Proceedings of the Annual General Donald R. Keith Memorial Conference
West Point, New York, USA
April 24, 2025
A Regional Conference of the Society for Industrial and Systems Engineering

System Dynamics Modeling of Cold Region Installation Resilience

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Author Note: The authors would like to acknowledge the team at Engineer Research and Development Center (ERDC) for their collaboration in this project. The expertise and numerous insights provided by ERDC significantly contributed to refining the research methodology and enhancing the overall quality of the project. The views and opinions expressed in this report are solely those of the authors and do not necessarily reflect the official policy or position of the United States Military Academy, the Department of the Army, or the Department of Defense.

Abstract: The team at Engineer Research and Development Center (ERDC) develops innovative solutions for science and engineering challenges in extreme environments, including evaluating the effects of seismic and icing events on installation infrastructure. The researchers in this study used datasets from ERDC and FEMA's *HAZUS Earthquake Model Technical Manual* to develop a system dynamics model to analyze recovery times from earthquakes and icing events on critical infrastructure on Fort Wainwright, Alaska. The team identified critical infrastructure vulnerabilities in two mission-essential functions: transportation and power systems. The analysis created a better understanding of Fort Wainwright's recovery capacity, with and without local community or external support, and aided in developing mitigation planning processes. The findings provide insight into infrastructure interdependence and offer strategies for enhancing readiness in extreme environments by identifying second-order effects not readily apparent through traditional analysis.

Keywords: Resilience Assessment, Causal Loop diagram, System Dynamics Modeling

1. Introduction

The arctic environment creates unique challenges for military infrastructure that have the potential to create critical vulnerabilities. (U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory [CRREL], 2018). Earthquakes and icing events threaten mission-essential functions to include transportation networks and power distribution. Icing can rupture pipes, cause structural damage to concrete, and halt transportation (USACE, 2018). Additionally, Alaska has one of the highest levels of seismic activity in the country (USGS, 2024, August 22; Powers et al., 2024). Fort Wainwright, Alaska's strategic location and mission set play a pivotal role in American national defense. The infrastructure on Fort Wainwright must be able to sustain the harsh environment and enable mission success. The Engineer Research and Development Center (ERDC) team's focus is to conduct studies to understand environmental impacts and develop mitigation strategies. In a collaborative research effort, the cadet research team from West Point developed a system dynamics model to evaluate recovery times for critical installation infrastructure following a seismic or icing event and proposed strategies to enhance operational stability. This project aligns with real-world Army engineering applications by providing data-driven insights to improve military installations' preparedness in extreme conditions. Additionally, the findings contribute to broader defense strategies by informing relevant decision makers of risk mitigation and recovery optimization in these locations. The interactive nature of the model enables real-time decision-making adjustments, making it an asset for both contingency planning and active response operations.

2. Background

The ERDC team collected data from subject matter experts and operational personnel at Fort Wainwright and surrounding communities near Fairbanks, Alaska, to assess the resilience of mission-essential functions (MEFs) such as airport runways, roadways, transportation services, and installation power. Using both qualitative and quantitative methods, ERDC converted community-provided insights into structured data through questionnaires and standardized coding, enabling pattern recognition and system dynamics (SD) modeling. The SD model simulated various disruption scenarios, quantified resilience metrics, and highlighted critical leverage points for enhancing adaptive capacity. Preliminary research emphasized the vulnerability of power plants and transportation systems to cold climate challenges, with a focus on seismic and icing events.

These findings in the SD model underscored the urgent need for modernization and the value of system dynamics and causal loop diagrams in identifying infrastructure weaknesses and improving continuity and resilience in extreme environments (FAA Advisory Circular 150/5200-30D, 2021; USGS, 2020; NTSB, 2018).

2. Modeling Simulation Methodology

The team employed Vensim, a system dynamics simulation software that facilitates the visualization, analysis, and forecasting of complex, interdependent systems over time to model cold weather resiliency on military installations at Fort Wainwright, Alaska. Vensim was selected due to its ability to handle complex feedback loops, time delays, and non-linear relationships inherent in resilience modeling (Sterman, 2000). Vensim also allowed the team to construct causal loop diagrams and stock-and-flow models to represent the dynamic interactions between infrastructure performance, environmental stressors, and mitigation strategies in extreme cold weather conditions. Additionally, the team integrated methodologies from the FEMA *HAZUS Earthquake Model Technical Manual*, which outlines quantitative techniques for assessing structural vulnerability, estimating damage probabilities, and calculating economic losses following hazard events (FEMA, 2024, July). While the manual focuses on seismic events, its probabilistic damage functions and inventory-based risk assessment framework provided a valuable foundation for adapting risk assessment metrics to cold weather hazards. Previous studies on infrastructure resilience in cold regions, including work by ERDC and USACE, often use static assessment frameworks or isolated case analysis. This study expands on those efforts by integrating a dynamic, user-interactive system modeling approach. Compared to similar civilian models, this military-specific framework incorporates mission-essential prioritization, allowing operational readiness to guide recovery timelines.

The models represented in this project are specific to Fort Wainwright and Fairbanks, Alaska, but are adaptable to other regions and other hazards. The scope of the model entails the recovery rates of several mission-essential functions to obtain an accurate span of time in which capabilities are fully functional (100 percent operational). The model isolates levels of severity for icing and earthquakes from other possible causes of damage to the infrastructure. While there have been other organizations that have modeled the earthquake or icing recovery curves, the group's mission was to create a living model that allows a user to input the severity of their current situation, so they can analyze its effect on the time required to return to complete operability. Narrowly defining the boundary reduces complexity and enables a better understanding of the effects of earthquakes and icing. The decision to focus exclusively on earthquakes and icing events was guided by both relevance and feasibility. The ERDC team advised narrowing the scope to the most frequent and impactful hazards. While other threats like solar flares and permafrost often pose risks, data availability and modeling complexity constrained the inclusion of these additional hazards in this phase.

3. Model Development and Structure

3.1 Earthquake System Dynamics Model

The system dynamics model shown in Figure 1 represents the impact of an earthquake event on infrastructure capacity and the recovery timeline, specifically for the transportation mission-essential function. The model contains two primary stocks, *Damaged Capacity* and *Repaired Capacity*, and a shadow stock called *Operational Capacity*, which is used to track and visualize the recovery timeline from the initial damage to full restoration. *Shadow variables*, like Operational Capacity, do not influence the behavior of the model directly; rather, they are used to monitor key system outputs or indicators that help in understanding system performance over time.

The model incorporates key feedback loops that govern the recovery process. A balancing (negative) feedback loop reduces *Damaged Capacity* over time as repair actions are implemented, while a reinforcing (positive) feedback loop may arise if delays in repair efforts lead to further degradation or bottlenecks in operational effectiveness. These feedback loops are essential for capturing the dynamic interactions between earthquake severity, repair frequency, and available resources. The damage state represents the impact of the earthquake event triggering damage and an increased *Damaged Capacity*. The *severity* and *repair frequency* variables determine how quickly the *Damaged Capacity* is restored, which reduces the *Repaired Capacity*. The repair rate manages the recovery of *Repaired Capacity*, restoring it to full operational functionality. The *total capacity* variable represents the recovery capacity of Fort Wainwright. This variable can be decreased if the base is not fully operational, which increases the recovery time.

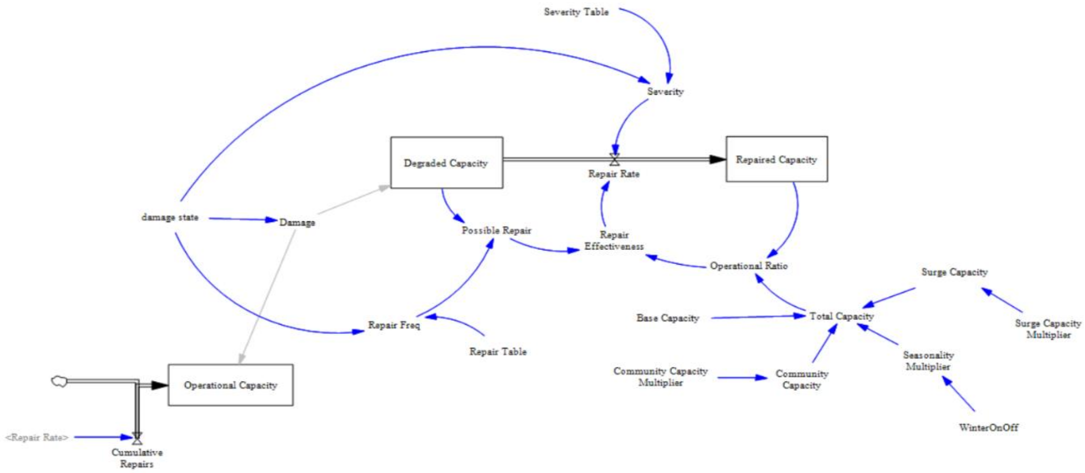
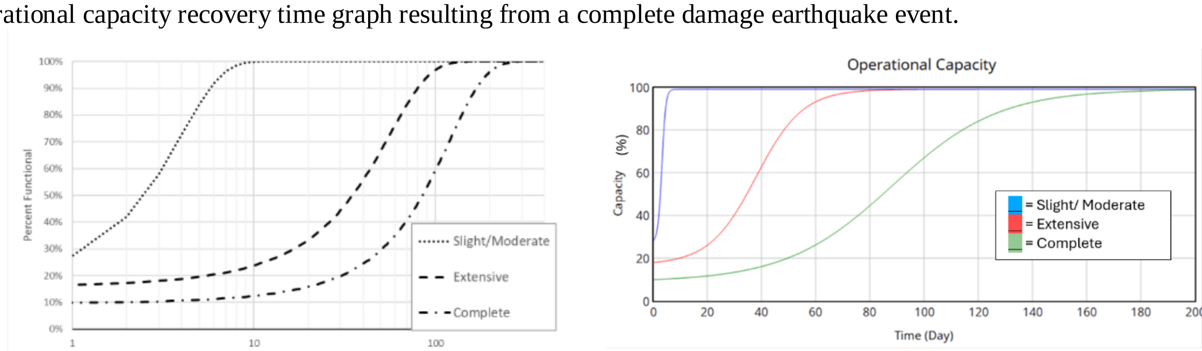


Figure 1: System Dynamics Earthquake Model for Transportation

3.2 Interactive Simulations

The model utilizes sliders to allow the user to easily change the parameters to align with the current state of nature. The sliders are located on *Damage State* and *Total Capacity*. The variable *Damage State* is a scale of 1-4 with values that correspond to the amount of damage caused by the earthquake consistent with HAZUS. The value of 1 represents slight damage, 2 represents moderate damage, 3 represents extensive damage, and 4 represents complete destruction (FEMA, 2024, July). The team used the variable *Damage* to align the model to the HAZUS data by using IF functions to correspond the initial damage point of the earthquake to the damage rating (1-4). The variables *Severity* and *Repair Frequency* both contain look up tables with decimals that further align the model to the HAZUS data (FEMA, 2024, July). The team matched the recovery curve output for *Operational Capacity* (in days and percent functionality) with those found in the HAZUS report. Figure 2 shows the HAZUS three earthquake restoration curves, slight/moderate, extensive, and complete damage, for runways as well as the operational capacity recovery time graph resulting from a complete damage earthquake event.



a. b.

Figure 2: Recovery Curves by Damage State a. HAZUS Restoration Curve, b. Model Recovery Curve

These variables enable the group to have an interactive model that is consistent with the HAZUS report. The only difference being the logarithmic scale used by HAZUS. However, when creating the model on the right, the team utilized HAZUS data points to ensure that the curves matched those of HAZUS at each damage state despite the different scale. The slider located on the variable *Total Capacity* allows the user to adjust the recovery capacity. Based on the qualitative survey data from ERDC, the team expanded the model to accurately reflect the effects of the additional capacity by separating the *Total Capacity* variable into four categories: organic installation recovery capacity (*Base Capacity*), additional capacity from the local community (*Community Capacity*), external capacity provided by the military or federal government agencies (*Surge*), and seasonality (*Winter* or *Summer*). These new variables allow policy makers to identify gaps in capacity and impact on recovery timelines given increased support from potential resources. Including a surge capacity in the model allows users to visualize the need for outside entities to assist with returning to operability.

3.3 Icing Event Modeling

Icing events severely impact transportation and power systems (Armstrong et al., 2016, July 1). However, the recovery times are significantly shorter than earthquake recovery timelines. As a result, the team created a separate icing model with a recovery time output shown in hours (Figure 3). The ERDC team provided guidance to limit icing events to occurrences of precipitation that freezes on the ground as opposed to snow or icing due to the melting and refreezing of snow. The modeling of icing severity was simplified to duration of icing event based on the ERDC team's recommendation to maintain tractability. While this model omits indirect icing impacts (e.g., pipe ruptures from ice freezing and thawing) this metric still provides a consistent input for transport related resilience. To model these, data from FAA guidelines on icing effects on airstrips and ground transportation were included as well as historical recovery timelines (FAA, 2019). Figure 3 displays the modified icing model, a simplified version of the initial model and a recovery curve from an icing event with the full organic base capacity.

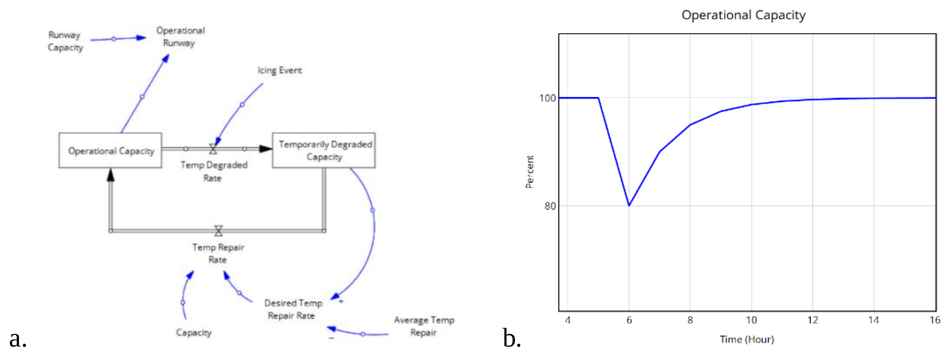


Figure 3: a. Icing Event System Dynamics Model, b. Recovery Curve from an Icing Event in Hours

3.4 Model Verification and Validation

To ensure the reliability of the model, the team used FEMA's HAZUS restoration curves as a benchmark for earthquake related infrastructure damage and recovery timelines. The simulated recovery curves closely matched these published benchmarks, validating the model's structural logic and calibration. For icing, FAA advisory circulars and ERDC-provided historical data served as external sources for validation. Additionally, feedback loops and time delays were reviewed by subject matter experts from ERDC to verify system behaviors under varying inputs.

4. Results

The findings concluded in synthesizing outputs from various resilience frameworks and identification of key dependencies and trends across different systems as well as hazards affecting military installations and their surrounding communities. The use of a causal loop diagram proved instrumental in visualizing critical relationships, feedback mechanisms, and interdependence between mission-essential functions and resilience characteristics.

The findings highlighted the interconnectedness of infrastructure and operational systems, revealing how disruptions in one area could propagate across multiple domains. Additionally, the study resulted in a catalog of best practices for adaptive design and mitigation strategies, integrating planning processes with existing infrastructure to enhance long-term resilience. The simulations yielded the insight that recovery time varies based on numerous factors: community help, base capacity, surge capacity, and seasons. There is an assumption that the recovery times of Fort Wainwright are slower than those outlined in the HAZUS data, derived from research of the location and knowledge of the austere conditions and limited resources available. Based off this evaluation, the baseline recovery times, with no community support or surge capacity, were modeled to be slower than HAZUS restoration curves by a factor of 50 days for complete damage, 20 days for extensive damage, and half of a day for slight and moderate damage. These results are shown in Figure 4. Community support enables the recovery times of the HAZUS data, outlined in Figure 3, to be reached. When the damage is slight or moderate 5% of community resources are applied to the installation. When the damage is extensive, the community will apply 25%, and they will apply 30 percent of their resources when the damage is complete.

ISBN: 97819384969-9-8

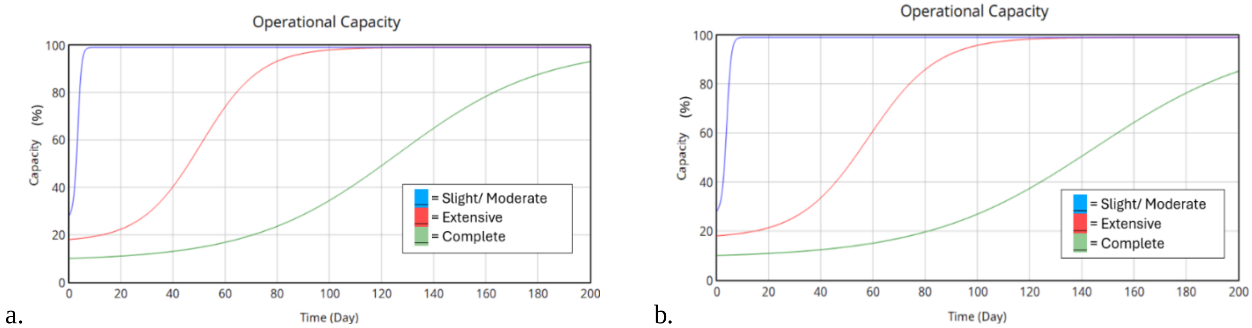


Figure 4: Baseline Recovery Times, No Community Support in, a. Summer, b. Winter

In harsh climates, the winter months increase operational risks and have a negative impact on missions. Figure 4b depicts the delayed recovery times during winter months as seen in the event of a complete earthquake, where it takes the installation approximately 140-days to return to 50% *Operational Capacity*. Under summer conditions, Figure 4a displays the same level earthquake with the resulting recover timeline of 120-days to return to 50% *Operational Capacity*. This difference of 20-days shows the impact of the season on the repair capacity of Fort Wainwright. This is intuitive as the climate and location factors of Alaska in the winter months, such as freezing temperatures, increased snowfall, and days of complete darkness, are modeled to cause recovery delays.

In addition to aid from the surrounding community, another factor that may contribute to the timeline of recovery is a surge capacity from an exterior entity, such as FEMA or additional, non-Alaska based military support. Figure 5 shows the baseline recovery curve recreated in red, alongside the effect of a successful surge capacity in blue. The baseline recovery curve shows the installation returning to 60% capacity at approximately 95-days, while the surge graph shows 60% capacity to be achieved in 75-days. This shows a decrease in 20-days when a surge capacity is utilized. The impact to the recovery period experienced from *community* and *surge* interventions can be altered by modifying the input variable level values as seen as appropriate.

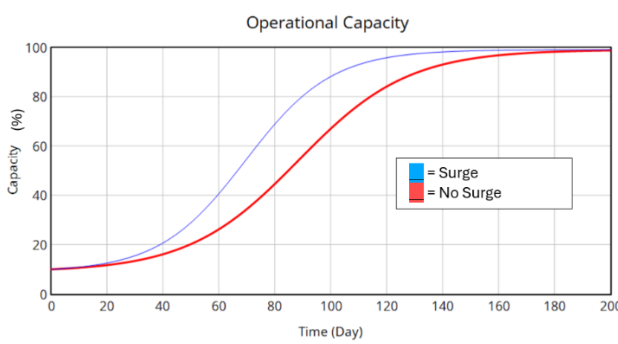


Figure 5: Impact of Surge Capacity on Recovery Timeline

5. Conclusion

The collaborative research between ERDC and the cadet team represents a significant step forward in understanding and enhancing cold weather resilience on military installations. By leveraging system dynamics modeling and causal loop diagrams, the complex interdependencies between mission-essential functions, infrastructure systems, and environmental stressors at Fort Wainwright were captured. The integration of FEMA's *HAZUS Earthquake Model Technical Manual* methodologies provided a robust quantitative foundation for assessing infrastructure vulnerabilities and recovery rates under both seismic and extreme cold weather conditions. Furthermore, the catalog of best practices developed through this study offers actionable insights for improving infrastructure resilience not only at Fort Wainwright but also across other military installations facing similar environmental challenges or natural hazards. This research lays the groundwork for future simulation tools and decision-support systems that will enable proactive planning, infrastructure modernization, and more resilient military operations in cold regions.

5.1. Recommendations

While this study focused in depth on modeling the transportation MEF, the team also developed a system dynamics model and analyzed recovery times for the electrical power system at Fort Wainwright. Similar to the transportation model, the team used data from the FEMA HAZUS Earthquake Model as the basis to establish base capacity recovery times. The team then modeled the recovery timelines for power infrastructure, specifically electrical generation facilities, under increased capacity from community and external support. The power model recovery times generally exhibit faster recovery compared to the transportation system under similar damage conditions and seasonal factors.

However, it is important to note that the current models treat each MEF in isolation. As a result, interactions between systems, such as how a delay in power recovery can impede transportation restoration, are not dynamically captured. Future development of the model should focus on integrating these mission-essential functions to simulate interdependencies and cascading effects. A more comprehensive model would provide better insights for real-time decision-making, especially in scenarios involving concurrent failures or resource constraints.

6.2. Policy Ramifications

To improve resilience and recovery capabilities for military installations in cold regions, specific policy changes focused on capacity enhancement should be considered. These policies address infrastructure vulnerabilities, response effectiveness, and operational continuity following seismic and icing events. The first of the recommendations is for communities to implement strategies to supplement traditional power sources in case of severe earthquakes that quickly deplete these power sources. The next recommendation is for communities to establish specialized rapid response teams to quickly and efficiently repair critical infrastructure damaged by the event. The final recommendation is to strengthen partnerships between military installations, state emergency management agencies, and local municipalities to enhance resource sharing during crises.

6.3 Future Work

Future iterations of this research should focus on expanding the scope and fidelity of the system dynamics model to enhance its utility and applicability across a broader range of scenarios. First, additional infrastructure components, such as communication and network systems, fuel supply chains, and wastewater systems need to be integrated into the model to reflect a more complete picture of the mission-essential functions in cold regions and capture the interdependencies of the systems. Environmental stressors beyond earthquakes and icing events, including solar flares, permafrost degradation, and prolonged polar darkness, should also be considered to capture the full range of operational risks faced by arctic installations.

Another key area of development involves refining the model’s decision levers to allow users to simulate policy interventions and emergency responses more directly. These enhancements include the ability to vary funding levels, prioritize critical infrastructure, and simulate the timing and magnitude of external resource surges. Future versions could conceivably incorporate real time data streams from sensors or weather systems as well as the current status of recovery equipment and personnel to improve the predictive accuracy of the model.

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