SAND2021-11394R

Critical Infrastructure Decision-Making under Long-Term Climate Hazard Uncertainty:

The Need for an Integrated, Multidisciplinary Approach

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September 2021

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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ABSTRACT

U.S. critical infrastructure assets are often designed to operate for decades, and yet long-term planning practices have historically ignored climate change. With the current pace of changing operational conditions and severe weather hazards, research is needed to improve our ability to translate complex, uncertain risk assessment data into actionable inputs to improve decision-making for infrastructure planning. Decisions made today need to explicitly account for climate change – the chronic stressors, the evolution of severe weather events, and the wide-ranging uncertainties. If done well, decision making with climate in mind will result in increased resilience and decreased impacts to our lives, economies, and national security.

We present a three-tier approach to create the research products needed in this space: bringing together climate projection data, severe weather event modeling, asset-level impacts, and context-specific decision constraints and requirements. At each step, it is crucial to capture uncertainties and to communicate those uncertainties to decision-makers. While many components of the necessary research are mature (i.e., climate projection data), there has been little effort to develop proven tools for long-term planning in this space. The combination of chronic and acute stressors, spatial and temporal uncertainties, and interdependencies among infrastructure sectors coalesce into a complex decision space. By applying known methods from decision science and data analysis, we can work to demonstrate the value of an interdisciplinary approach to climate-hazard decision making for long-term infrastructure planning.

1. INTRODUCTION

Investment decisions made today for critical infrastructure planning have long-term consequences for both reliability and resilience. Thus, anticipating future operational conditions is crucial to ensure that these investments provide adequate service and meet system needs for the duration of their design lifetime. Infrastructure assets often have large upfront costs and are designed to last for several decades. Given the rapid pace of climate change, both the risks to and requirements of our infrastructure systems will evolve; looking backwards at what worked in the past will no longer suffice when planning for new investments. Decisions made today need to explicitly account for climate change – the driving force behind a future of increased risk, more frequent hazards, and direct impacts to our national security (Campbell 2007, Fant 2020).

The consequences of ignoring climate change are dire. The number of billion-dollar disasters is increasing, largely driven by severe storms and flooding (NOAA 2021). As a nation, we can no longer express surprise at the regularity with which the United States experiences frequent severe weather-induced disasters – this is our new normal, and it is likely only to worsen. Our ability to withstand future severe weather events as a society depends largely on our critical infrastructure systems and their continued provision of services. Interruption of these essential services can turn even a minor event into a major disruption to lives, livelihoods, and national security. Government and industry organizations cannot afford to become complacent to infrastructure disruptions caused by severe weather events, and it is important to recognize the critical reliance on that our nation has on functional infrastructure. As researchers at a national laboratory, we have a critical role in supporting industry decision-makers as they plan for an uncertain future, as we all rely on the infrastructure services that they are providing. Doing so with urgency is very much in the national interest.

There are numerous tools to help decision-makers better plan for resilient infrastructure, including several approaches developed at Sandia National Laboratories (Watson 2014, Bynum 2021, Jeffers 2017). These tools lay out a framework to assess, model, and measure resilience. Most notably, the Resilience Analysis Process provides a step-by-step guide to quantify impacts and act to improve resilience (Watson 2014). However, each step along the way comes with challenges for implementation, and researchers too often do not provide sufficient guidance on how to populate these steps using real-world (i.e., noisy or uncertain) data or how to prioritize decisions when faced with real-world constraints. In large part, this gap exists because it is challenging to guide decision-makers in this space. The uncertainties are vast and there is no one-size-fits-all solution given the unique constraints of a specific region, utility company, or regulatory environment. However, we can and must do better.

The first step towards filling the discussed gap is translating the vast world of climate data into meaningful assessments of infrastructure impact. A framework alone is useless unless we also provide users with the tools needed to turn complex, multisource data into appropriate framework inputs. To this end, the driving factors of climate hazards and infrastructure failures can be assessed by combining risk assessment processes with previously developed data analytic approaches, as they are often not intuitive (Alemazkoor 2020, Staid 2014, Panteli 2015, Jackson 2021, Pierre 2021, Bynum 2021). From there, we would identify the uncertainties present both in the data itself and in infrastructure asset impact models. Physical damage or a failure of an interdependent component can both result in a loss of function, but models to predict these different failure modes are drastically different. Researchers need to recognize the space of uncertainty that is present when modeling complex system interactions and, critically, employ methods to communicate appropriate outcomes and results to decision-makers. There are some robust best-practices when it comes to uncertainty quantification, and, combined with sensitivity analysis, these methods can provide the insight needed to support confidence in decision-making (Maupin 2018, Benjamin F. Emery 2020). The final step in providing robust climate-hazard planning support relies on better decision making. Experts in decision analysis need to work with infrastructure planners to determine their unique requirements. From this, researchers can work to translate model outputs into meaningful and interpretable conclusions that, when combined with application-specific constraints, provide the needed input for improved decision-making.

2. PLANNING FOR CLIMATE RISK

Climate risk assessment relies on the foundation of general circulation models (GCMs). These provide the input needed to further refine what may happen on a finer scale, whether spatially or temporally (Randall 2007). GCMs provide projections of climatic conditions across the globe, allowing for a coarse understanding of trends and changes in extremes. For decisions facing infrastructure planners, however, the projections need to be brought down to a local level in order to be relevant, and this is done by downscaling to a specific region or site of interest (Hewitson 1996). For example, one may need an assessment of expected sea level rise at the site of an existing electric substation, as opposed to an estimate that covers the entire coastline of the state. Often, additional models are needed to provide these more refined assessments for local hazards. Uncertainty is present at each step along the way, as each additional model adds yet another layer. This can be challenging for decision-makers to manage, as the ballooning spread of possible future realizations can be daunting.

The uncertainty present in GCM projections and hazard risk assessments needs to be explicitly incorporated into planning processes, instead of being treated as an afterthought or something only useful to 'band' an estimate. Thus, we argue that there is a need for a new product: one that combines climate projections, natural hazard models, and decision science to better meet the needs of users who are faced with decision-making under multidimensional uncertainties.

There are a number of planning frameworks that take climate change into consideration (AECOM 2015, OECD 2018), but it is difficult to assess the role that individual extreme weather events play in a future climate scenario, and thus these are often left out. Given the increasing frequency and severity of extreme weather events under climate change, however, it is crucial to incorporate those hazards directly into long-term planning and resilience assessments. As is often the case, individual events can be the driving factor behind infrastructure upgrades, changes in policy, and budget determination (Brundiers 2018, Solecki 2014). The cost considerations of repairing assets after a single severe storm are vastly different from repairs needed after multiple severe storms within a short time frame. Thus, the occurrence of natural hazards in a future climate needs to be present in a planning tool, as decisions to abandon assets start to become more appealing when repeated events are directly considered.

Even when hazards are considered, it is often not clear how to assess the resilience of a system. There is active research focused on resilience metrics yet little consensus on how best to populate and apply performance-based metrics in practice. Given this challenge, any decision framework needs to incorporate metrics that are of value for users by ensuring that they truly address resilience in ways that matter for infrastructure services (Anya Castillo 2020).

2.1. The Need for a Better Approach

While daunting, the complex uncertainties of climate risk need to be integrated into decision-making frameworks to safeguard our investments and best position our infrastructure systems to meet the needs of a changing world. While already subject to a wide range of constraints, infrastructure planning processes will only become more difficult as climate change exacerbates the existing complexity by forcing us to deal with uncertainty directly. This is an uncomfortable position for many, as organizations have largely been able to rely on historical data to model optimal decisions. As present conditions quickly begin to diverge from the past, we need to instead rely on models that project plausible future conditions, both in terms of normal operating environments and the risk of extreme weather hazards.

Decision-making in the face of this uncertainty requires reframing decision objectives away from "optimal" and towards "robust" in order to capture a new suite of strategies that focuses on minimizing regret, creating flexibility, and, most importantly, maximizing the resilience of these critical services over a long-term decision horizon (Mortazavi-Naeini 2015, Mondoro 2018, Li 2014). Current decision-making tools focus on single hazards or static planning horizons, while overlooking the complex, multifaceted impacts of climate change (Reilly 2017). Today's decisions need to account for an operational life with evolving chronic stressors, repeated acute hazards, and changing demands. Thus, there is a need in our collective research approaches to be intentional about coupling detailed climate hazard data with uncertainty projections of infrastructure asset damages and changing demands on the system. Only then can we support robust decisions in this space by allowing decision-makers to assess the interplay between long-term resilience and decisions made today in the face of climate change.

The world of climate modeling is mature and well-established. Similarly, for individual hazards, we have robust modeling capabilities that link climate projections to extreme weather events (Mann 2006, Hallegatte 2011, Hirabayashi 2013). Still, we cannot predict when or where the next disaster may occur, and this results in a challenge for populating decision frameworks. Instead of predicting with confidence, we can create a broad set of scenarios that represent plausible realizations of future climate timeseries. This provides the level of detail to assess the impact of different decisions on true system resilience. Of course, the quality of the outcomes relies directly on the quality of scenarios, and this is where new research is needed. Using the uncertainties that we know exist, we can create statistical models to guide the creation of realistic spatio-temporal weather projections – projections that explicitly include extreme weather events and infrastructure impact assessments. This approach will provide interpretable input for decision-support tools, while incorporating both climate and hazard modeling expertise. Figure 1 provides an overview of the dependencies to go from climate projections to the inputs needed for decision-making.

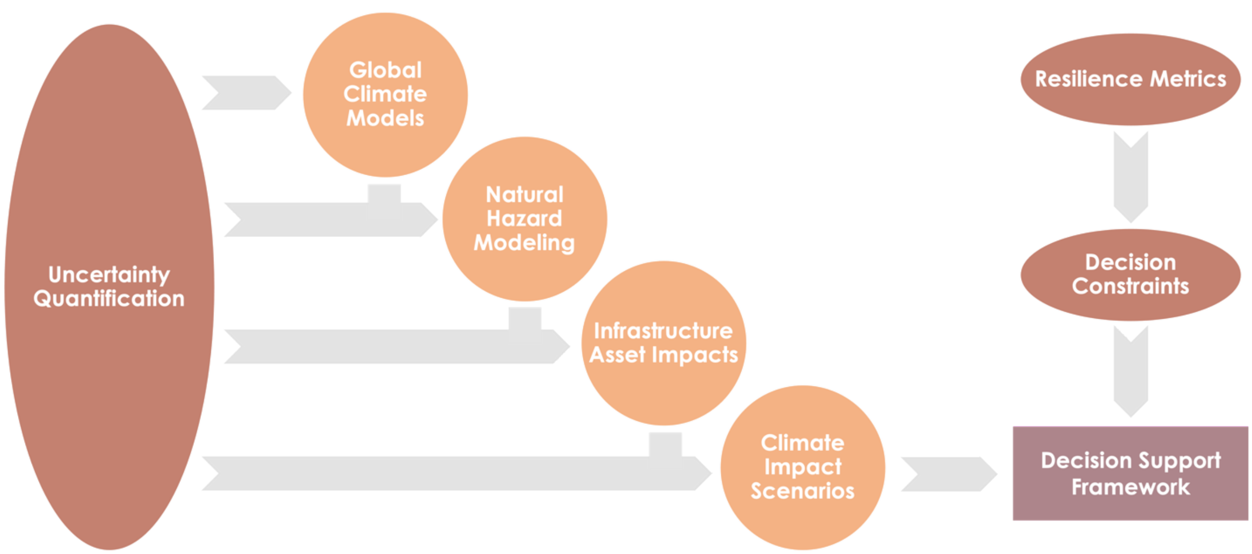

Figure 1 **Overview diagram of the process to populate a robust decision support framework for infrastructure risks from climate change hazards.**

This work is not easy, but many of the ingredients of improved decision-making in this space already exist. What we need now is a concerted effort to bring together expertise from the worlds of climate models, extreme weather event projections, infrastructure asset vulnerability, resilience, uncertainty quantification, and decision science. By combining robust uncertainty quantification of available climate models, natural hazard projections, and infrastructure asset damages, we can create scenarios to then model performance impacts and study sensitivities that determine worst-case outcomes or critical thresholds. Bringing in decision analysis research, we can create a framework that is able to handle these inputs in a meaningful way for users. There are benefits to be gained from explicitly considering long-term climate risk, repeated hazards, and acceptable levels of resilience in infrastructure planning decisions – something that current methods fail to account for adequately.

3. PROPOSED SOLUTION: COUPLING RESEARCH PRODUCTS

The approach presented here would significantly improve how climate data is effectively leveraged to inform resilient infrastructure decision-making and reduce unintended consequences (Alemazkoor 2020, Macintosh 2013, Manski 2021). Although researchers have shown the impact of climate uncertainty on driving power outage risks for extreme events, this work has not informed the methodologies for current hazard assessments, which are often limited to specific locations and/or hazard type, nor has it provided the decision-support needed to ensure that investments made today will result in resilient infrastructure in decades to come (Alemazkoor 2020, Reilly 2017, Staid 2014). We, as researchers, need to take a systems-level approach to bridge the gap between climate scenarios and hazard assessments – capturing multi-hazard exposures while accounting for actual system state, and identify different ways to inform climate-relevant infrastructure resilience analysis. We have identified three main pillars of analysis in order for this work to be successful: 1) multisource climate-hazard assessment, 2) asset-level exposure-impact models, and 3) demonstrated decision-making criteria.

3.1. Multisource Climate-Hazard Assessment

Current assessments of natural hazards are limited to a specific type of event (e.g., high winds or hurricanes). However, climate risk evaluations need to incorporate the complexity of weather events, such as rapid transitions between drought and high rainfall, and the occurrence of multiple event types within a region, such as a hurricane followed by a winter storm a few months later. The occurrence of repeated damages is likely to be a driving force behind the most critical of adaptation decisions. Thus, any risk assessment must account for the likelihood of repeated hazards over the entire operating lifetime of an asset. A multi-decadal risk assessment is needed to capture the full exposure of critical infrastructure assets under consideration. By providing decision-makers with projections of these plausible future realities, they will be forced to consider the pitfalls of what may seem like obvious decisions at the time – for example, repairing the same asset six times instead of abandoning and building a new asset elsewhere. Researchers can combine the uncertainty present in both climate and hazard models to provide long-term views on the hazards in a region. This can be done by collecting, aggregating, and analyzing multi-source climate data to develop representative distributions of weather events for a set of natural hazards, while ensuring that correlations in both space and time are accounted for.

Presenting future risk in the form of scenarios is likely to provide valuable insights, as decision-makers can assess how a set of decision rules or best-practices play out under each of the plausible scenarios. Each scenario could represent a multi-decadal time series of severe weather occurrence, along with changing operating demands and chronic stressors. Multi-hazard models (i.e., compounding events) for each region must capture interdependencies among events in order to create realistic scenarios for use in a planning context. This cannot be done haphazardly, as there are known correlations between certain types of events (e.g., wildfires may lead to landslides the following year). The analysis in this space must ensure that the complex interactions across underlying climate variables and the hazards themselves are incorporated.

3.2. Asset-Level Exposure-Impact Models

Asset-level exposure-impact functions already exist for a wide range of hazards and asset types. In many cases, the application of these models depends on a detailed knowledge of asset design criteria and vulnerabilities, which may only be known to the industry operators. Failures often depend on the presence or absence of protections in place against certain hazards, such as elevation to avoid flooding or insulation to withstand cold snaps. For a particular hazard, we can employ existing models to determine the likelihood of damage or disruption at the asset level, subject to knowledge of asset details. For example, fragility curves can be used to determine the vulnerability of transmission lines to high winds or the probability of water availability for a hydropower plant during a drought. For larger scale analyses, we can rely on existing data and modeling efforts to generalize expected vulnerabilities for a particular class of assets. In these cases, sensitivity analysis becomes more important to ensure that the implications and limitations from any assumptions made are well understood and accounted for in the final product.

Once impacts are understood and modeled for a set of hazard scenarios, we can translate these impacts into the expected loss of performance or function of the services provided. Given the role of critical infrastructure, resilience must be assessed based on whether or not adequate service are provided and not on the presence or absence of damage to a component. In the case of redundant assets, the loss of performance from a damaged component may be negligible, whereas in other cases, the loss of a key asset will be disastrous. Thus, in many instances, true system-level simulations are needed to quantify resilience and determine the level of disruption to communities and critical facilities. These performance-based simulations can incorporate interdependencies and backup plans in order to project accurate operational impacts. In the electric sector for example, production cost modeling can be used to study power grid response to component outages, ensuring that the physical constraints of the system are represented.

3.3. Demonstrated Decision-Making Criteria

There are critical metrics that are needed to drive human decision-making within long-term infrastructure planning problems. These metrics may include a variety of technical and non-technical criteria, such as cost (construction as well as maintenance or repair costs), strategic location considerations, zoning constraints, and management priorities. In identifying critical decision metrics, we must also highlight the importance, or weighting, of each metric toward overall decisions and decision outcomes. Further, we can examine how the combination, integration, or inclusion of specific metrics may alter the human's final decision. Once individual and integrated metrics have been identified, the data-driven modeling products discussed here can be used as test cases to demonstrate how varying priorities and strategies alter infrastructure resiliency and overall costs.

Given the complexity of infrastructure decisions, it is likely that the individual decision metrics and weighting criteria will need to come directly from the types of people faced with making these decisions. Thus, gathering input using semi-structured Subject Matter Expert (SME) interviews is needed to ensure that a decision framework accounts for the needs of the industry. To do this well, it is important to capture a wide range of perspectives. For example, spiral sampling and inductive thematic analysis can be used to collect input from experts with a more general view of hazard analysis (G. K. Guest 2011). Additionally, we can ask SMEs to weight how they would employ different decision metrics in an infrastructure planning scenario, and then compare these approaches using our set of climate hazard scenarios. This would allow us to quantify the comparative performance of various decision metrics and weighting criteria, as the quality of resulting decisions depends both on the data provided as input *and* on the ability to provide the context needed to an analyst (G. E. Guest 2020). We can then demonstrate how differing decision strategies, weighting criterion, and available information alters infrastructure planning decisions. Ideally, this results in a set of best practices that applies across hazard types, asset types, and decision makers.

4. CLOSING THOUGHTS

Sandia National Labs brings expertise in systems-level modeling, infrastructure risk and resilience analysis, uncertainty quantification, and decision support. If done successfully, the research approaches highlighted here would result in a robust framework that provides infrastructure operators, planners, and regulatory bodies with the tools needed to analyze decisions in the context of long-term hazard scenarios, assess the resilience implications of different decision strategies, and consider tradeoffs for long-term planning. With demonstrated improvements to decisions in this space, the entire nation stands to benefit, as critical services will be sustained through a future of more frequent and more severe weather hazards. While we cannot control the hazards themselves, we can better design our infrastructure systems to withstand the hazards and we can dedicate resources towards minimizing disruptions to our lives, economies, and national security.

This work requires a large, concerted effort to bring together expertise from a variety of fields. The problem space is large, both in terms of the spatio-temporal considerations and the combination of individual data and modeling products. Close industry engagement is likely critical to ensure that any modeling and decision framework created is able to incorporate the needs and constraints of decision makers. In addition, a real-world application of a climate hazard planning problem requires industry input to populate the detailed asset-level information that is needed for impact modeling. While recognizing the many challenges, this research is important, the application space is vast, and the urgency is high.

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