EXECUTIVE SUMMARY

Modeling Compound Threats to Interdependent Infrastructure Systems on Military Installations

Daniel Eisenberg
David Alderson
Naval Postgraduate School

Meredith Pringle
Michael Wu
Adair Douglas
Converge Strategies, LLC

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SERDP Project RC20-1091

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ACRONYMS AND ABBREVIATIONS

CECOS	Civil Engineer Corps Officer School
DoD	Department of Defense
IMN	interdependent multilayer network
MCBH	Marine Corps base Hawaii
MDI	mission dependency index
NAVFAC	Naval Facilities Engineering Command
NAVSTA	Naval station
SERDP	Strategic Environmental Research and Development Program
SON	statement of need
USN	U.S. Navy

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1.0 INTRODUCTION

Military installations are susceptible to extensive damage when extreme events impact interdependent infrastructure systems and cause loss of critical services. Past events and subsequent failures on Department of Defense (DoD) installations have highlighted the interconnected nature of these systems, with problems in one system (e.g., electric power) cascading into others (e.g., fuel). In response to these challenges, DoD services are seeking to better understand compound threats to installation infrastructure and enhance the resilience of these systems, especially during extreme events. For the purposes of this work, the project team considered resilience as defined across DoD services and requirements—the ability of infrastructure systems to withstand threats, continue functioning, recover within 14 days after an event, and adapt for future combat readiness.

Achieving DoD resilience goals aligns with the need to understand how the loss of interdependent infrastructure services affects mission readiness, which often hinges on the restoration and functioning of electricity distribution systems, and which rely on interconnected services such as water for cooling, communications for control, and fuel supply for operation. Essentially, the vulnerability of any infrastructure system directly impacts the operation and management of all other critical systems. To address this, there is a growing need to model multiple systems together, focusing on their interdependencies and the missions they support. An integrated perspective such as this can overcome limitations in infrastructure protection solutions that typically target specific threats and may not adapt to unforeseen circumstances.

This report summarizes the outputs of the Strategic Environmental Research and Development Program (SERDP) funded project entitled Modelling Compound Threats for Interdependent Infrastructure Systems on Military Installations (Project RC20-1091). The primary objective of this work being to develop a new framework for modeling compound threats on military installations, emphasizing the identification of infrastructure vulnerabilities across interdependent systems and supporting decisions to ensure mission readiness in the face of unknown events. This project was selected for funding in FY2020 to fulfill SERDP Statement of Need (SON) entitled Installation Resilience Research: Theoretical Frameworks for Compound Threats (SON RCSON20-C1). The project began March 2020 with an originally proposed end date of March 2023 extended to October 2023.

2.0 OBJECTIVES

The purpose of this project was to develop methods that measure worst-case disruptions across interdependent infrastructure systems on U.S. DoD military installations and to create models that support infrastructure management. The specific aim was to advance models of operational resilience for DoD installations by designing and managing interdependent infrastructure systems capable of adapting to worst-case failures, regardless of the specific initiating event or threat. Where traditional methods for assessing infrastructure disruptions relied on assessing the likelihood and consequences of known threats to prioritize protective measures, it was more prudent to prioritize protection activities based on the potential for worst-case disruptions, regardless of what initiated them.

3.0 TECHNICAL APPROACH

Three integrated hypotheses were developed to motivate the development of worst-case failure assessment methods for interdependent infrastructure systems:

- Hypothesis 1: Existing frameworks for interdependent infrastructure systems do not yet serve military needs.
- Hypothesis 2: Operator models for interdependent infrastructure on military installations will reveal new compound threats.
- Hypothesis 3: Mission Dependency Index (MDI), a key metric guiding DoD infrastructure decisions, can be calculated, and improved with infrastructure operator models.

The research activities, results, and conclusions were organized into thrusts to study these hypotheses. Thrust 1 focused on advancing new understanding of compound threats to interdependent installation infrastructure systems and was motivated by hypotheses 1 and 2. Thrust 2 focused on hypothesis 3, vulnerabilities and decisions.

4.0 RESULTS AND DISCUSSION

Thrust 1—Hypothesis 1—Framework Development. This project's proposed framework was centered on the development of operator models for infrastructure systems. In general, an operator model is a mathematical program that embeds engineering physics and decision-making constraints that dictate infrastructure use. Operator models were the foundation for the design of military infrastructure systems and formed the basis for understanding the provision of electricity, water, mobility, communications, food, and other services critical to installation readiness. The most common operator models are network flow models consisting of: (1) parameters that remain unchanged in normal and contingency operations, but influence infrastructure use (e.g., powerline capacity), (2) decision variables that represent what operators do to control the flow of infrastructure services, (3) constraints that relate parameters and decision variables to ensure that operator decisions do not violate real-world physics, protocols, and regulations (e.g., power flow may not exceed powerline capacity), and (4) objectives that define how operators want to provide services.

The project team completed two key research tasks that addressed this hypothesis and developed a novel framework for interdependent infrastructure analysis. First, the project team implemented a new technique to simplify the combination of multiple operator models into an interdependent multilayer network (IMN) model, useful for interdependent vulnerability analysis. The new technique leveraged existing research on how to formulate IMN models and used object-oriented programing to generate relevant objectives and constraints for vulnerability analysis. The project team demonstrated a modeling method by developing interdependent fuel, electric power, and transportation networks never previously studied. In addition, the project team further reviewed network literature to categorize existing resilience analysis techniques that would be relevant for interdependent systems. The results informed vulnerability analyses and provided a basis for future work to manage compound threats for diverse systems.

Thrust 1—Hypothesis 2—Vulnerability Analysis. This second part of Thrust 1 leveraged methods to identify worst-case failures in interdependent infrastructure. Having a standard interdependent infrastructure modeling architecture was not necessarily useful for resilience analysis without effective tools to study worst-case infrastructure failures across systems. Identifying the worst-case impacts in a single infrastructure system could easily be achieved even in large systems with brute-force (i.e., exhaustive search) calculations that re-calculated operator actions for every possible infrastructure failure.

Several applied case studies were completed to address Hypothesis 2. These included detailed analyses of two important military installations and disaster decision-making contexts: evacuation planning for Naval Station (NAVSTA) Newport and emergency food and fuel distribution to Marine Corps Base Hawaii (MCBH). Several models and studies were completed across both installations that led to real-world decisions. Detailed assessment of evacuation clearance times of Aquidneck Island and NAVSTA Newport informed real-world hurricane evacuation planning for the installation during Hurricane Henri. The resulting model was extended into a simulation-optimization framework to assess go/no-go decisions for civilian and military decision-makers on Aquidneck Island. For MCBH, models were developed to assess the effectiveness of divergent emergency food distribution concepts and community pre-positioning used across the state of Hawaii. Studies also identified emergency refueling needs for MCBH and non-installation entities. Results were adopted in state-level plans for emergency food distribution and form the basis of future updates to the state emergency energy plans.

Thrust 2—Hypothesis 3—Vulnerabilities and Decisions. Thrust 2 focused on linking new understandings of infrastructure interdependencies to decision tools used within the DoD for infrastructure management and planning. Infrastructure readiness across the DoD is determined by two indices, the Facility Condition Index measuring infrastructure quality and condition, and the MDI measuring the importance of an asset or facility to military missions. This work analyzed how well MDI served its role for guiding infrastructure investment, especially from a perspective using interdependent operator models.

To assess the effectiveness and flaws of MDI for infrastructure decisions, the project team developed a multilayer network model that recreated MDI calculation and analysis in a manner that directly associates measures to IMN models. The resulting network formalism enabled the identification of several significant flaws in MDI as currently implemented across the DoD and federal government. Flaws included issues with measure sensitivity, interpretation, and calculation. The project team organized identified flaws into six critiques and provide recommendations to overcome these issues. Results were presented to the Naval Facilities Command (NAVFAC) Civil Engineer Corps Officer School (CECOS) to discuss and train military engineers to recognize MDI issues and more effective use.

Overall, the project team found that MDI had profound implications for DoD infrastructure decisions as its calculation and use impacted short-term and long-term infrastructure planning across all branches. Despite the importance of MDI for guiding investments, methods to calculate MDI remained ad hoc and inappropriate for decision-making. The project team argued that the key elements comprising MDI service—interrupt ability, relocate ability, and replaceability—could be included in the project framework using operator models developed in Thrust 1, and leveraging research from Thrust 1, the project team defined a new MDI calculation to provide benefits to long-term decision-making.

5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

Overall, research outputs produced throughout this project addressed the project goals as initially proposed. The results from this project responded directly to the objectives articulated in the FY2020 SON. Specifically, the results provided a "tractable method to map the interaction of threats that identify installation and facility vulnerabilities to multiple types of events" (SON Objective 2). Moreover, by linking modeling efforts for infrastructure systems to readiness and investment priorities at DoD installations, results provided a way to, "assess the gains of resilience with specific strategies/structures, considering the costs and benefits without specific disruptive events and unknown systematic threats" (SON Objective 1).

Results from this project included models and methods to identify disruptions to infrastructure systems on military installations, case studies on installation vulnerability and emergency decision-making, and linking assessments to infrastructure investment. These methods and models led to technical advances already being used by other researchers and experts. For example, the combo-model techniques developed to integrate and study IMN models has been utilized by other researchers at Pacific Northwest National Laboratories to study fuel, electric power, and transportation vulnerabilities. Results identifying flaws in MDI have been used in training and education materials taught to NAVFAC CECOS.

Several important conclusions were drawn from results that provided more detail on the vulnerability of military installation infrastructure and the civilian systems in which they were embedded. Results showed that there was a growing need for greater integration of military and civilian vulnerability analysis. Importantly, the vulnerability of installation infrastructure systems was tied to the vulnerability of civilian systems. For example, the capability to evacuate NAVSTA Newport was dependent on decisions and operations by surrounding municipalities. The resilience of MCBH depended on access to critical resources like food and fuel that may only be available outside the fence line.

Still, there are DoD technologies and activities that support resilience and should be implemented to manage compound threats. Analysis of port refueling operations showed the tradeoffs and benefits of some port restoration technologies already used within the DoD. The new methods could compare their resilience benefits and show which are better for fast recovery and which are better for longer term extensibility and adaptability. Future research can build on these assessments to better choose between resilience technologies to protect ports and related pipeline systems. Moreover, the methods developed can be applied to other interdependent infrastructure systems.

Results also showed the benefits of integrating simulation and optimization methods together. Simulation techniques were helpful for studying infrastructure system dynamics before and after failures occur. The project team demonstrated advanced methods for port refueling and hurricane evacuation. Operator models built on network flow optimization were helpful to determine optimal operations and estimate real-world response by system operators, which the project team demonstrated through NAVSTA Newport and MCBH case studies. Methods that can integrate these techniques have the potential to study system vulnerability and resilience together. Future research should focus on integrating these techniques for military installation systems and needs.

A special feature of this project was that all studies were completed with the support of active-duty military officers from U.S. and foreign services, i.e., the project outputs were published in a series of master's theses completed by military officers for their graduation from the Naval Postgraduate School, alongside research articles written by the project team. This meant that all work completed in this project, theoretical or applied, supported transitions to the DoD and allies by means of training and education.

Additionally, there was significant effort for stakeholder outreach and coordination. Throughout the project this effort included presenting results, offering support, and fostering collaboration directly to, and between, decision-makers at military installations, government agencies, disaster relief organizations, and in surrounding communities.