Multi-Stakeholder Resilient Infrastructure Decision Support Under Dynamic Environmental and Adaptive Adversarial Settings

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***Abstract*— The 2017 U.S. National Security Strategy indicates a need to reduce risk and build resilience against targeted and natural hazards. Simultaneously, these targeted and natural hazards pose a risk beyond the immediate system for which they are impacting due to the interconnectivity of our social, cyber, and infrastructure networks. Each stakeholder—including, but not limited to, policy makers and system operators—have competing and cooperative interests for the ultimate functionality of the individual and overarching system. These multi-criteria and multi-stakeholder problems require a risk assessment and resource allocation tool that is generalizable for multiple stakeholders in order to inform optimal decision making practices in an effort to prepare for any given hazard. This research aims to incorporate resilience alternatives alongside risk assessment metrics using an optimization based decision making framework based upon a multiple-criteria decision making (MCDM) methodology. It will demonstrate a Resilient Infrastructure Decision Support (RIDS) toolset with a top-down decision analysis and bottom-up risk assessment. Through the use of combined simulated and truth-grounded data, infrastructure asset and portfolio-level resource allocation will be determined and multi-stakeholder decision making patterns will be evaluated. Boston Logan Airport and Port Authority will be used as a case study to inform and evaluate the toolset and results can be grounded based upon stakeholder buy-in and historical event inter-comparison. Results intend to be informative to a game theoretical framework.**

Keywords*— *optimization, decision making, infrastructure, cooperative games

I. Introduction

The 2017 U.S. National Security Strategy emphasizes the importance of risk-informed investments and resource prioritization to reduce risk and build resilience against intentional, accidental, or natural hazards [1]. Environmental and adversarial risks may disrupt an installation infrastructure's operational missions in physical and cyber space, necessitating the adoption of a practical and generalizable risk management approach for risk-aware investment decision making [2-5]. Design and deployment of such a modeling approach, within an end-to-end data-to-decisions computational pipeline for large-scale urban infrastructure systems, is subject to challenging data and computational gaps.

The state-of-the-art in top-down decision analysis with bottom-up risk assessments within an optimization setting includes the National Aeronautics and Space Administration (NASA's) risk-informed decision making approach [6]; and infrastructure risk analysis approaches need to be extended to include longer-term policy decisions, systemic uncertainties, differing impacts of risk perceptions, and dynamic threat and system evolution [7-8].

The objective of this paper is to develop a prototypical Resilient Infrastructure Decision Support (RIDS) toolset that helps prioritize adversarial and natural risks directed toward critical assets and networks, and prioritize optimal decision options to mitigate these risks. Based upon resilience curve metrics, options for each stakeholder are provided in an attempt to satisfy the differing stages of risk and resilience. This operates in a game theoretical space and lends itself to future cooperative game analyses.

II. Decision Support problem framing

To develop a RIDS toolset requires the ability to combine asset and network mission level priorities with hazard specific risks and uncertainties to inform resilient infrastructure investment decisions. This effort serves two functions. First, it demonstrates a prototypical RIDS toolset with synthetic/proxy data that combines top-down decision analysis (from mission objectives to asset performance) with bottom-up risk assessments (from asset performance to mission objectives). This collectively accounts for stakeholder values, resilience strategies, and both environmental and adversarial hazard-related uncertainties. Furthermore, this work highlights data and computational gaps within a data-to-decisions framework.

The research team's currently deployed operational infrastructure risk assessment and resource allocation tools are customized for aviation and maritime security [9-10]. In this effort, we extend our current optimization-driven decision making framework, based on a multiple-criteria decision-

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making (MCDM) approach, and demonstrate a flexible computational toolset (RIDS) that can identify data and computational gaps and evaluate resilience alternatives. Infrastructure asset and portfolio level resource allocation optimization challenges are also incorporated in the toolset within a simulation setting.

alternatives—based on decision maker preferences—is desired from a finite collection of known alternatives, and 2) Design Problems – where an alternative(s) (or feasible solution(s)) is desired from infinite and/or a finite but large number of alternatives (representing continuous and/or discrete variables) that are not known a priori [11].

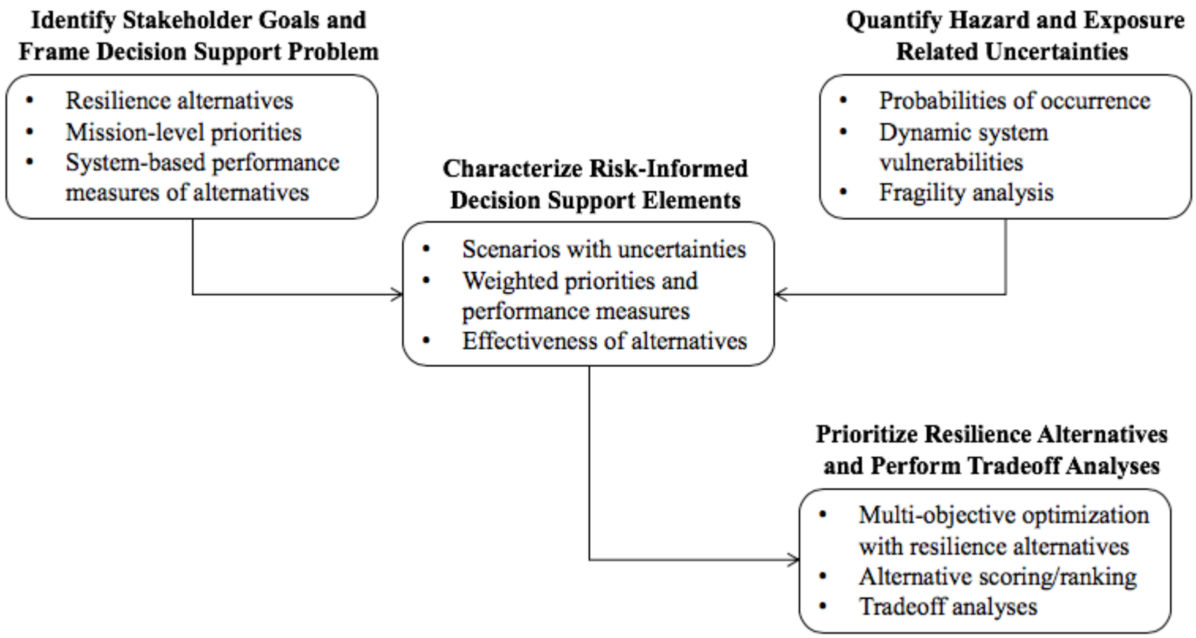

Figure 1. Overarching Resilient Infrastructure Decision Support (RIDS) Methodology used to guide stakeholders.

We seek stakeholder guidance to establish a decision hierarchy and identify criteria and objectives of concern that are most appropriate to the multiple decision makers. These criteria inform risk and value-focused computations based upon the associated hazards, organizational resilience, and costs of responding to events, which are typically represented in terms of probabilities, dollars, or downtime. We also consider how the decision hierarchy may differ based on environmental versus adversarial risks. In turn, the RIDS toolset enables infrastructure managers and policy decision makers to identify top infrastructure security investment decisions that meet mission assurance goals while weighing possible resilience options and their tradeoffs.

In order to demonstrate the feasibility of a RIDS toolset, we use the case study of hazard events occurring at Boston Logan International Airport. This case study was selected due to availability of previous insights of stakeholder preferences from former workshops and hazard simulations. This serves to make the case of use for additional stakeholders and industries, thus transcending sectors.

III. MUTIPLE-CRITERIA DECISION MAKING APPROACH

MCDM is an established sub-discipline in the scientific field of operations research that addresses decision-support problems influenced by multiple, and at times conflicting, criteria. MCDM problems may be broadly classified into two categories: 1) Evaluation Problems – where the “best” alternative or set of

Decision-maker preferences are essential for defining both Evaluation and Design type of MCDM problems; and mathematical programming approaches are typically applied for solving such problems [11]. These mathematical decision modeling approaches are well-established in the scientific literature and this effort will apply and demonstrate them in an infrastructure network security environment. We will begin by formulating the RIDS problem as an Evaluation type of MCDM problem. Overarching technical steps that combine top-down decision analysis with bottom-up risk assessments are presented in Fig. 1.

Given a feasible and discrete set of resilience alternatives, installation site mission level priorities, and exposure-based criteria, we will initially apply the MCDM based method called multi-objective optimization by ratio analysis (MOORA) algorithm to generate weighted resilience alternative effectiveness estimates. The MOORA algorithm for asset level resource allocation is comprised of the following five steps [12]:

Step 1: For each mission level priority, populate a matrix of quantitative estimates associated with the effectiveness of resilience alternatives in satisfying various criteria represented as x_{ij} for alternative j and criterion i; where j=1,2,…,m and i=1,2,…,n. These x_{ij} values will be determined via hazards analysis and subject matter experts familiar with the installation hazards and potential resilience alternatives.

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Step 2: Normalize these estimates for each criterion.

Step 3: Generate weighted estimates as: $w_i \cdot x_{ij}^*$ where w_i represents the priority weight associated with criterion i.

Step 4: For criteria-based optimization, aggregate weighted estimates across criteria in case of maximization or minimization respectively as:

$$y_j^* = \sum_{i=1}^{k} w_i x_{ij}^* - \sum_{i=k+1}^{n} w_i x_{ij}^* \tag{1}$$

where y_j^* is the overall weighted score for an alternative across all criteria, i=1,2,…,k are indices for criteria to be maximized and i=k+1, k+2,…,n are the indices for criteria to be minimized.

Step 5: Generate an ordinal ranking of overall weighted resilience alternative estimate y_j^* to identify best alternatives for each mission level priority.

Further, for portfolio level analysis, an additional four steps include:

Step 6: Generate resilience alternative portfolios (with binary inclusion/exclusion assumption) by considering all permutations of alternatives under each mission level priority.

Step 7: Use the overall weighted estimates for each resilience alternative and weights assigned to mission priorities to produce overall portfolio-level weighted estimates across multiple mission level priorities.

Step 8: Generate an ordinal ranking of portfolio estimates to identify the best portfolio alternatives across multiple mission priorities.

Step 9: Conduct portfolio tradeoff analyses with conflicting criteria to identify Pareto frontier with non-dominated resilience portfolios [13].

In taking these steps the objective is to both understand and ultimately inform multiple stakeholder goals and priorities. This is therefore developed to provide infrastructure resilience decision support within and beyond the transportation sector with an aim in future work to address multi-layer infrastructure network cascading failures.

Then nature of this work serves to complement stakeholder interactions and workshops in which prior work has revealed the value of stakeholder buy-in through personal interaction. Thus the following case study of Boston Logan International Airport is used as a demonstration of the potential deployment of the RIDS toolset and methodology.

IV. RIDS Toolset Case Study

Boston Logan International Airport is located on recovered land situated within close proximity to the Boston Harbor. The airport contains four passenger terminals that are physically separated from one another and thus relatively self-contained with a connection to two lines of the Massachusetts Bay Transportation Authority (MBTA) public transit. Seven stakeholders were selected to represent the various entities that operate within the airport and whom would have control over resilience practices and outcomes in the event of a hazard. Thus, for example, vendors and similar personnel were not included as stakeholders for the purpose of this case study.

A standard resilience framework was used to create objectives for each stakeholder [14]. These objectives remain the same for each stakeholder and are visualized in Fig. 2. Objectives include minimizing the probability of an event occurring, minimizing the disruption extent through minimization of the area of the system disruption, minimizing

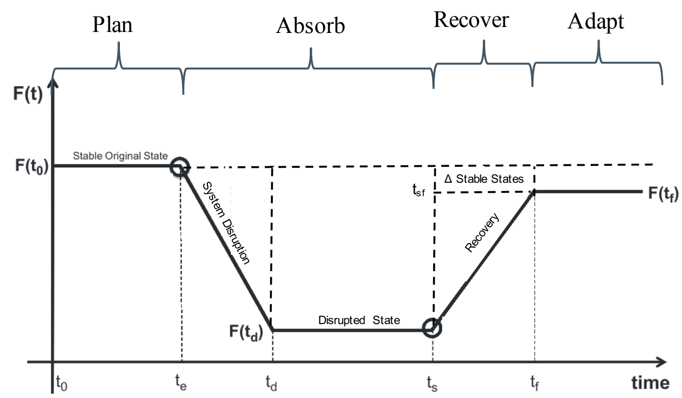

Figure 2.Resilience framework used to inform stakeholder objectives. This framework was designed specifically to demonstrate resiliency in terms of calculable areas and include a return to a possible stable state that is less functional than the original stable state.

the disruption duration by minimizing the area of the disrupted state, and minimizing the recovery profile by minimizing the area of recovery combined with the area of the change in stable state if the new stable state is less than the original stable state.

Based upon how stakeholders perceive the importance of each objective, weights were assigned to the four objectives for each stakeholder using a rank ordinal centroid process [13]. This is calculated using the following standard equation:

$$r_{in} = \frac{1}{n}\sum_{j=i}^{n}\frac{1}{j} \tag{2}$$

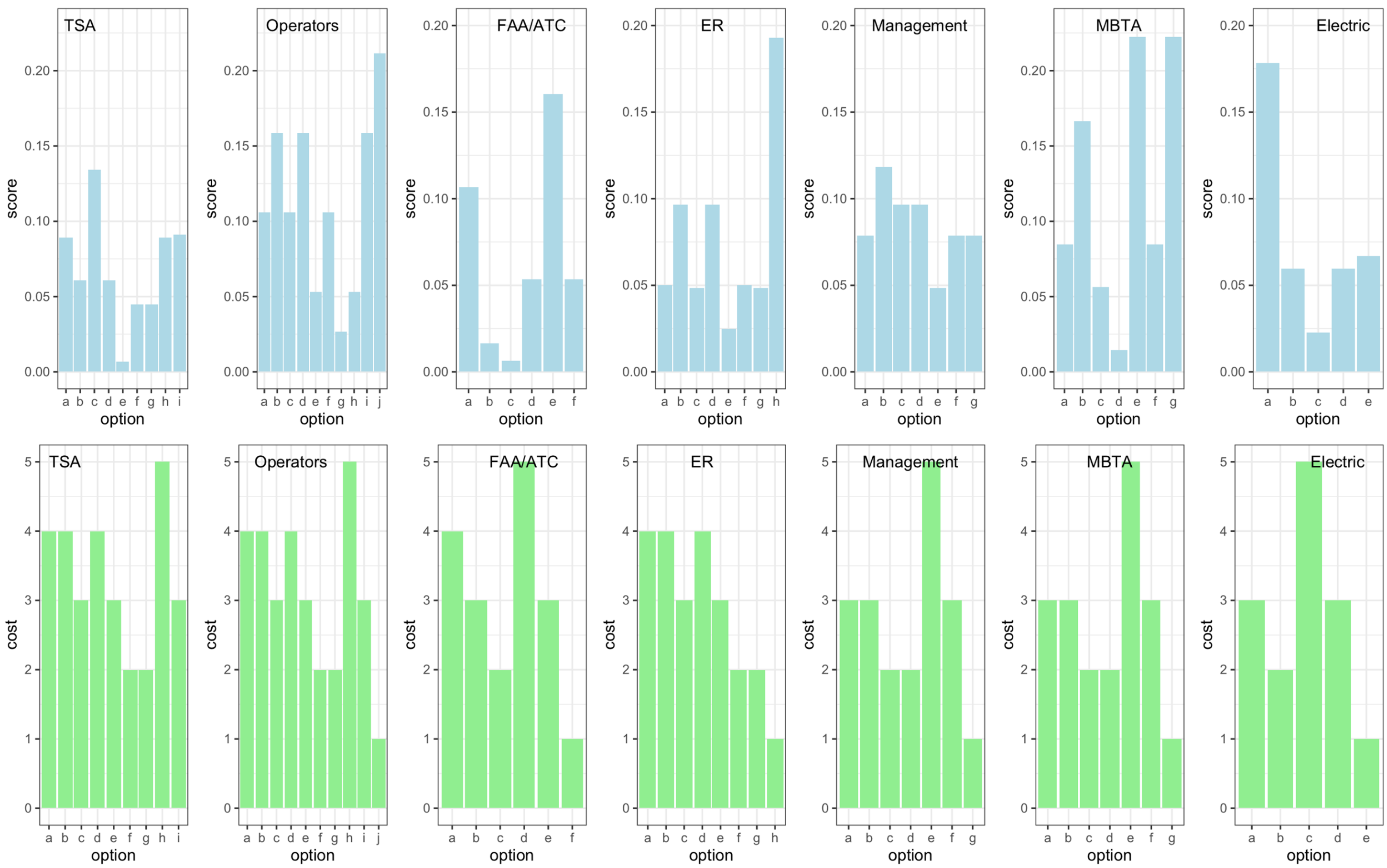

Figure 3.Relative opportunity scores and costs for each stakeholder and their respective alternative options.

Therefore, there exist *n* objectives, *r* is their respective rankings, and *i* represents the number of options that exist. The weights will vary depending upon each stakeholders' overall missions and responsibilities at Boston Logan Airport.

There were seven primary stakeholders identified for the purpose of this case study including:

Federal Aviation Administration (FAA)/Air Traffic Control (ATC): The FAA is a federal agency whose primary mission at an individual airport is to control and maintain ATC on site through ATC towers that communicate with national and international ATC [15].

Airline Operators: Operators are private companies that provide baggage transportation and flights to customers through their hired staff both on-site as well as en route in company-owned airline equipment. These operators typically rent terminal space at the airport [16].

Transportation Security Administration (TSA): TSA is a federal agency that works in conjunction with the airport management to provide security screenings of both individuals as well as luggage [17].

Airport Management: Airport management include owners and operators of the airport facilities who work to create profit for the airport as well as to provide security by creating seamless cooperation and coordination between other stakeholders using their facilities [16].

Emergency Response/Law Enforcement: Boston Logan Airport has an emergency response team located on site that serves as the fire station and firemen assigned to the airport specifically. Additionally, there is a law enforcement unit that consists of local Boston policemen whose service area is Boston Logan Airport [16].

MBTA: Massachusetts Bay Transportation Authority has two subway lines that service the airport including access to the blue and silver lines. The MBTA operates separately from the airport yet in conjunction to provide safe and secure transportation to and from the terminals [18].

Electric Utility: The New England ISO provides power supply to the Boston area including power supply for Boston Logan Airport. This utility and service are separate from the airport itself but are critical to airport functioning [19].

The first five aforementioned stakeholders were selected for their direct affiliation with Boston Logan Airport and the two remaining stakeholders were used for consideration to attempt to accurately capture outside yet impactful agents.

Each stakeholder has differing alternatives from which they can choose to fulfill each objective. Ten alternatives were selected as possible options for each stakeholder to consider

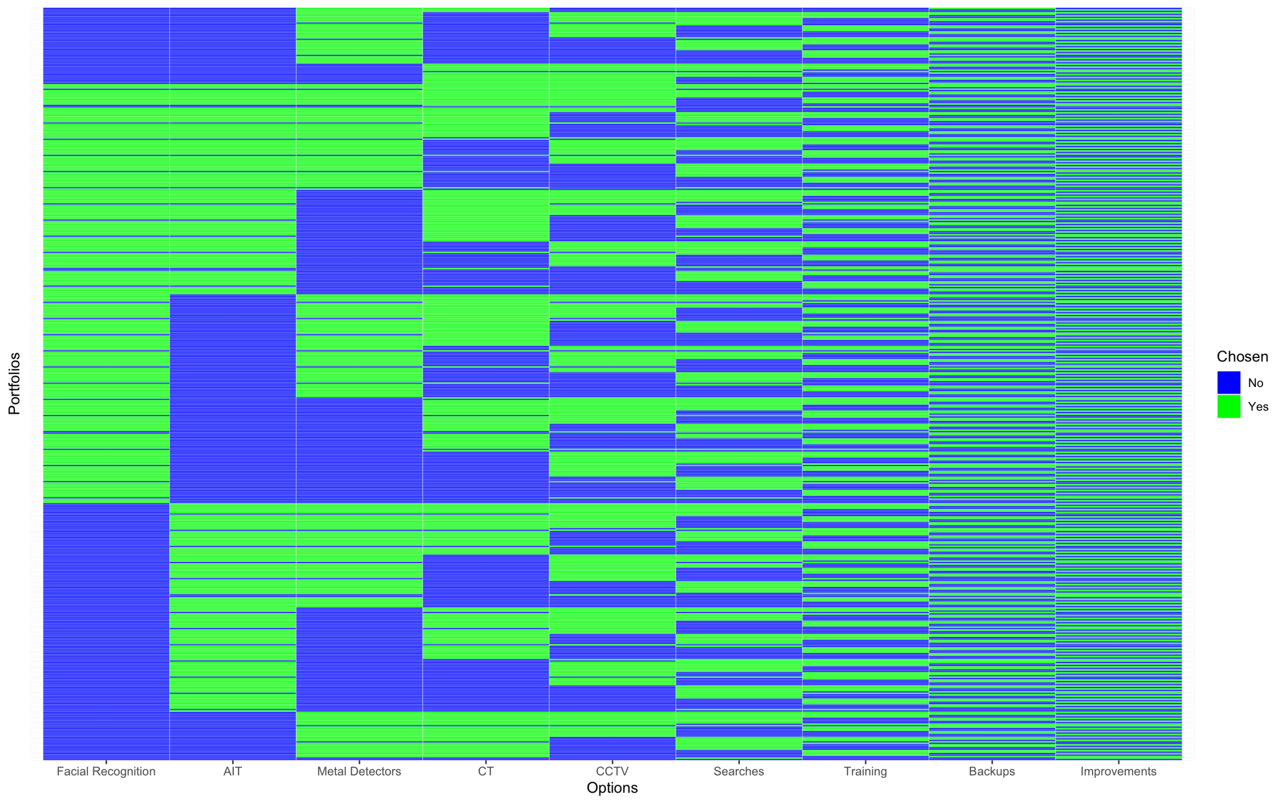

Figure 4. A sample portfolio for the TSA. Each portfolio shows the options available to the TSA and whether the TSA would choose or not choose to implement one of those options in a hazard event. The portfolios of options range from one in which no options are implemented to a portfolio in which all options are implemented. This is true for every stakeholder but with each stakeholder having different options available to them.

including the following: Facial recognition, advanced imaging technology (AIT), metal detectors, computed temography (CT), closed-circuit television (CCTV), random searches, employee training, structural backups/duplication, structural improvements and updates, and flood barriers. Not all alternatives are considered for each stakeholder dependent upon whether an alternative is a feasible solution option for that stakeholder. Additionally, structural backups, improvements, and barriers aim to address the ability for stakeholders to respond while the other alternatives attempt to address risk mitigation thus cumulatively creating a resilience portfolio.

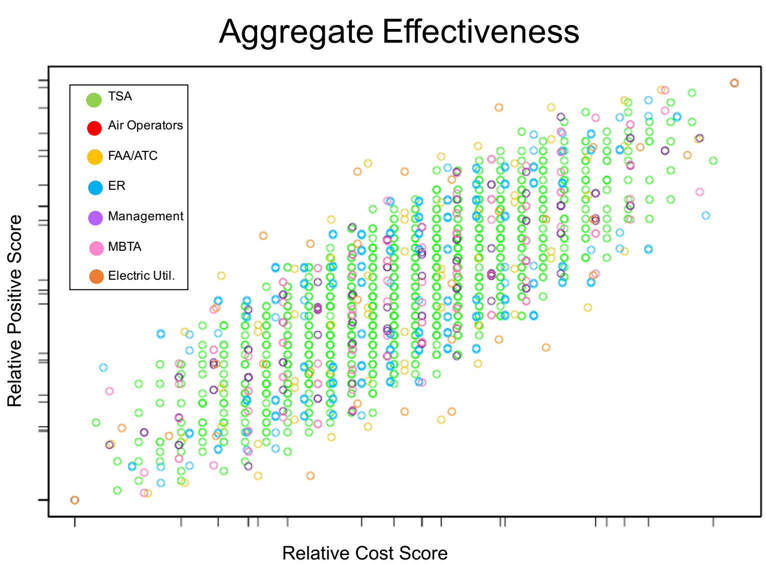

Figure 5. The aggregate effectiveness scores for each stakeholder are represented as the calculated cost and benefit for each stakeholder portfolio. These costs and benefits are based upon aforementioned rank and weight system of each option available to the individual stakeholder.

For each stakeholder a portfolio of options is generated. These portfolios correspond to all possible options from which stakeholders can choose including whether to employ an alternative or not. Alternatives are evaluated through costs versus opportunity scores. Costs and scores are calculated using a Likert scale and these costs and opportunity scores for each stakeholder are represented in Fig. 3 to demonstrate relative impacts.

In Fig. 3 the options correspond to alternatives available to each stakeholder and, due to the use of a Likert scale, should be considered relatively to one another. These opportunity scores and costs can thus be considered upon the generation of portfolios to determine optimal solution strategies. Portfolios vary for each stakeholder dependent upon the alternatives available to each stakeholder and an example of the

TSA portfolio is visualized in Fig. 4 where a blue level corresponds to a stakeholder selecting not to deploy the use of that alternative and a green level corresponds to a stakeholder selecting to use that alternative. This demonstrates each possibility for one stakeholder whereas every stakeholder has similar but unique portfolios from which to select various options

Each portfolio for each stakeholder contains every possible option of deployment in which actions can be taken or not taken and each option comes with both an associated cost as well as an associated positive score. This is demonstrated in Fig. 5 in which you can see the costs versus benefits of each stakeholder's portfolio options. Therefore, stakeholders would seek to choose portfolios for which the score is highest without a correspondingly high associated cost. Stakeholders can use this information to effectively evaluate the various portfolios available to them that meet these criteria and this can inform others on how each stakeholder might choose to optimally act and therefore cooperatively plan for hazard mitigation.

V. Discussion and Conclusion

The use of this methodology is critical to understanding the contrasting and comparative actions any given stakeholder might take in a hazard scenario. The use of a Likert scale makes this easy to translate to stakeholders and simultaneously allows for those stakeholders to adapt this framework to their needs and priorities. It fundamentally allows for stakeholders to evaluate costs and opportunities for any given action and is easily transferable to multiple scenarios including, but not limited to, adversarial and natural hazards.

Nonetheless, additional stakeholder engagement should be conducted to determine if patterns emerge in the ways in which stakeholders routinely rank or classify their respective priorities. This work is currently being doing through partnership with the Global Resilience Institute at Northeastern University through simulations and roundtables of collections of stakeholders.

Additionally, RIDS is being built upon through a game theory based approach in which cooperative transferable-utility games will be evaluated in order to incentivize cooperative research between stakeholders. The aim of this future research intends to provide quantiative rationalization for stakeholders with varying priorities to reduce costs associated with time and financing. Stakeholders can use the portfolios that meet their respective needs and compare and contrast to inform this game theoretical framework.

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