and the other six across three stages, with no benchmark categories placed across all four stages (Table 10). Placement of the benchmark categories into a domain was more consistent with 26 of the 32 categories (81.25%) having consensus amongst at least three of the four SMEs into which domain the benchmark category should be placed. The evaluation of the amount of consensus of the other six categories showed that three were split across two domains, two were split across three domains, and one was split across all four domains (Table 10).

Table 10. Modified Delphi Method Round 2: Benchmark Categorization Consistency.

Consistency	Resilience Stage Count	Resilience Stage Percent	Domain Count	Domain Percent
(4 of 4) 100%	6	18.75%	17	53.13%
(3 of 4) 75%	12	37.50%	9	28.13%
(2 of 4) 50%	14	43.75%	5	15.63%
(None-all different)	0	0.00%	1	3.13%

The impact of the individual categorization completed by each SME was visually demonstrated by mapping their selection of resilience stage and domain into the MARM and incorporating the average Benchmark Scores to calculate the appropriate Cell Scores (Figure 5). SME 1 and 4 categorized all benchmark categories in the Prepare resilience stage. The other two SMEs had a broader spread of categorization across stages, but still most benchmark categories were assigned to the Physical-Prepare, Physical-Absorb, or Information-Prepare cells. Though all the SMEs were given the same guidance and definitions (Table 1), the differences across SME MARMs and the internal imbalance within each MARM (Figure 5) confirmed the difficulty in defining which cell some categories should belong to (Mustajoki and Marttunen 2019) and that it may be difficult to find indicators for the cognitive domain (Fox-lent and Linkov 2018). There were significant differences in the MARMS created based SME categorization. The Physical-Prepare cell had the highest Cell Score for three of the four SME MARMs, though the scores were spread from a high of 50 to a low of 28.75. The Physical-Absorb cell had either the highest or second highest Cell Score in one MARM each., again with a significant spread of score values in each instance (Figure 5).

3.3. MODIFIED DELPHI METHOD ROUND 3

Round 3 results (Figure 3 and Table 11) indicate that there was a high amount of agreement (at least three of the SMEs agreed with the prioritization of the project based on its Cost Impact Score) for six of the eight (75%) categories. Five of those categories (62.5%) had a mean Likert score of at least 3.75 and three of the categories (37.5%) had a mean Likert score of 4.0 or greater.

SME 1	Prepare	Absorb	Recover	Adapt
Physical	48.25	0.00	0.00	0.00
Information	6.00	0.00	0.00	0.00
Cognitive	0.00	0.00	0.00	0.00
Social	6.75	0.00	0.00	0.00

SME 2	Prepare	Absorb	Recover	Adapt
Physical	18.50	29.00	3.75	0.00
Information	6.00	0.00	0.00	0.00
Cognitive	2.00	0.00	0.00	0.00
Social	0.00	1.75	0.00	0.00

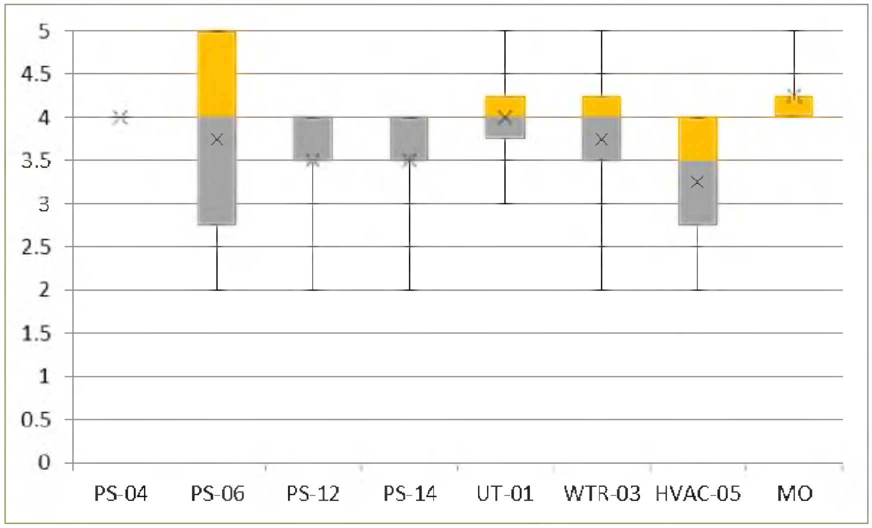
SME 3	Prepare	Absorb	Recover	Adapt
Physical	28.75	19.50	0.00	3.75
Information	9.00	0.00	0.00	0.00
Cognitive	0.00	0.00	0.00	0.00
Social	0.00	0.00	0.00	0.00

SME 4	Prepare	Absorb	Recover	Adapt
Physical	50.00	0.00	0.00	0.00
Information	11.00	0.00	0.00	0.00
Cognitive	0.00	0.00	0.00	0.00
Social	0.00	0.00	0.00	0.00

Note: A higher Cell Score indicates less resilience since it has a greater cumulative Delta from Ideal for its assigned categories.

Figure 5. Round 3: Mission Assurance Resilience Matrix by SME.

The highest amount of disagreement occurred in categories PS-06 and HVAC-05. PS-06 had the lowest Most Likely Cost, but the highest Cost Impact Score while HVAC-05 had a low Most Likely Cost with a medium Cost Impact Score (Table 11). This may indicate a heuristic amongst some of the SMEs that the lower cost projects will not produce as big an impact on resilience and verifies that the MARM does identify projects that may be overlooked for their impact.



Note: X = Mean Likert score with the spread of the responses indicated by the "whiskers, and quartiles indicated by the shaded boxes. The smaller the shaded box, the greater the level of consensus.

Figure 6. Round 3: Cost Impact Score Amount of Agreement.

The individual SME amount of agreement (Table 12) was used to conduct a hypothesis test to validate that the MARM prioritizes improvement projects differently than the heuristics the SMEs use to prioritize the projects.

Table 11. Modified Delphi Method Round 3: Cost Impact Score Consistency.

ID	Most Likely Cost Estimate	Cost Impact	Strongly Agree or Agree	Neither Agree nor Disagree	Strongly Disagree or Disagree
PS-04	$183,333	1.36	100%	0%	0%
PS-06	$17,885	20.97	50%	25%	25%
PS-12	$478,333	2.09	75%	0%	25%
PS-14	$478,333	2.35	75%	0%	25%
UT-01	$41,333	4.84	75%	25%	0%
WTR-03	$21,000	8.33	75%	0%	25%
HVAC-05	$39,167	3.83	50%	25%	25%
MO	$267,500	4.67	100%	0%	0%

The mean number of non-agreement responses (“Neither agree or disagree, Disagree, and Strongly Disagree) for each SME was 25% and standard deviation of 20.41% were used as the sample mean and standard deviation to compare to the hypothesized population mean to determine if the study’s sample mean is significantly different (Gerald 2018). Since the sample size is small (n=4), a one sample t test using the Excel Add-In, Real Statistics (Zaiontz n.d.) with a Type I acceptable error of 5% (alpha = 0.05), is appropriate to evaluate whether to reject the null hypothesis that the MARM model and US Army Africa heuristic project selection methods perform the same and have a mean disagreement with the category Cost Impact Scores equal to 0%. The alternate hypothesis is that the MARM prioritizes projects differently than SME heuristic project selection methods leading to a mean disagreement with the category Cost Impact Scores greater than 0%.

The results of the hypothesis test rejected null that there is no difference between the MARM and SME heuristic project selection methods (Figure 7). These results validate that the MARM performs differently than heuristic project selection methods, but more data is required to quantify the amount of that impact and validate the MARM as an effective decision support tool.

Table 12. Modified Delphi Method Round 3: Cumulative Cost Impact Score Amount of Agreement.

	SME 1	SME 2	SME 3	SME 4	Total
Agree	6	8	4	6	75.00%
Neutral	1	0	1	1	9.38%
Disagree	1	0	3	1	15.63%
Percent non-agree	25%	0%	50%	25%	25%

SUMMARY			Alpha	0.05			
Count	*Mean*	*Std Dev*	*Std Err*	*t*	*df*	*Cohen d*	*Effect r*
4	0.25	0.204124	0.102062	2.44949	3	1.224745	0.81649[illegible]

T TEST			Hyp Mean	0	
	p-value	*t-crit*	*lower*	*upper*	*sig*
One Tail	0.045861	2.353363			yes

Figure 7. One Sample t-Test Results (Real Statistics Output).

To investigate potential indication of SME bias, the responses of each SME to the 72 opportunities to provide a level of agreement were aggregated (Table 14). Analyzing the response distribution from each SME shows potential bias, specifically when considering SME2 and SME3. SME2 demonstrated a cumulative agreement response rate greater than one standard deviation above the mean, a neutral response rate lower than one standard deviation from the mean, and no disagreement responses throughout the study. SME3 demonstrated the opposite with a cumulative agreement response rate lower than one standard deviation from the mean and a cumulative disagreement response rate greater than one standard deviation from the mean. SME3 accounted for nearly half of the total non-agreement responses across the study (32 of the 65, 49.23%). These cumulative results do indicate that the MARM may be impacted by bias, though further investigation needs to be conducted as to the underlying sources and impact of this potential bias either towards over assessing or under assessing the category rating, priority weight, or Cost Impact Score. This indicates that inconsistencies in infrastructure resilience education and training may contribute to differing SME heuristics that can bias their assessments.

Table 13. Modified Delphi Method Cumulative Count of Level of Agreement by SME.

	SME 1		SME 2		SME 3		SME 4		Mean	SD
	Count	Percent	Count	Percent	Count	Percent	Count	Percent	Count	Count
Agree	60	83.33%	67	93.06%	40	55.56%	56	77.78%	55.75	11.44
Neutral	9	12.50%	5	6.94%	14	19.44%	10	13.89%	9.5	3.70
Disagree	3	4.17%	0	0.00%	18	25.00%	6	8.33%	6.75	7.89

Note: Agree = Strongly agree + agree responses
Neutral = Neither disagree or agree responses
Disagree = Strongly disagree or disagree

3.4. SYSTEM USABILITY SCALE

The responses from each SME for their level of agreement on each of the ten SUS questions were collected and converted from the qualitative level of agreement to a SUS score using Equation (7) (Lewis 2018).

$$SUS = 2.5(20 + SUM(SUS01, SUS03, SUS05, SUS07, SUS09) - SUM(SUS02, SUS04, SUS06, SUS08, SUS10)) \tag{7}$$

The mean score from the four subject matter experts was 68.75 with a mode score of 70, maximum score of 72.5, and minimum score of 62.5. The mean result of 68.75 grades the MARM as a “C” and places the MARM in the average rankings when compared to other systems assessed with the System Usability Scale (Table 3). This is not unexpected since the tool was built in Excel, which is perceived as a low usability system with a mean SUS score of 56.5 (Lewis 2018). The Excel platform was chosen for development of the MARM since MAA data collection tools have already been built using the software and it has usage amongst the DoD MAA community (Richards et al. n.d.). A further indication of the ranking of this system as “average” is that the vast majority of ratings were assessed as Agree, Neutral, or Disagree with only three “Strongly Agree” ratings and no “Strongly Disagree” ratings. This verifies the MARM as an acceptable, though not an excellent computer system for infrastructure assessment data collection and decision support tool through tradespace analysis.

Consistency of the level of agreement (strongly agree or agree) or disagreement (strongly disagree or disagree) for individual questions was quite high (Table 15). Analysis can also be done for each question; a better performing system would have a higher amount of agreement for positive (odd) toned questions and would have a higher amount of disagreement for negative (even) toned questions. Three of the five positive toned questions had 100% agreement, one question had a 75% neutral (neither agree nor disagree) amount of agreement, with the fifth question having a spread across all levels of agreement. For the negative toned questions, one question had 100% disagreement, two had 75% disagreement, one question was split between disagreement and neutral, with one question spread across all levels of agreement.

Table 14. System Usability Scale Results.

Please indicate your level of agreement to the following statements regarding the use of the MAA Resilience Excel Tool:	Tone	Strongly Agree or Agree	Neither Agree nor Disagree	Strongly Disagree or Disagree
1. I think that I would like to use this system frequently in conjunction with MAA assessments.	Positive	100%	0%	0%
2. I found the system unnecessarily complex.	Negative	0%	0%	100%
3. I thought the system was easy to use.	Positive	50%	25%	25%
4. I think that I would need the support of a technical person to be able to use this system.	Negative	0%	25%	75%
5. I found the various functions in this system were well integrated.	Positive	100%	0%	0%
6. I thought there was too much inconsistency in this system.	Negative	0%	50%	50%
7. I would imagine that most people would learn to use this system very quickly.	Positive	100%	0%	0%
8. I found the system very cumbersome to use.	Negative	0%	25%	75%
9. I felt very confident using the system.	Positive	25%	75%	0%
10. I needed to learn a lot of things before I could get going with this system.	Negative	25%	25%	50%

The analysis of low levels of agreement or consensus by question identified areas for improvement of the MARM as a system. Question 3, "I thought the system was easy to use" and Question 10, "I needed to learn a lot of things before I could get going with this system" both had a lower amount of agreement. Considering that a user manual was not developed or provided for the use by the subject matter experts and their only instructions were over email, these results are both expected and reasonable, but indicate that better guidance will lead to a better user experience. Two other questions showed a strong neutral trend, with at least 50% of the users indicating a rating of neither agree nor disagree: Question 6, "I thought there was too much inconsistency in this system", and Question 9, "I felt very confident using the system". The results for these questions indicate additional opportunities for improvement in the consistency of how assessment information is collected, processed, and presented as well as instruction provided to the user to enable them to become comfortable with the MARM as a computer-based decision-support tool.

4. CONCLUSIONS

4.1. CONCLUSIONS

This study implemented several model verification (building the model right) and validation (building the right model) techniques on the MARM through the Modified Delphi Method framework. The results verify that the MARM methodology is acceptable and applicable and warrants further refinement and development as a computer-based resilience assessment and decision support tool.

Though the sample size was small, this study did validate that the MARM does perform differently from SME project selection heuristics, though more work needs to be done to quantify the amount of that impact and determine underlying factors (experience, training, education, etc.) contributing to differences. Additionally, the study does indicate that SME bias, which may be due to inconsistent resilience experience, education, and/or training, may enter into the assessment process. There is potential for this bias to lead to an assessment team creating an unbalanced MARM due to the flexibility built in to the framework that allows the team to determine where to place each category into the matrix. The impacts of having an imbalance matrix and its impact on resilience assessment and decision-making need to further investigated. Due to the anonymous structure of the data collection process used in this study's Modified Delphi Method, further insight into the SME levels of experience and education are not available, but deserves additional investigation in subsequent research. This study's results indicate that the MARM can improve upon typical heuristic decision-making processes and merits further development for application as a decision support tool.

The results of the SUS verified the MARM as an acceptable, though not excellent, computer system for infrastructure assessment data collection and decision support and identified opportunities for improvement to increase the system usability by refining the MARM interface and develop a short user manual/tutorial which will make it easier to use as a decision support tool and improve the user experience. Along with this usability assessment, this study verifies that the amount of consistency within the MARM methodology is acceptable enough to broaden this methodology to incorporate all the

MAA functions and expand to assess infrastructure across the Army's landscape of installations.

4.2. FUTURE WORK

There are three significant areas for future work resulting from this study: 1) improve and refine the MARM based on the results and feedback from the study, 2) conduct additional research into the impact of resilience experience, education, and training on SME uncertainty and bias within the MAA framework, and 3) expand the MARM and verify and validate the expanded mode.

Specific aspects of the MARM that were identified to improve are: 1) increase the system usability by refining the MARM interface and, 2) develop a short user manual/tutorial which will make it easier to use and utilize as a decision support tool. Also, clearer guidance and specific definitions should be provided to assessors as to how to categorize the benchmark categories into the appropriate resilience stage and management domain. This will help mitigate concerns of creating imbalanced matrices, the impacts of which deserve further investigation. Additional research into SME resilience experience, education, and training and its impact on the MARM framework will identity improvements to the MARM to mitigate impacts due to SME bias and uncertainty. This research will also contribute to the broader discussion on incorporation of resilience education at the undergraduate, graduate, and professional levels. These improvements will improve consistency between assessment professionals and help mitigate introduction of uncertainty of assessor judgments or conflicts of opinion.

Finally, the MARM should be expanded beyond the MAA engineer function to include benchmark categories from all the other assessment functions. Additional data from all the functions and across multiple installations should be included to broaden the statistical verification and validation that consistency still holds when incorporating increased number of functions. This additional information should also be used to validate that the tool does outperform, or is at least on par with, the currently utilized heuristic based assessment and decision-making process to prioritize projects to improve infrastructure resilience decision making. This expanded research should also include investigation of the propagation of uncertainty within in the MARM due to SME assessment of priority weights and ratings and their impact on the sensitivity of the Resilience Scores used to calculate the Cost Impact Scores and drive tradespace analysis for project selection decision-making.

ACKNOWLEDGEMENTS

We thank the US Army Africa Deputy Chief of Staff Engineer (DCSENG) division to include Ms. Annie Savage, Mr. Eric Doro, Sergeant First Class Ryan Swanson, and Lieutenant Colonel Jakob Bruhl for their expert input throughout the Modified Delphi Method and review of the manuscript.

REFERENCES

Andradhttir, S., Healy, K. J., Withers, D. H., and Nelson, B. L. (1997). "Proceedings of the 1997 Winter Simulation Conference." Winter Simulation Conference Proceedings.

Bakkensen, L. A., Fox-Lent, C., Read, L. K., and Linkov, I. (2017). "Validating Resilience and Vulnerability Indices in the Context of Natural Disasters." Risk Analysis, 37(5), 982–1004.

Balasubramanian, R., and Agarwal, D. (2012). "Delphi Technique-A Review." International Journal of Public Health Dentistry, 3(2), 16–25.

Bentley, M. W., Kerr, R., Anaes, J., Powell, S., Health, G., and Management, S. (2016). "The Use of a Modified Delphi Technique to Inform the Development of Best Practice in Interprofessional Training for Collaborative Primary Healthcare." 6, 1–39.

Cardoso, S. R., Barbosa-póvoa, A. P., Relvas, S., and Novais, A. Q. (2015). "Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty." Omega, Elsevier, 56, 53–73.

Department of Defense. (2018). DoD Mission Assurance Assessment Benchmarks. Washington, D.C.: DoD.

Fox-Lent, C., Bates, M. E., and Linkov, I. (2015). "A matrix approach to community resilience assessment: an illustrative case at Rockaway Peninsula." Environment Systems and Decisions, Kluwer Academic Publishers, 35(2), 209–218.

Fox-lent, C., and Linkov, I. (2018). "Resilience Matrix for Comprehensive Urban Resilience Planning." Resilience-Oriented Urban Planning, Lecture Notes in Energy, Y. Yamagata and A. Sharifi, eds., Springer International Publishing.

Gerald, B. (2018). "A Brief Review of Independent, Dependent and One Sample t-test." International Journal of Applied Mathematics and Theoretical Physics, 4(2), 50.

Kerner, D. A., and Thomas, J. S. (2014). "Resilience attributes of social-ecological systems: Framing metrics for management." Resources, 3(4), 672–702.

Kleijnen, J. P. C. (1997). "Sensitivity analysis and related analyses: A review of some statistical techniques." Journal of Statistical Computation and Simulation, 57:1–4, 111–142.

Lewis, J. R. (2018). "The System Usability Scale: Past, Present, and Future." International Journal of Human-Computer Interaction, Taylor & Francis, 34(7), 577–590.

Lewis, J. R., and Sauro, J. (2018). "Item Benchmarks for the System Usability Scale." Journal of Usability Studies, 13(3), 158–167.

Ling, Y., and Mahadevan, S. (2013). "Quantitative model validation techniques: New insights." Reliability Engineering and System Safety, Elsevier, 111, 217–231.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., and Seager, T. P. (2013a). "Measurable resilience for actionable policy." Environmental Science and Technology, 47(18), 10108–10110.

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., and Kott, A. (2013b). "Resilience metrics for cyber systems." Environment Systems and Decisions, 33(4), 471–476.

Miller, K. A., Collada, B., Tolliver, D., Audi, Z., Cohen, A., Michelson, C., and Newman, L. R. (2020). "Using the Modified Delphi Method to Develop a Tool to Assess Pediatric Residents Supervising on Inpatient Rounds." Academic Pediatrics, Elsevier Inc., 20(1), 89–96.

Mustajoki, J., and Marttunen, M. (2019). "Improving resilience of reservoir operation in the context of watercourse regulation in Finland." EURO Journal on Decision Processes, Springer Berlin Heidelberg, 7(3), 359–386.

Prakash, V. (n.d.). "3 Point Estimate: Triangular Distribution vs Beta Distribution (PERT)." PMChamp, <https://www.pmchamp.com/3-point-estimate-triangular-distribution-vs-beta-distribution-pert/> (Jul. 13, 2020).

Richards, J., Bruhl, J., Richards, J., and Long, S. (n.d.). "Improving Mission Assurance Assessment for Resilience." Natural Hazards Review.

Richards, J., and Long, S. (2019). "A Mixed Method Study of Infrastructure Resilience Education and Instruction." Proceedings of the 2019 International Annual Conference of the American Society for Engineering Management, 1.

Roege, P. E., Collier, Z. A., Mancillas, J., Mcdonagh, J. A., and Linkov, I. (2014). "Metrics for energy resilience." Energy Policy, Elsevier, 72, 249–256.

Sargent, R. G. (2013). "Verification and validation of simulation models." Journal of Simulation, Nature Publishing Group, 7(1), 12–24.

Tversky, A., and Kahneman, D. (1974). "Judgment under Uncertainty: Heuristics and Biases." Science, 185(4157), 1124–1131.

Wood, M. D., Wells, E. M., Rice, G., and Linkov, I. (2019). "Quantifying and mapping resilience within large organizations." Omega (United Kingdom), Elsevier Ltd, 87, 117–126.

Yaniv, I. (1997). "Weighting and Trimming: Heuristics for Aggregating Judgments under Uncertainty." Organizational Behavior and Human Decision Processes, 69(3), 237–249.

Zaiontz, C. (n.d.). "Real Statistics Using Excel." <https://www.real-statistics.com/> (Jul. 10, 2020).

IV. USING SENSITIVITY ANALYSIS TO IMPROVE MISSION ASSURANCE ASSESSMENTS OF MILITARY INSTALLATIONS

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ABSTRACT

The Department of Defense has been mandated to incorporate resilience into its assessment, planning, and resourcing of its critical infrastructure. There is a gap between this guidance and the ability to identify the resiliency of a military installation as a system and identify which improvements would most impact resilience. Based on resilience matrix research, the Mission Assurance Resilience Matrix (MARM) was developed to close this gap and integrate resilience quantification into the existing infrastructures assessment construct. This study extends previous research to verify the usability of the MARM as a decision support tool by investigating the impact of uncertainty in this model. Monte Carlo simulation was used to conduct a sensitivity analysis of the assessment ratings and prioritization of the benchmark categories utilized to calculate the scores of the cells in the MARM.

The results of this analysis demonstrate the ability to use sensitivity analysis to investigate uncertainty in the MARM, verify the usability of the MARM as a decision support tool, highlight the challenges of extending the MARM to the other functions within the existing DoD Mission Assurance Assessment, and provide recommendations on improvements to the integration and use of the MARM.

Keywords: Infrastructure resilience, mission assurance assessments, resilience matrix, decision support tool, Monte Carlo simulation

1. INTRODUCTION

A decision support tool is most useful when the impact of underlying uncertainty inherent in the model is understood. This study extends previous research to verify the usability of the Mission Assurance Resilience Matrix (MARM) a decision support tool through analysis of the model's sensitivity to uncertainty. The MARM is a decision support tool developed by Richards et. al based on previous resilience matrix research to integrate resilience into the existing Department of Defense (DoD) Mission Assurance Assessment (MAA) infrastructure assessment construct. The use of Monte Carlo simulation to determine the sensitivity of the cells within the MARM to uncertainty in the prioritization and rating of the physical infrastructure benchmark categories identified improvements to the MARM as a decision support tool.

Linkov et al. developed a matrix-based assessment procedure for cyber resilience based on the National Academy of Sciences definition of resilience as a framework to assess the performance of integrated complex systems (Fox-Lent et al. 2015; Linkov et al. 2013a; Wood et al. 2019). One goal of the Resilience Matrix (RM) as a guiding framework is to organize data collection and facilitate communication (Fox-lent and Linkov 2018) since the RM is flexible enough to be used as a screening tool but detailed enough to support actionable decision making (Linkov et al. 2013a). RM is a 4x4 matrix such that the four columns of the resilience matrix describe the four stages of disaster management (plan/prepare, absorb/withstand, recover, adapt). The rows describe the four general management domains of a complex system, (physical, information, cognitive, and social), as described in the US Army's Network-Centric Warfare doctrine (Alberts and Hayes 2005). The RM integrates assessment of resilience at the functional and system levels, so that the evaluation is not solely based on the features of the infrastructure and helps decision makers answer the question " How is the system's ability to [plan/prepare for, absorb, recover from, adapt to] a cyber disruption implemented in the [physical, information, cognitive, social] domain? "(Linkov et al. 2013a). This RM methodology has been applied to several different infrastructure systems; cyber (Linkov et al. 2013b), energy (Roege et al. 2014), coastal and community resilience assessment (Fox-Lent et al. 2015), urban resilience planning (Fox-lent and Linkov 2018), and reservoir operations (Mustajoki and Marttunen 2019).

The RM methodology is highly applicable to military infrastructure assessments due to the unique, complex, and highly integrated nature of military infrastructure as a system of systems. Richards et. al adapted the RM construct to develop the MARM to incorporate resilience measurement and quantification into the existing DoD MAA framework for infrastructure assessment. The MARM was developed for the physical infrastructure subset of mission assurance benchmarks assessed by the engineer function with the objective to expand the methodology to all 23 functions within the DoD MAA framework. Additionally, the MARM methodology extends the RM framework by automating the decision support tool framework and resilience assessment process.

The MARM differs in three significant respects from the RM framework that supports the investigation of uncertainty in the MARM through sensitivity analysis, which has not been previously done with the RM framework. First, each cell in the RM is constructed from metrics specified for that cell that can be independent from the other cells and utilizes a linear function scaled from 0 to 10 to determine the score in each cell (Fox-lent and Linkov 2018). This could lead to the incorporation of up to sixteen different units of measure throughout the matrix, making it a challenge to compare the impact of uncertainty throughout the matrix through sensitivity analysis. Conversely, the MARM was constructed from benchmark categories that all apply a common qualitative assessment that is converted to a unitless and similarly scaled quantitative resilience matrix cell score. These cell score qualities support the conduct of analysis of the sensitivity of the resilience cells to the uncertainty of the assessment of the category ratings and priority weights.

Second, this similarity of unitless and scale throughout the matrix also allows for the flexibility to combine benchmark categories into cells of the MARM according to the assessment team’s determination of where the benchmark category best fits. The RM methodology does allow for combination of multiple metrics within a cell, but only if the units and scale were similar (Fox-Lent et al. 2015). The MARM’s structure to incorporate multiple benchmarks into one cell provides flexibility but leads to the task of determining the best method to combine the individual scores in a cell of the MARM, either a summation or an average of the individual category scores. Sensitivity analysis was used in this study to investigate this difference in cell score calculation methodology.

Finally, the overall system resilience in the RM framework is determined from the aggregation of the sixteen metrics that result from multi-criteria decision analysis methods (Heinimann and Hatfield 2017). A system with robust safeguards where all elements of the resultant matrix have been addressed can be considered to be highly resilient. In contrast, a lack of attention to one or more elements in the resilience matrix would indicate a point of vulnerability, which may be used to direct attention to improve the security of the system as a whole (Zussblatt et al. 2017). Similarly, for an infrastructure system to be considered using the MARM methodology, every category within each cell would need to be rated in its ideal condition for the system be considered resilient. The realities of operating in a fiscally constrained environment lead to the opportunity to utilize the MARM to support a tradespace analysis of the impact of potential projects that would improve certain benchmark categories as part of decision analysis during the project selection process. In this regard, the MARM is more than just a tracker for whether a benchmark category meets its metrics, but also seeks to scale the prioritization and closeness of the benchmark to its metrics that creates a tradespace to support decision making and resource allocation.

1.1. MISSION ASSURANCE RESILIENCE MATRIX CONSTRUCT

The Department of Defense (DoD) uses the Mission Assurance Assessment (MAA) benchmarks for the basis of assessing its installations to meet its mandate to incorporate resilience measurement and quantification into its existing decision-making framework (Department of Defense 2018c). The MAA framework divides the assessment into twenty-three distinct functions, such as antiterrorism, physical security, and emergency management, with each function comprised of multiple categories to be assessed, for a total of over 200 benchmark categories. Responsibilities for assessing the functions are assigned to members of the assessment team depending on their expertise.

The specific benchmarks utilized for this study are taken from the DoD Mission Assurance Benchmarks dated 28 March 2018, which are unclassified but designated as For Official Use Only (FOUO) (Department of Defense 2018c). Therefore, they cannot be published in this article in full, but the broad categories and representative identification numbers are summarized and implemented in this paper to allow for easier connection back to the base document. Assessment reports are created for military installations and provide important input for leaders to understand risk, inform the development of specific requirements for future infrastructure projects, and assist in making decisions about which ones to fund.

The MARM was developed to close the gap between the guidance for the Army to address resilience in its assessment process and the fact that the current assessment process does not specifically nor directly assess resilience. There is currently not a direct method to identify the resiliency of a military installation as a system nor identify which improvements would impact resilience the most. The MARM was developed to convert qualitative infrastructure assessment data into quantitative data that can be analyzed and presented in a format that improves the visualization of the cost-benefits of potential infrastructure improvement projects and allow leaders to understand the influence on resilience that one project may have on multiple functions or systems (Richards et al. n.d.). The MARM was built by categorizing a subset of 41 of the Mission Assurance Benchmark Categories (Department of Defense 2018c) most pertinent to military installation infrastructure resilience based on input from subject matter experts from the US Army Africa Deputy Chief of Staff Engineer (USARAF DCSENG) section. To identify the role that each benchmark plays in resilience, each benchmark category was further categorized based on its description and metrics into one of the sixteen cells within a resilience matrix (Table 1). For example, the Antiterrorism benchmark AT-19 was deemed to best relate to the cognitive domain within the prepare phase. All benchmark categories were included in the categorization and placed where they most logically fit into the matrix, which led to an imbalance of categories within the cells.

Table 1. Example Mission Assurance Categories to Resilience Matrix Categorization.

	Prepare	Absorb	Recover	Adapt
Physical	EP-02 MO-07	EP-05 FP-02 FP-03 HVAC-04 HVAC-05 MO-03 PS-04 PS-12	EP-04 WTR-03	EP-01 WTR-01
Information	AT-20 HVAC-03 WTR-02	HVAC-02 NG-02	FP-01 FP-04 UT-02	HVAC-01 NG-01
Cognitive	PS-11 AT-19 EMP-01 FP-05 MO-02 PS-06	PS-14 UT-01	UT-03	PS-15 MO-06
Social	FP-06 PS-13	UT-04	UT-05 EP-03	MO-08

Note: Antiterrorism (AT)
Electromagnetic Environment (EMP)
Electrical Power (EP)
Fire Protection Infrastructure (FP)
Heating, Ventilation, Air Conditioning (HVAC)
Munition Operations (MO)
Natural Gas Supply/Maintenance (NG)
Physical Security (PS)
Utilities (UT)
Water Systems (WTR)

The model was built to convert the qualitative ratings of Black (B), Red (R), Amber (A), and Green (G), identified for each category by the assessment team into a quantitative value using a qualitative assessment conversion factor (Table 2). Previous research using resilience matrix methodology found that users identified a weakness when all categories are treated similarly (Mustajoki and Marttunen 2019), which was reinforced through discussions with the USARAF DCSENG subject matter experts. To account for the fact that decision makers do not prioritize all categories equally, a priority weight factor, similar to the priority matrix developed to model resilience time (Ramachandran et al. 2015), was incorporated (Table 3). It is the uncertainty in the assessment of these qualitative ratings and priority weight factors that are the focus of the sensitivity analysis conducted in this study.

Table 2. Qualitative Assessment Conversion.

Qualitative Rating	Score
Green	1
Amber	2
Red	3
Black	4

Table 3. Priority Weight Factor.

Qualitative Weight	Score
Highest	5
	4
Neutral	3
	2
Lowest	1

The Benchmark Score was calculated for each category using the converted quantitative factors and Equation (1). A larger Benchmark Score indicates a category with a poor condition at a higher importance.

$$Benchmark\ Score = Quantitative\ Assessment\ Conversion\ x\ Priority\ Weight\ Factor \quad (1)$$

In an ideal installation assessment, every benchmark category, no matter its priority, would be assessed as "Green" and its Benchmark Score would equal its priority weight as per Equation (2).

$$\textit{Benchmark Ideal Score} = \textit{Weight x 1 ("Green")} \quad (2)$$

This allows for the calculation of the difference from the ideal score (Delta from Ideal) using Equation (3) for each benchmark category, which is then mapped back into the MARM for which an example is provided in Table 4.

$$\textit{Delta from Ideal} = \textit{Benchmark Score} - \textit{Benchmark Ideal Score} \quad (3)$$

A Delta from Ideal score equal to zero means that the benchmark category is assessed as "Green" and cannot be improved. A larger Delta from Ideal score indicates that category is further from ideal and may have a large negative impact on resilience if not improved.

Table 4. Example Delta from Ideal by Benchmark Category.

	Resilience Phase			
Domain	Prepare	Absorb	Recover	Adapt
Physical	0 3	3 8 3 0 3 0 2 8	8 0	5 10
Information	6 4 4	2 0	3 0 5	9 2
Cognitive	15 15 3 3 0 0	0 10	0	15 10
Social	8 4	6	8 12	0

Most cells in the MARM contained multiple benchmark categories, so the Cell Score was calculated as the summation of the individual benchmark Delta from Ideal scores from each category in the cell using Equation (4). This method captures the impact that the categories with the highest priority that were furthest from ideal would have on the Cell Score. The summation of the benchmark Delta from Ideal scores was selected rather than the average to maintain the impact of categories that are both highly weighted and a significant difference between their assessed score and ideal score. For example, if a category was deemed to be a priority “5” and assessed “Black” but was averaged with several categories that have a lower priority and assessed “Green”, the impact of the high priority category would be lost.

$$Cell\ Score = \sum_{i=1}^{n} Benchmark\ Delta\ from\ Ideal \tag{4}$$

The cell scores were aggregated to create the Initial Mission Assurance Resilience Matrix (Table 5). In this example, the Cognitive-Prepare is the furthest from ideal and the Cognitive-Absorb and Social-Adapt are already at ideal, so they do not warrant further attention.

Table 5. Example MARM.

	Prepare	Absorb	Recover	Adapt
Physical	3.00	27.00	8.00	15.00
Information	14.00	2.00	8.00	11.00
Cognitive	36.00	10.00	0.00	25.00
Social	12.00	6.00	20.00	0.00

The quantification of these qualitative assessments into a unitless and similarly scaled Cell Score allow for the implementation of sensitivity analysis to understand the impact of uncertainty within the assessment of benchmark category priority weights and ratings. Previous research identified that while there was no evidence of a significant amount of uncertainty and differences of opinion, subject matter judgement may have an impact on the MARM methodology that should be further investigated (Richards and Long n.d.).

1.2. SENSITIVITY ANALYSIS

The benefits of sensitivity analysis on the MARM are to gain basic insight on the system, to indicate whether the model operates as intended, to identify the key components of the model that require further calibration and/or study, and to assess the relative importance of input variables for guidance in data collection and model calibration (Manache and Melching 2008). To achieve this, a global, all-at-a-time sensitivity analysis for decision-making (Pianosi et al. 2016) was used to analyze the impact of uncertainty arising from an assessment team's selection of the benchmark category weights and criteria within the model to verify the consistency of the MARM with expected real-world behavior. Sensitivity analysis explores the relationships between the output and the inputs of a modeling application and is crucial to the verification, validation, and calibration of numerical models. It can be used to check the robustness of the final outcome against slight changes in the input data and can help reduce uncertainty in multi-criteria decision-making and the stability of its outputs by illustrating the impact of introducing small changes to specific input parameters on evaluation outcomes (Chen et al. 2010). The MARM, constructed as a quantitative conversion of the qualitative assessment priority and ratings into a singular score, is a good candidate for sensitivity analysis to determine relations between parameters and outputs of a simulation model (Norton 2015).

Sensitivity analysis was used to determine how the scores in the resilience cells of the MARM changed due to uncertainty in the starting conditions, i.e. the benchmark category weights and ratings, in order to improve the decision making process by identifying the critical criteria and then reevaluating more accurately the weights of these criteria since in this model, there is subjectivity causing difficulty in accurately representing the importance of these criteria (Triantaphyllou and Sánchez 1997). This information will be useful in decision making since it explains synthetically how much the assessment may be biased by the assessor judgements (Zavadskas et al. 2007). In typical optimization applications, uncertainty is considered a potentially harmful factor and the aim of analysis is to explore and discover the degree of sensitivity of the optimal solution to changes in key factors. An insensitive solution is considered advantageous (Muñoz et al. 2016). Since the MARM is not an optimization tool, but rather an assessment and decision support tool, it is intended to be sensitive to allow the initial conditions to determine which cell in the matrix is the furthest from ideal and needs the most attention to conduct projects to bring it to the ideal state. Sensitivity analysis was utilized to determine how the model as originally constructed responds to the uncertainty in assessment of benchmark category priority weights and ratings as well as applied to assess the difference between the summation versus average of benchmark category cells in each resilience matrix cell.

1.3. MONTE CARLO SIMULATION

Based on the construction of the MARM and its design to be a decision-support tool, the exploration of the sensitivity of the cells within the MARM due to uncertainty of the assessments is very suitable for Monte Carlo simulation (Van Hoey et al. 2014). This is similar to the approach that Nguyen et. al took with development of resilience indices for Multi Echelon Assembly Supply Chains (MEASC), though that research sought to optimize the supply chain network. Both the supply chain resilience indices and the MARM can help decision makers make the trade-off between resilience and cost (Nguyen et al. 2020).

The impact of these assumptions on the sensitivity of the ranking of the overall Cell Score for the sixteen cells in the MARM was captured by creating a frequency histogram for the ranking of each MARM cell from 1 (the highest cell score in the MARM) to 16 (lowest cell score in the MARM) for 1000 trials in each simulation. The highest scores in the MARM indicate the cells that need the most attention to improve resilience and the lowest scores would need the least attention.

The first set of Monte Carlo simulations compared the difference in sensitivity in the MARM between using a summation of individual benchmark category Delta from Ideal scores versus an average of those scores in each cell of the MARM. The MARM methodology uses the summation of the benchmark scores within a cell to facilitate the comparison of resilience assessment across the matrix as well as support the project selection tradespace analysis. The RM framework allows combining of metrics in a cell by either averaging or using a weighted sum of multiple metrics after the individual metrics have been contextualized with a linear utility function (Fox-Lent et al. 2015). This study investigates the differences between the two methodologies.

A uniform distribution was assumed for the selection of priority weights from 1 to 5 and the rating of each category, G, A, R, and B (quantified from 1 to 4 respectively) which were used to compute the Benchmark Score (Equation 1), Benchmark Ideal Score (Equation 2), and Delta from Ideal (Equation 3). The first Monte Carlo simulation utilized Equation (4) to calculate each Cell Score from the sum of the individual benchmark category Delta from Ideal scores within the cell, since this method was selected in the original development of the MARM to capture the impact of categories that are both highly weighted and a significant difference between their assessed score and ideal score. The second Monte Carlo simulation employed an average of the benchmark category Delta from Ideal scores to compute the Cell Score using Equation (5).

$$Cell\ Score = \frac{\sum_{i=1}^{n} Benchmark\ Delta\ from\ Ideal}{Number\ of\ Categories\ in\ Cell} \tag{5}$$

For example, if a category was deemed to be a priority "5" and assessed "Black" there would be a distinction between how that score would impact the Resilience Cell Score if added to the others versus averaged with several categories that have a lower priority and assessed "Green". The calculation of the average of the scores would mute the impact of the higher priority, lower assessed categories.

A second set of the Monte Carlo simulations were run to investigate the impact of using a non-uniform distribution of the frequency of the priority weight and rating based on data extracted from an actual Mission Assurance Assessment recently completed by the USARAF DCSENG section (Tables 6 and 7). Though not a robust data set, the analysis illuminates the impact of potential bias within the assessment process that will lead to the result that a uniform distribution is not the most accurate depiction of the probability of occurrence for the weights and ratings selected by a real-world assessment team. The analysis supports the logical conclusion that due to operations maintenance and funding as well as regular capital improvement projects, not all benchmark category ratings will be evenly distributed from Black to Green, and in fact, a significant proportion of the infrastructure will be in decent to good shape. Also, without a function to force assessors to evenly distribute the prioritization of the benchmark categories, they may tend to weight more categories higher.

Table 6. Case Study Benchmark Category Priority Weight Frequencies.

Weight Factor	% Frequency
1	8.06
2	9.68
3	29.03
4	20.97
5	32.26

Table 7. Case Study Benchmark Category Assessment Rating Frequencies.

Assessment Rating	% Frequency
B	7.81
R	9.48
A	15.63
G	67.29

The final set of Monte Carlo simulations investigated the impact of changing the MARM to include an equal number of benchmark categories in each cell to compare the results of the previous simulations to a resilience matrix where all the cells have the same number of categories contributing to the score rather than an unequal distribution of categories.

2. RESULTS

For each Monte Carlo simulation, the results are shown for selected representative cells of the MARM, one for each of the number of categories in a cell (since there were multiple MARM cells that contained three, two, or one benchmark categories, which all behaved similarly in each simulation the results of a representative cell is shown). Each of the columns in the results table represent one example of a MARM cell with that number of benchmark categories and includes the number of benchmark categories, the results for the Mean Resilience Cell Score with its standard deviation, the Mean Resilience Cell Rank within the MARM for each trial with standard deviation, since the standard deviation is an important measure of the uncertainty involved (Fagerholt et al. 2010). The results for each simulation also include the frequency of that cell in the top quartile and bottom quartile of the rankings, as well as the percent of trials that the Cell Score equaled zero, “ideal”. For the top quartile, each simulation collected the frequency that the category was in the top four rankings. For the bottom quartile, there was a significant difference between the simulations assuming a uniform distribution versus the case study distribution. For the uniform distribution, the bottom quartile generally aligned with the bottom four rankings (13-16), while for the case study frequency distribution, due to the higher frequency of categories in each trial having an ideal score, the bottom quartile generally aligned with the bottom seven rankings (10-16). Additionally, a frequency histogram was built to display the distributional pattern for the number of occurrences for each ranking of each of the selected cells across the 1000 trials in the simulation with a rank of 1 = highest Resilience Cell Score in the MARM and furthest from ideal, the rank of 16 = lowest Resilience Cell Score in the MARM and the histogram displayed for each representative cell.

The first Monte Carlo simulation selected the benchmark category priority weights and ratings from a uniform distribution and totaled the benchmark categories within the cell to determine the Cell Score. From this simulation, the MARM is shown to be insensitive to uncertainty in the weights and ratings (Table 8). The cells containing the highest number of categories (Physical-Absorb and Cognitive-Prepare) dominate the model, appear almost exclusively in the top quartile (96.80% and 85.80% respectively), do not have any occurrences of having an Ideal Cell Score, have a significantly higher Mean Resilience Cell Score, and standard deviation than the cells containing only one or two categories. Those cells containing only one or two categories are dominated, appear disproportionally in the bottom quartile of the rankings, and have a significantly lower Mean Resilience Score and much higher Mean Resilience Cell Rank, indicating they will also be the low priority. The frequencies shown in Figure 1 graphically display the skewed results and the insensitivity of the MARM as originally constructed under the assumption of a uniform distribution of weights and ratings.

Table 8. Simulation 1: Total Cell Score with Varying Categories per Cell (Uniform Distribution).

	Social - Adapt	Social - Recover	Information - Recover	Cognitive - Prepare	Physical - Absorb
Categories in Cell	1	2	3	6	8
Mean Resilience Cell Score	4.61	8.97	13.35	26.98	36.19
Standard Deviation	4.36	6.25	7.44	10.37	12.05
Mean Resilience Cell Rank	11.73	8.77	6.52	2.50	1.51
Standard Deviation	3.46	3.97	3.67	1.82	1.11
Frequency Top Quartile (1-4)	3.00%	18.00%	41.20%	85.80%	96.80%
Frequency Bottom Quartile (13-16)	51.80%	22.00%	6.10%	0.50%	0.00%
Ideal Percent	25.60%	6.30%	1.50%	0.00%	0.00%

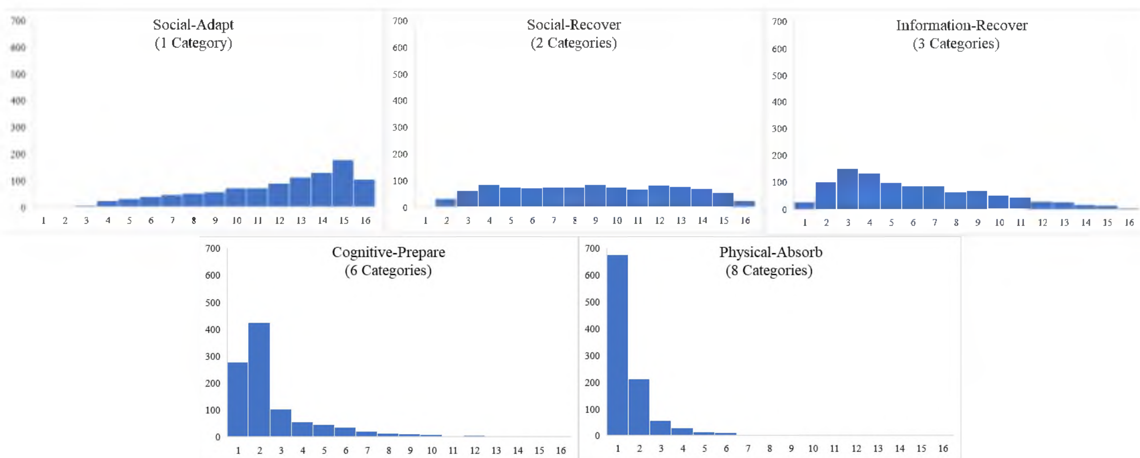

Figure. 1. Simulation 1: Cell Ranking Frequency. Total Cell Score with Varying Categories per Cell (Uniform Distribution).

The second Monte Carlo simulation selected the benchmark category priority weights and ratings from a uniform distribution but averaged the benchmark categories within the cell to determine the Cell Score. From this simulation, the MARM is also shown to be insensitive to uncertainty in the weights and ratings, but in a different manner from the first simulation. The cells containing only one category dominate the model, appear disproportionally in both the top and bottom quartiles, and have a much higher standard deviation of Mean Resilience Scores (Table 9). The Mean Resilience Cell Scores and Cell Ranks are much closer across the varying number of categories per cell, but the frequencies shown in Figure 2 graphically display how the distribution of the rankings results in the insensitivity of the MARM utilizing the average category benchmark Delta from Ideal Score under the assumption of a uniform distribution of weights and ratings. As in the summation of the Cell Scores, the Physical-Absorb and Cognitive-Prepare cells do not have any occurrences of Ideal Cell Scores.

Table 9. Simulation 2: Average Cell Score with Varying Categories per Cell (Uniform Distribution).

	Social - Adapt	Social - Recover	Information - Recover	Cognitive - Prepare	Physical - Absorb
Categories in Cell	1	2	3	6	8
Mean Resilience Cell Score	4.51	4.58	4.49	4.41	4.37
Standard Deviation	4.25	2.95	2.56	1.63	1.51
Mean Resilience Cell Rank	8.76	7.97	8.18	7.92	8.05
Standard Deviation	5.40	4.51	4.21	3.30	3.09
Frequency Top Quartile (1-4)	30.40%	29.30%	22.60%	19.60%	14.30%
Frequency Bottom Quartile (13-16)	34.20%	22.70%	18.30%	8.60%	7.30%
Ideal Percent	24.60%	6.20%	1.80%	0.00%	0.00%

The third and fourth Monte Carlo simulations employed the case study frequency distributions and the results mirrored those using the uniform distribution whether using the total or average benchmark category Delta from Ideal scores (Figures 3 and 4), just with a lower Mean Resilience Score and much higher Ideal Percent due to the higher frequency of “Green” ratings in the case study data than would be from a uniform distribution. This indicates that for either assumption of the distribution of priority weights and ratings, uniform or from the case study frequency, the MARM is insensitive to their uncertainty. This shows the impact of potential bias from the assessment team and further reinforces the insensitivity in the MARM as initially constructed.

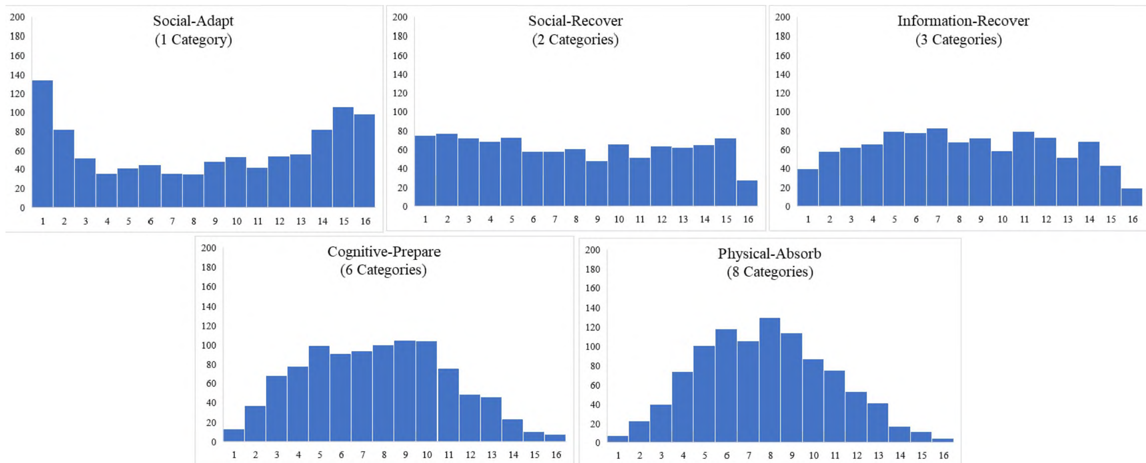

Figure. 2. Simulation 2: Cell Ranking Frequency. Average Cell Score with Varying Categories per Cell (Uniform Distribution).

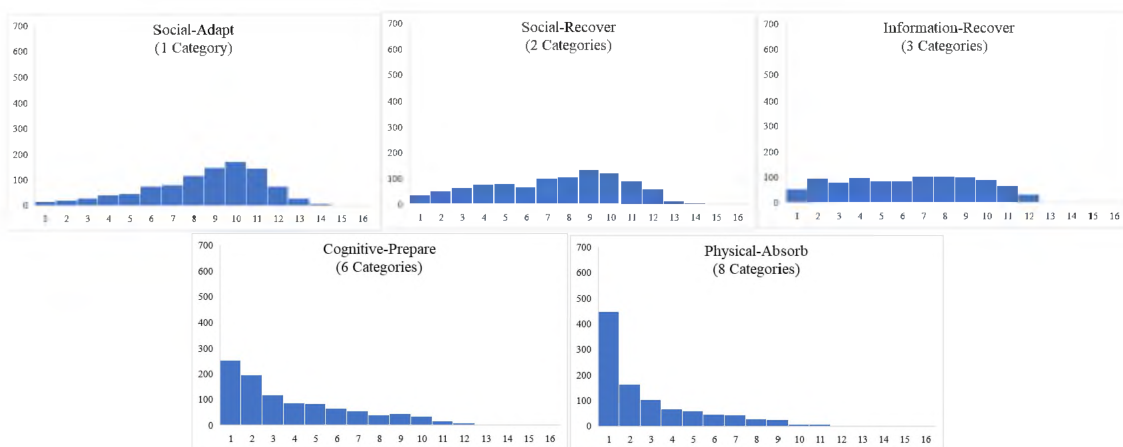

Figure. 3. Simulation 3: Cell Ranking Frequency. Total Cell Score with Varying Categories per Cell (Case Study Frequency Distribution).

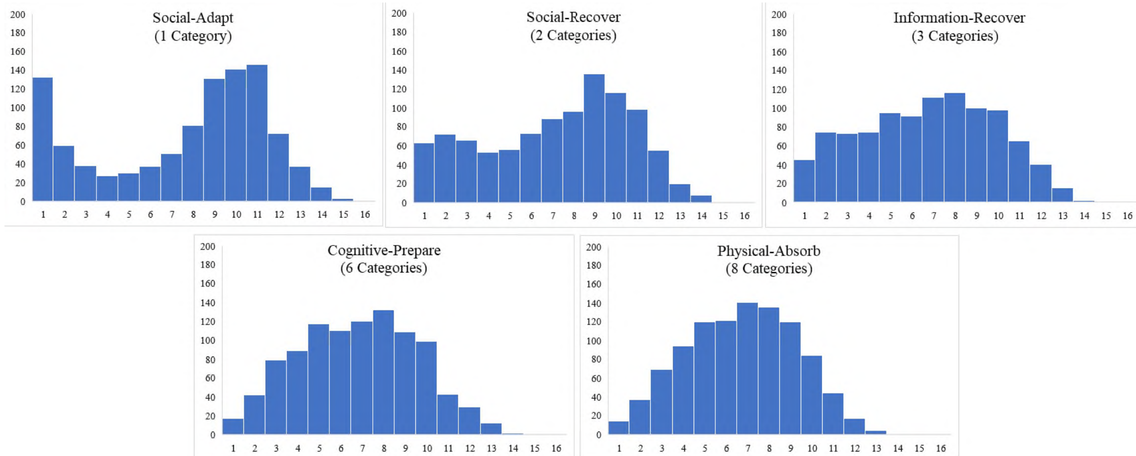

Figure. 4. Simulation 4: Cell Ranking Frequency. Average Cell Score with Varying Categories per Cell (Case Study Frequency Distribution).

The final set of Monte Carlo simulations investigated the difference in sensitivity in the MARM if each cell was forced to contain the same number of benchmark categories. The number of benchmark categories incorporated into the MARM was reduced from the original 41 to 32 and redistributed evenly throughout the matrix so that each cell would have two categories. Two Monte Carlo simulations were run on this adjusted MARM, both times using the assumption of a uniform distribution for the weights and ratings but either taking the total (Table 10 and Figure 5) or average (Table 11 and Figure 6) of the benchmark category Delta from Ideal Scores to calculate the Cell Score to compare the results between sets of Monte Carlo Simulations. Changing the model to where each cell in the MARM is forced to have the same number of categories makes the MARM sensitive to the uncertainty of benchmark category priority weights and ratings. The Mean Resilience Cell Score and its standard deviation, along with the Mean Resilience Cell Rank and standard deviation are all similar across all cells in the adjusted MARM model (Tables 10 and 11). The frequency of distribution of the cells in the top and bottom quartile are also similar across the adjusted MARM model (Figures 5 and 6).

This sensitivity holds true whether the model uses the total or average of the benchmark categories for the Cell Score. Comparing Tables 10 and 11, the only significant difference is in the Mean Resilience Cell Score, which is about half when taking the average as opposed to the total benchmark category Delta from Ideal scores.

Table 10. Simulation 5: Total Cell Score with Two Categories per Cell (Uniform Distribution).

	Social - Adapt	Social - Recover	Information - Recover	Cognitive - Prepare	Physical - Absorb
Categories in Cell	2	2	2	2	2
Mean Resilience Cell Score	8.972	8.776	8.97	8.84	8.97
Standard Deviation	6.10	6.09	5.98	6.12	6.15
Mean Resilience Cell Rank	8.16	8.31	8.04	8.19	8.10
Standard Deviation	4.52	4.59	4.54	4.53	4.55
Frequency Top Quartile (1-4)	26.40%	25.60%	27.60%	27.10%	27.70%
Frequency Bottom Quartile (13-16)	21.50%	23.80%	20.20%	22.80%	21.50%
Ideal Percent	2.90%	2.90%	3.70%	3.40%	3.20%

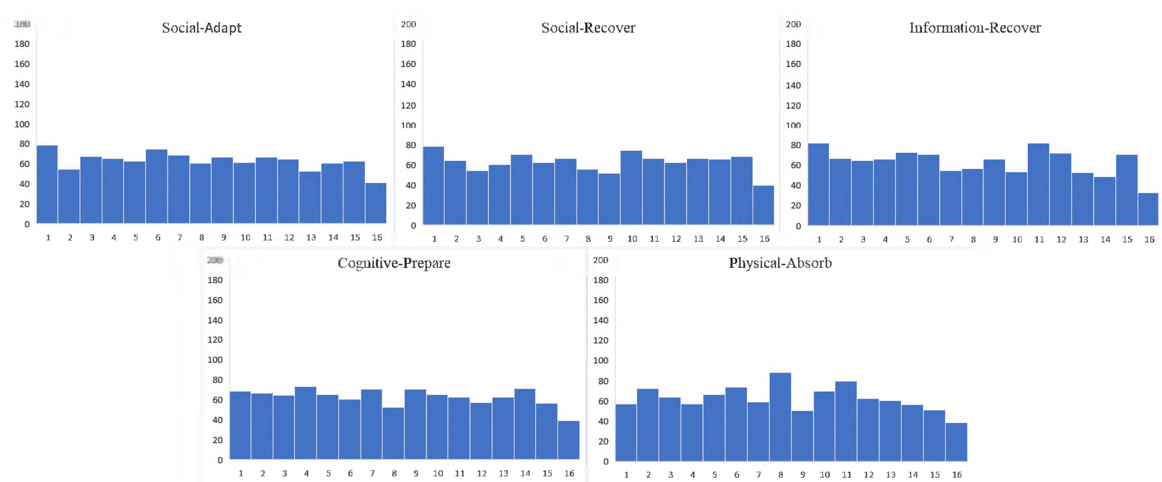

Figure. 5. Simulation 5: Cell Ranking Frequency. Total Cell Score with Two Categories per Cell (Uniform Distribution).

This sensitivity holds true whether the model uses the total or average of the benchmark categories for the Cell Score. Comparing Tables 10 and 11, the only significant difference is in the Mean Resilience Cell Score, which is about half when taking the average as opposed to the total benchmark category Delta from Ideal scores.

Table 11. Simulation 6: Average Cell Score with Two Categories per Cell (Uniform Distribution).

	Social - Adapt	Social - Recover	Information - Recover	Cognitive - Prepare	Physical - Absorb
Categories in Cell	2	2	2	2	2
Mean Resilience Cell Score	4.47	4.59	4.38	4.59	4.46
Standard Deviation	3.02	3.06	2.98	3.09	3.11
Mean Resilience Cell Rank	8.17	7.97	8.31	7.92	8.16
Standard Deviation	4.56	4.60	4.52	4.50	4.66
Frequency Top Quartile (1-4)	27.90%	29.00%	26.10%	27.40%	28.20%
Frequency Bottom Quartile (13-16)	22.90%	21.90%	23.20%	19.60%	23.20%
Ideal Percent	7.00%	6.70%	6.40%	6.70%	6.70%

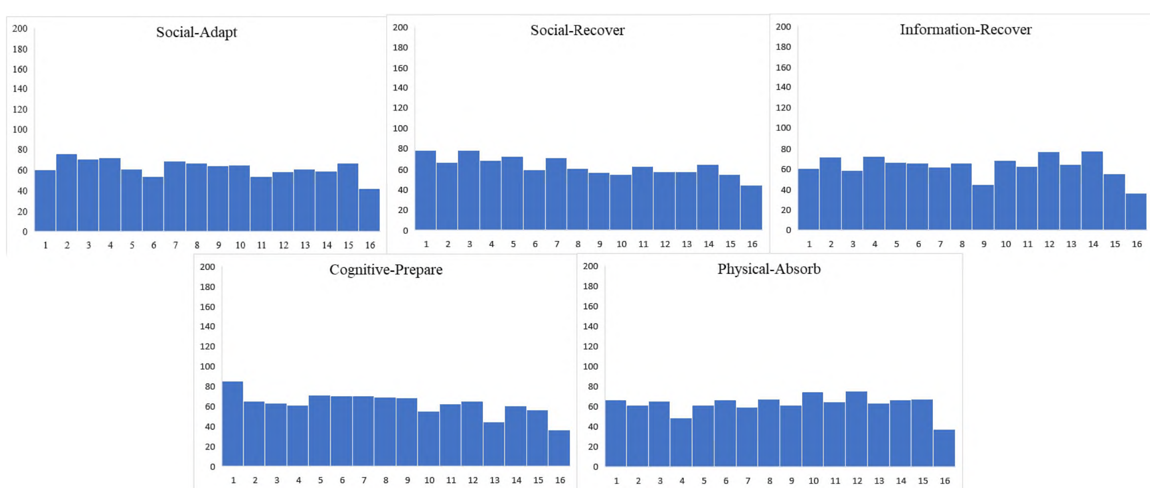

Figure. 6. Simulation 6: Cell Ranking Frequency. Average Cell Score with Two Categories per Cell (Uniform Distribution).

3. DISCUSSION

The MARM, as originally constructed with the number of benchmark categories varying by cell based on categorization of the benchmark descriptions and each Resilience Cell Score calculated from the total of its individual Delta from Ideal Scores, leads to a model that is insensitive to uncertainty in the benchmark category weights and ratings. This result holds whether the priority weights are selected from a uniform distribution (Simulation 1) or using the frequency distribution from the case study data (Simulation 3). The result of this insensitivity is that the cells containing the highest number of benchmark categories almost always have the largest Resilience Cell Scores and would draw the most attention from decision makers using the MARM as a decision support tool. The MARM cells with the fewest benchmark categories will nearly always be near the bottom of the cell rankings, no matter how high the priority weight it was given or how poorly rated the condition of the benchmark, leading to that cell likely not receiving the attention of decision makers.

Changing the MARM model to use the average of the benchmark category Delta from Ideal scores still yields an insensitive model whether using a uniform (Simulation 2) or frequency (Simulation 4) distribution of the benchmark category priority weights and ratings, but changes the dynamics, whereby the MARM cells with the fewest categories results in a bimodal distribution (approximately 30% in each of the top and bottom quartiles) while the MARM cells with the most categories show a more normal distribution of results.

While insensitivity might be acceptable and even desired in an optimization application, the desire is for the MARM model to be sensitive to uncertainty in the benchmark category priority weights and ratings. Since the benchmark category priority weights and ratings are independent, the MARM resilience cell ranking should have a uniform distribution allowing the cells to be sensitive to the results of the assessment of priority weights and ratings for each of the benchmark categories so that the categories given a higher priority or a worse rating impact the MARM and drive decisions. Therefore, the insensitivity in the model as constructed leads to inherent bias in the model and is undesirable.

When the model was changed to limit each cell in the MARM to only two categories, the model does become sensitive to uncertainty in benchmark category weights and ratings, and the difference between using the total or average Cell Score is eliminated. The simulations run with the uniform distribution of priority weights and ratings show a very even distribution of the frequency of the ranking of each category whether using the total or average of the benchmark categories to calculate the Resilience Cell Score and similar standard deviations across all cells in the matrix, indicating a sensitive model.

4. CONCLUSIONS

4.1. CONCLUSIONS

The results of this study demonstrate that sensitivity analysis is useful and applicable for investigating uncertainty within the MARM due to methodology used to convert the qualitative benchmark category assessments into a unitless and similarly scaled quantitative assessment. The results indicate that there is not a significant difference in the sensitivity of the model to use the total or average of the benchmark scores to calculate the Resilience Cell score, so that does not need to be changed in the MARM. This result is significant because the aggregation of category scores within a cell supports the use of the MARM as a tradespace analysis tool.

The results of the Monte Carlo sensitivity analysis indicate that the model as originally constructed is insensitive and biased by the unequal number of categories assigned to various cells within the MARM. Changing the MARM to force all cells to have an equal number of benchmark categories to determine the resilience score would eliminate that insensitivity and improve the MARM that is uniformly sensitive to uncertainty in the prioritization and rating of the benchmark categories.

The insensitivity of the model highlights the challenge of trying to integrate a resilience matrix into the existing mission assurance framework and expand the MARM model to encompass the entire set of 200 individual benchmark categories within the DoD MAA construct to determine the overall resilience of an infrastructure system. In the original RM created by Linkov et. al, all cells in RM must meet its metric to be considered resilient. This is straightforward when integrating one metric for each of the sixteen cells in the RM, but becomes more challenging as more metrics are added to each cell. This large amount of data to incorporate leads to critical questions of which categories should be mapped to the MARM and which, if any, should be excluded? How much flexibility, discretion, and guidance should be given to the individual assessment teams to select benchmark categories to include in the MARM to assess infrastructure resilience or should it be centralized and standardized? What flexibility and guidance should be given on how assessment teams should map the benchmark categories to the MARM? Further investigation of the usability of the MARM in light of these questions is required to validate the model.

4.2. FUTURE WORK

The next step in incorporating the MARM into the DoD MAA framework is to categorize the entire set of over 200 benchmark categories to the MARM while forcing each cell to have an equal number of benchmark categories. This will entail difficult decisions on which categories to include and which to leave out, since there may not be an even distribution across the matrix. Fox and Linkov cautions that forcing everything into the assessment can lead to over-weighting specific processes within the assessment (although the cellular structure of the matrix will minimize that effect) (Fox-lent and Linkov 2018). Additional analysis will be needed to verify and validate the feasibility of incorporating the larger amount of data and an equal number of categories into the MARM or if separate sets of MARM should be created to capture the various functions and missions of the system.

Another step will be to incorporate a more robust set of actual MAA data to determine if there is a difference in the sensitivity due to using different distribution assumptions to determine if the MARM would be biased to specific cells, i.e. categories in specific cells tend to have a higher priority and/or assessed at a specific rating.

Finally, this study did not incorporate cost uncertainty and its impact on the potential use of the MARM as a tradespace decision support tool. Exploring how to incorporate cost uncertainty and its impact on the MARM as a decision tool will be crucial to validating its applicability to assessment practitioners.

REFERENCES

Alberts, D. S., and Hayes, R. E. (2005). Power to the Edge: Command and Control in the Information Age. Washington DC: Department of Defense Command and Control Research Program.

Chen, Y., Yu, J., and Khan, S. (2010). "Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation." Environmental Modelling and Software, 25(12), 1582–1591.

Department of Defense. (2018). DoD Mission Assurance Assessment Benchmarks. Washington, D.C.: DoD.

Fagerholt, K., Christiansen, M., Magnus, L., Johnsen, T. A. V, and Vabø, T. J. (2010). "A decision support methodology for strategic planning in maritime transportation." Omega, Elsevier, 38(6), 465–474.

Fox-Lent, C., Bates, M. E., and Linkov, I. (2015). "A matrix approach to community resilience assessment: an illustrative case at Rockaway Peninsula." Environment Systems and Decisions, Kluwer Academic Publishers, 35(2), 209–218.

Fox-lent, C., and Linkov, I. (2018). "Resilience Matrix for Comprehensive Urban Resilience Planning." Resilience-Oriented Urban Planning, Lecture Notes in Energy, Y. Yamagata and A. Sharifi, eds., Springer International Publishing.

Heinimann, H. R., and Hatfield, K. (2017). "Infrastructure Resilience Assessment, Management and Governance – State and Perspectives." Resilience and Risk. NATO Science for Peace and Security Series C: Environmental Security, I. Linkov and J. Palma-Oliveira, eds., Springer, Dordrecht, 147–187.

Van Hoey, S., Seuntjens, P., van der Kwast, J., and Nopens, I. (2014). "A qualitative model structure sensitivity analysis method to support model selection." Journal of Hydrology, Elsevier B.V., 519(PD), 3426–3435.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., and Seager, T. P. (2013a). "Measurable resilience for actionable policy." Environmental Science and Technology, 47(18), 10108–10110.

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., and Kott, A. (2013b). "Resilience metrics for cyber systems." Environment Systems and Decisions, 33(4), 471–476.

Manache, G., and Melching, C. S. (2008). "Identification of reliable regression- and correlation-based sensitivity measures for importance ranking of water-quality model parameters." 23.

Muñoz, B., Romana, M. G., and Ordóñez, J. (2016). "Sensitivity Analysis of Multicriteria Decision Making Methodology Developed for Selection of Typologies of Earth-retaining Walls in an Urban Highway." Transportation Research Procedia, Elsevier B.V., 18, 135–139.

Mustajoki, J., and Marttunen, M. (2019). "Improving resilience of reservoir operation in the context of watercourse regulation in Finland." EURO Journal on Decision Processes, Springer Berlin Heidelberg, 7(3), 359–386.

Nguyen, H., Sharkey, T. C., Wheeler, S., Mitchell, J. E., and Wallace, W. A. (2020). "Towards the development of quantitative resilience indices for Multi-Echelon Assembly Supply Chains." Omega, Elsevier Ltd, 102199.

Norton, J. (2015). "An introduction to sensitivity assessment of simulation models." Environmental Modelling & Software, Elsevier Ltd, 69, 166–174.

Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., and Wagener, T. (2016). "Sensitivity analysis of environmental models: A systematic review with practical work flow." Environmental Modelling and Software, Elsevier Ltd, 79, 214–232.

Ramachandran, V., Long, S. K., Shoberg, T., Corns, S., and Carlo, H. J. (2015). "Framework for modeling urban restoration resilience time in the aftermath of an extreme event." ASCE Natural Hazards Review, 16(4).

Richards, J., Bruhl, J., Richards, J., Long, S. (n.d.). "Improving mission assurance assessments for resilience of military installations." 1–27.

Richards, J., and Long, S. (n.d.). "Verifying the Mission Assurance Resilience Matrix through the Modified Delphi Method and System Usability Scale."

Roege, P. E., Collier, Z. A., Mancillas, J., Mcdonagh, J. A., and Linkov, I. (2014). "Metrics for energy resilience." Energy Policy, Elsevier, 72, 249–256.

Triantaphyllou, E., and Sánchez, A. (1997). "A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods." Decision Sciences, 28(1), 151–194.

Wood, M. D., Wells, E. M., Rice, G., and Linkov, I. (2019). "Quantifying and mapping resilience within large organizations." Omega (United Kingdom), Elsevier Ltd, 87, 117–126.

Zavadskas, E. K., Turskis, Z., Dejus, T., and Viteikiene, M. (2007). "Sensitivity analysis of a simple additive weight method." International Journal of Management and Decision Making, 8(5–6), 555–574.

Zussblatt, N. P., Ganin, A. A., Larkin, S., Fiondella, L., and Linkov, I. (2017). "Resilience and Fault Tolerance in Electrical Engineering." Resilience and Risk. NATO Science for Peace and Security Series C: Environmental Security, I. Linkov and J. Palma-Oliveira, eds., Springer, 427–447.

SECTION

2. CONCLUSIONS AND RECOMMENDATIONS

2.1. CONCLUSIONS

This research contributes to closing the gap in resilience education within engineering management education, addresses gaps in the current DoD infrastructure assessment and decision-making framework, and extends the literature in several unique and novel aspects.

2.1.1. Engineering Management Education. The first contribution of this research identified the gaps of how and where modeling under uncertainty, infrastructure systems management, and resilient systems are integrated into standard undergraduate and graduate engineering management curriculum. Currently, there is no formal methodology for which to evaluate undergraduate or graduate engineering programs in their incorporation of a multidisciplinary approach to instruction of infrastructure resilience topics. In fact, the trend is for infrastructure resilience to be siloed into graduate civil engineering programs and not strongly linked to faculty and/or research centers. This is detrimental to the DoD's ability to cultivate engineer managers with the requisite skills to incorporate resilience into infrastructure assessment and decision making and may contribute to inconsistency and uncertainty within the infrastructure assessment framework.

Based on the nature of the discipline, engineering managers are uniquely postured to lead the design, analysis and response to improving the resilience of complex and multidisciplinary infrastructure systems. This posture makes it critical they possess the requisite skills to integrate resilience into decision making processes and frameworks. The information from this research enables engineering management programs ensure that the future workforce has the necessary instruction regarding the implementation of tools and techniques to improve infrastructure resilience. These include combining a topic mix of design and analysis of resilient infrastructure systems with disaster response in the curriculum, incorporating a multidisciplinary approach, and integrating research into classroom instruction.

Finally, this research will extend literature on infrastructure resilience education with the identification of five dimensions upon which to assess EM programs to detect trends and gaps in infrastructure resilience education, both current and future.

2.1.2. Mission Assurance Resilience Matrix Development. The second contribution of this research is to quantify resilience from current human-expert centered qualitative decision-making methods, which removes subjectivity from the decision-making process. This, combined with the ability to conduct tradespace analysis, will facilitate and improve selection of potential infrastructure improvement projects. This research developed and demonstrated the use of the Mission Assurance Resilience Matrix (MARM), a visual and interactive tool that converts the existing qualitative infrastructure assessments completed as required by the DoD Mission Assurance Strategy into a quantitative decision support tool. This tool provides consistency across the infrastructure assessment framework and enables decision makers to visualize where the installation infrastructure is deficient in terms of resiliency and then assess where to most efficiently allocate limited resources to improve critical military infrastructure systems to improve the infrastructure resiliency.

This tool extends previous resilience matrix methodology and applies it in a novel way. In previous applications of the resilience matrix methodology, direct comparison of individual cells in the matrix was problematic, since the scoring of cells could be built on independent and unrelated units and scaling. The MARM converts the qualitative infrastructure assessment data into unitless and similarly scaled cells within the matrix so it can be used as a decision support tool to compare and prioritize infrastructure improvement projects through tradespace analysis. It also extends previous tradespace analysis literature on the ability to communicate the impact of project selection to enhance resilience of military infrastructure systems and assist decision makers in understanding how a singular project may influence the resilience of multiple systems using the tradespace analysis.

2.1.3. Mission Assurance Resilience Matrix Verification and Validation. The third contribution of this research was to implement several techniques across two separate studies to verify the use of the MARM as an infrastructure resilience decision support tool. The first study utilized the Modified Delphi Method to examine the amount of potential uncertainty in the MARM due to subject matter expert assessment of benchmark category priority weights and ratings as well as validating the hypothesis that the MARM does perform differently from the SME project selection heuristics, though further research must be conducted to quantify the amount of that impact. The study also incorporated a System Usability Scale to establish the level of usability of the MARM as an information technology tool.

The second study investigated the behavior of the MARM due to uncertainty by using a Monte Carlo simulation to conduct a sensitivity analysis of the prioritization and ratings of the benchmark categories imbedded into the cells of the matrix. The MARM, as originally constructed, is insensitive to uncertainty in the individual benchmark category priority weights and ratings, which is problematic. To overcome this issue, two significant improvements were identified; expand the MARM to include all functions within the DoD MAA framework and ensure that all cells within the MARM contain an equal number of benchmark categories.

The results of these two studies extend current literature by demonstrating the ability to use sensitivity analysis to investigate uncertainty in the MARM, highlighting the challenges of incorporating the MARM into the entire DoD Mission Assurance Assessment construct to assess infrastructure resilience, verifying the usability of the MARM as a computer-based, decision-support tool, and identifying opportunities to improve the integration and use of the MARM for extension and expansion to the broader infrastructure resilience community.

2.2. RECOMMENDATIONS

The Mission Assurance Resilience Matrix developed and verified through this research integrates existing infrastructure assessment methods with emerging resilience research to enable military decision makers to easily visualize deficiencies in infrastructure resilience and assess where to most efficiently allocate resources. While the implementation of this research is specific to military installations, the framework developed expands the menu of tools in the multi-criterial decision-making process for infrastructure systems with a framework that can be both specific to an individual installation as well as generalizable to various types of facilities which can be extended to assess the resilience of public and private non-military infrastructure systems. The flexibility and ability to visualize, both support the DoD's mandate for the Mission Assurance framework to "contain sufficient flexibility to enable its decentralized application across disparate geographies, functional domains, programs, and asset types, and allow for continuous innovation as threats and vulnerabilities change"(Department of Defense 2018a). The results of this dissertation, which are built for a specific installation, are broadly applicable and can support engineers in the design and/or management of infrastructure systems to improve resilience in an efficient manner. This research warrants further development to extend and expand the MARM to encompass the entire DoD Mission Assurance Assessment framework and application at all levels of infrastructure assessment throughout the DoD.

2.3. FUTURE WORK

There are several opportunities to continue and expand and extend this research on infrastructure assessment and resilience as both are enduring and vital efforts for the DoD to incorporate resilience into its infrastructure education, assessment, and decision-making processes.

2.3.1. Expanding the Resilience Education Study. One area for continued research is to expand the study of resilience and infrastructure assessment education beyond just ASEM and ABET accredited engineering management programs. There are a significant number of additional engineering programs across the country that should be assessed using the framework developed in this research to determine additional best practices to incorporate across the engineering management education field. Additionally, several professional societies, Federal agencies, and cooperative programs offer professional education courses or programs in infrastructure resilience which ought to be included in the expanded assessment of infrastructure resilience education. Conducting a survey of practicing engineering managers in the field of infrastructure resilience will identify gaps in resilience education that need to be filled to assist them in their work, such as conducting Mission Assurance Assessments. It is likely that a lack of consistent resilience education and training contributed to the SMEs implementing differing heuristics throughout the Modified Delphi Method portion of this research. This was demonstrated in the variation of the assessment of benchmark category ratings, priority weights, and level of agreement.

Expanding the research of resilience education and training will not only provide a larger menu of best practices from which programs can incorporate infrastructure resilience, but also provide a more holistic look at infrastructure education to identify system gaps and opportunities for improvement across the spectrum of engineering education; undergraduate, graduate, and professional. This will help improve the consistency of implementation of resilience tools and techniques by infrastructure managers and decisionmakers.

2.3.2. Validation of an Expanded Mission Assurance Resilience Matrix. The verification of the usability of the MARM as a decision support tool by this research presents the opportunity to expand the MARM to account for the full complement of DoD MAA functions consisting of over 200 benchmark categories. This will involve first determining which benchmarks are the most appropriate for the measurement and assessment of resilience. Secondly, as this research determined, it must be ensured that the matrix is constructed so that it is balanced with an equal number of categories placed in each cell. Based on the results from other research, this can be a challenge, will require significant stakeholder involvement, and may involve the combination of functional assessments (Fox-lent and Linkov 2018; Mustajoki and Marttunen 2019). Representatives from the Defense Threat Reduction Agency, which has the lead for the Joint Mission Assurance Assessment program, have expressed interest in the outcomes of this research, which indicates there will be support and input available to work through the challenges of expanding the MARM to incorporate the other MAA functions.

One of the biggest challenges to effective risk assessment and management is the cost to replace products, harden the system, or change operational procedure (Linkov et al. 2018). This model integrates resilience assessment and project cost so that potential infrastructure improvement projects can be evaluated in a tradespace so project selection can have the greatest impact to manage resilience residual risk. Further work and additional data will be required to incorporate not just the immediate project cost, but complete life cycle cost estimation factors into the MARM to address the challenge.

Analysis of the performance of the expanded MARM, including the additional project life cycle cost component, must be completed to validate it as an effective decision support tool. It will be essential to investigate the impact of uncertainty within the expanded MARM through additional sensitivity analysis or potentially through the application of correlation-based sensitivity analysis of rank transformed data (Manache and Melching 2008). Previous research shows that the validation process may employ empirical validation, correlation analysis, or regression analysis to compare results from the MARM to actual assessment and decision-making results. The challenge will be obtaining sufficient data to perform a quantitative analysis to determine if the model is just picking up different facets of resilience or if it is indeed performing better than the current resilience assessment techniques (Bakkensen et al. 2017). Quantitative analysis is critical to validate that the MARM performs better than current heuristic project selection methods. Finally, a clear and concise user manual with education, training, and guidance implementing the MARM, categorizing benchmark categories, and conducting tradespace analysis should be created. The user manual will address the usability issues revealed through this research to ensure consistent application of the MARM to asses infrastructure resilience and support improvement project decision making across the DoD Mission Assurance Assessment Community.

2.3.3. Risk and Resilience. A third area in which to extend this research regards the relationship between resilience and risk. This relationship has been a topic of much discussion in literature. Despite multiple views of the differences between risk and resilience, the bottom line is that concepts and practice of risk and resilience both advance how uncertainties should be confronted (Aven and Thekdi 2018) and are an effort to address remaining known, but unmitigated, risk and enhance the overall ability of the system to respond to unknown or emerging threats (Linkov et al. 2018). Resilience assessment should build upon the more qualitative methods of risk assessment to include consideration of the interaction between physical, information, and social systems, recovery and adaptation after the initial emergency response, and offer an approach that acknowledges the uncertainty around emerging threats and guides determining acceptable tradeoffs in performance (Bostick et al. 2018). To achieve the DoD mission assurance vision, capabilities development, resource prioritization, and future protection investments must all be integrated and risk informed. At the installation level, this framework will ensure that information gathered from their mission and asset decomposition and risk assessment processes guide their risk mitigation decisions and resource investments (Department of Defense 2018a).

A weakness of risk-management approaches is that they can only deal with risk where probability or impact can be estimated. However, there are also many threats which are unknown before their occurrence, and which can be realized either as sudden shocks or as increasing stresses that slowly build up. So a more comprehensive (resilience) approach needs to be taken due to the complex interferences of the system (Mustajoki and Marttunen 2019).

The MARM addresses these considerations by incorporating the interaction of the four management domains (physical, information, cognitive, and social systems), all four stages of resilience (prepare, absorb, recover, and adapt), and allows for tradeoff analysis within the model. This supports a broader and more robust risk-based decision-making methodology and satisfies the requirement that risk management should weigh the potential benefit of investing in additional protective measures versus focusing on additional capacity for resilience.

The DoD Mission Assurance Strategy identifies that a comprehensive, integrated, and well-understood risk assessment methodology and process is at the heart of the mission assurance concept (Department of Defense 2018a). Vulnerability is a component of the risk formula: risk = hazard x vulnerability x consequence (Bakkensen et al. 2017).

Linkov et al. further distinguishes risk and resilience by conceptualizing vulnerability as a factor in system risk or the maximum losses at one point in time, whereas resilience represents the integral across all disaster time steps, including recovery and adaptation (Bakkensen et al. 2017). This contextualizes vulnerability into the stages of resilience, lending to its application into the MARM framework to close the gap that exists in the DoD Mission Assurance framework. This gap is due to the lack of a consistent, standardized, and commonly accepted methodology to synthesize, analyze, and integrate DoD-wide mission assurance-focused threat, vulnerability, and consequence information (Department of Defense 2018c), which are used to calculate a risk score for each asset. There currently is no capability to directly connect risk calculation to resilience measurement and assessment. The MARM, as initially developed, does not directly incorporate quantitative uncertainty due to threats. There is the opportunity to extend this research to integrating the vulnerability component of the DoD Risk Score methodology into the MARM benchmark prioritization weighting process. Additionally, one of the biggest challenges to effective risk assessment and management is cost, so further integration of Life Cycle Cost analysis will lead to improvements in the connection between risk and resilience. Incorporation of the capability to directly integrate current DoD risk calculation and management into the MARM will bridge the gap between risk management and reliance assessment.

The benefits of continuing to expand this research in these three lines of effort will improve military infrastructure assessment and decision-making leading to more resilient infrastructure prepared to absorb, respond, and adapt to the increasing frequency and severity of disasters around the world.

BIBLIOGRAPHY

116th Congress, U. S. (2019). H.R. 3041 Military Installation Resilience Assuredness Act. Washington DC: 116th Congress.

Alberts, D. S., and Hayes, R. E. (2005). Power to the Edge: Command and Control in the Information Age. Washington DC: Department of Defense Command and Control Research Program.

Andradhttir, S., Healy, K. J., Withers, D. H., and Nelson, B. L. (1997). "Proceedings of the 1997 Winter Simulation Conference." Winter Simulation Conference Proceedings.

Aven, T., and Thekdi, S. (2018). "The importance of resilience-based strategies in risk analysis, and vice versa." IRGC resource guide on resilience (vol. 2): Domains of resilience for complex interconnected systems, B. D. Trump, M.-V. Florin, and I. Linkov, eds., EPFL International Risk Governance Center (IRGC), Lausanne, CH.

Bakkensen, L. A., Fox-Lent, C., Read, L. K., and Linkov, I. (2017). "Validating Resilience and Vulnerability Indices in the Context of Natural Disasters." Risk Analysis, 37(5), 982–1004.

Balasubramanian, R., and Agarwal, D. (2012). "Delphi Technique-A Review." International Journal of Public Health Dentistry, 3(2), 16–25.

Berger, R. (2019). "All the Ways the US Military's Infrastructure Crisis Is Getting Worse." Defense One, <https://www.defenseone.com/ideas/2019/03/us-militarys-infrastructure-crisis-only-getting-worse/155858/?oref=d1-related-article> (Apr. 29, 2020).

Bostick, T. P., Connelly, E. B., Lambert, J. H., and Linkov, I. (2018). "Resilience science, policy and investment for civil infrastructure." Reliability Engineering and System Safety, Elsevier Ltd, 175(March), 19–23.

Cardoso, S. R., Barbosa-póvoa, A. P., Relvas, S., and Novais, A. Q. (2015). "Resilience metrics in the assessment of complex supply-chains performance operating under demand uncertainty." Omega, Elsevier, 56, 53–73.

Chen, Y., Yu, J., and Khan, S. (2010). "Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation." Environmental Modelling and Software, 25(12), 1582–1591.

Committee on Increasing National Resilience to Hazards and Disasters. (2012). Disaster resilience: A national imperative. Disaster Resilience: A National Imperative, Washington, D.C.: The National Academies Press.

Congressional Research Service. (2019). Military Construction: Authorities, Process, and Frequently Asked Questions. Washington, D.C.: Congressional Research Service.

Department of Defense. (2016a). Directive 3100.10 Space Policy. Washington, D.C.: DoD.

Department of Defense. (2016b). DoD Directive 4715.21 Climate Change Adaptation and Resilience. Department of Defense.

Department of Defense. (2017). DoD Manual 3020.45, Defense Critical Infrastructure Program (DCIP): DoD Mission-Based Critical Asset Identification Process (CAIP). Washington, D.C.: DoD.

Department of Defense. (2018a). Mission Assurance (MA) Construct. Washington, D.C.: DoD.

Department of Defense. (2018b). 2018 National Defense Strategy Summary. Washington, D.C.: DoD.

Department of Defense. (2018c). DoD Mission Assurance Assessment Benchmarks. Washington, D.C.: DoD.

Department of Defense. (2019). Report on Effects of a Changing Climate to the Department of Defense. Washington, D.C.: DoD.

Ewing, P. L., Tarantino, W., and Parnell, G. S. (2006). “Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis.” Decision Analysis, 3(1), 33–49.

Farr, J., Gandhi, S. J., and Merino, D. N. (Eds.). (2016). The Engineering Management Handbook. The American Society for Engineering Management, Huntsville, AL.

Fox-Lent, C., Bates, M. E., and Linkov, I. (2015). “A matrix approach to community resilience assessment: an illustrative case at Rockaway Peninsula.” Environment Systems and Decisions, Kluwer Academic Publishers, 35(2), 209–218.

Fox-lent, C., and Linkov, I. (2018). “Resilience Matrix for Comprehensive Urban Resilience Planning.” Resilience-Oriented Urban Planning, Lecture Notes in Energy, Y. Yamagata and A. Sharifi, eds., Springer International Publishing.

Hagen, J., Morgan, F., Heim, J., and Carroll, M. (2017). The Foundations of Operational Resilience -- Assessing the Ability to Operate in an Anti-Access/Area Denial (A2/AD) Environment: The Analytical Framework, Lexicon, and Characteristics of the Operational Resilience Analysis Model (ORAM). The RAND Corporation, Santa Monica, CA.

Heinimann, H. R., and Hatfield, K. (2017). “Infrastructure Resilience Assessment, Management and Governance – State and Perspectives.” Resilience and Risk. NATO Science for Peace and Security Series C: Environmental Security, I. Linkov and J. Palma-Oliveira, eds., Springer, Dordrecht, 147–187.

Van Hoey, S., Seuntjens, P., van der Kwast, J., and Nopens, I. (2014). “A qualitative model structure sensitivity analysis method to support model selection.” Journal of Hydrology, Elsevier B.V., 519(PD), 3426–3435.

Kerner, D. A., and Thomas, J. S. (2014). “Resilience attributes of social-ecological systems: Framing metrics for management.” Resources, 3(4), 672–702.

Klassen, M., Reeve, D., Rottmann, C., Sacks, R., Simpson, A. E., and Huynh, A. (2016). “Charting the landscape of engineering leadership education in North American universities.” ASEE Annual Conference and Exposition, Conference Proceedings, 2016-June.

Kleijnen, J. P. C. (1997). “Sensitivity analysis and related analyses: A review of some statistical techniques.” Journal of Statistical Computation and Simulation, 57:1–4, 111–142.

Labaka, L., Hernantes, J., and Sarriegi, J. M. (2015). “A framework to improve the resilience of critical infrastructures.” International Journal of Disaster Resilience in the Built Environment, 6(4), 409–423.

Lewis, J. R. (2018). “The System Usability Scale: Past, Present, and Future.” International Journal of Human-Computer Interaction, Taylor & Francis, 34(7), 577–590.

Lewis, J. R., and Sauro, J. (2018). “Item Benchmarks for the System Usability Scale.” Journal of Usability Studies, 13(3), 158–167.

Ling, Y., and Mahadevan, S. (2013). “Quantitative model validation techniques: New insights.” Reliability Engineering and System Safety, Elsevier, 111, 217–231.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., and Seager, T. P. (2013a). “Measurable resilience for actionable policy.” Environmental Science and Technology, 47(18), 10108–10110.

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., and Kott, A. (2013b). "Resilience metrics for cyber systems." Environment Systems and Decisions, 33(4), 471–476.

Linkov, I., Fox-Lent, C., Read, L., Allen, C. R., Arnott, J. C., Bellini, E., Coaffee, J., Florin, M. V., Hatfield, K., Hyde, I., Hynes, W., Jovanovic, A., Kasperson, R., Katzenberger, J., Keys, P. W., Lambert, J. H., Moss, R., Murdoch, P. S., Palma-Oliveira, J., Pulwarty, R. S., Sands, D., Thomas, E. A., Tye, M. R., and Woods, D. (2018). "Tiered approach to resilience assessment." Risk Analysis, Blackwell Publishing Inc., 38(9), 1772–1780.

Lostumbo, M. J., McNerney, M. J., Peltz, E., Eaton, D., Frelinger, D. R., Greenfield, V. A., Halliday, J., Mills, P., Nardulli, B. R., Pettyjohn, S. L., Sollinger, J. M., and Worman, S. M. (2013). Overseas Basing of U.S. Military Forces: An Assessment of Relative Costs and Strategic Benefits. The RAND Corporation, Santa Monica, CA.

Manache, G., and Melching, C. S. (2008). "Identification of reliable regression- and correlation-based sensitivity measures for importance ranking of water-quality model parameters." 23.

Miller, K. A., Collada, B., Tolliver, D., Audi, Z., Cohen, A., Michelson, C., and Newman, L. R. (2020). "Using the Modified Delphi Method to Develop a Tool to Assess Pediatric Residents Supervising on Inpatient Rounds." Academic Pediatrics, Elsevier Inc., 20(1), 89–96.

Muñoz, B., Romana, M. G., and Ordóñez, J. (2016). "Sensitivity Analysis of Multicriteria Decision Making Methodology Developed for Selection of Typologies of Earth-retaining Walls in an Urban Highway." Transportation Research Procedia, Elsevier B.V., 18, 135–139.

Mustajoki, J., and Marttunen, M. (2019). "Improving resilience of reservoir operation in the context of watercourse regulation in Finland." EURO Journal on Decision Processes, Springer Berlin Heidelberg, 7(3), 359–386.

NAVFAC, (Naval Facilities Engineering Command). (2017). "Climate change planning handbook installation adaptation and resilience final report climate change planning handbook." (January).

Nguyen, H., Sharkey, T. C., Wheeler, S., Mitchell, J. E., and Wallace, W. A. (2020). "Towards the development of quantitative resilience indices for Multi-Echelon Assembly Supply Chains." Omega, Elsevier Ltd, 102199.

Norton, J. (2015). "An introduction to sensitivity assessment of simulation models." Environmental Modelling & Software, Elsevier Ltd, 69, 166–174.

Patton, M. (2014). Qualitative Research & Evaluation Methods. SAGE Publications, St. Paul.

Perry, S. J., Hunter, E. M., Currall, S. C., and Frauenheim, E. (2017). "Developing Engineering Leaders: An Organized Innovation Approach to Engineering Education." EMJ - Engineering Management Journal, Taylor & Francis, 29(2), 99–107.

Pianosi, F., Beven, K., Freer, J., Hall, J. W., Rougier, J., Stephenson, D. B., and Wagener, T. (2016). "Sensitivity analysis of environmental models: A systematic review with practical work flow." Environmental Modelling and Software, Elsevier Ltd, 79, 214–232.

Pope, A. (2016). "Designing for a Resilient Future." White House Press Release, <https://obamawhitehouse.archives.gov/blog/2016/10/31/designing-resilient-future> (Jul. 9, 2019).

Ramachandran, V., Long, S. K., Shoberg, T., Corns, S., and Carlo, H. J. (2015). "Framework for modeling urban restoration resilience time in the aftermath of an extreme event." ASCE Natural Hazards Review, 16(4).

Ramirez, C. D. (2012). "Advancing Curricula Development for Homeland Security Education through a Survey of DHS Personnel." Journal of Homeland Security Education, 1(1).

Roege, P. E., Collier, Z. A., Mancillas, J., Mcdonagh, J. A., and Linkov, I. (2014). "Metrics for energy resilience." Energy Policy, Elsevier, 72, 249–256.

Sargent, R. G. (2013). "Verification and validation of simulation models." Journal of Simulation, Nature Publishing Group, 7(1), 12–24.

Shah, H., and Nowocin, W. (Eds.). (2015). A Guide to the Engineering Management Body of Knowledge. The American Society for Engineering Management, Huntsville, AL.

Sitterle, V. B., Freeman, D. F., Goerger, S. R., and Ender, T. R. (2015). "Systems engineering resiliency: Guiding tradespace exploration within an engineered resilient systems context." Procedia Computer Science, Elsevier Masson SAS, 44(C), 649–658.

Stember, M. (1991). "Advancing the social sciences through the interdisciplinary enterprise." The Social Science Journal, 28(1), 1–14.

Triantaphyllou, E., and Sánchez, A. (1997). "A Sensitivity Analysis Approach for Some Deterministic Multi-Criteria Decision-Making Methods." Decision Sciences, 28(1), 151–194.

Wilt, B., Long, S., and Shoberg, T. (2016). "Defining resilience: A preliminary integrative literature review." 2016 International Annual Conference of the American Society for Engineering Management, Concord, NC, 1–11.

Wood, M. D., Wells, E. M., Rice, G., and Linkov, I. (2019). "Quantifying and mapping resilience within large organizations." Omega (United Kingdom), Elsevier Ltd, 87, 117–126.

Yaniv, I. (1997). "Weighting and Trimming: Heuristics for Aggregating Judgments under Uncertainty." Organizational Behavior and Human Decision Processes, 69(3), 237–249.

Zavadskas, E. K., Turskis, Z., Dejus, T., and Viteikiene, M. (2007). "Sensitivity analysis of a simple additive weight method." International Journal of Management and Decision Making, 8(5–6), 555–574.

Zussblatt, N. P., Ganin, A. A., Larkin, S., Fiondella, L., and Linkov, I. (2017). "Resilience and Fault Tolerance in Electrical Engineering." Resilience and Risk. NATO Science for Peace and Security Series C: Environmental Security, I. Linkov and J. Palma-Oliveira, eds., Springer, 427–447.

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