ABSTRACT

IVEY, CARLAN A. Identifying Best Performance Scenarios for Micro Nuclear Reactors during Grid Disruption. (Under the direction of Brandon M. McConnell.)

Micro Nuclear Reactors (MNRs) are an emerging innovation in nuclear technology as small, portable, and self-sufficient reactor units in the size of a standard 40-foot shipping container. An MNR functions as a “nuclear battery," where each unit can power load capacities from 500 kilowatts (kW) to 5 megawatts (MW) over the lifetime of 1 to 10 years. This technology may deploy by the end of the 2020 decade, so private and government organizations have prepared for potential operational use for energy resilience. In addition to the growing number of grid disruption events from severe weather events, cyber and physical threats potentially challenge dependence on the traditional above-ground grid infrastructure. This research develops an emergency grid disruption timeline with MNR deployments to respond and recover grids after severe weather events. This response integrates a series of models for transportation networks, power distribution, and decision strategies that utilize MNR capabilities while using real-world disruption events within the past decade for scenarios. The study then seeks to analyze the performance of MNRs when using different deployment strategies for emergency grid disruption response. First, this research investigates the trade-offs between time and cost in the emergency grid disruption timeline when integrating MNRs. This research also explores the conditions of disruption scenarios that contribute to the best MNR performance in grid recovery.

Identifying Best Performance Scenarios for Micro Nuclear Reactors during Grid Disruption

by
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DEDICATION

For my family. Thank you for all your sacrifices and the continuous support you give me everyday.
For my wife, Celine. Though miles apart, I know your love and support is only moments away.

BIOGRAPHY

Carlan Ivey earned his commission from the United States Military Academy in 2019 and graduated with a B.S. in Nuclear Engineering. He had the unique opportunity for his first assignment to pursue the National GEM Consortium Fellowship immediately after graduation at North Carolina State University. During this fellowship, 1LT Ivey interned in the Nonproliferation and National Security Department at Brookhaven National Laboratory.

1LT Ivey grew up in Conyers, Georgia, 20 miles east of Atlanta. His desire to be more than a student led him to West Point, New York. At the academy, Carlan focused on all four pillars of performance. While studying Nuclear Engineering, he competed nationally on the Army West Point Boxing Team all four years. He became the first cadet in academy history to win four consecutive national championships. He gained further military experience by graduating from Air Assault School, earning a German Proficiency Badge at the gold standard, and attending Mountain School at the Brazilian Military Academy.

Following graduation from North Carolina State University, Carlan will complete Armor Basic Officer Leadership Course at Fort Benning, Georgia. He will then join his wife at Fort Bliss, Texas, to serve the remainder of his Armor Lieutenant time.

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API Application Program Interface

BA Balancing Authority

BNL Brookhaven National Laboratory

DG Distributed Generation

DoD U.S. Department of Defense

DoE U.S. Department of Energy

DOE Design of Experiment

EIA U.S. Energy Information Administration

GW Gigawatt

HALEU High-Assay Low-Enriched Uranium

INL Idaho National Laboratory

kW kilowatt

kWh kilowatt-hour

LEU Low-Enriched Uranium

LWR Light Water Reactor

LANL Los Alamos National Laboratory

MNR Micro Nuclear Reactor

MW Megawatt

MWh Megawatt-hour

NEI Nuclear Energy Institute

NRC U.S. Nuclear Regulator Commission

OPF Optimal Power Flow

P2P Point-To-Point

PV Photovoltaic

SMR Small Modular Reactor

SOC State-of-Charge

TL Truckload

V Volts

VA Volt-Ampere

VAR Volt-Ampere Reactive

CHAPTER

1

INTRODUCTION

1.1 Micro Nuclear Reactors

Micro Nuclear Reactors (MNRs) represent the newest generation of advanced nuclear technology as small, portable, and self-sufficient reactor units in the size of a standard 40-foot shipping container. Characteristically, an MNR functions as a "nuclear battery," where each unit can power load capacities from 500 kilowatts (kWs) to 20 megawatts (MWs) over their lifetime of 1 to 10 years. Compared to traditional nuclear reactor technology, the MNR unit's entirety is factory-fabricated and developed with specifications that fit their desired use. This new generation of reactor technology has piqued the interest of nuclear industry companies and government organizations alike. Some U.S. Department of Energy (DoE) facilities have released numerous reports highlighting the potential capabilities and specifications of MNR technology [Ste17] [Her19]. One laboratory has committed to industry partners to develop this technology; Los Alamos National Laboratory (LANL) has combined efforts with the Westinghouse Electric Company to develop the eVinci™ Micro Reactor, which will potentially be the soonest introduction to the use of this technology [Ara19].

The prospect of critical load-sustaining power sources with truck-load shipment capabilities has garnered academia, industry, and government's attention to determine their applications. The Nuclear Energy Institute (NEI) prepared a roadmap report in 2018 focusing on the actions needed to support the development and deployment of MNRs in domestic U.S. Department of Defense (DoD) installations [Nic18]. This report emphasizes an essential question about MNR technology coming to fruition in the near future: How can MNRs be most effectively used upon their initial deployment? Although many situations could warrant the use of MNRs, effective immediate use for MNR capabilities would be a distributed generation response system to grid disruption scenarios.

1.2 Grid Disruption

The U.S. electrical grid has evolved into a complex system that provides customers with consistent and reliable power. The typical process begins with electricity generation at plants (coal-fire, gas-fire, nuclear, etc.). Transformers then increase the voltage to transmit the electricity over long distances to substations, decreasing the voltage and distributing the power locally to meet customer demand. This initial infrastructure of linear power production was susceptible to disruption if a person or incident damaged one element, so adaptations led to interconnected systems that increased reliability. Specifically, transmission lines became highly interconnected to multiple generation plants, local distribution lines, and each other. However, grid interconnection cannot prevent traditional above-ground grid lines' vulnerability to natural and non-natural impacts. From 2016 to 2017, Eaton [Eat17] reports that the number of customers affected by grid disruptions doubled to 36 million and that the duration of outages increased to an average of 8 hours per disruption. Most of these disruptions arise from weather-related incidents, but other cases involve errors in planned outage procedures. To meet the challenge of increased grid disruption in the coming decades, elements of micro-grids, distributed generation, and energy storage have gained support as sustainable solutions.

1.3 Distributed Generation

The long-term solution of remodeling the U.S. electric grid may involve more expensive methods to protect and maintain long-distance transmission, and distribution lines [Fol16]. Distributed Generation (DG) instead provides the short-term solution for temporary and emergency grid disruption with power generated directly to customers on a local level. DG systems introduce security and reliability to these local customers with up to 100 MWs of generation capacity, which depends on the type of electricity generation used. DG systems usually consist of high-capacity diesel generators and allow renewable power generation from photovoltaic cells or wind turbines. However, issues arise for DGs sources during emergency grid disruption. Diesel generators rely on a constant fuel supply, which adds fuel logistic requirements that are difficult to meet during a natural or non-natural disaster. The renewable sources are often intermittent and not reliable for a consistent generation.

MNRs introduce the solution to DG systems by providing consistent power generation during their specified lifetimes, having power capacities comparable to the highest grade industrial generators, and eliminating the need for constant fuel transport or other resources needed to keep DG systems functioning. With MNR's development and test expected completion by the end of the 2020 decade, their application to DG systems could immediately impact grid disruption scenarios.

1.4 Research Goals

This research evaluates the conditions, resources, and demand requirements in which MNRs would perform optimally. Specifically, the study bases its assessment of MNRs for use during emergency grid disruptions. There is limited literature on the applications MNRs due to their early phase in development. However, high-level analyses from Nichol et al. [Nic19] and Lee [Lee20a] describe their specifications and implications for future markets. This research's uniqueness comes from its modeling application of emerging MNR technology for emergency grid recovery. More so, this research uses grid demand information obtained from previous disruption events to evaluate MNR performance during these operations. Evaluating these performances and the trade-offs of time and cost in the proposed recovery models will give insight into suitable scenarios.

1.5 Structure of the Paper

The paper follows the structure of the chapters described. Chapter 2 reviews the current literature in the fields of MNR Development, Distributed Generation, and Emergency Logistics. Chapter 3 provides an overview of the series of decision making and evaluation models that generate the essential outputs. Chapter 4 investigates these outputs for classification patterns and prediction metrics. Chapter 5 will explore the results of analyzing these metrics. Chapter 6 concludes the research with a discussion of implications, limitations, and future work in this field of study.

CHAPTER

2

LITERATURE REVIEW

This chapter will go further in depth on the critical technology and concepts introduced in Chapter 1. This will include the current state of MNR technology in its development, potential for integrating sustainable DG systems to local grids, and the organized response to temporary grid disruptions.

2.1 Micro Nuclear Reactors

Recent evidence shows that the nuclear power industry is abandoning its large-scale, Light Water Reactor (LWR) dominant infrastructures that produced 20% of the U.S. electricity in 2019 and directing their next generation development towards smaller, cheaper, and safer designs. Specifically, ten reactors have been decommissioned since 2013, with twenty more reactors currently in the process [Dep19]. Comparatively, the U.S. Department of Energy (DoE) has invested $60 million in cost-shared research and development funding for projects in the research area of modular nuclear reactors [Dep19]. These reactors, also known as small modular reactors (SMRs), are reactor unit designs with outputs of less than 300 MW and take advantage of factory fabrication and series production. Although SMR units would only require a third of the land area used in traditional nuclear power plants, continuing innovation in small nuclear technology introduced the potential for 30 MW output MNR units with mobile capabilities [Ara19].

The introduction of alkali metal heat pipes in recent MNR designs has been the largest step in innovation. Heat pipes are heat transfer devices with self-adjusting behavior due to evaporation and condensation functioning at different ends of the device [Jou17]. Figure B.2 in Appendix B shows how vapor and condensate flow within the heat pipes to opposite ends naturally based on state density. Heat pipes efficiently regulate reactor cores' high temperatures, which eliminates the need for pressurized and bulk coolant structures used in larger reactors [Ara19]. This contributes to the inherently safe design since all components of the MNR are solid-state. Hernandez et al. [Her19] analyzes the performance and safety of heat pipe MNRs using Serpent models for reactor physics calculations. While Westinghouse Electric Co. could improve their current fuel cycle performance based Hernandez et al. [Her19]'s analysis, it reinforces the belief that MNRs should target decentralized markets for short-term energy sources.

2.1.1 Markets and Competitiveness

Lee [Lee20a] evaluates the market opportunities for MNRs based on their current design specifications and capabilities. Their lower production capacity address off-grid and remote markets and could provide these markets with an estimated three GW by 2030. MNRs also have opportunities in urban areas because of growth in microgrid markets. Micro-grid markets operated 3.2 GW in the U.S. in 2017, with an annual growth of 14.1% per year since [Lee20a]. MNRs have the potential to contribute to this growing micro-grid capacity depending on their capital and operation cost. The capital cost of energy generation plants and sources is different because the energy generation cost over their entire lifetimes can change. The cost of power production, usually $ per kWh, decreases over the plant lifetime due to the "learning curve" of operations [Ene13]. Since capital cost has such a significant influence on total delivered cost, some methods estimate plant lifetime costs before construction. The “Overnight Capital Cost" concept combines capital, generation setup, installation, and construction interest cost into one value as if an electricity plant was built overnight [Koo07]. Although estimations can vary with large-scale plants, the overnight capital cost may be more accurate for MNRs with manufacturable specifications. Nichol et al. [Nic19] estimates the overnight capital cost of MNRs for their study, analyzing their cost competitiveness against diesel DGs and find the production cost of production MNRs can be lower in specific markets.

For MNRs to realize their potential in the market and compete with other emission-free energy resources, the developing industries must fulfill their nuclear safety and security assurance. The socio-economic concern determines the level of use and distribution, especially for nuclear technology [Lee20b]. Radiation safety is described as protecting people and the environment from radioactive dispersion and effects. Radiation security is the protection of nuclear materials and sources from people that desire malicious acts [And16]. These aspects are evaluated by the U.S. Nuclear Regulatory Commission (NRC) when conducting the initial safety and security evaluations of the reactor unit designs when determining license specifications.

2.1.2 Deployment State

The state of MNR development has a high impact on policy planning for licensing, market applications, and deployment timeline. The most consistent design aspect from MNRs developers, such as LANL and DoE discussed in Section 1.1, is in the fuel type planned for use. The Idaho National Lab (INL) conducted a phenomena identification and ranking table (PIRT) assessment on LANL's 2017 2 MW “special purpose reactor" design [Ste17]. The specifications show that MNRs would use uranium oxide fuel form with enrichment at 19.75%. This categorizes the fuel as high-assay low-enriched uranium (HALEU) being between 5–20%. HALEU fuel provides high enough enrichment for small unit reactors by increasing power production per volume [Hol19]. HALEU also contributes to longer core life and more efficient fuel burn-up before the entire unit cores decommission. Although the NRC will evaluate every aspect of MNRs designs upon completion, preliminary reports in the Nuclear Regulatory Commission [Nuc19] Interim Staff Guidance state they will modify policy originally dedicated to large-scale LWRs. It mentions that with designs showing “low potential for transients and accidents, low potential for radioactive releases, low potential consequences from radiological release," there is the need for scaling when working with advanced reactors with small MW output. Based on NRC’s current policy, MNR deployments would require certain safety exemptions since its target application would place them in DGs application areas. Information about MNR development is continuously updating, so their current specification modeling could change in the future.

2.2 Distributed Generation

The concept of low capacity generation and small volume customers is not novel in power distribution. Pepermans et al. [Pep05] explains that the interest in the DG market returns to the original methods of energy distribution. Generation plants originally supplied power directly to local customers through direct current (DC) short-distance grids. The rise of alternating current (AC) technology opened the doors to long-distance transmission, higher capacity generation plants, and the current grid infrastructure.

Adefarati & Bansal [Ade19] describe the multiple applications of DGs today and their growing integration with renewable energy resources. The most common application for new DGs today is the need for an emergency energy supply. Backup diesel generators fit this profile of emergency supply most commonly for customers. They temporarily provide power to smaller loads like individual homes or larger loads like hospitals, focusing on supplying critical loads. DGs also offer efficiency when used for peak shaving, generating independent power when demand is at its highest. This technique can reduce cost since electricity charges $ per kW hour, and electricity is most expensive at peak times. Extra capacity generation at these peak demand hours reduces cost from the utility.

The potential for renewable energy sources in DGs primarily exists in solar/photovoltaic (PV), or wind turbines [Ade19]. The World Energy Council expects natural resources to provide 34% of power worldwide by 2030 based on the 23% usage in 2010 [Sal13]. PV systems have the option of being standalone or grid-connected and have energy storage capacity or are coupled with other energy sources [Ade19]. The flexibility combined with low operation and maintenance cost shows PV’s advantages as it grows. However, PV plans should consider the disadvantages of low efficiency, environment dependence, and high land area. Similarly, wind turbines have an optimal placement that ensures each unit is taking advantage of wind speeds and flow patterns. Multiple configurations (horizontal or vertical axes) also provide options for wind power collection. It has similar disadvantages of PV in the large land requirements and intermittent production [Ade19].

2.2.1 Micro-grids

Krishnamurthy & Kwasinski [Kri19] emphasize DGs as only one of the three micro-grid resilience characteristics. The other elements are energy storage units that help support island operations and the lifeline resources of what supplies the DGs. The most common lifelines are diesel fuel sources, which require a continuous supply over time to be sustainable. For renewable sources, this could entail solar energy availability for photovoltaic cells to absorb or wind flow to provide aerodynamic force to turbines. Although energy storage can temporarily compensate for disruptions in the lifeline behavior, uncertainty in its supply drastically reduces micro-grid resilience.

2.2.2 Power Distribution Evaluation

There is an overwhelming variety of power distribution studies conducted in the fields of electrical and systems engineering. The literature in this research focuses directly on power distribution studies that fit the ideal model's characteristics of optimizing limited DGs resources for critical loads. First, Krishnamurthy & Kwasinski [Kri19] discuss discrete event model of fuel-dependent DGs during a disruption in supply. With the methodology of a Markov chain model due to repeated refueling states, the model evaluates resiliency probabilistically given the chance of disruption.

Krishnamurthy & Kwasinski [Kri19] evaluate the distribution systematically instead of using optimization in other electrical engineering methods. Georgilakis & Hatziargyriou [Geo15] emphasize these methods as having single objective functions that could minimize a variety of net present cost values in the problem. The constraints introduce power flow equality, bus voltage limits, feeder capacity limits, or transformer specifications, which call for various optimization methods. Haffner et al. [Haf08] is a numerical method example that used mixed-integer linear programming (MILP) to minimize the installation cost of new feeders and substations. Numerical methods like this provide an advantage in evaluation speed and efficiency, but nonlinear methods such as mixed-integer nonlinear programs (MINLP) provide far more accuracy due to nonlinear constraints. Heuristic methods also model and evaluate power distribution, such as in the study by Falaghi et al. [Fal11] to expand distribution networks with DGs. Specifically, a combined genetic algorithm and optimal power flow (OPF) equation minimize annual cost over a planning phase and then an operational horizon of a year. Heuristic methods require more computational effort to design the model but provide solutions that do not require conversion of solutions.

Specific tools in power systems allow users to experiment with the many controls and capture the dynamic and transient behavior of power grids in a less challenging way. The Matlab/Simulink-based program, Simscape, provides specialized power system libraries that construct models with generation, controls, and grid equipment [Del18]. Designs can scale from simple DC connections to loads that emulate the Western North American Power System [Del18]. Studies using these Matlab/Simulink tools [Mat21] have started to integrate more renewable energy sources as DGs, clustering them in a micro-grid infrastructure. Boudoudouh & Maâroufi [Bou18] present a model that manages DGs from photovoltaic and wind turbine sources while supported by energy storage.

These tools allow for the photovoltaic and wind DGs to have characteristic functions and outputs, making this multi-agent design comparable to transient behavior that could appear in an actual grid. The Simscape power system library in Matlab/Simulink contains numerous more components and equipment, allowing the closest possible simulations and dynamic power grids studies.

2.3 Emergency Response

Jiang & Yuan [Jia19] discusses large-scale emergency response logistics still being in the early stages of research for the operations research community. This study highlights Altay & Green III [Alt06] work that states, “[t]he seeming randomness of impacts and problems and uniqueness of incidents demand dynamic, real-time, effective and cost-efficient solutions, thus making the topic very suitable for OR/MS research." Unlike humanitarian logistics, emergency response logistics manage the emergency resources and rescue services to minimize damage to life, property, and infrastructure. Jiang & Yuan [Jia19] summarize that current research in this area focuses on traditional logistics objectives (minimized distribution time, cost, or shortest path) instead of focusing on objectives that directly benefit the customer and aid in their recovery [Jia19].

2.3.1 Utility and Government Response

The National Electricity Emergency Response Capabilities report for the DoE describes the organized structure of how government and utility provider entities respond to disruptions. Government organizations, starting from the local level, coordinate the response, gather/share information, and communicate with stakeholders and the public. They communicate with utility providers who physically repair damaged infrastructures and restore services. The severity of the disruption and availability of government and utility resources decide what echelon of coordinated response is required, with the highest level being a declared a national response event [Fol16].

The timeline of disruption events is critical in reducing the number of customers affected and the amount of damage done to the current infrastructure. An expected disaster moves the grid operations from steady-state to preparation in the Pre-Event Phase, prioritizing resiliency. The grid operations then prioritize mitigation operations to minimize infrastructure damage. The Post-Disruption first involves a coordinated response, and recovery operations follow this to repair the damaged infrastructure [Fol16].

2.4 Military Implications

This venture into MNRs is not the U.S. Military’s first endeavor with this technology. The U.S. developed multiple small-megawatt output nuclear reactors under the Army Nuclear Power Program (ANPP) from 1954 to 1977 [Lee20b]. The U.S. military abandoned the program despite developing eight reactors due to a lack of application and suitability during its era. However, interest has renewed due to U.S. Congress setting a requirement for the DoD to prioritize energy security and resilience, as defined in Holland [Hol19]. The 10 U.S. Code §101 describes energy security as the assured access to a reliable supply of energy and the ability to meet and deliver energy to meet mission requirements [Usca]. This code also describes energy resilience as the ability to prepare for, minimize, and adapt to anticipated/unanticipated disruptions while ensuring energy availability and reliability for readiness and mission assurance [Uscb].

There is no congressional requirement or established operational need for the DoD to pursue the integration of MNRs, so active planning by the individual branches has not begun. As mentioned in Section 2.1.2, the integration of MNRs depends on when designs completion, testing, and licensing. However, there is participation in research from the DoD and related organizations. The Strategic Capabilities Office (SCO), located in the Office of the Deputy Secretary of Defense, issued contracts and expects to invest nearly $400M for preliminary MNRs designs under “Project PELE" [Str20]. These plans for 1 to 5MW(e) MNRs that use Tristructural Isotropic (TRISO) solid fuel instead of uranium oxide, which still contains HALEU enrichment but has more security concerns in mind [Eds16]. The Defense Science Board, a civilian advisory board to the DoD, produced a report that recommended that the Army be designated as the “executive agent" for the DoD being the first to integrate MNRs and demonstrate their operational use [Str20]. Although the DoD’s primary considers operational deployment of MNRs, MNR may be immediately suitable for domestic installation sustainment.

2.4.1 Current Installation Approach

The study by Marqusee et al. [Mar17] investigates over 30 domestic military bases’ energy security infrastructure. DoD installations are the largest customers to their regional utility providers, but they use the same utility infrastructure to surround customers. Also, most installations operate fleets of standalone backup generators due to control and affordability. Reliance on decentralized backup generators reduces efficiency in operations and maintenance cost while also diminishes preparedness and security. An uncoordinated response to disruptions leaves gaps in both physical and cybersecurity.

The recommended approach to addressing this from Marqusee et al. [Mar17] introduces a micro-grid infrastructure to domestic DoD installations. In comparison to the numerous small capacity (1 to 5 MW) generators located at various sites, a smaller number of larger capacity (6 to 10 MW) generators would be stationed and interconnected with each other, high capacity batteries, and the utility grid. During a disruption of the utility grid, the micro-grid would switch the base to island mode and prioritize demand to critical loads with the energy stored from battery storage and diesel generators. As previously mentioned, these microgrids can hybridize with renewable energy sources, potentially even MNRs in the future. Marqusee et al. [Mar17]’s modeling study of a hypothetical 20 MW critical load installation across regions showed that even a diesel generator only micro-grid could reduce the cost of crucial load during a disruption from $85/kW to $31/kW in the Southeast and save at least $25/kW in other regions. Although nuclear energy is not considered renewable, Nichol et al. [Nic19] discuss MNR’s potential energy savings cost in this market. MNRs do not require a lifeline like renewable and diesel sources and can sustain loads for up to 5 years without refueling. These units provide a constant supply of energy that can address energy security and energy resilience concerns of the DoD.

CHAPTER

3 MODEL METHODOLOGY

The general research methodology designs emergency grid disruption scenarios and requires critical decisions, logistics transportation, and power distribution to recover the disrupted grid. Scenarios are based on historical grid demand data of disruption events in the U.S. within the past six years. This setup permits modeling the real-time grid interaction between demand and generation in the face of recent disruptions. MNRs are then integrated into these scenarios to observe their performance as a primary DG resource during customer utility recovery. Figure 3.1 visualizes the series of models and shows how each process outputs contribute to scenario generation.

3.1 Assumptions

The following assumptions are made for the series of models applied in this research.

Case Study/Decision Strategy

1. **Known Grid Demand:** The grid demand required for recovery in each scenario is known after the 24 hours of initial impact. This situation creates a horizon between the Pre-Disruption and Post-Disruption Phases of the disruption timeline and drives the model's trade-off of decision strategies.

2. **Capacity Reshipment:** In the scenario where the initial MNR capacity shipment does not meet grid demand, an additional MNR shipment initiates in the Post-Disruption Phase. This additional shipment is additive to the MNR capacity already present in the area.

Transportation Model

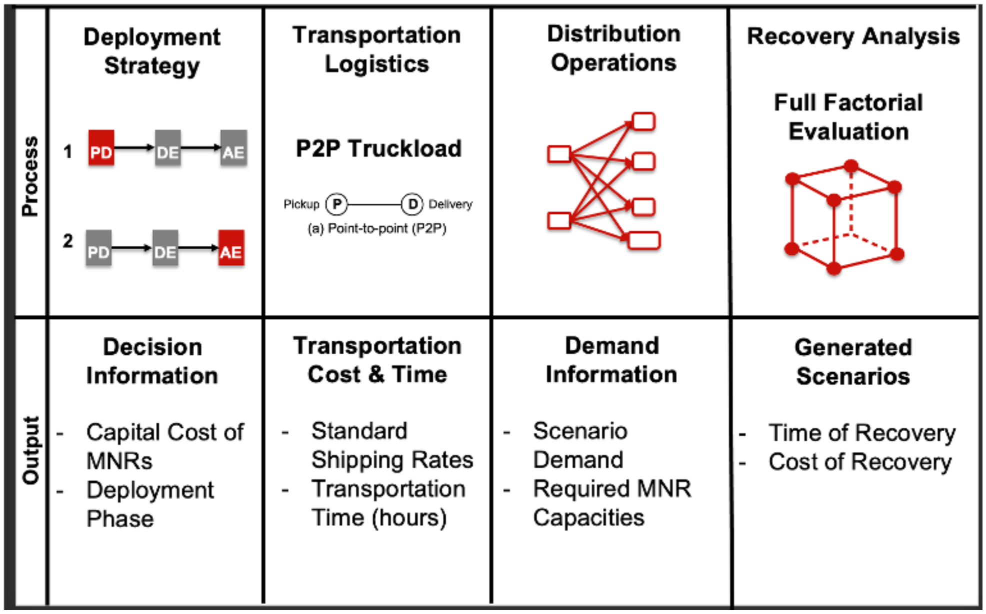


Figure 3.1 The methodology for the series of models in the research. Note: PD: Pre-Disruption; DE: Disruption Event; AE: After Disruption; P2P: Point-to-Point.

3. **Truckload Rates:** The model uses Producer Price Index (PPI) and Truckload (TL) revenue for 2004 to estimate the case study year's TL revenue. The U.S. Bureau of Labor Statistics provides the PPI database for each month and year [LS20].

4. **Transport Charge:** The transportation model confirms the transport charge before deploying MNRs from the pickup point to the delivery point. One-time shipment structures utilize this strategy in accordance with Kay [Kay19] for freight logistics.

5. **Distance and Speed:** The transportation model uses a constant speed rounded to 55 miles per hour for freight truckload carriers as reported by the U.S. Department of Transportation [Dep10]. The model uses Google Maps to find the exact road distance from the pickup point to the delivery point [Goo05].

6. **Pickup Point:** The pickup point in the point-to-point shipment model is in the city of the headquarters for Westinghouse Electric Company, Cranberry Township, Pennsylvania. The pickup and delivery points in the model only scale down to city limits.

7. **Hours-of-Service Regulations:** This model disregards the Federal Motor Carrier Safety Administration's Hours-of-Service (HOS) regulation that truck drivers drive no more than 11 hours in a 14-hour duty window [Kay19].

Distribution Model

8. **Case Study Demand:** The model uses demand during the first 24 hours of impact on the distribution model's daily demand.

9. **Individual MNR Units:** MNRs capacities range from 1 to 5 MW. Demand greater than 5 MW requires additional units that are additive towards total MNR capacity. Each unit requires a separate TL shipment.

10. **MNR Capital Cost:** Section 2.1.1 defines the total MNR capital cost as all costs required to build an electric power plant overnight. This research does not consider reducing generation cost over time from the learning curve of distribution operations.

3.2 Case Studies

The National Electricity Emergency Response Capabilities report emphasizes the typical causes of disruption events are weather-related events [Fol16]. It states from 2000 to 2014, severe weather and natural disasters account for more than 50% of grid disruptions. The exploration of grid disruption data from the U.S. Energy Information Administration (EIA) confirms this was additionally true for the last six years [Woo18]. Therefore, the case study data for this research are for natural disruption events within the past decade. Specifically, they were hurricanes and tropical storms that impacted the eastern U.S. from 2016 to 2020, causing millions of customer outages and billions of dollars in recovery damage within the past decade. Table 3.1 depicts the details of the selected case studies.

Table 3.1 Case Study Details Selected for Scenario Generation. Note: H: Hurricane.

Label	Case Study Event	Category	Disruption Date	P2P Distance	Grid Balancing Authority
1	H. Michael	5	10/11/18	615 Miles	NC Duke Energy Progress East
2	H. Irma	5	9/11/17	1157 Miles	FL Power and Light Co.
3	H. Matthew	5	10/7/16	668 Miles	SC Public Service Authority
4	H. Isaias	1	8/4/20	436 Miles	NY Independent System Operator

The case study data is retrieved from the EIA-930 U.S. Electric System Operating Database [Ene21], which collects hourly electricity input from all Balancing Authorities (BA) of the lower 48 states. This system uses an Application Programming Interface (API), seen in Figure 3.2, to easily allow users to access time-series data from the BA of each region. The data includes the hourly demand, the amount of energy customers use, and the hourly net generation, which is the energy supply from all sources. The day-ahead demand forecast is a power planning tool that helps utilities schedule the generation capacity needed a day ahead to prepare the energy generation. The database provides energy measurements as megawatt-hours (MWh), which is later divided over the distribution model's 24-hour time horizon to convert to power units (MW).

As previously mentioned, the case studies require observations of the difference between grid demand and net generation of energy during the disruption event, the unfulfilled demand. DoE's Office of Cybersecurity, Energy Security, and Emergency Response provides this information through real-time situation reports of disruption timelines [Dep18]. These federal reports provide timelines of the updated disruption event status, interactions of grid infrastructures and affected areas, and

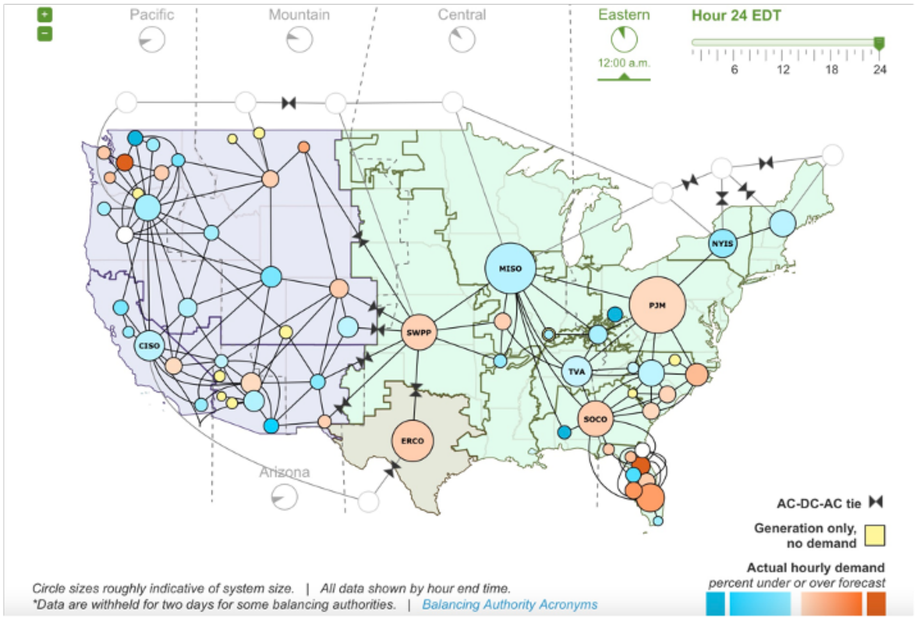


Figure 3.2 Main view of the EIA-930 API database for Balancing Authorities in the U.S. [Ene21].

estimates of the number of customers with outages. The situation reports for potential case studies were closely examined and compared with the hourly demand and generation of the local grid through the EIA database [Ene21]. A disruption event is selected when a significant change between the day-ahead demand forecast and the actual demand occurs during their timeline. This change indicates an unexpected change in the grid capabilities due to the disruption event, and the case data should be extracted for further study.

3.3 Decision Strategies

The decision strategies drive the initial timeline for MNRs use later in the model. It determines what MNR specification to deploy for emergency grid disruption response and when. The term “specification" refers to the capacity of the MNR being used, based on current state designs of MNRs described in Section 2.1.2. The initial decision influences the general time-cost trade-off that develops throughout the series of models. However, the initial trade-off in decisions begins with the amount of information known about the disrupted grid between the Pre-Disruption Phase and Post-Disruption Phase.

3.3.1 Pre-Disruption Deployment

The Pre-Disruption phase starts when a disruption event is expected and ends once the disruption event occurs. The key aspect of deploying an MNR in the Pre-Disruption phase is that the necessary capacity to fulfill the disrupted grid is unknown. Therefore, the Pre-Disruption Deployment decision has two different decision pathways that impact the subsequent recovery timeline differently. The following sections provide more details about these pathways.

3.3.1.1 Strategy 1(-)

The Strategy 1(-) decision deploys MNRs in the Pre-Disruption phase without information known about the disruption event's exact impact on the grid. This decision pathway represents the possibility of underestimating the MNR capacity required for recovery due to this unknown information. The lack of demand fulfillment occurs after the initial 24 hours of MNR support to the disrupted grid. This scenario triggers a reshipment of MNR capacity in the Post-Disruption phase that is additive to the initial MNR capacity shipped. This scenario incurs additional capital and transportation costs but delivers the necessary MNR capacity to fulfill grid demand.

3.3.1.2 Strategy 1(+)

The Strategy 1(+) decision also deploys MNRs in the Pre-Disruption phase when the grid's effect is unknown. However, this decision pathway represents the possibility of the deployed MNR capacity overestimating or equaling the demand required for recovery. Because the first shipment fulfills grid demand, there is no requirement to reship MNR capacity. The unknown demand in this deployment phase creates a cost horizon for the overestimated MNR capacity. Just as in Strategy 1(-), this strategy has the MNR set up by the grid before the disruption occurs.

3.3.2 Post-Disruption Deployment (Strategy 2)

The Post-Disruption Phase is the period after the initial 24 hours of the grid disruption event. The Post-Disruption Deployment decision only has one pathway. In the Post-Disruption phase, the grid demand is known after the duration of the initial disruption period. This scenario allows for guaranteed fulfillment of known grid demand before deciding MNR specifications. Therefore, Strategy 2 decision deploys MNRs in the Post-Disruption phase with the necessary capacity to support the grid demand.

3.4 MNR Cost Structure

The cost impact of the decisions strategies between the Pre-Disruption and Post-Disruption phases is essential because of the considerable capital cost of MNR units. The decision strategies between the Pre-Disruption and Post-Disruption phases highlight the consequences to the disruption timeline based on MNR deployment periods. These strategies also influence cost since MNR capital costs are relatively large in the model. This research adapts estimates and ranges of MNR cost from Nichol et al. [Nic19]. As mentioned in Section 2.1.1, there are limited studies that provide cost estimates for MNRs since they are still in development. Therefore, interpolated data from Nichol et al. [Nic19] formulate the cost structure of MNRs. Current studies on MNRs estimate the highest capacity of a single unit to be 5 MW [Ste17], so additional MNR units must be shipped to accommodate higher demand. The upper bound is set for four shipments of the highest capacity MNR (20 MW), and the lower bound is one shipment of the lowest capacity MNR (1 MW). Table 3.2 shows these costs in detail.

Table 3.2 Cost Structure of MNRs based on capacity and number of units. Adapted from Nichol et al. [Nic19].

MW Capacity	Cost	# of Units	
1	$10,000	1	Individual MNR Capacities
2	$12,500	1	
3	$15,000	1	
4	$17,500	1	
5	$20,000	1	
6	$30,000	2	Additional MNRs Units
7	$32,500	2	
8	$35,000	2	
9	$37,500	2	
10	$40,000	2	
11	$50,000	3	
12	$52,500	3	
13	$35,000	3	
14	$37,500	3	
15	$60,000	3	
16	$70,000	4	
17	$72,500	4	
18	$75,000	4	
19	$77,500	4	
20	$80,000	4	

3.5 Transportation Logistics

The strategy selection also provides decision information that initiates the transportation model in the emergency disruption timeline. The transportation logistics model requires only one-time truckload (TL) shipments. This model is a point-to-point (P2P) network design, where a known supplier transports freight to a known delivery point. This shipment strategy is an operational decision in transportation logistics, where the shipment size is known beforehand, and the transport charge depends on distance and rate [Kay19].

In the proposed emergency response timeline, the primary objective is to take advantage of the TL transport capabilities of MNRs to deploy MNRs quickly. The MNR dimensions and weight specifications from Arafat & Van Wyk [Ara19] meet truckload (TL) shipments specifications. The load size (ft^3) and load value ($\$/ft^3$) determine the transport cost and transport mode, respectively [Kay19]. Figure 3.3 describes this relationship for freight payloads. Appendix A discusses the payload weight and cubic capacity measurements used in the model to validate MNR for TL shipment further.

The first key output from this model is transportation time based on the averaged truck speed stated in the assumptions from Section 3.1, multiplied by the P2P distance for each case study (see

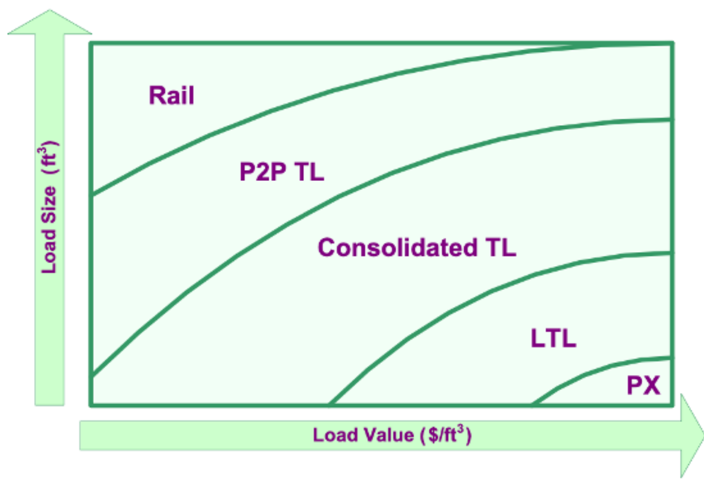


Figure 3.3 Freight Load Value versus Load Size from Kay [Kay19]. Note: P2P: Point to Point; TL: Truckload; LTL: Less Than Truckload; PX: Package Express.

Figure 3.1). The second output is the transportation charge. The transport charge calculation follows Kay [Kay19] for P2P TL shipment of MNRs with the simple

$$C_{\mathrm{TL}} = \left\lceil \frac{q}{q_{\max}} \right\rceil r d, \tag{3.1}$$

with variable definitions,

C_{TL}	Transportation charge ($),
r	TL revenue per loaded truck-mile ($/mi),
PPI_{TL}	Producer Price Index for current year ,
d	Distance from pickup to delivery point (mi),
q	Shipment weight (tons), and
q_{max}	Maximum payload (tons).

The model's transportation charge represents a single MNR delivery charge since the maximum payload for any single TL is one unit. Therefore, multiple units of MNRs required for distribution operations will incur separate transportation charges. Another changing parameter in equations 3.1 is the $\mathrm{PPI}_{\mathrm{TL}}$. This details the average revenue per loaded truck-mile for the year 2004 ($2.00/mi), and the year's $\mathrm{PPI}_{\mathrm{TL}}$ of 102.7 is used to estimate the revenue for the desired P2P shipment year. The model uses the case study year and month's $\mathrm{PPI}_{\mathrm{TL}}$ found in the Labor Statistics [LS20] archives to provide accuracy for its transportation charge.

3.5.1 Road Conditions

An additional level of evaluation in the model is the road conditions during the emergency disruption event. As mentioned in Section 3.2, the disruption events used for the model were all severe weather events, which have a likelihood of impacting transportation conditions. This factor was applied directly to the transportation model as delays in P2P delivery. Normal, intermediate, and poor are the three levels of road conditions used. Intermediate conditions represent minor damage to road networks. Poor conditions represent significant damage to the road network. However, road conditions do not impact the transport charge since they are confirmed before deployment in this logistics model (see assumptions in Section 3.1).

3.6 Power Distribution Model

The power distribution model uses MathWorks' Simscape Specialized Power Systems library and the MATLAB programming language to simulate grid operations in this study effectively. Simscape Specialized Power Systems operates in a "click-and-drag" Simulink environment. Function blocks representing physical electric components and machines are configurable without directly interacting with the underlying equations in the power system [Mat20b]. The Simscape interface builds systems of equations automatically that model these physical components when connected and makes the necessary calculations to ensure they meet power flow balance constraints [Mat20b]. For this research, the power system uses hourly grid demand data from the case studies and the capacity of MNRs as inputs to the model. A simulation method in the Simscape interface then provides output metrics to determine if the MNR capacity sustains the input demand for the specified time period.

The Simscape Specialized Power Systems tool reduces power systems' complexity when integrating transmission systems, generator and load units, and the associated operational constraints. Bacher [Bac93] further describes how the mathematical formulation of these power systems could be enormous due to many complex variables with their electrical states and magnitudes and make optimal power flow solutions challenging to solve. Consequently, this library allows the distribution model's basis on a simplified, grid-connected microgrid while still achieving practical output. A grid-connected microgrid best represents this study's distribution model because local utilities still provide power despite damaged infrastructure or lower generation capacity. The local DGs in a microgrid represent deployed and installed MNRs at the disruption site [DA20]. This research's model, seen in Figure 3.4, is modified from Mita [Mit20] Simscape Specialized Power Systems example design and adapted to integrate MNR capacity and address critical load infrastructures at the grid site. The essential modifications involved transitioning the input from hourly solar energy to MNR capacity, eliminating unneeded breakers, modifying the battery controller, and adding critical loads required for emergency response. See Appendix A for details of these changes.

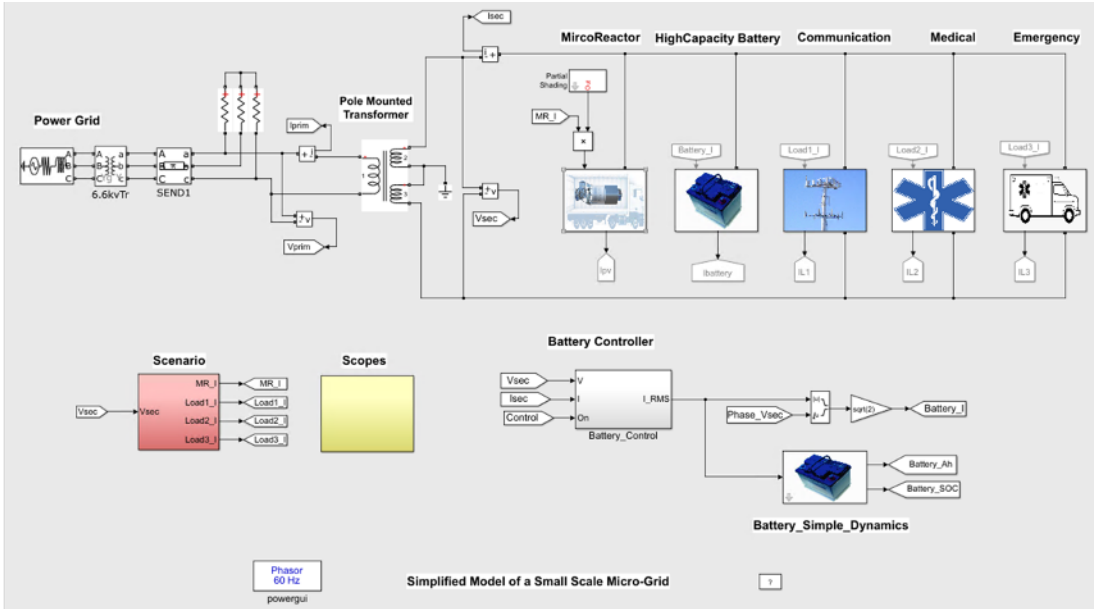


Figure 3.4 Simscape Specialized Power Systems distribution model adapted from Mita [Mit20].

3.6.1 Essential Power System Block Formulation

While the Specialized Power Systems library reduces the complexity in modeling an accurate OPF with transmission and generator/load constraints, there are some key function blocks whose underlying equations are emphasized to better understand the model. These equations and definitions are referenced from the MathWorks' documentation [Mat20a; Mat20b].

- **Power Measurement Block**

  The calculation of power at any major bus, load, or generator in the system can be taken due to the measurement blocks. This is fundamental to the function of power measurements taken over time in the model. Power measurements are taken as a function of time in any system, and is the main goal of this distribution model for determining if generation meets the demand of the customer at any time. In the system, power at time t with the step size of hours in $[0,24]$ is

$$P = \frac{V(t)}{\sqrt{2}} \times \frac{I(t)}{\sqrt{2}} \times \cos\theta, \tag{3.2}$$

$$Q = \frac{V(t)}{\sqrt{2}} \times \frac{I(t)}{\sqrt{2}} \times \sin\theta, \text{ and} \tag{3.3}$$

$$t = t + \Delta t. \tag{3.4}$$

  Active power P, in Watts, and reactive power Q, in Volt-Ampere Reactive (VAR), are primary outputs based on voltage V and current I inputs. The phase angle θ is determined by the phase difference of V and I.

- **Three-Phase Source**

  The utility grid generated power is represented as a three-phase source block. This emulates a synchronous generator machine that has controls on the active power and voltage output. The reactive power is set with no bounds. This metric is important for this block since the source generation requires balance by its internal resistance, R in Ohms, denoted by

$$R = \frac{2\pi f L}{X/R} = \frac{120\pi L}{7}. \tag{3.5}$$

  The model specifies frequency $f = 60$ Hz and ratio $X/R = 7$, which makes the internal resistance a function of inductance L at the source. This metric ensures that calculations of the internal resistance can be made at any time in the system.

- **Transmission Machines**

  The model integrates three-phase transformers for both stepping up voltage to travel far distances and stepping down voltage at the grid site, as well as transmission line models. As previously mentioned, the transmission constraints that raise complexity of OPF models are largely impacted by these transmission elements. They simplify into the resistance and inductance equations,

$$R(pu) = \frac{R(\Omega)}{R_{\text{base}}}, \text{and} \tag{3.6}$$

$$L(pu) = \frac{L(H)}{L_{\text{base}}}, \tag{3.7}$$

  where,

$$R_{\text{base}} = X_{\text{base}} = \frac{(V_{\text{n}})^2}{P_{\text{n}}}, \text{and} \tag{3.8}$$

$$L_{\text{base}} = \frac{X_{\text{base}}}{2\pi f_{\text{n}}}. \tag{3.9}$$

  The terms R, in Ohms Ω and L, in Henries (H), make transformer calculations based on its "winding". There are three windings in the distribution model as an AC power system, and the nominal values estimated are $P_n = 75000$ VA and $f_n = 60$ Hz. Accurate base resistance and inductance calculations provide output resistance and inductance for each winding that represents the voltage step-down at the local grid level. The model is consistent with Mita [Mit20] in the transmission machines not representing ideal transformers since the magnetization metrics are not zero. This simplifies the model by preventing additional parameter requirements at the transformer block and letting the Simscape interface address the transformer parameter efficiently.

- **State-space Model**

  The state-space model shows the mathematical representation of a physical power system created with the Specialized Power Systems library. It provides inputs, outputs, and state variables related to the model's first-order differential equation [Mat20a]. Even with a dynamic model design that uses generation and transmission machines, the "power-analyze" command computes an equivalent state-space structure. Equation 3.10 and 3.11 define this formulation for a functioning circuit or grid. Let **A**, **B**, **C**, and **D** represent output matrices with dimensions equivalent to states, inputs, and outputs in the circuit. Next, let state vector **x** represent inductor currents and capacitor voltages, while input vector **u** represents voltage and current sources defined in the circuit. Lastly, let output vector **y** represent the output states for final current and voltage measurements over time t. These variables define the state-space equations given by

$$\dot{x} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}, \text{and} \tag{3.10}$$

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{D}\mathbf{u}, \tag{3.11}$$

  where,

$$\dot{x}(t) = \frac{d}{dt}\mathbf{x}(t). \tag{3.12}$$

  In this formulation, output vector $\dot{x}$ is the first-order derivative of state vector **x**, which is equivalent to state matrix **A** and **B** multiplied by their respective state and input vectors. This study uses a grid in a discrete system, where $t = k$ for $k = 24$ hours. Appendix A provides more details about the mathematical formulation of the state-space input and output matrices for this study's grid-connected MNR microgrid. As previously described in Section 3.6, this state-space formulation for generation models results in large matrix outputs. However, phasor simulation in Simscape generates the output needed to evaluate MNRs in power distribution.

3.6.2 Power System Simulation

The state-space formulation shows that all components and their underlying constraints are linear despite the power system's extensive mathematical formulation. Therefore, Simscape Specialized Power Systems can use the phasor solution method to simulate the read-in demand and MNR capacity data for 24 hours. The phasor method solves larger generation power systems by focusing on the magnitude, current, and voltage changes over the evaluation period. It computes these metrics as phasors, complex numbers representing sinusoidal voltage and current equations in a constant frequency. Phasor methods ignore the electrical states and the sizeable mathematical representation from the state-space and solve the algebraic equations over the set model time-period. The output is a time series plot of simulation metrics used to determine MNR suitability. The battery-controlled state of charge (SOC) status determines whether an MNR capacity is feasible for a case study demand input. This block is modified to only operate as a discharge unit over the simulation period. Although the MNR power output is constant, the SOC metric discharges if MNR capacity cannot sustain it at any given hour. The simulation requires a larger MNR capacity if the SOC reaches zero with the 24 hours simulation period. Appendix A shows some of the time series outputs from simulation trials.

3.7 Scenario Generation and Evaluation

The processes mentioned above and outputs in the modeling methodology (see Figure 3.1) are lastly integrated into a recovery model. This evaluates each of the model outputs provided as a full factorial design, which uses every combination of case study, strategy, demand factor, and road conditions. These inputs are either uncontrolled (case study demand), controlled (strategy), or magnifying (demand factor and road conditions) variables in this evaluation model. This is also referred to as the recovery analysis in Figure 3.1 because the outputs from this evaluation are recovery time, in hours, and recovery cost, in dollars. Figure 3.5 shows a high-level view of the pseudo-code.

This evaluation first records the total recovery time in the model. Time is accumulated in the model, beginning with the deployment strategy decision, and ends with the MNR capacity satisfying the grid demand. The total recovery cost is the second output of this evaluation recorded. The MNR capital cost and transportation cost drive the recovery cost. The intersection point of the output recovery time and cost and all the inputs in the factorial design for that point are scenarios. The experimental studies will analyze the trade-offs, find unique relationships with input variables, and classify the best performance of MNRs in the generated scenarios.

```
High Level Pseudo-Code for Evaluation of Scenarios
For Base Case Study Demand
        For Deployment Strategy
                For Demand Factor
                        For Road Conditions
                                Select Case Study Demand
                                Apply Demand Factor
                                Select Deployment Strategy
                                Apply Road Condition
                                MNR Power Distribution
                                Record Accumulated Time
                                Record Accumulated Cost
                        End Road Conditions
                End Demand Factor
        End Deployment Strategy
End Base Case Study
```

Figure 3.5 High-Level Psuedo-Code for the evaluation of key variables and decisions in scenario generation.

CHAPTER

4

STUDY 1: TRADE-OFF ANALYSIS

4.1 Objective

This section explores the trade-offs between cost and time of recovery in the performance of MNRs for grid disruption scenarios. Section 3.7 describes the evaluation method used to generate 288 total scenarios. Each scenario in the full factorial evaluation contains the input variables of case studies, strategies, demand factors, and road conditions, and the outputs of recovery time (hr) and recovery cost ($). This first experimental study visualizes the outputs in MathWork's MATLAB programming language [Mat21] and JMP by SAS [SAS21]. This chapter analyzes the scenario outputs, focusing on the general trade-offs between recovery time and cost based on case study scenarios. Experimental Study 1 aims to provide evidence from the initial data observations used to design experiments in Chapter 5.

4.2 Output Highlights: Recovery Cost and Time

Figures 4.1 – 4.4 visualize trade-offs between recovery time and cost in the modelled disaster timeline. They are scatter plots with recovery time, in hours, on the horizontal axis, and recovery cost, in dollars, on the vertical axis. Insights provided below.

Figure 4.1 first highlights the base case study used to generate the output scenarios. The case studies differ by point color as directed in the legend. General observations show that each case study recovery time's outputs are grouped on the horizontal axis, while recovery cost has far more variation on the vertical axis. Visually comparing the plot shows that scenarios based on H. Irma have a higher average and maximum recovery time than the other case studies. This is likely due to this case study's P2P distance of 1157 miles, which is 438 miles greater than the average P2P distance. Another insight from this plot shows a higher concentration of scenarios from H. Isaias near the maximum recovery cost of $160000. This case study requires 20 MW of MNRs for most scenarios despite the demand factor, because the net generation of power at this grid is far lower than the demand after disruption.

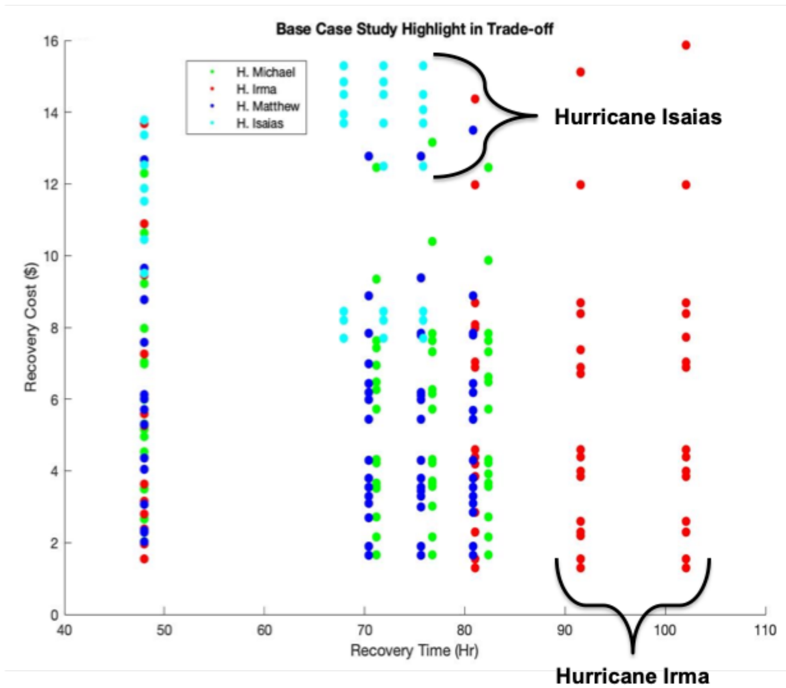


Figure 4.1 (color online) Case Study highlight of the generated output scenarios. Note: Recovery Cost in thousands of dollars ($).

Figure 4.2 provides more initial insight regarding the critical decision of deploying MNRs either in the Pre-Disruption or Post-Disruption Phase. Section 3.3 describes the two pathways possible from a Pre-Disruption deployment of MNRs. These pathways represent an underestimate for Strategy 1(-), and an overestimate for Strategy 1(+). The figure clearly distinguishes certain areas of the trade-off plot where specific strategies dominate. The majority of Strategy 1(-) scenarios are distributed higher on the recovery cost axis, while the opposite is true for Strategy 2. Both Strategy 1(-) and Strategy 2 appear to have similar recovery timelines but differ in potential cost. Strategy 1(+) has a constant recovery time grouping since a successful Pre-Disruption deployment of MNRs result in 48 hours of recovery, but there is greater variation in potential cost than Strategy 1(-).

Figure 4.3 visualizes the varying factors of impact applied to the original case study demands. The 100% demand factor represents normal grid demand after disruption impact, and the demand factors range from 25% to 200%. The general overview displays lower demand factors corresponding to lower recovery cost and vice-versa in the scenarios generated. However, this does not correspond

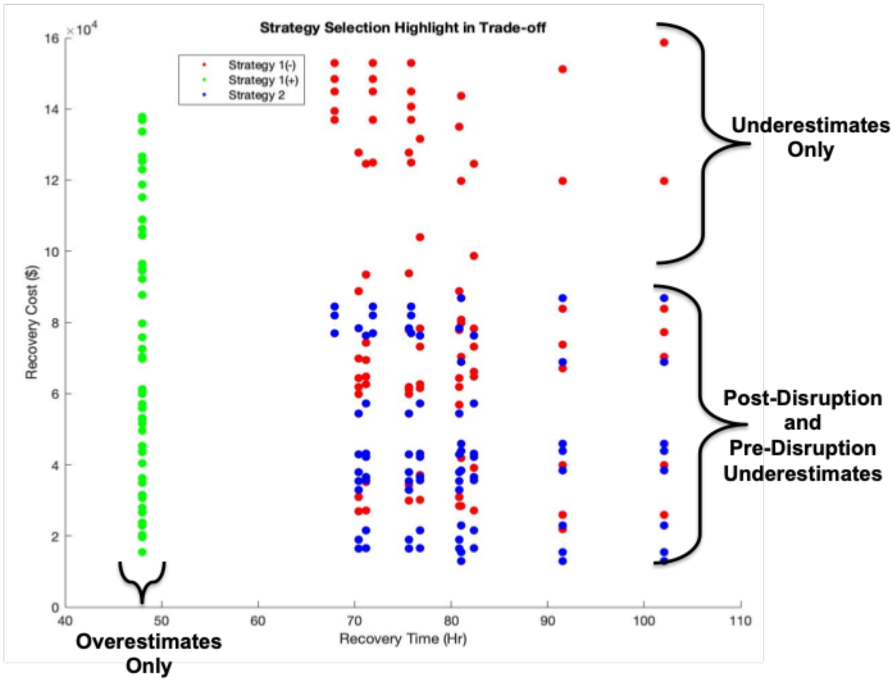


Figure 4.2 (color line) Strategy selection highlight of the generated output scenarios. Note: Recovery Cost in thousands of dollars ($)

to recovery time, where each time group has the full array of demand factors. Investigating the individual impacts of the demand factor on their subsequent inputs and the outputs will give more evidence for patterns in scenarios.

Figure 4.4 lastly shows the impact of road conditions in the scenario outputs. The initial observations of recovery time by strategy note that each case study's recovery times have time groups on the horizontal axis. Based on the evaluation model, Strategy 1(+) scenarios do not experience road condition impact since MNRs deployment occurs before the disruption timeline begins. Another insight for the other two strategies is that recovery times range from about 68 to 103 hours for the strategies that produce higher variability. More analysis of the individual scenarios will be required to deduce information from this plot.

4.3 Case Study Comparison

Experimental Study 1 specifically investigates the base case study inputs because they are the only uncontrollable factors in the evaluation setup (see Section 3.7). The Strategy input is the primary decision variable, while the demand factor and road condition inputs seek to multiply and vary the output scenarios. Therefore, they conduct multiple comparisons between each of the case study means. Mean comparison helps in the goal of determining if changes in certain inputs correspond to changes in output, which is a relationship of causality [SAS21]. This analysis uses the Tukey-Kramer Honest Significant Difference (Tukey HSD) for comparing means with similar variance. The

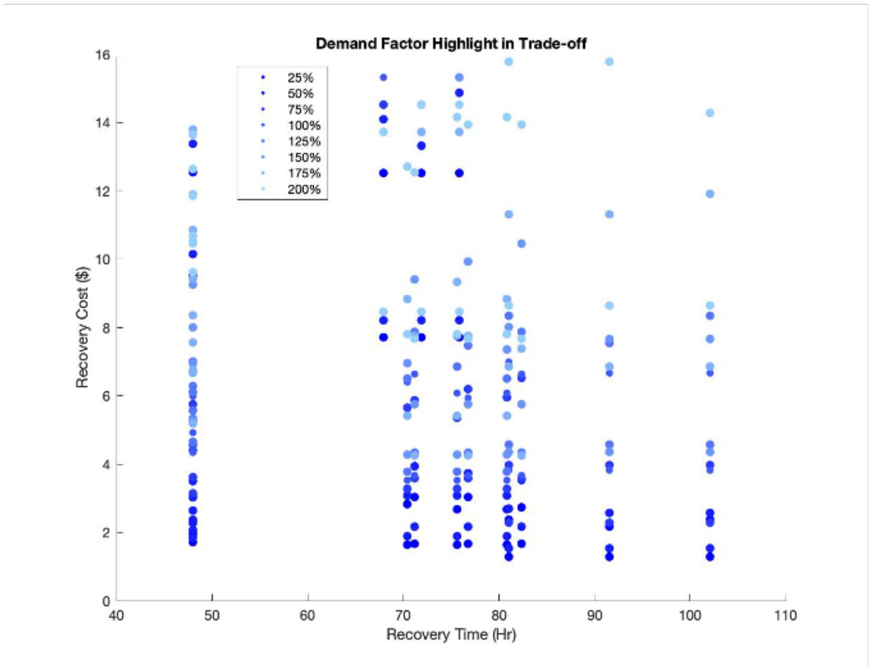


Figure 4.3 (color online) Demand Factor highlight of the generated output scenarios. Note: Recovery Cost in thousands of dollars ($)

Tukey HSD takes the differences between the factor means to test if they have significance when individually compared to the response. Figure 4.5 and Figure 4.6 depict the comparison of means for recovery cost and recovery time, respectively.

Figure 4.5 shows the results of the Tukey HSD for recovery cost and time based on historical demand case studies. The pairwise comparison of means shows that only Case Study 4 (H. Isaias) results in significant differences among mean recovery costs. This analysis highlights that Case Study 4 possibly has a different causal relationship to recovery cost than the other case studies. This may indicate that the larger mean for H. Isaias overshadows other case studies' potential effects in experimental design applications. For recovery time, the results contrast with recovery costs, where all case studies have a significant difference in means for recovery time. The recovery time output format may influence the differences since they tend to cluster based on generated scenario inputs.

Next, Figure 4.6 shows the Tukey HSD for recovery cost and time based on MNR deployment strategy. This output provides expected result based on 4.2 with the outputs highlighting deployment strategies. The output recovery cost means all have significant differences, meaning the individual deployment strategies have different effects that lead to the displayed outputs. For recovery time, the only non-significant mean differences are between the Pre-Disruption Underestimate and Post-Disruption Exact Estimate. However, these are expected to be the same since in the evaluation model, these two strategies are on the exact same recovery timeline.

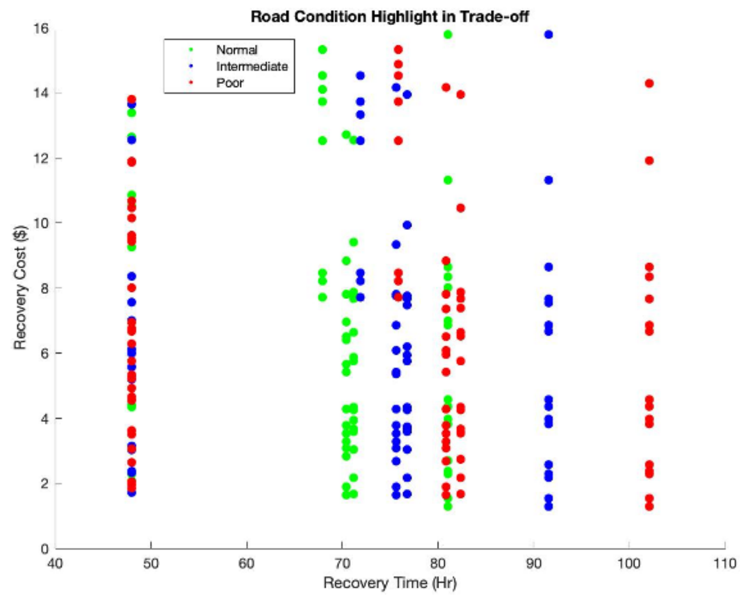
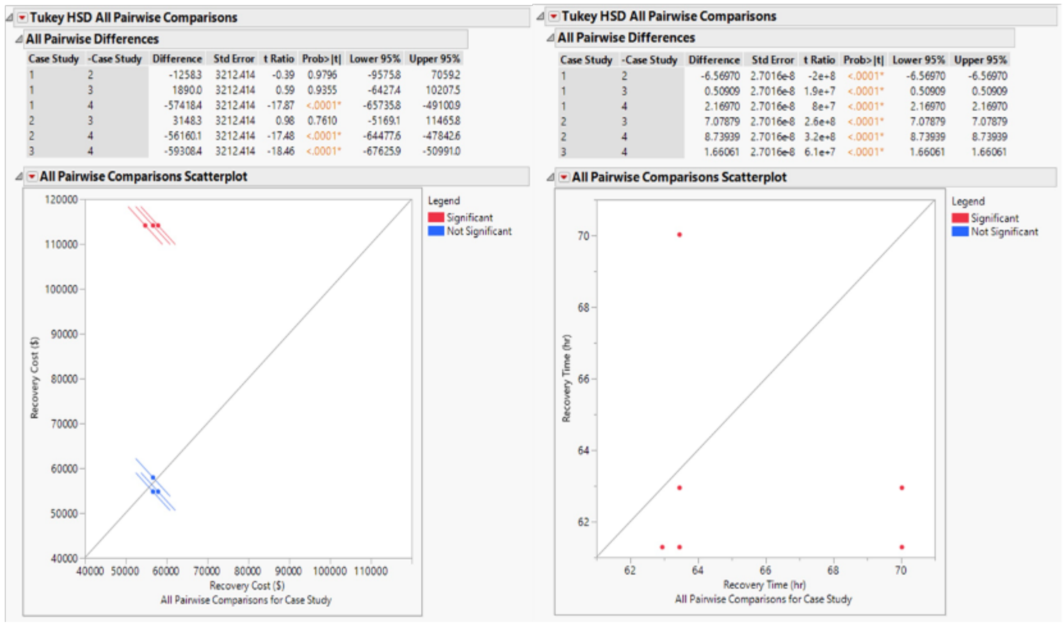


Figure 4.4 (color online) Road Condition highlight of the generated output scenarios.

4.4 Experimental Study 1 Insights

The evaluation model generates many visualizations of the trade-offs between recovery cost and recovery time among the scenarios. Experimental Study 1 speculates on these many outputs to determine how to analyze this data further, and helps reach the end-state of finding data-driven evidence towards the best scenarios of MNR performance. Therefore, this study provides insights in general and individually for each primary output.

Figure 4.2 gives insight into the specific regions where certain deployment strategies dominate. Overestimation and underestimation calculations from the Strategy 1 pathways could strengthen the case for selecting between Pre- or Post-Disruption deployment. Next, both the Figure 4.1 and Figure 4.5 highlight Case Study 4's (H. Isaias) greater recovery cost. H. Isaias' base demand starts at the upper bound of 20 MWs of MNR power for recovery, where the minimum demand factor of 25% results in 17 MWs of required capacity. This case study level may impact the effects of the other levels in the for recovery cost experiment, so omitting it from designs could provide better evidence for best performance scenarios. Lastly, Figure 4.1 also shows the maximum recovery times belong to Case Study 2 (H. Irma). H. Irma-based scenarios in poor road conditions require up to 102 hours, which is 50% greater than the average recovery time for all case studies (68 hours). Yet, Figure 4.6 describes that all mean recovery times have significant differences, so this case study may not negatively impact the other factors in recovery time experiments. Scenarios generated from case studies like H. Irma, where P2P distance is greater than 1000 miles, still may not represent the best scenario for Post-Disruption deployment. Study 2 in Chapter 5 considers these insights in its experimental design approach.



Tukey HSD All Pairwise Comparisons

All Pairwise Differences

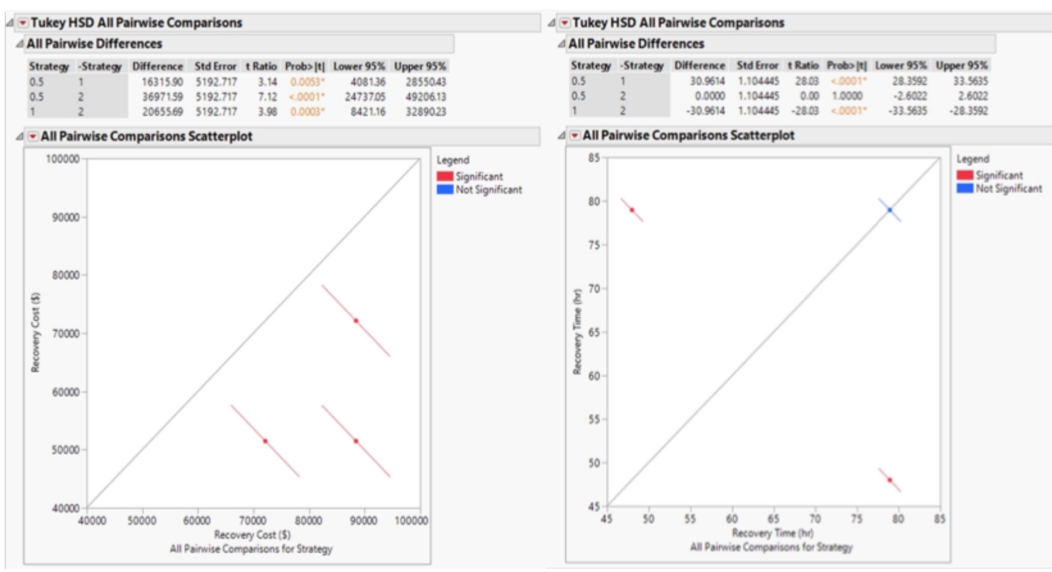
Case Study	-Case Study	Difference	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
1	2	-1258.3	3212.414	-0.39	0.9796	-9575.8	7059.2
1	3	1890.0	3212.414	0.59	0.9355	-6427.4	10207.5
1	4	-57418.4	3212.414	-17.87	<.0001*	-65735.8	-49100.9
2	3	3148.3	3212.414	0.98	0.7610	-5169.1	11465.8
2	4	-56160.1	3212.414	-17.48	<.0001*	-64477.6	-47842.6
3	4	-59308.4	3212.414	-18.46	<.0001*	-67625.9	-50991.0

Tukey HSD All Pairwise Comparisons

All Pairwise Differences

Case Study	-Case Study	Difference	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
1	2	-6.56970	2.7016e-8	-2e+8	<.0001*	-6.56970	-6.56970
1	3	0.50909	2.7016e-8	1.9e+7	<.0001*	0.50909	0.50909
1	4	2.16970	2.7016e-8	8e+7	<.0001*	2.16970	2.16970
2	3	7.07879	2.7016e-8	2.6e+8	<.0001*	7.07879	7.07879
2	4	8.73939	2.7016e-8	3.2e+8	<.0001*	8.73939	8.73939
3	4	1.66061	2.7016e-8	6.1e+7	<.0001*	1.66061	1.66061

Figure 4.5 (color online) Comparison of Recovery Cost (Left) and Time (Right) by Historical Demand Case Study. Note: 1: H. Michael, 2: H. Irma, 3: H. Matthew, 4: H. Isaias.



Tukey HSD All Pairwise Comparisons

All Pairwise Differences

Strategy	-Strategy	Difference	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
0.5	1	16315.90	5192.717	3.14	0.0053*	4081.36	28550.43
0.5	2	36971.59	5192.717	7.12	<.0001*	24737.05	49206.13
1	2	20655.69	5192.717	3.98	0.0003*	8421.16	32890.23

Tukey HSD All Pairwise Comparisons

All Pairwise Differences

Strategy	-Strategy	Difference	Std Error	t Ratio	Prob>|t|	Lower 95%	Upper 95%
0.5	1	30.9614	1.104445	28.03	<.0001*	28.3592	33.5635
0.5	2	0.0000	1.104445	0.00	1.0000	-2.6022	2.6022
1	2	-30.9614	1.104445	-28.03	<.0001*	-33.5635	-28.3592

Figure 4.6 (color online) Comparison of Recovery Cost (Left) and Time (Right) by Strategy. Note: 0.5: Pre-Disruption - Underestimate, 1: Pre-Disruption - Overestimate, 2: Post-Disruption - Exact Estimate.

CHAPTER

5

STUDY 2: SCENARIO CLASSIFICATION

5.1 Objective

This chapter conducts the different analysis methods to classify the best performance of MNRs in the generated output scenarios. The objective is to classify varying degrees of disruption conditions to determine appropriate MNR response strategy and specifications. The analysis bases its approach in the design of experiments (DOEs) in SAS's JMP software [SAS21]. The DOE emphasizes the outputs recovery time and cost as "responses" influenced by the input "factors" of the evaluation model. The DOE prioritizes the individual factors that impact response while also optimizing the analysis to reach a specified goal (i.e., maximize, minimize, or target). Experimental analyses seek to find causality and prove model adequacy by reducing bias in its prediction of future values [Har20]. Therefore, this chapter presents supporting evidence for model adequacy along with the DOE results. This experimental study addresses the research question of what specific disruption scenarios contribute to the best MNR performance.

5.2 General Regression Models

The first step in analysis requires a general regression fit model for both of the responses: recovery cost and time. This fit produces output models for recovery cost and recovery time with the impact of all individual factors. The "factorial sorted" option fits this design by additionally generating the effects of all factor interactions up to the four-way interaction between inputs. Table 5.1 displays the categorization of factors in these analyses.

The initial fit model's goal is to understand the initial factor effects for each response and then

Table 5.1 Table of factor categories for general fit in JMP.

Input	Factor Type	Description
Case Study	Categorical	Discrete inputs with no relation between factor levels
Strategy	Categorical	Discrete inputs with no relation between factor levels
Demand Factor	Continuous	Specified upper and lower limits
Road Condition	Ordinal	Discrete inputs with relation between factor levels

observe the desirability function for multiple responses. A desirability function optimizes all input factor settings to reach an ideal response through maximizing, minimizing, or targeting a value [NIS13b]. Desirability (D) ranges 0 to 1 inclusively, where values approaching 1 have the highest desirability. Equation 5.1 depicts the minimization desirability function used for these analyses. In this model with multiple responses, a 2D prediction profiler determines the combination of input factors that maximizes desirability as

$$d_i\,Y_i = \begin{cases} 1 & \text{if } Y_i(x) < T_i \\ \frac{Y_i(x)-U_i}{(T_i-U_i)^s} & \text{if } Y_i(x) > U_i \\ 0 & \text{if } Y_i(x) > U_i \end{cases} \tag{5.1}$$

where

$d_{\mathrm{i}}\,Y_{\mathrm{i}}$ = Desirability, $d_i\,Y_i \in [0,1]$;

$Y_{\mathrm{i}}(x)$ = Input response in the DOE model;

T_{i} = Target value in desirability;

U_{i} = Upper bound of responses; and

s = Importance ($s = 1$).

5.2.1 Results: Regression Model

Figure 5.1 depicts the initial regression fit for the 288 response outputs of recovery cost and time using the factorial sorted option. Overall, the fit models provide more details about the recovery cost response than recovery time. As previously mentioned in Section 4.4, the output of recovery time in a time bucket format may limit initial statistics. The recovery cost fit model provides evidence linearity (Adjusted $R^2 = 0.918$), and a significant F-Test supports that factor coefficients are the source of it. This F-test statistic tells that Case Study, Strategy, and Demand Factor inputs, and some of their interactions, drive the regression model's fit and the causal relationship to the response. The high number of samples builds a strong relationship between the factors and response so that the residuals will give insight into model adequacy.

Figure 5.2 displays the residuals by predicted plot. This plot shows slight heteroscedasticity in the residual, meaning that the residual data variance changes as prediction values increase. It is

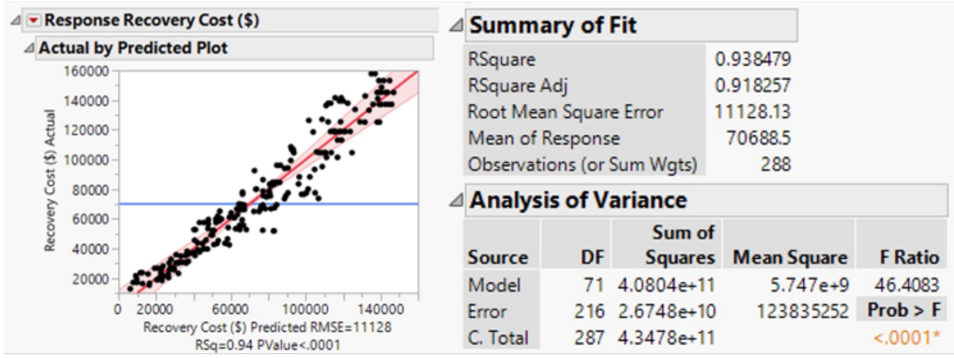


Figure 5.1 General fit model and statistics for Recovery Cost response.

only present towards the lower prediction values, but its presence challenges the assumption of constant variance in a regression model. Heteroscedasticity implies that a potential factor transformation could improve the model. The model improvement involved fitting natural logarithmic transformation to the base factors. This transformation show that both case study and demand factor inputs contribute to the heteroscedasticity. This transformation is not carried over into the DOE because this regression analysis aims to understand the base factor effects from the evaluation method, and enough evidence of normality is present in the other residuals plots.

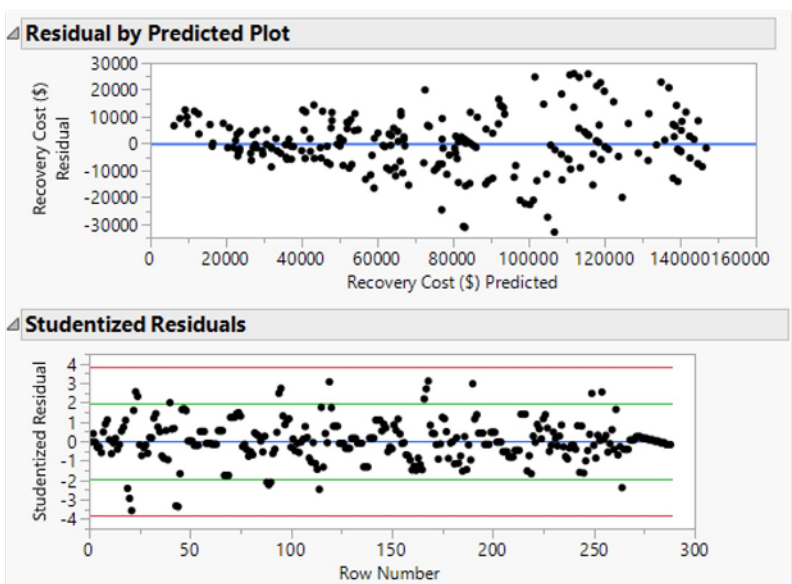


Figure 5.2 General fit model residuals for Recovery Cost response.

Although the recovery time model fits a biased regression and residual statistic, it still identifies active factors in the response. The half-normal plot in Figure 5.3 depicts these significant factors with labels. A half-normal plot identifies factors whose normalized estimates are greater than the normalized mean of the sample distribution [SAS21]. This plot labels all the input factors and even a two- and three-way interaction as significant, except for Demand Factors. This analysis distinguishes significant factors, enabling their use for multiple response observations within the recovery cost. The JMP prediction profiler tool in Figure generates the desirability function for multiple responses based on the same input factors. The desirability goal is minimization, where desirability increases as response values decrease. Figure 5.4 also shows the highest desirability in the prediction profiler as $D = 0.961$ under factor settings Case Study = 2 (H. Irma), Strategy = 1(+), Demand Factor = 0.25 (25%) and Road Condition = 2 (Intermediate - but no impact on recovery time).

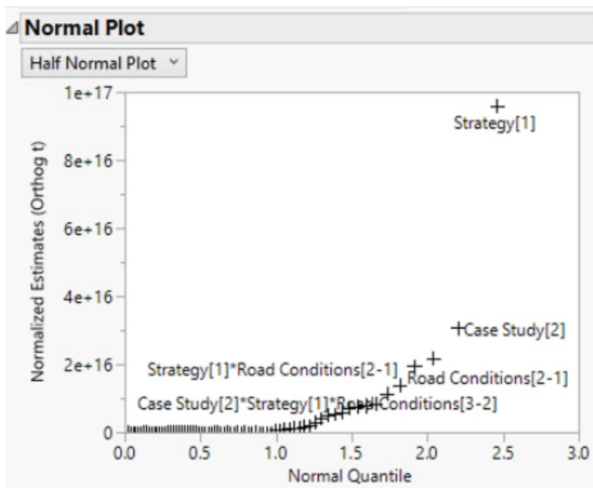
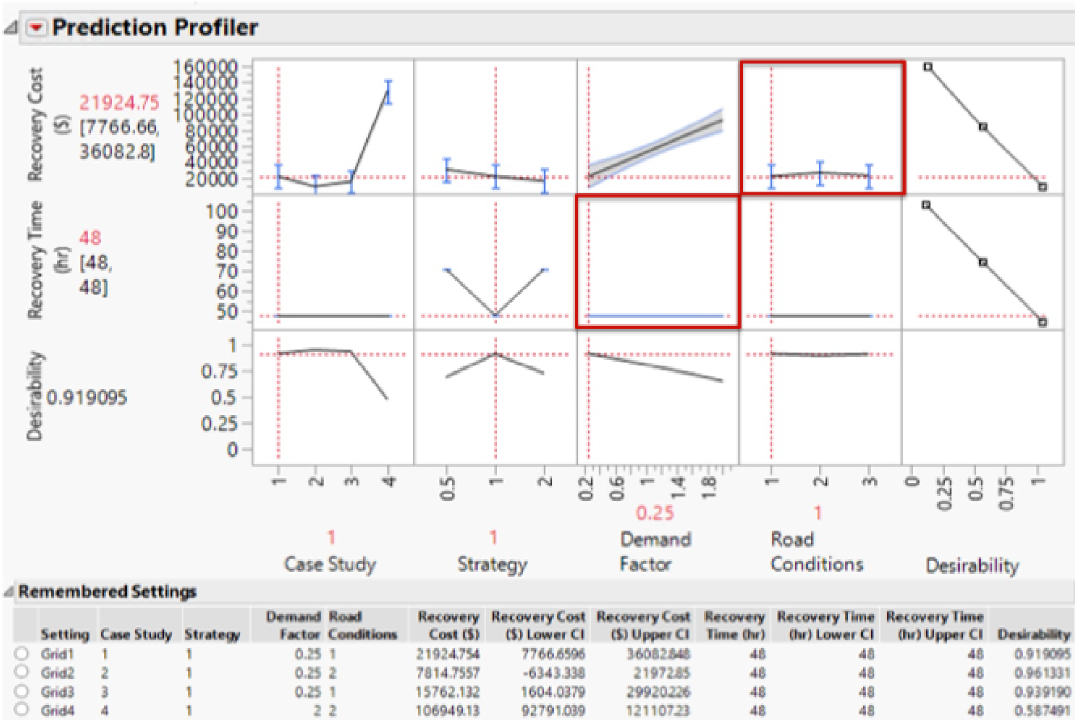


Figure 5.3 General fit model residual for Recovery Time response.

Figure 5.4 then provides the maximum desirability for each case study. Case Study 4 with H. Isaias falls far below the other case studies' desirabilities ($D = 0.587$). This scenario follows the insights provided in Experimental Study 1, which claims H. Isaias generated case studies may not represent the best scenario for MNRs. These initial fit model results help in the individual response analysis by using DOEs to obtain more accurate models and screen the data to estimate specific effects.

5.3 Full Factorial Design

The JMP platform offers multiple DOE options for users. In this analysis, a full factorial design best fits the experimental design objectives. A full factorial has a screening objective in design, which is to "screen out" or select the factors that have the most impact on models [NIS13a]. These factors are the main effects that the DOE distinguishes and estimates for significant impact. The DOE screens the responses separately to investigate specific main effects within the factors. It also codes factors if continuous (range $[-1,1]$) or categorical ($L1, L2, \ldots, Ln$) to increase the efficacy of parameter estimates [SAS21]. Residuals also provide evidence of model adequacy and are used to



Setting	Case Study	Strategy	Demand Factor	Road Conditions	Recovery Cost ($)	Recovery Cost ($) Lower CI	Recovery Cost ($) Upper CI	Recovery Time (hr)	Recovery Time (hr) Lower CI	Recovery Time (hr) Upper CI	Desirability
Grid1	1	1	0.25	1	21924.754	7766.6596	36082848	48	48	48	0.919095
Grid2	2	1	0.25	2	7814.7557	-6343.338	2197285	48	48	48	0.961331
Grid3	3	1	0.25	1	15762.132	1604.0379	29920226	48	48	48	0.939190
Grid4	4	1	2	2	106949.13	92791.039	12110723	48	48	48	0.587491

Figure 5.4 Prediction Profiler and Desirability for both responses.

refine run iterations. The DOEs for each response aim to distinguish and estimate the factors and interactions that significantly affect the response. This goal then transitions to again finding the maximum desirability of the response based on all input factors. The DOE also assesses desirability for every combination of factors and leverages it to visualize best MNR performance scenarios further.

5.3.1 Results: Recovery Cost DOE

The previous Section 5.2 demonstrates evidence that Road Conditions have insignificant interactions with other inputs and the response of Recovery Cost. With this insight, DOE contains a $4 \times 3 \times 8$ level setup for case studies, strategies, and demand factors, respectively. Additionally, insights from both the previous Section 5.2 and Chapter 4 show that Case Study 4 (H. Isaias) is an outlier parameter estimate with low variation in mean cost. It implies this factor level may not influence the model's overall trend besides providing additional output points. A second DOE, the adjusted model, compares to this first model by removing the Case Study 4 categorical level (DOE now $3 \times 3 \times 8$). Figure 5.5 depicts the critical output comparison between these models.

The $4 \times 3 \times 8$ DOE contains some expected statistical and parameter estimate effects due to more observations and response means from Case Study 4 (H. Isaias). First, it has a higher adjusted R^2 (0.92) than the adjusted model ($R^2 = 0.87$) due to 24 additional observations. It also emphasizes more factors as significant drivers of cost given the higher mean difference in case study recovery

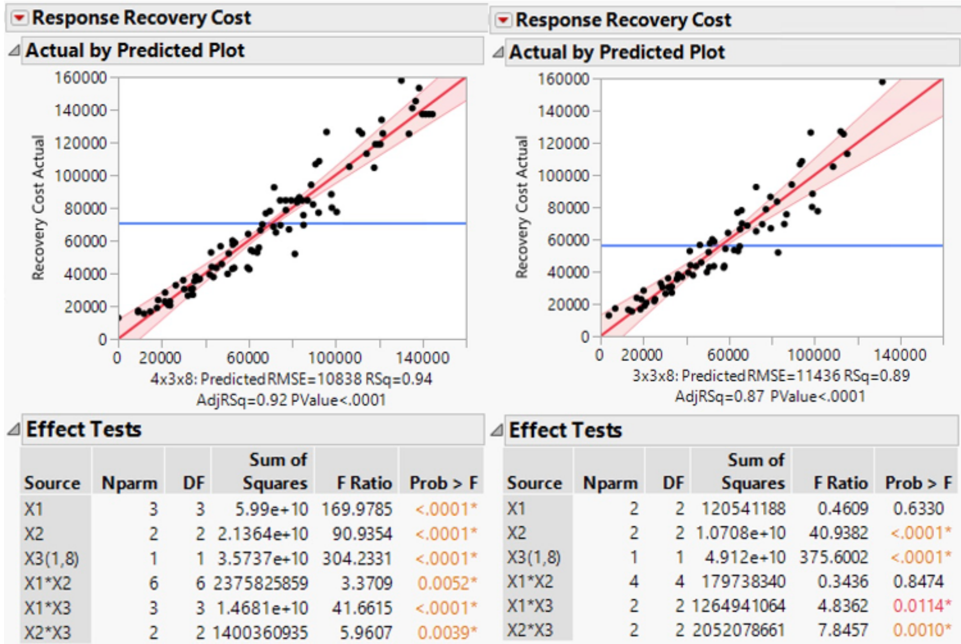


Figure 5.5 Comparison of the original (left) and adjusted (right) DOE setup for Recovery Cost analysis. Note: X1: Case Study; X2: Strategy; X3: Demand Factor.

costs. The adjusted model provides better insight since it no longer compares the case study factors to the outlier level. This model enhancement contributes to the maximized desirability $D = 0.901$, with Case Study = 2 (H. Irma), Strategy = 2 (Post-Disruption Exact Estimate), and Demand Factor = 0.25 (25%).

The DOE setting for prediction profilers also calculates desirability for every input combination of factors. Figure 5.6 visualizes this as a contour plot that identifies higher desirability regions by recovery cost. This plot separates the three strategies and shows the density of scenarios generated relative to the desirability and recovery cost. The contours display a similar trend with desirability increasing as recovery cost decrease, but the key insight comes from comparing these strategies. Strategy 2 has the smallest range of desirability, while Strategy 1(-) has the largest. It indicates that Strategy 2 leads to the lowest variability in recovery cost and the highest chance of a desirable solution.

5.3.2 Results: Recovery Time DOE

Section 5.2 also gives evidence that the Demand Factor has an insignificant impact on Recovery Time. The DOE contains a $4 \times 3 \times 3$ level setup for the factors case study, strategy, and road conditions (demand factor set at normal grid conditions). Figure 5.7 provides some of the statistical results of the DOE model without any modifications. The half-normal plot continues to be a better representative of parameter impact due to categorical bias in the linear fit. This DOE produces a residual plot for recovery time, but it contains prediction points outside of the 95% limit that challenges the

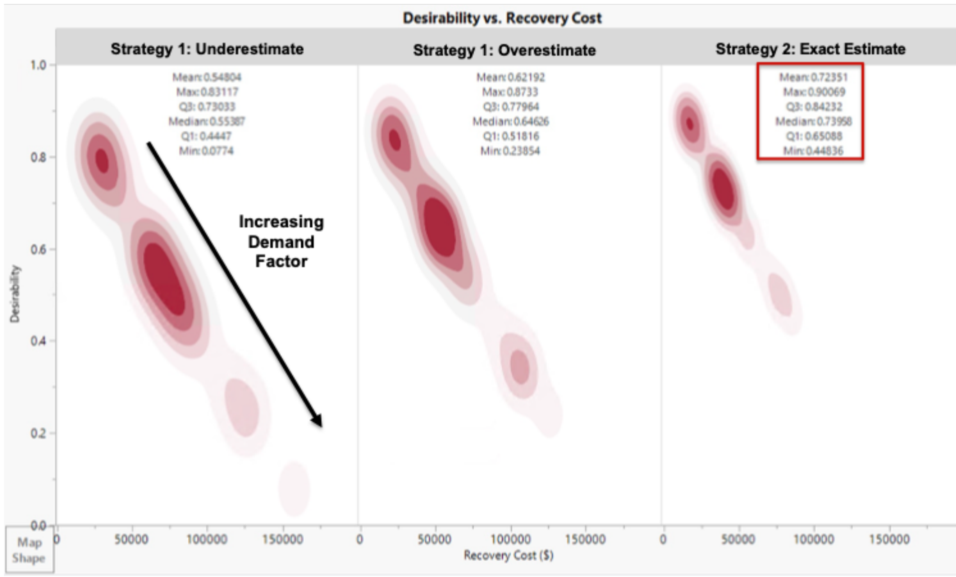
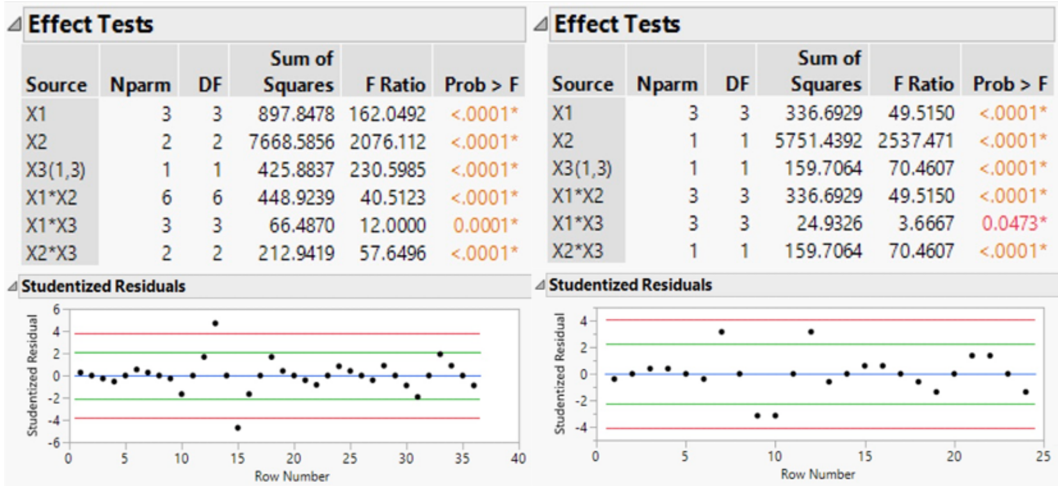


Figure 5.6 Contour plot showing the density of scenarios when measuring desirability against Recovery Cost for each strategy. Post-Disruption Exact Estimate contains the highest mean and smallest range of desirabilities. This indicates deployment strategy provides a greater opportunity of obtaining a desirable solution for Recovery Cost.

basic model assumptions. The results also provide little distinction in parameter estimates, creating further motivation to search for improvements in the DOE.

Unlike the Recovery Cost DOE, there are no individual factor levels that inversely impact the model. However, further model adjustments allow a more detailed investigation of the response variation limits in recovery time. The Pre-Deployment Strategy 1(-) pathway produces the exact or overestimates required MNR capacity, which results in the lower-bound recovery time (48 hours) based on the model methodology (Section 3.3. Additionally, Strategy 1(-) and Strategy 2 recovery time outputs have the same timelines since recovery occurs in the Post-Disruption Phase. Therefore model adjustments involved removing one level of the strategy factor to only compare Strategy 1(+) for the lower limits and Strategy 2 for the upper limits of recovery cost. This adjusted model has a $4 \times 2 \times 3$ level setup, and Figure 5.7 also shows the analysis results.

The adjusted model produces better residual plots and distinguishes parameter estimates better than the original design. The improvements allow for the maximizing of desirability in the prediction profiler. This produces $D = 0.871$ from Case Study = 2 (H. Irma), Strategy = -1 (coded for Strategy 1(+)) and Road Condition = 1 (Normal). The DOE prediction profiler calculates the desirability for every factor combination and visualizes the contour plots of desirability for recovery time. Figure 5.8 attempts to make the same comparison as conducted with Recovery Cost when based on strategies. However, the format of the output for Recovery time leads to inconclusive visualizations. The Pre-Disruption Overestimate, Strategy 1(+), always leads to 48 hours of recovery, and the Pre-Disruption Underestimate and Post-Disruption Exact Estimate have the exact same recovery timelines. Figure 5.9 separates the outputs by case study since the strategies are distinguishable



Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
X1	3	3	897.8478	162.0492	<.0001*
X2	2	2	7668.5856	2076.112	<.0001*
X3(1,3)	1	1	425.8837	230.5985	<.0001*
X1*X2	6	6	448.9239	40.5123	<.0001*
X1*X3	3	3	66.4870	12.0000	0.0001*
X2*X3	2	2	212.9419	57.6496	<.0001*

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
X1	3	3	336.6929	49.5150	<.0001*
X2	1	1	5751.4392	2537.471	<.0001*
X3(1,3)	1	1	159.7064	70.4607	<.0001*
X1*X2	3	3	336.6929	49.5150	<.0001*
X1*X3	3	3	24.9326	3.6667	0.0473*
X2*X3	1	1	159.7064	70.4607	<.0001*

Figure 5.7 Results for the original (left) and adjusted (right) DOE setups for Recovery Time. Note: X1: Case Study; X2: Strategy; X3: Road Condition.

within the contour plot. These visuals show that only H. Irma, Case Study 2, has a significant difference in output statistics. This insight corresponds to the DOE analysis of H. Irma, having the highest significance for this factor. However, H. Isaias has the highest mean desirability and the smallest range. This plot indicates that the scenarios result in a more desirable solution in terms of recovery time. Although the nature of the recovery time response contributes to limited analysis, this adjusted DOE provides enough insights for discussion in Chapter 6.

5.3.3 Experimental Study 2 Insights

This chapter approaches best scenario classifications by first understanding how all factors interact with multiple responses and each other. This general fit model provides initial statistics for a linear model highlighting certain factor characteristics, such as factors with no impact on the response. This information helps create DOEs for the individual responses and their main factors that influence them. Further model adjustment narrows down the key insights that the DOEs provide about the causal relationship between factors and the experiments' responses. Lastly, a desirability function minimizes the output response and shows input factors generate the best scenarios. This entire analysis process produces a couple of best performance scenarios for MNRs discussed in Chapter 6. Figures 5.6 and 5.9 provide the best visualizations for the desirable scenarios. In both figures, the mean and quantile range for each of the categories differ. Despite the response, the contours with a higher mean and smaller range represent a greater opportunity for desirable solutions.

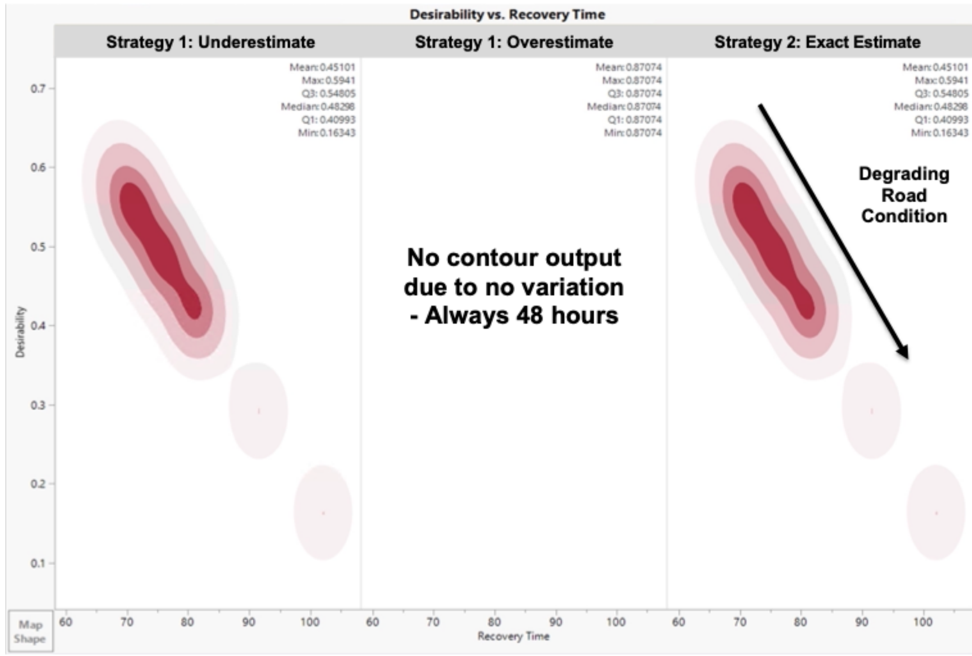


Figure 5.8 Contour plot showing the density of scenarios when measuring desirability against Recovery Time for each strategy. No variation in the Pre-Disruption Overestimate, and the same timelines between the Pre-Disruption Underestimate and Post-Disruption Exact Estimate display limited conclusions from this output.

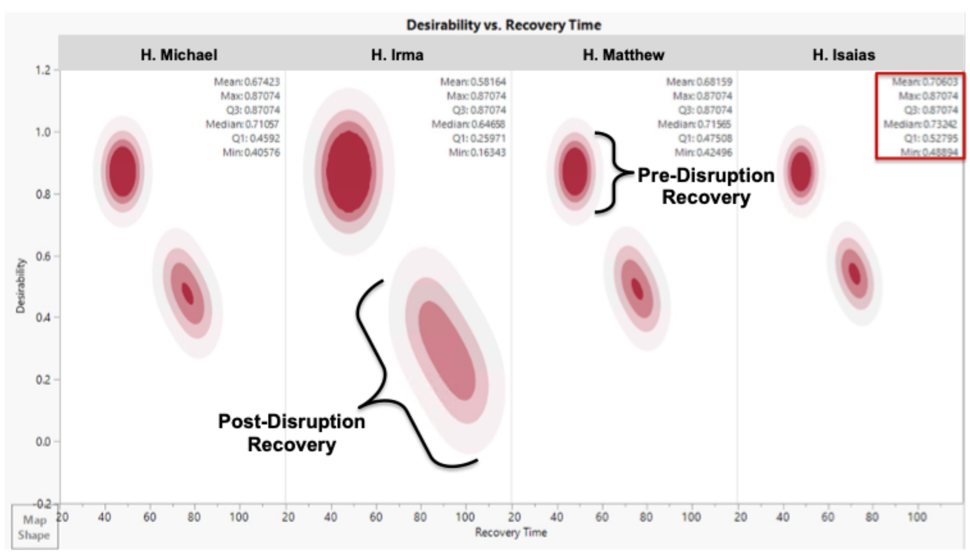


Figure 5.9 Contour plot showing the density of scenarios when measuring desirability against Recovery Time for each case study. H. Isaias contains the highest mean and smallest range of desirabilities. This indicates Isaias scenarios have a better of obtaining a desirable solution for Recovery Time.

CHAPTER

6

CONCLUSION

6.1 Main Conclusions

The goal of this research is to design an emergency response model that utilizes MNRs for recovery operations and identifies scenarios of best performance. Scenarios base their grid demand on real-world input from regional balancing authorities, while other controllable factors provide variety in the scenario outputs of recovery cost and recovery time. Overall, this emergency logistic model integrates critical decision strategies, transportation logistics, and power distribution to generate multiple scenarios. Table 6.1 summarizes the findings from this research's experimental studies. This chapter answers the primary research questions, "What scenarios do MNRs perform the best in for emergency grid disruption?"

Experimental Study 1 findings focused the search for what conditions for severe disruption events in the case studies affect the deployment decision strategies. This search shows the average difference in grid demand and net generation, which is the unfulfilled demand, contributes to the MNR capacity required and primarily drives recovery cost. The P2P distance to the disrupted grid site contributes to longer recovery times if any Post-Disruption MNR deployment occurs. Among the case studies used, Case Study 4 (H. Isaias) contains an outlier for average unfulfilled demand (2502 MWh), and Case Study 2 (H. Irma) contains an outlier value for distance (1157 miles). These conditions are not ideal for MNR deployment since they drastically increase recovery cost and time. Therefore, Figure 6.1 depicts the analysis-driven recommendations for deployment strategies based on these case study conditions. This strategy selection plot shows unfulfilled demand on the vertical axis and P2P distance on the horizontal axis using the average of the non-outlier values from each case study and expressing it as the median value of decision points on the plot. Figure 6.1 shows

Table 6.1 Table of research objectives and their conclusions.

Research Objective	Conclusion
Explore recovery cost and time trade-offs in generated scenarios	▪ Strategy selection should depend on case study conditions ▪ H. Isaias case study demand leads to impractical recovery cost ▪ H. Irma case study distance leads to impractical recovery time
Classify varying degrees of disruption conditions for best MNR use	▪ Scenarios have similar patterns for recovery cost/time desirability when based on strategy and case study, respectively ▪ Smaller ranges in recovery cost/time leads to greater opportunity of a desirable solution

Pre-Disruption deployment (Strategy 1) is best for scenarios with smaller demand requirements despite the P2P distance. The chance of underestimating demand is smaller when that unfulfilled demand is lower than 280 MWh, leading to grid recovery within 48 hours based on the research's models. Post-Disruption is best for higher demand expectations since it is costly to underestimate MNR capacity past the 280 MWh median point. This strategy deploys MNRs in the Post-Disruption phase, so a P2P distance less than 573 miles would create a more desirable scenario. If both the unfulfilled demand and P2P distance are past the median points, the grid conditions do not favor MNR for emergency response.

Experimental Study 2 provides data-driven results that directly answer the research questions. Table 6.2 describes this with the maximum desirability values for each of the analyses conducted and displays scenarios with the best performance and their corresponding recovery costs and times. The the optimal combination of input factors in each DOE produce the maximum desirability values are $D = 0.901$ for recovery cost and $D = 0.871$ for recovery time. However, JMP also provides this calculation when considering both responses. This desirability function calculates $D = 0.93$. The model also calculates desirability when grid conditions are normal (demand factor = 1) since this reflects the real-world demand values for case studies, where $D = 0.845$. The overall trend of best performances reveals that scenarios with an exact or overestimate in the Pre-Disruption strategy lead to the most desirable solutions. This finding aligns with expectations from the first study since Strategy 1 always results in a 48-hour recovery period. Also, the chance of a drastic overestimation of MNR capacity is uncommon when the unfulfilled demand is close to the non-outlier case studies' average. If the DOE analysis focused only on recovery cost, the Post-Disruption strategy gives desirable solutions.

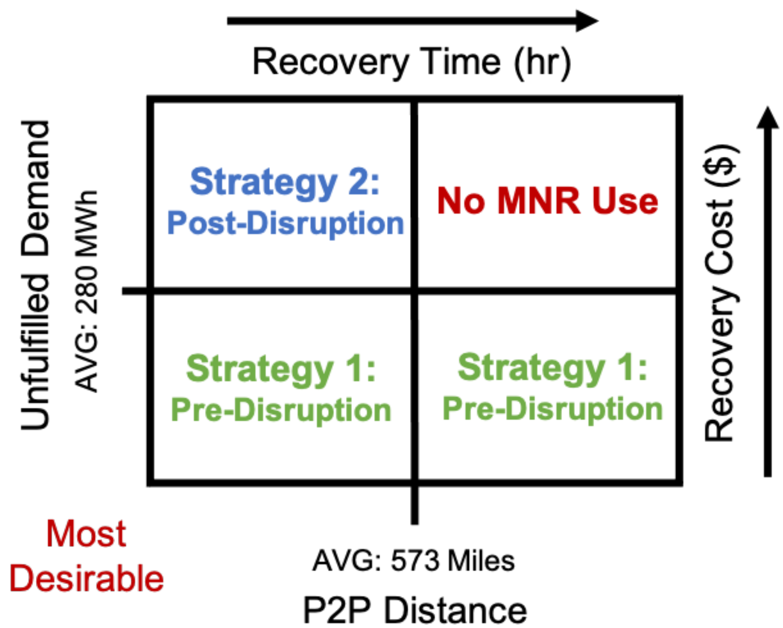


Figure 6.1 (color online) Strategy selection recommendations based on case study characteristics.

6.2 Limitations

The several limitations within this study are discussed below.

1. **Limited Literature.** MNRs have little scholarly literature that models their operational use in potential markets. Most MNR literature discusses their characteristics and future markets without any applied methods. MNRs also possess different properties from normal DGs that limit model comparisons. Therefore this research addresses the operational use of MNRs with specific modeling methods with limited literature as its basis.

2. **Case Studies.** The four base case studies provide real-world elements to the modeling methods and scenario generation. However, a greater variety of case studies would have improved the model and potential outcomes. The EIA-930 database has a limited number of balancing authorities that retrieve data. The selected case studies fit the narrow criteria discussed in Section 3.2, and were the only case studies screened in the interest of time.

3. **Power Distribution Modeling.** MATLAB's Simscape Specialized Power Systems Library provides the necessary power distribution modeling to confirm MNR support for disrupted grids. This modeling, however, limits the range of time output metrics in other parts of the model. Specifically, the phasor simulation in Simscape evaluates MNR grid operations over a fixed 24 hour period instead of a continuous-time horizon. This simulation method constrains the power distribution model to specific time blocks and limits the recovery time variation.

Table 6.2 Table of best performance scenarios for MNRs seen throughout the study. Note: CS: Case Study; St: Strategy; DF: Demand Factor; RC: Road Condition.

Best MNR Performances			
Analysis Type	**Desirability**	**Recovery Cost & Time**	**Factors**
General Fit Model (All Scenarios)	0.961	$12,852 | 48 Hours	CS = 2 | St = 1(+) | DF = 0.25 | RC = 2
Recovery Time DOE	0.871	$60,007 | 48 Hours	CS = 2 | St = 1(+) | DF = 1 | RC = 1
Recovery Cost DOE	0.901	$12,852 | 81 Hours	CS = 2 | St = 2 | DF = 0.25 | RC = 1
Multiple Response	0.930	$17,138 | 48 Hours	CS = 2 | St = 1(+) | DF = 0.25 | RC = 1
Multiple Response (Normal Demand)	0.845	$43,395 | 48 Hours	CS = 3 | St = 1(+) | DF = 1 | RC = 1

The knowledge gap in electrical modeling prevented other approaches to power distribution modeling.

6.3 Future Work

Recent disruption events, such as the 2020 Wildfires in California or the 2021 Polar Vortex in Texas, stress the importance of having a reliable and resilient grid infrastructure. Regional and federal authorities recognize disruption events are incoming during the Pre-Disruption phase but lack the necessary resources to ensure customers' reliable utilities. Section 2.1.1 describes the many applications for MNRs, where their portability and small MW capacities are a better solution to emergency backup power than industrial diesel generators. As MNR development progresses, more literature should focus on modeling their DG capabilities for future markets.

Previously discussed studies from Krishnamurthy & Kwasinski [Kri19] provide insight into potential methods to evaluate DG performance and resilience in the face of disasters. Krishnamurthy & Kwasinski [Kri19] uses discrete event modeling for disaster events and refuelling of diesel generators to support local loads. Their findings show DG resiliency relies solely on capacities of the generators and energy storage. Fuel DGs however contrast to MNRs, which have lifetimes of 1 to 5 years between core refuelling. MNRs in this modeling setup would need additional study to understand their resilience in these circumstances. Using this discrete event setup to evaluate MNR operations has potential for providing more variation in the grid recovery time than the methods used in this research, where the grid operations could only be evaluated over 24 hours. Reviewing this literature

Additional recommendations for future work first would be to further modify the Simscape model used for this research. The researcher was limited in the electrical engineering concepts needed to design a more comprehensive grid-connected microgrid model used from the Simscape Specialized Power System Library. This comprehensive model, integrated into the emergency MNR deployment designed in this research could increase value of the findings. Another future work recommendation applies this research directly to domestic military installations. Domestic military installations are susceptible to natural or man-made disruption events like other grids and do not possess organized energy systems for a proper response [Mar17]. Future work in this area would require obtaining specific balancing authority information for grids connected to installations when using this research's methods. Although screening installation demand data will be more challenging, a military installation case study's potential insights could help address these domestic force sustainment challenges.

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APPENDICES

APPENDIX

A

MODEL METHODOLOGY SUPPLEMENT

A.1 Transportation Logistics

A.1.1 MNR Freight Estimates

This research takes advantage of MNR's portability through truckload transportation to quickly deploy them for emergency grid support. The calculations for the class of freight transportation is based on Figure A.1's metrics that outline payload and cubic capacities.

MNR literature reports the following specification estimates:

- Payload Weight: 35700 lbs (17.85 tons), and [Ste17]
- Cubic Capacity: 2496 ft^3 [Ara19]

These estimates meet requirements for TL transportation used in the P2P network model. The specific truck capacities were 50 tons and 3500 ft^3. The measurements also indicate that only one MNR can be shipped per TL, so multiple units require multiple transportation charges in the model.

A.2 Power Distribution Model

A.2.1 Modified Simscape Model

The Simscape Specialized Power Systems library assists in comprehensive modeling of the desired power system that uses read-in grid demand and MNR capacity. The model is an adaptation from Mita [Mit20] which presents a small scale grid-connected microgrid which possessed the generation,

	TL	LTL	PX
Minimum payload	10,000 lb	150 lb	2 lb
Average payload[12]	30,000 lb	1000 lb	10 lb
Maximum payload	50,000 lb	10,000 lb	70 (UPS) – 150 lb
Average length of haul	294 mi	752 mi	894 mi
Average value	$775/ton	$7002/ton	$37,538/ton

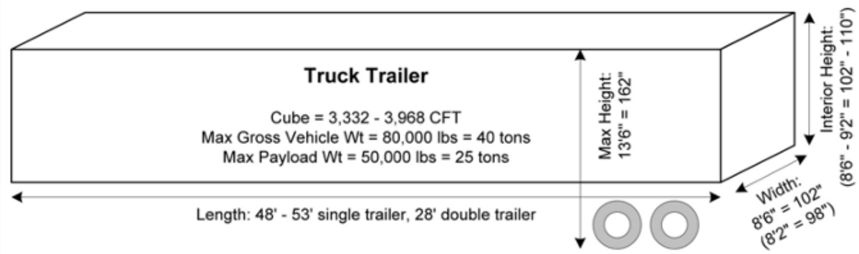

Figure A.1 Displays the weight and cubic capacities of freight transportation by class from Kay [Kay19]. Note: TL: Truckload, LTL: Less-Than-Truckload, PX: Package Express.

transmission, and battery control elements for immediate use. Modifications are documented and explained below.

- **Exchanged PV Source for MNR Source.** PV (solar) power generation is the original DG source for this microgrid, where power output follows a user-specified generation schedule for 24 hours. Modifications involved redefining the block variable and inputting a consistent MNR capacity for this generation schedule.
- **Redefined Critical Loads.** The original model defines the critical loads as three homes connected to the grid. Redefining these elements is in name only, since they would have the same voltage interaction at the bus as emergency response critical loads. The actual load is defined by the demand schedule for 24 hours. This read-in demand section requires 24 hours of load input for the phasor simulation.
- **Removed Unnecessary Breakers and Controls.** These changes are related to the original simulation characteristics. This involved exploring switches and battery control behaviors in the phasor simulation. The modifications removed the breaker connected to one of the critical loads that triggered behavior change, and disabling battery control. This change allows for steady-state operation of this grid model with the read-in data inputs.

A.2.2 State-Space Representation Example

Section 3.6.1 in Chapter 3 describes the essential functional blocks that design the grid-connected microgrid used in the study. This section discusses that the original modeling of this complex grid would be based on its state-space model. However, the numerous transmission, battery, and generation elements makes this representation challenging to work with [Bac93]. The state-space is given by

$$\dot{x} = \mathbf{Ax} + \mathbf{Bu}, \text{and} \tag{A.1}$$

$$\mathbf{y} = \mathbf{Cx} + \mathbf{Du}, \tag{A.2}$$

where,

$$\dot{x}(t) = \frac{d}{dt}x(t), \tag{A.3}$$

and we define

A	State Matrix,
B	Input Matrix
C	Output Matrix,
D	Feeder Matrix,
x	State Vector,
u	Input Vector, and
y	Output Vector.

The interested reader may benefit from seeing the structure of the state-space analysis in MATLAB/Simulink as an example of this complex operation. The MATLAB programming language creates a structure of the analyzed grid from the research, including the dimensions and elements within the state-space matrices shown above. It also includes lists of the state variables, input and outputs arrays, and the state values at initialization (x_0). Table A.1 describes the structure of state-space.

Table A.1 Table of state-space structure for the power distribution model.

Variable	Dimension	Description
A	23 x 23	Matrix of states-by-states
B	23 x 8	Matrix of states-by-inputs
C	9 x 23	Matrix of outputs-by-states
D	9 x 8	Matrix of outputs-by-inputs
$\mathbf{x}_0$	23 x 1	Vector of initial states

Table A.1 indicates there are 23 states within this model, 8 input states, and 9 output states. Since the power distribution model includes an AC power source, transmission lines, and transformers, it calculates complex numbers for some of these states. With the Simscape Specialized Power Systems Library, a simulation provides the necessary outputs from this large power flow formulation.

A.2.3 Phasor Simulation Output Example

The phasor simulation mode provides the outputs used in this study. Figure A.2 shows an example trial for the normal demand of Hurricane Irma (Case Study 2). The phasor output shows time series plots of 24 hours on the horizontal axes (output in seconds) and power (kW) on the vertical axes. The state of charge (SOC) plot is the only output measured as a percentage of its initial charge level on the vertical axes. This SOC plot is the primary indicator of demand fulfillment. Section A.2.1 describes that battery control was disabled so that only additional demand and generation could impact battery discharge/charge. This means demand and net generation schedules indicate whether discharge (demand greater than net generation) or charge (net generation greater than demand) adjusting the SOC. Battery capacity is designated the alternate generation source (behind MNR and grid generation). A complete discharge indicates that the generation sources could not support the 24-hour demand schedule. If the scenario results in a complete discharge, the simulation repeats with a higher capacity of MNR added. Therefore, Figure A.2 shows the outcome of a 10MW MNR satisfies the normal grid demand for Hurricane Irma.

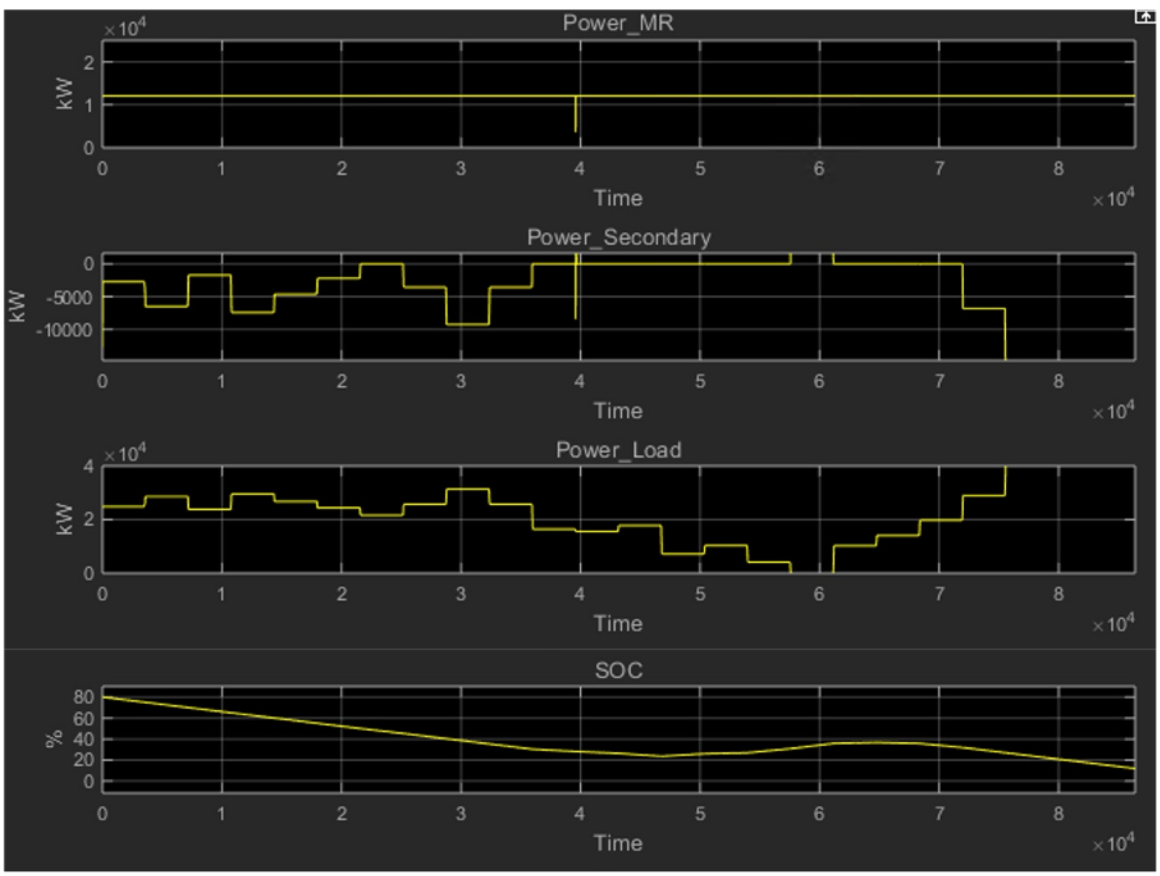

Figure A.2 The time-series outputs of phasor simulation mode in the Simscape Specialized Power System interface.

APPENDIX

B

MNR SAFEGUARD ASSESSMENT

This appendix includes a report written by the author about MNR Safeguards while working as an intern under the supervision of Dr. Biays Bowerman, Group Leader, Detector Systems R&D and Applications, Nonproliferation and National Security Department at Brookhaven National Laboratory (BNL) during the Summer of 2019 and 2020. Their research assessed the safeguards of the emerging MNR technology and distinguished what aspects of the licensing should differ from conventional LWRs in the U.S. The author presented this report to the Nonproliferation and National Security Department and included essential portions of this report in the thesis appendix because it has major implications for the safety evaluation of MNR technology.

B.1 Challenges to MNR Deployment

The MNR deployment schedule phases estimate that the technology is in the overlapping design development and regulatory processes [Eds16]. Besides confirming a functional design, the regulatory process is the most crucial phase in the deployment schedule. This first begins with the consideration of the risks associated with the handling of nuclear material. There have been several different options evaluated for the type of fuel. Most analysis-based technical reports show MNRs will use Low Enriched Uranium (LEU) in oxide, metallic, or silicide forms. At the same time, government organization (GO) like the NRC, DoE and NEI mention the use of High-Assay Low Enriched Uranium (HALEU) [Nic18]. Despite the fuel type, the MNR's design has nonproliferation in mind, where the entire core and unit is contained in a 316-stainless steel monolith and requires no access after factory assembly. The units themselves must still be closely accounted for and subject to scrutiny similar to that of the nuclear material fuel cycle. Management of the MNR must monitor initial enrichment of fuel, factory fabrication of the units, transportation security, unit operation, and unit disposal, as shown in the Figure B.1.

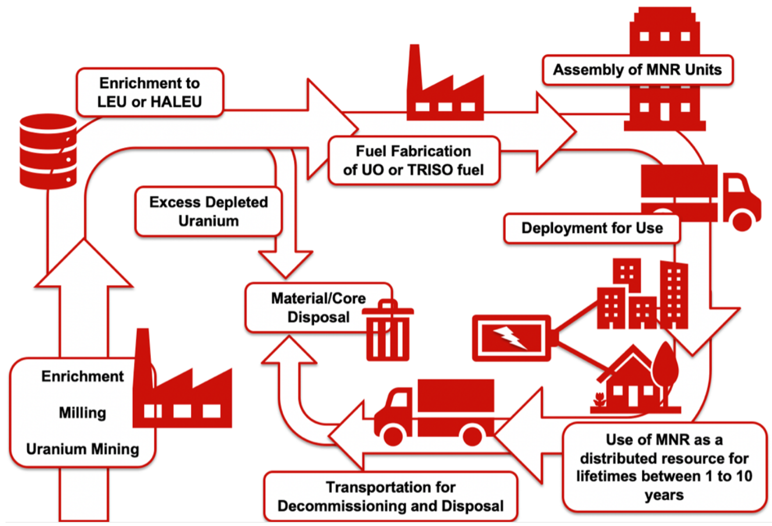

Figure B.1 Visualization of the potential MNR fuel cycle based on its current development state and NRC guidelines described in Nuclear Regulatory Commission [Nuc19].

The NRC leads in setting regulatory standards and requirements for nuclear technology. MNRs have potential use in public, private, and defence settings, so licensing and regulation must remain very strict. The specific applications of MNRs will also be subject to regulatory processes, where location, purpose, and time of use for the generators is base-level information [Nuc19]. Although the NRC notes that they pose less of a threat and risk than conventional reactors, their applications' management is essential to MNRs as a long-term power solution.

B.2 Regulator Process

B.2.1 Government Organization Roles

The DOE is involved in the development of MNRs through supporting their member national laboratories. Los Alamos National Laboratory (LANL) is the primary lab in this process and working with a corporate partner to assist in the development and use of nuclear material. LANL pioneered the design concept of using heat pipes, which are heat transfer devices that can remove heat using thermal conductivity and phase transition between its hot and cold pipe endings [Her19]. Figure B.2 shows depict the operations of heat pipes. This technology's original design was for heat transfer of other power generation devices in space, but LANL's development partner, Westinghouse, saw the opportunity to use them in nuclear technology.

The NRC previously licensed and regulated the construction and operation of Light Water Reac-

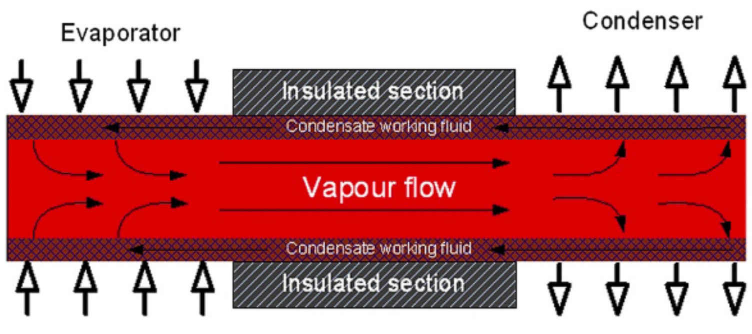

Figure B.2 Display of heat pipe structure and thermodynamic process from Jouhara et al. [Jou17].

tors (LWRs) domestically. The primary roadblocks in this process were the consistent management of large land areas (640 acres) and the multiple construction licenses needed for varying site needs. This situation also increases the development costs of LWR and causes difficulty obtaining operation licenses, contributing to their declining development [Koo07]. MNRs occupy 0.06 acres in space. Although they will require factory licenses managed by the NRC for their fabrication and handling, one acre of an MNR development site could lead to multiple units' production [Ara19]. It is important to highlight that even if MNRs were to be used by DoD (Westinghouse Defense/DeVinci™ MNRs), it would still involve a much different licensing process than the Naval Propulsion Program. A presidential executive order in 1982 gave the Department of the Navy the responsibility for the handling of their nuclear program and development, while the NRC provides oversight and support [Nuc19].

B.2.2 Non-Government Organization Roles

The Westinghouse Electrical Company leads commercial development with the eVinci™ MNR design. Their partnership with LANL allows this work, and they expect to have operable MNRs before the end of the 2020 decade [Ara19]. Their role focuses on the development, factory fabrication, and deployment of this technology. Westinghouse will conduct most of the construction and testing with monetary and research support from LANL. MNRs will likely apply to other private sector and commercial deployment. What role would non-government customers play in the MNR fuel cycle? The best recommendation would be to extend the government's commercial usage regulations, but this would still require an entity to meet federal requirements. This scenario may cause the slower deployment of MNR for commercial use and need more policy initiatives to ensure proper oversight.

B.3 Safety and Security Guidance

In reference to nuclear materials and technology, safety is protecting people and the environment from radioactive sources and dispersion. The concern for nuclear materials is exposure from radioactive sources and the potential dose-equivalent received by occupational/non-occupational people, animals, and plants in the surrounding environment. The whole-body limits for occupational and non-occupational persons are five rem/yr and 0.1 rem/yr, respectively. There are many survey and monitoring devices for occupational and non-occupational people, from personal dosimeters to Geiger-Muller Counters. The NRC emphasized the numerous advantages that MNRs potentially have over conventional nuclear reactors, specifically that MNRs

- Occupy a small amount of land/space resources,
- Require minimal outside resources of water or fuel,
- Output zero emissions/pollution to natural surroundings, and
- Have lower levels of maintenance and operational management [Nuc03].

Compared to conventional LWRs developed in the U.S. and even to Small Modular Reactors (SMRs) currently under development, MNRs create the safest situation for their surrounding environments [Ste17]. MNRs operate without ever compromising the integrity of the steel containment monolith, making the technology inherently safe. With most MNR designs using HALEU fuel, the radiation source concern would be the emission of neutrons and gamma during the fuel's fission within the core. An NRC investigation of MNR designs reports that no radiological releases occur during its operation. Further development of these designs needs to ensure dose limits meet the NRC's Standards for Protection Against Radiation [Nuc03]. The recommended methods for monitoring dosage rates would be using survey devices or monitors installed immediately outside of the monolith. The current efforts in evaluating the safety of MNRs focus on designing and reviewing postulated accident scenarios to lead toward updated standards.

B.3.1 Material and Transportation Security

In contrast to safety, security is the protection of nuclear materials and sources from those that desire nuclear proliferation [And16]. The increase in material safety and decreased use of nuclear reactors in the U.S. has shifted the focus from safety to security. Proliferation concerns in the 21st century entail sabotage, cyber threats, and terrorism in both stationary and transportation scenarios. Therefore, security risk will naturally surround the deployment of MNRs in private and public sectors. The MNR's inherently safe design provides security from accessing the fuel rods within its core. A stainless-steel monolith serves a dual purpose of absorbing/attenuating neutrons or gammas that escape the core's fission reaction and encapsulates the core to ensure no access after its deployment. The MNR core in most designs contains HALEU with 19.75% enriched uranium. Although the NRC Code of Federal Regulation (CFR) 10 Part 73: Physical Protection of Plants and Materials specifies security requirements for reactors, they may need updating to acknowledge certain MNR design features [Nuc03]. For example, MNRs will contain no liquid fuel or moderator, making them less susceptible to sabotage and dispersal threats. Transportation is the second half of security concerns for MNRs, especially given their truck-load freight capabilities. Transportation security is a susceptible area because the general public shares the U.S. Road System. The nature of transportation security concerns less protection, longer response times to malicious acts, and the ability for adversaries to have pre-determined actions based on transportation routes [And16]. During the MNR fuel cycle, units will have multiple steps where transportation is required. The U.S. contains more radioactive material than most countries, corresponding to higher amounts of malicious acts involving these materials [And16]. Therefore, federal entities must maximize security and set expectations for the MNR transportation process. The Department of Transportation (DoT) works with the NRC to address nuclear materials' transportation domestically, leading to specific standards and regulations. The two primary regulations that address transportation security aspects are

Part 37:Transportation in Transit, and

Part 71: Packaging and Transportation of Nuclear Materials [Nuc03].

Transportation of nuclear materials domestically poses different challenges than international transport, so this section will only focus on domestic MNR use. The approach to addressing this potential risk is standardizing response protocols at the state-level. These protocols should address domestic travel requirements between states when using nuclear material. The protocols would likely resemble existing guidance from the DOT and NRC on individual nuclear materials listed in the NRC above regulations, which already addresses interstate material transportation [Nuc03].

B.4 Next Steps for MNRs

MNRs are an emerging technology that can help offset the decline of nuclear energy availability and reduce dependence on diesel fuel generators with lower generation capacities, fuel storage requirements, and pollution emissions. The applications for MNRs are growing in this electricity-dependent world, where the challenge is no longer how do you obtain power, but how do you protect it? The terms commonly used in the defense sector are energy security, protection of resources from outside threats, energy resilience, and disruption prevention. The first next step to deployment is the continued development and safeguard assessment of MNRs. When the technology moves towards its testing phase, where all concepts are now apart of the MNR process, proper risk assessment, postulated accidents, and severe accident mitigation alternatives (SAMAs) should be reviewed [Nuc19]. Their development phase currently limits active safety modeling, but these methods should confirm MNR safety features and prepare for extenuating scenarios. The next step following production would be to re-establish the economic competitiveness of the domestic nuclear industry. The MNR concept addresses some of the issues that have caused the nuclear sector to fall behind with LWRs and proves that policy and regulation need to be updated to match it. The two competing perspectives mentioned by The Breakthrough Institute are whether nuclear technology should be managed top-down or bottom-up [Pyp18]. The top-down approach conducts management traditionally where the NRC and DoE oversee every level of MNR implementation. This approach comes from conventional nuclear technology that requires large reactor developments plus operation staff, specific management of nuclear materials and waste, and highly detailed plans if a safety threat occurs (motivated by policy from previous reactor incidents). The bottom-up approach conversely gives more autonomy to local authorities and commercial organizations that apply MNRs to future markets. This approach would apply directly to MNRs as a new technology with updated NRC regulations that actively recommend policy revisions to lessen risk-levels and streamline approval for the first set of MNR units domestically and develop the rest of the safety/policy concerns after [Pyp18]. Both perspectives hold ground, first because a lack of overall government management could bring about safeguard concerns. But MNRs differ from conventional reactor concerns that fast action is needed to update policy and kick-start the industry. With the combination of these perspectives, the deployment of this technology will be upon us in the next ten years, and essential decisions will decide the transition from conventional to Micro Nuclear Reactors.