System Importance Measures:  
Development and Initial Application  

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Distribution Note: We are preparing this work for a journal submission in the coming weeks. Please do not post this work on any public forum.

1 INTRODUCTION

Our research focuses on developing System Importance Measures (SIMs) to characterize resilience. Our measures are applicable to systems and systems-of-systems that are characterized by diversity in nodes and functions. The system importance measures help identify and rank components or systems that have the most impact on different aspects of the overall resilience. Because systems-of-systems (SoS) pose a particularly challenging and interesting resilience design problem, we use SoS to illustrate the development of the SIMs and to demonstrate their application. Section 2 provides background on SoS and introduces some of the terminology we will use. In Section 3, we present three System Importance Measures (SIMs) that rank or prioritize the constituent components or systems based on their resilience significance. We say that a system is resilience significant if a disruption of the system contributes significantly to measures of SoS performance. These measures help determine “where” in the SoS resources need to be targeted so that they provide the most benefit in the event of disruptions. In Section 4, we demonstrate the use of the SIMs using two case studies. Section 5 discusses our current effort and Section 6 concludes our report.

2 BACKGROUND: DISRUPTION, RESTORATION, AND MITIGATION IN SOs

Figure 1 shows a much-simplified version of an urban transportation network and has been chosen for ease of explanation. The SoS, comprising three systems (a bus, a
subway, and a ferry), enables transportation of passengers from A to B. Thus, the overall capability of this simple SoS is the movement of people from A to B.

![Diagram of a simple SoS](image)

**Figure 1: Illustrative example SoS**

There are many different ways to describe SoS performance. For instance, in urban transportation SoSs, measures of interest include average delay, frequency of service, demand, and vehicle throughput. Also, the various modes of transportation serve different types of passengers with different preferences. Thus, the utility of an SoS is driven by a range of performance measures and stakeholder preferences. Section 4 discusses some potential ways of incorporating SIMs into cost-benefit analyses. For ease of explanation we define this SoS’s performance as the number of passengers (passenger ridership) transported between A and B.

![Disruption table]

**Figure 2: Defining a single-system disruption**

We define a *disruption* as an event that can interrupt some activity or process (of the SoS). *Instigating events* cause disruptions. For example, the closure of an airport, such as O’Hare International (ORD), due to some adverse weather situation (e.g.
snowstorm in Chicago) is a disruption. The instigating event here is the snowstorm. Typically a disruption definition consists of three parts (see Figure 2): impact of the disruption (at the SoS-level), likelihood of the disruption, and cause (instigating event) of the disruption. Our focus here is on the impact, we leave the stochastic aspects for future work.

### Figure 3: Defining multi-system disruptions

Instigating events can also cause multi-system disruptions. We term these events as common cause disruptions. For instance, a snowstorm (instigating event) in the New York region can cause the disruption of the three major airports in the area – John F. Kennedy International Airport (JFK), LaGuardia Airport (LGA), and Newark Liberty International Airport (EWR) (see Figure 3). The SoS-level impact is the total impact of the three airport closures. When disruptive impacts propagate through the SoS with systems failing in sequence (see Rinaldi et al. [2001]), we refer to the disruptions as cascading disruptions.
Returning to our simple illustrative SoS, we consider three single-system disruptions: (a) disruption of the bus, (b) disruption of the ferry, and (c) disruption of the subway train. This set is described by eq. (1).

\[
\text{Set of potential disruptions} = \{(\text{Bus}), (\text{Ferry}), (\text{Subway})\} \tag{1}
\]

![Disruption curve with gradual restoration of the disrupted System i and no mitigation actions](image)

Figure 4: Disruption curve with gradual restoration of the disrupted System i and no mitigation actions

Figure 4 shows performance as a function of time for a generic SoS. The dotted line is the desired (nominal) curve, that is, the desired performance \(P_{\text{Nominal}}\) that the SoS is designed to maintain while in operation. The performance level and operational timeframe are specific to each SoS. In practice, \(P_{\text{Nominal}}\) may experience minor fluctuations. For instance, airports regularly experience changes in traffic flow due to the prevailing winds. In such cases, we use the mean value across these fluctuations to determine a suitable \(P_{\text{Nominal}}\). The solid line on Figure 4 represents the disruption curve in the absence of mitigation measures. Here, System \(i\) is disrupted at \(T_{\text{initial}}\), decreasing performance from \(P_{\text{Nominal}}\) to a minimum value \(P_{\text{Loss}}\).

Partial disruptions are also possible. For example, a landing gear malfunction may require an entire runway to be sprayed with foam for an emergency aircraft landing. Depending on the airport, such a situation can disrupt services on one runway for
several hours while other runways are still in operation. Thus, the airport functions at a performance level between its nominal and full disruption (e.g. blizzard) values (see Figure 5).

![Diagram showing SoS Performance vs Time for full and partial disruptions]

**Figure 5**: Notional example of full and partial disruptions: (a) impact of complete shutdown of ORD on National Air Space (NAS) and (b) impact of a runway closure at ORD on NAS

We define *restoration* as a strategy to return the disrupted system(s) to nominal performance after a disruption (through the repair or replacement of the disrupted systems). In this case, service is fully restored at $T_{f\text{inal}}$, but partial restoration begins immediately after the disruption (for example, allowing aircraft to land on runways cleared of snow, while clearing continues on other runways).

A similar curve can be used to represent multi-system disruptions where multiple systems are disrupted and restoration of all the disrupted system results in a return to $P_{\text{Nominal}}$.

We have assumed that SoS performance is eventually restored to its nominal level. In some instances, for example in time-constrained military missions, failed systems are not repaired or replaced within the mission’s time frame. Instead, the mission continues with the available resources, as shown in our military case study.

System-of-systems typically have some recovery strategies and contingency plans in place to handle disruptions. **We define a mitigation/recovery as a strategy using other systems to reduce the impact of a disruption.**
Figure 6: Example of a resilience curve with partial mitigation

The resilience curve in Figure 6 provides an example of one mitigation measure: here System $j$ provides partial recovery when System $i$ is disrupted. System $j$ is deployed at time $T_{mitigation}$, raising the SoS performance to $P_{Mitigated}$ till the original system(s) that provided the capability is (are) restored. In our example, unscheduled line repairs on subway tracks can reduce throughput and cause delays, resulting in a reduction in the overall performance of the urban transportation network. Additional bus service between stations on the affected rail line can compensate for some of this lost performance.

Figure 7: Notional resilience curves indicating different mitigation strategies
The mitigation path can take many different forms, depending on a variety of factors, including SoS topology and the specific system(s) used in the recovery. For example, the resilience curve may follow a linear path (as shown by the dashed line in Figure 6), a step path (dotted line), or perhaps even a recovery path that provides increased performance for a short duration before returning to the nominal SoS performance level (dashed-dotted line).

3 System Importance Measures

We develop three metrics. The first focuses on the effect of unmitigated disruptions, while the second and third metrics consider the possibility of mitigations.

3.1 Overview of SIM-based Resilience Design

Table 1: Four steps in SIM-based Resilience Design

<table>
<thead>
<tr>
<th>Step</th>
<th>Task</th>
<th>Stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identify potential disruptions. What can go wrong?</td>
<td>SIM Analysis</td>
</tr>
<tr>
<td>2</td>
<td>Determine impacts of disruptions. What are the consequences of unmitigated disruptions?</td>
<td>SIM Analysis</td>
</tr>
<tr>
<td>3</td>
<td>Determine current resilience. How well is the current SoS able to handle the disruptive impacts?</td>
<td>Application of Design Principles</td>
</tr>
<tr>
<td>4</td>
<td>Determine design modifications to improve resilience. What can be done to improve SoS resilience?</td>
<td>Application of Design Principles</td>
</tr>
</tbody>
</table>

Our resilience design process is inspired by classic risk-based design approaches and comprises four steps (see Table 1). The first three steps constitute the SIM analysis where current SoS resilience is evaluated. The outcome of third step is a resilience map that summarizes how well or how badly the system or SoS currently handles disruptions. Step 4 is design improvement and asks: What can be done to increase the overall resilience? The outcome of this step is a set of potential design improvements. While resilience is witnessed at the operational level (how does the system survive and recover from disruptive impacts?), the intent of the proposed approach is to facilitate design-related decisions, the results of which have implications for system operations.
This approach provides specific design guidance by identifying where in the system resources should be targeted to improve the overall resilience and providing guidance on how the improvements can be realized.

3.2 System Disruption Importance

The System Disruption Importance captures the impact of unmitigated disruptions. To develop this measure, we follow two steps. First, we determine how much each disruption affects the overall, and second, we determine how important this effect is relative to other disruptions. The hatched region in Figure 4 (see pg. 4) represents the impact of an unmitigated disruption on the overall SoS (for simplicity, the figure does not show restoration). This \(\text{Impact}_D\) is the difference between the areas under the two curves:

\[
\text{Impact}_D = \int_{T_{\text{initial}}}^{T_{\text{final}}} f(t) - h_D(t)
\]  

Here the subscript \(D\) refers to a disruption from the set identified in Step 1.

The System Disruption Importance (\(SDI_D\)) determines the relative importance of an unmitigated disruption \(D\):

\[
SDI_D = \frac{\text{Impact}_D}{\text{Worst-case SoS impact}}
\]

The denominator is a measure of the worst-case impact on the SoS and is used to normalize the \(SDI\) to be between 0 and 1. This value is domain and SoS specific and can be estimated using, among others, historical data (e.g., closure of the National Airspace in the three days following the 9/11 attacks can be a measure of worst-case disruption impact) or simulation tools (as shown in our naval warfare case study). Disruptions with large \(SDI_D\) values, that is, those with large hatched regions, have the greatest impact on the SoS when they occur. Thus, based on the \(SDI_D\) values, a ranking can be obtained of the relative importance of different disruptions.
Assuming a worst-case SoS impact of 110 units for our simple example, Table 2 shows the $SDI_D$ for the three disruptions in Figure 8. A low $SDI_D$ ranking (e.g.: Ferry disruption) indicates a relatively low impact on SoS performance, while a high ranking (e.g. Subway disruption) indicates a disruption that has a large impact on the SoS.

![Figure 8: Disruption curves for illustrative SoS example (numbers in bold indicate $Impact_D$ values)](image)

<table>
<thead>
<tr>
<th>Disruption ($D$)</th>
<th>System Disruption Importance ($SDI_D$)</th>
<th>Importance ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway</td>
<td>$SDI_{Subway} = 0.45$</td>
<td>1</td>
</tr>
<tr>
<td>Bus</td>
<td>$SDI_{Bus} = 0.27$</td>
<td>2</td>
</tr>
<tr>
<td>Ferry</td>
<td>$SDI_{Ferry} = 0.09$</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2: $SDI_D$ and importance ranking for illustrative example
3.3 System Disruption Conditional Importance

Referring to the hatched area in Figure 9, the System Disruption Conditional Importance ($SDCI_{D,M}$) is calculated using eq. (4) and answers the question: What is the relative importance of a mitigated disruption?

\[
SDCI_{D,M} = \frac{\int_{T_{\text{recovery}}}^{T_{\text{final}}} f(t) - g_{D,M}(t)}{Worst-case SoS impact} \tag{4}
\]

Here, as before, the subscript $D$ refers to a specific disruption from the set identified in Step 1, and the subscript $M$ refers to a mitigation measure that can provide partial recovery of SoS performance when $D$ occurs.

Since mitigations reduce the impact of disruptions, the hatched area in Figure 9 is smaller than in the unmitigated case. A low $SDCI_{D,M}$ shows that the impact of the disruption has been well mitigated, and vice versa. Note that when mitigation is not provided or designed, $SDCI_{D,M}$ is undefined. We discuss in the case studies how the analyst can determine what value of $SDCI_{D,M}$ constitutes an adequate mitigation.
3.4 System Disruption Mitigation Importance

System Disruption Mitigation Importance ($SDMI_{D,M}$) answers the question: what is the relative importance of the effectiveness of a mitigation measure in reducing the impact of a disruption? $SDMI_{D,M}$ is represented by the solid grey region in Figure 9 and calculated using:

$$SDMI_{D,M} = \frac{\int_{t_{\text{recovery}}}^{T_{\text{final}}} g_{D,M}(t) - h_D(t)}{\text{Worst-case SoS impact}}$$

(5)

Similar to $SDI_D$ and $SDCI_{D,M}$, $SDMI_{D,M}$ is also normalized by the earlier worst-case value and is undefined when mitigation is not possible. The larger the value of $SDMI_{D,M}$, the more important the mitigation measure is to reducing the impact of the corresponding disruption. Conversely, a low $SDMI_{D,M}$ indicates that the mitigation measure does not significantly alleviate the disruption impact.

In summary, $SDI_D$ provides an assessment of the impact of unmitigated disruptions on the SoS while $SDCI_{D,M}$ and $SDMI_{D,M}$ evaluate effectiveness of mitigation measures in reducing these disruptive impacts (see Table 3).

<table>
<thead>
<tr>
<th>SIM</th>
<th>Question answered by SIM</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Disruption Importance ($SDI_D$)</td>
<td>What is the relative importance of an unmitigated disruption.</td>
<td>Disruption has low adverse impact on SoS.</td>
</tr>
<tr>
<td>System Disruption Conditional Importance ($SDCI_{D,M}$)</td>
<td>What is the relative importance of a mitigated disruption.</td>
<td>Disruption, given its impact is mitigated, has low adverse effect on SoS.</td>
</tr>
<tr>
<td>System Disruption Mitigation Importance ($SDMI_{D,M}$)</td>
<td>What is the relative importance of the effectiveness of a mitigation measure?</td>
<td>Mitigation measure contributes little to SoS resilience.</td>
</tr>
</tbody>
</table>

In summary, $SDI_D$ provides an assessment of the impact of unmitigated disruptions on the SoS while $SDCI_{D,M}$ and $SDMI_{D,M}$ evaluate effectiveness of mitigation measures in reducing these disruptive impacts.
4 APPLICATION OF SIM-BASED RESILIENCE DESIGN

In this section, we use two case studies to demonstrate how the SIM-based design framework can be used to inform decision-making in the context of SoS resilience.

The first case study is a naval warfare SoS and illustrates the application of SIMs to military missions, while the second case study focuses on an urban transportation SoS. The two SoSs have different objectives and different characteristics. These features enable us to show how the SIM-based approach is applicable to different types of SoSs and to highlight major aspects and results of the design process. For instance, while the primary focus of the urban transportation SoS is the efficient movement of people, the objectives of time-sensitive military missions can vary widely, such as search-and-rescue, surveillance, or target elimination. Also, transportation SoSs typically have longer operational lifetimes, with new systems being interfaced with legacy systems, than combat SoSs. Consequently, both SoSs face different types of disruptions. We use each case study to draw attention to different aspects of the resilience framework.

In the naval warfare case study, we describe how the resilience framework can leverage existing simulation models to support end-to-end design. We proceed through the four steps of the approach using an agent-based model (ABM) that enables us to demonstrate how simulation tools and analytical models can be used to determine the necessary inputs for the framework and subsequently, to inform decision-making regarding SoS resilience.

The urban transportation case study in contrast focuses on interpreting the results of the resilience framework and on describing how they can be used to guide design choices in large infrastructure networks. We use different resilience maps to highlight the range of design-related information that can be obtained from the framework.
4.1 **Case Study 1: Naval Warfare SoS**

The mission of the naval warfare SoS studied here is to conduct near-shore search-and-destroy operations, similar to those carried out by the Coast Guard and littoral combat units in the Navy. Figure 10 illustrates the area of interest and the systems in the SoS. The specific task of the SoS is to find and destroy the enemy boat within the planned mission time (PMT) of 4 hours. Table 4 shows the capabilities of each system and the communication links between them.

![Figure 10: Naval warfare SoS](image)

**Table 4: Systems in naval warfare SoS**

<table>
<thead>
<tr>
<th>System</th>
<th>Capabilities</th>
<th>Communication links</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
<td>Detect enemy (radar)</td>
<td>Send to and receive information from Helicopter and UAV</td>
</tr>
<tr>
<td></td>
<td>Eliminate enemy (weapons)</td>
<td>Receive information from Satellite</td>
</tr>
<tr>
<td>Helicopter</td>
<td>Detect enemy (radar)</td>
<td>Send to and receive information from Ship</td>
</tr>
<tr>
<td></td>
<td>Eliminate enemy (weapons)</td>
<td></td>
</tr>
<tr>
<td>UAV</td>
<td>Detect enemy</td>
<td>Send to and receive information from Ship</td>
</tr>
<tr>
<td>Satellite</td>
<td>Detect enemy</td>
<td>Send information to Ship</td>
</tr>
</tbody>
</table>
We use an agent-based model (ABM) (adapted from Mour et al. [2013]) to simulate and study the naval warfare SoS. Parameters such as weapons range, velocity, fuel tank capacities, and radar detection ranges for each agent can be varied to simulate different recovery options.

4.1.1 Step 1: Identify Potential Disruptions

![Disruptions Diagram]

**Disruptions**

- **Single-system disruptions**
  - Satellite
  - UAV
  - Ship
  - Helicopter

- **Multi-system disruptions**
  - Two-system disruptions:
    - Satellite and UAV
    - Satellite and Ship
    - Satellite and Helicopter
    - UAV and Ship
    - UAV and Helicopter
  - Three-system disruptions:
    - Satellite, UAV, and Ship
    - Satellite, UAV, and Helicopter

- **Partial disruptions**
  - Communications failure on Ship
  - Failure of propulsion subsystem on Ship
  - Inability to launch weapons on Helicopter

**Figure 11: Potential disruptions in naval warfare SoS**

We consider three types of disruptions: single system disruptions (due to targeted enemy attacks or random failures), multi-system disruptions (due to common cause failures and/or cascading failures), and partial disruptions (see Figure 11).

Since only the Ship and Helicopter carry weapons and given that mission success depends on the ability to eliminate the enemy boat, we do not consider disruptions that have both these systems failing. In these cases, we assume that the mission is aborted. Additionally, we consider partial disruptions of the Ship and Helicopter. The Ship has two important functions in the mission: (1) collect, integrate, and distribute information to the other systems and (2) eliminate the enemy boat using weapons. Hence, we consider two partial disruptions of the Ship: (1) failure of the communications subsystem on the ship rendering it unable to co-ordinate with the
other systems and, (2) inability of the Ship to launch its weapons. Similarly, partial disruption of the Helicopter is a weapons failure.

4.1.2 Step 2: Estimate Unmitigated Impacts of Disruptions

Here we focus on mission success (elimination of the enemy boat within the planned mission time) as a measure of the SoS performance.

We used a Monte Carlo analysis with 1000 runs to account for uncertainty and randomness in agent behavior and calculated the average mission success rate for each configuration as:

\[
\text{Mission success} = \frac{\text{No. of successful missions}}{n_{\text{runs}}}
\] (6)

To establish nominal SoS performance, we ran the ABM without any disruptions and recorded the resulting mission success percentage (94%, 1000 runs).

<table>
<thead>
<tr>
<th>Table 5: Impact of disruptions on mission success rates (naval warfare SoS)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of disruptions</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Single system disruptions</td>
</tr>
<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Two-system disruptions</td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Three-system</td>
</tr>
<tr>
<td>Type of disruptions</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Disruptions</td>
</tr>
<tr>
<td>Communications subsystem on Ship</td>
</tr>
<tr>
<td>Partial disruptions</td>
</tr>
<tr>
<td>Failure to fire weapons on Helicopter</td>
</tr>
</tbody>
</table>

Next, we determine the impact of the disruptions. We assume that failed systems cannot be repaired or restored within the planned mission time. Disruption timing is important in this mission. For instance, a disruption to the satellite late in the mission would have limited impact if the satellite had already detected the enemy and relayed the relevant information to other systems before being disrupted. Here, we looked at the potential disruptions and evaluated their impacts when they happen relatively early in the mission (at 1 hour) or late in the mission (at 2.5 hours). Table 5 summarizes the results (Since our focus is on the use of SIMs, and not on the particular results, we do not report on variance and other statistical parameters here.). As expected, when disruptions happen early, they tend to have a greater impact on the SoS performance than when they occur late in the mission. Exceptions are when either the Helicopter or communications on board the Ship are disrupted at 2.5 hours. Hence, through the rest of this section, we consider only early disruptions.

In the worst case, the mission success falls to zero. We now use this result to determine the worst-case SoS impact as follows: subtract the worst-case mission success rate (0%) from the nominal SoS performance (94%), and then multiply the resulting number by the duration of the disruption (4 hours, since in the worst case the disruptions can occur at the start of the mission). The process is shown in eq. (7).

\[
\text{Worst-case SoS impact} = (94 - 0) \cdot 4 = 376 \text{ units}
\]  

(7)
Next, the $\text{Impact}_D$ and $\text{SDI}_D$ of each disruption are determined using eqs. (2) and (3). Table 6 presents the fourteen disruptions sorted in order from most to least important based on their $\text{SDI}_i$ values. Some interesting observations include:

- Eleven unmitigated disruptions have fairly severe effects ($\text{SDI}_D > 0.6$) on the mission when they occur. Most of these disruptions include either the Ship or the Helicopter (fairly obvious since these are the only two systems that can carry weapons.

- The two types of partial disruptions of the ship have dramatically different impacts on the SoS. When the propulsion subsystem fails, rendering the ship immobile but still able to communicate with the other agents, the mission is not jeopardized ($\text{SDI}_D = 0.02$). However, a communications failure ($\text{SDI}_D = 0.75$) can stymie the mission even if the ship can proceed towards the enemy. This result is intuitive since the SoS configuration (see Table 4) shows that the ship is the central communications hub, and any failure of its communications capabilities implies that important tracking information does not get delivered to the other systems.

- Disruption of the UAV alone has little impact on the SoS mission. However, when both the UAV and the Satellite are disrupted, the combined impact on the SoS is larger than their individual impacts. Clearly, while the UAV alone may be redundant in the un-disrupted SoS, it contributes to surveillance when the Satellite is disrupted.

<table>
<thead>
<tr>
<th>Disruption (D)</th>
<th>$\text{SDI}_D$</th>
<th>Importance Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Satellite and Ship</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>UAV and Ship</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Satellite and Helicopter</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Helicopter and UAV</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Satellite, UAV, and Helicopter</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Disruption (D)</td>
<td>SDI_D</td>
<td>Importance Ranking</td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>-------</td>
<td>--------------------</td>
</tr>
<tr>
<td>Satellite, UAV, and Ship</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Communications subsystem on Ship</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>Satellite and UAV</td>
<td>0.74</td>
<td>9</td>
</tr>
<tr>
<td>Helicopter</td>
<td>0.71</td>
<td>10</td>
</tr>
<tr>
<td>Failure to fire weapons on Helicopter</td>
<td>0.68</td>
<td>11</td>
</tr>
<tr>
<td>Satellite</td>
<td>0.54</td>
<td>12</td>
</tr>
<tr>
<td>Propulsion subsystem on Ship</td>
<td>0.02</td>
<td>13</td>
</tr>
<tr>
<td>UAV</td>
<td>0.01</td>
<td>14</td>
</tr>
</tbody>
</table>

4.1.3 Step 3: Determine Current SoS Resilience

Next, we evaluate the current SoS resilience and identify areas where improvements are needed or where downgrades can be made. We assume that the baseline SoS has three mitigations available to deal with disruptions:

1. The Ship is armed with additional higher-range weapons to compensate for a Helicopter disruption.
2. The UAV is equipped with a more powerful secondary radar (Mode 2 radar) to provide wide-area search capability when the Satellite is disrupted. This measure results in a heavier UAV that requires frequent returns to the Ship for refueling.
3. If the UAV is disrupted, it can be repaired within a certain time frame, here 1.5 hours after the disruption. The UAV would need to return to the Ship for inspection, repair, and re-deployment.

Again, we used the agent-based model to implement the above mitigations and evaluate their effectiveness. Next, we recorded the new mission successes to determine $SDCI_{D,M}$ values using eq. (4) (see Figure 12) and $SDMI_{D,M}$ values using eq. (5) (see Figure 13). The rows in both figures indicate disruptions while the columns represent mitigation
strategies. Where mitigation is possible, the corresponding cells are populated with the calculated $SDCI_{D,M}$ and $SDMI_{D,M}$ values.

**Figure 12: SDCI$_{D,M}$ (Phase 3) for naval warfare SoS**

<table>
<thead>
<tr>
<th>Set of Disruptions</th>
<th>Set of Mitigations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion subsystem on Ship</td>
<td>Switch to mode 2 radar on UAV</td>
</tr>
<tr>
<td>Satellite + UAV + Ship</td>
<td></td>
</tr>
<tr>
<td>Satellite + UAV + Helicopter</td>
<td></td>
</tr>
<tr>
<td>Propulsion subsystem on Ship</td>
<td></td>
</tr>
<tr>
<td>Satellite + UAV + Ship</td>
<td></td>
</tr>
<tr>
<td>Helicopter + UAV</td>
<td></td>
</tr>
<tr>
<td>Satellite + Helicopter</td>
<td></td>
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<tr>
<td>Satellite + UAV</td>
<td></td>
</tr>
<tr>
<td>Satellite</td>
<td></td>
</tr>
<tr>
<td>Ship</td>
<td></td>
</tr>
<tr>
<td>Helicopter</td>
<td></td>
</tr>
<tr>
<td>Satellite + UAV</td>
<td>0.04</td>
</tr>
<tr>
<td>UAV</td>
<td>0.55</td>
</tr>
<tr>
<td>Helicopter</td>
<td>0.67</td>
</tr>
<tr>
<td>Ship</td>
<td>0.66</td>
</tr>
<tr>
<td>Satellite + UAV</td>
<td>0.71</td>
</tr>
<tr>
<td>Satellite + Helicopter</td>
<td>0.73</td>
</tr>
<tr>
<td>Satellite + Ship</td>
<td>0.74</td>
</tr>
<tr>
<td>UAV + Ship</td>
<td>0.74</td>
</tr>
<tr>
<td>Helicopter + UAV</td>
<td>0.74</td>
</tr>
<tr>
<td>Satellite + UAV + Helicopter</td>
<td>0.74</td>
</tr>
<tr>
<td>Weapons failure on Helicopter</td>
<td>0.52</td>
</tr>
</tbody>
</table>
Next, we show how these results can be incorporated into a resilience map and used to make decisions about where and how to change the SoS design. First, we need some kind of decision threshold to determine whether the resilience is acceptable.

In reliability and risk analysis, practitioners frequently specify minimum acceptable performance levels to assess risk mitigation measures and safety training—if the performance of a system or subsystem falls below a pre-determined level, immediate steps must be taken to address this undesirable situation. These minimum acceptable levels depend on many factors such as regulatory standards, operator workload and

---

**Figure 13: SDMI\(_{DM}\) (Phase 3) for naval warfare SoS**

<table>
<thead>
<tr>
<th>Set of Disruptions</th>
<th>Set of Mitigations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite</td>
<td>0.50</td>
</tr>
<tr>
<td>UAV</td>
<td></td>
</tr>
<tr>
<td>Helicopter</td>
<td>0.16</td>
</tr>
<tr>
<td>Ship</td>
<td></td>
</tr>
<tr>
<td>Satellite + UAV</td>
<td>0.08</td>
</tr>
<tr>
<td>Satellite + Helicopter</td>
<td>0.02</td>
</tr>
<tr>
<td>Satellite + Ship</td>
<td></td>
</tr>
<tr>
<td>UAV + Ship</td>
<td></td>
</tr>
<tr>
<td>Helicopter + UAV</td>
<td>0.09</td>
</tr>
<tr>
<td>Satellite + UAV + Helicopter</td>
<td>0.01</td>
</tr>
<tr>
<td>Satellite + UAV + Ship</td>
<td>0.01</td>
</tr>
<tr>
<td>Propulsion subsystem on Ship</td>
<td>0.01</td>
</tr>
<tr>
<td>Communications subsystem on Ship</td>
<td>0.01</td>
</tr>
<tr>
<td>Weapons failure on Helicopter</td>
<td>0.23</td>
</tr>
</tbody>
</table>

---
training, system design, and public acceptance. In a similar vein, here we introduce a decision threshold ($\alpha$) to assess the importance of the different systems.

The value of $\alpha$ can range between 0 and 1, where 0 indicates that the SoS is disruption proof while 1 indicates that the SoS is completely un-resilient. Determining a suitable $\alpha$ depends on multiple factors such as the particular SoS under investigation, available resources, cost of the mitigation measures, and the decision-maker’s judgment. Additionally, in practice, due to the same factors, the value of $\alpha$ may need to be varied during the decision-making process. Potential ways to determine an initial value include considering the minimum acceptable performance level for an SoS (e.g.: average delay in a transportation network should not exceed 45 min), historical data (e.g.: delays experienced in the National Air Space during previous disruptions such as snowstorms and hurricanes), and expert opinion. In practice, such a limit can be reached through analysis and consensus across a range of stakeholders such as among others commanding officers and combat operations specialists.

Varying $\alpha$ changes the resilience map. While the overall SIM values do not change, the color of each cell changes as $\alpha$ varies from low (risk averse analyst) to high (risk taking analyst). So, in terms of practical usefulness, an analyst can study how colors on the resilience map change as the value of alpha “slides” between high and low values. By identifying the cells that remain red across a range of alpha values, the analyst can determine mitigation strategies that need to be improved (prioritize resource allocation) or studied in further detail (guidance for simulations and field tests).

In this case, to determine the initial decision threshold we first establish a minimum acceptable mission success level. Here, we assume that the minimum acceptable mission success is 60% if one or more systems are disrupted early (one hour into the mission). Substituting 60% into eq. (4), we see that the $SDCI_{D,M}$ corresponding to this minimum acceptable mission success rate is 0.27. Thus, the initial $\alpha$ is set to 0.27.
Using this value, we develop a *resilience map* for the naval warfare SoS (Figure 14). The resilience map summarizes the relevant resilience information in two ways: (1) high level overview of which disruptions have been mitigated adequately and which ones have not, and (2) detailed information about which disruption-mitigation combinations need attention. At the high-level, by comparing the first and last columns of the resilience map, we see which disruptions have been mitigated (when the $SDI_D$ value is red and the corresponding average $SDCI_{D,M}$ is green), and which ones have not (when $SDI_D$ and average $SDCI_{D,M}$ are both red). The extent to which the strategies mitigate the
disruptive impacts is proportional to the difference between these two values in each row.

The first column in the map represents impact of unmitigated disruptions ($SDI_D$), while the last column denotes the impacts of the same disruptions once they have been mitigated (average $SDCI_{D,M}$). Each cell in the map is allocated a color: red when $SDCI_{D,M} > \alpha$ and green when $SDCI_{D,M} < \alpha$. The hatched green lines indicate cases where there is no mitigation, but the disruption impact is less than $\alpha$, so it is not necessary to add mitigations.

At first glance, we note that in some cases the recovery strategies are adequate (green cells) while in most other cases the strategies are inadequate (red cells). Now we step through the map to identify problems or opportunities and potential design solutions (see Uday and Marais (2015)) to address them as follows.

First, we identify the disruptions that are being adequately managed, that is, the green cells in the final column. In this case, disruption of the satellite is well mitigated by using the UAV. Two other disruptions (UAV and Ship Propulsion) do not have mitigations, but their effects on mission success are minimal (low SDI), therefore no additional mitigations are needed.

Second, we identify disruptions that are mitigated, but not adequately, that is, the red numbered cells in the final column. Some mitigations have very little effect ($SDCI \approx SDI$), for example, better weapons or repairing the UAV has almost no effect on the disruption of Satellite, UAV, and Helicopter. It is therefore necessary to identify additional or better mitigations for each disruption. For example, considering the third row in the table:

- **Specific problem:** The mitigation measures (i.e., weapons on the Ship) have **insufficient range** to eliminate threats in the event of an Helicopter disruption.
• **Potential solution:** Physical redundancy can improve the capacity of the mitigation measures. One way to realize physical redundancy is to maintain a backup Helicopter on the periphery of the mission that can be deployed as necessary.

Third, we identify disruptions that have no mitigations and a high SDI, that is, the grey cells in the last column. It is therefore necessary to identify mitigations for each disruption, or to reduce the unmitigated impact of the disruption. For example, considering disruption of the communication systems:

• **Specific problem:** The remaining systems are unable to communicate with each other, meaning any mitigation measures cannot be accessed due to lack of communication capabilities.

• **Potential solutions:** Inter-node interaction can increase communication links between systems. Some ways to realize this principle include:
  - Provide capability for Helicopter to receive information directly from the Satellite if the Ship is disrupted. Resources needed to implement this recovery feature include increased bandwidth allocation and modifications to communication ports.
  - If the Ship is disrupted, provide capability for UAV to receive information directly from the Satellite and in turn for the Helicopter to communicate with the UAV. Resources needed to implement this recovery feature include increased bandwidth allocation and modifications to communication ports.

The last row in the resilience map provides a summary of the mitigation effectiveness of each strategy (average $SDMI_{p,M}$). The higher this value, the greater the contribution of the mitigation to SoS resilience. Note that repairing the UAV and using better weapons on the Ship have relatively minor mitigation impacts.
4.1.4 Step 4: Improve SoS Resilience

In Step 4 of the resilience framework, the potential design improvements suggested in Step 3 are implemented. The updated resilience map shown in Figure 15 indicates whether the design changes have yielded the desired results.

On the one hand, clearly the design instances of the inter-node interaction principle are quite effective at mitigating the disruptions of the Ship’s communication systems. On the other hand, the backup Helicopter is no better at addressing the Helicopter disruption than incorporating advanced (better) weapons on the Ship.

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1 Caveat: All times of recovery are relatively conservative and have been chosen to highlight the impact of late recoveries on the SoS.
From this new map, we conclude that the most pressing disruptive impact that needs to be addressed is the disruption of the Helicopter. Potential suggestions include:

- Improve weapons on Ship: increase the range and/or accuracy of the weapons.
- Improve back-up Helicopter: use a faster helicopter or perhaps even a different one.

Two interesting observations arise from considering the last row (average $SDMI_{D,M}$ values) in the resilience map. First, we can pinpoint those mitigations that contribute significantly to overall resilience, that is, measures with a high average value, and subsequently ensure that these mitigations are available and ready to be deployed when needed. Second, by focusing on those measures that have high average $SDMI_{D,M}$ values, we propose that one way to improve resilience is to combine some or all these highly-effective mitigations so that the resulting "super-set" mitigation strategy is effective across a range of disruptions.

4.2 Case Study 2: Urban Transportation SoS

The purpose of this case study is to illustrate the usefulness of the information that can be gleaned from the results of the resilience framework. We provide a brief discussion on methods that can be used to determine the relevant inputs (resilience curves and potential disruptions), and then offer a detailed description of the design guidance obtained from the resilience maps.
4.2.1 Determining Potential Disruptions and their Impacts

Figure 16: Overview of Boston Urban Transportation SoS [MBTA, 2014a]

The Massachusetts Bay Transportation Authority (MBTA) oversees the fifth largest mass transit system in the United States. The Authority maintains the following modes of transportation: (1) rapid transit using heavy rail, light rail, and streetcars, (2) commuter rail (typically connecting the city center to the suburbs) using locomotives and coaches, (3) bus service, and (4) a commuter boat that provides ferry rides between various points in inner Boston harbor (see Figure 16).
Different types of instigating events can disrupt transportation services in a city. For instance, instigating events can be organization-related (e.g. strikes by bus drivers and ticket takers), weather-related (e.g. snowstorms and hurricanes), due to mechanical/electric failures (e.g. power loss and brake failures), or terrorist attacks. These events can cause a wide range of disruptions. For example, a mechanical failure may only impact one bus or one train, while a snowstorm can ground multiple modes of transportation.

The task of identifying potential disruptions can be carried out by a team of analysts and using relevant methods such as brainstorming in a group setting and by leveraging historical data (e.g. age of vehicles, maintenance data, weather information, policy changes) to determine a list of potential disruptions.

Next, for an urban transportation network, there are several ways to assess the impacts of unmitigated and mitigated disruptions. Most authorities that oversee transit services either have in-house tools that are used to carry out various studies regarding network level metrics such as on-time performance and average delays, or have such evaluations carried out by consultants (e.g. RAILSIM software [SYSTRA, 2014]). Additionally, transportation related research has resulted in models that specifically simulate urban transit services (see for example, Balakrishna et al. [2008] and Koutsopoulos and Wang [2007]) Similar to the agent-based model in the previous case study, these simulation tools and analytical models can be directly leveraged to assess the impacts of different disruptions.

A popular metric of interest to quantify SoS level performance in urban transportation networks is unlinked passenger ridership, that is, the number of passengers who board public transportation vehicles [MBTA, 2014b]. Passengers are counted each time they board vehicles irrespective of the number of vehicles they use to travel from their origin to their destination. Table 7 summarizes typical passenger ridership on weekdays as published by the MBTA [2014b].
Table 7: Typical weekday ridership in 2013 on the select modes of transportation in Boston [MBTA, 2014]

<table>
<thead>
<tr>
<th>Mode</th>
<th>Line</th>
<th>Typical Weekday Ridership</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subway</td>
<td>Red Line</td>
<td>272,684</td>
</tr>
<tr>
<td></td>
<td>Orange Line</td>
<td>203,406</td>
</tr>
<tr>
<td></td>
<td>Blue Line</td>
<td>63,225</td>
</tr>
<tr>
<td></td>
<td>Green Line</td>
<td>227,645</td>
</tr>
<tr>
<td>Bus</td>
<td>Silver Line</td>
<td>29,839</td>
</tr>
<tr>
<td></td>
<td>Trackless Trolley</td>
<td>11,588</td>
</tr>
<tr>
<td></td>
<td>Bus</td>
<td>346,388</td>
</tr>
<tr>
<td>Commuter Boat</td>
<td>Ferry</td>
<td>4439</td>
</tr>
</tbody>
</table>

4.2.2 Reading the Resilience Map

In this section, we discuss pertinent information that can be obtained from resilience maps of the Boston urban transportation network. Assuming we have determined the values of the SIMs using the equations presented in Section 3, we then use example resilience maps to indicate how resilience-related design improvements can be made.

First, a note about determining an initial decision threshold for urban transportation networks. In these SoSs, $\alpha$ can be specified as the product of two parameters: (1) minimum acceptable SoS performance level, and (2) maximum acceptable time to mitigation. These parameters can be estimated as follows:

1. The first parameter is driven by the specific measure used to evaluate SoS performance. For example, if the SoS performance is measured as passenger ridership, the decision-maker can specify a minimum acceptable level of ridership that the SoS needs to satisfy in the event of a disruption.

2. The second parameter can be estimated in different ways based on stakeholder preferences. For example, one approach is to study historical data and determine
how long, on average, are passengers willing to wait after a disruption (see, for example, Kaufman et al. [2012]).

Figure 18 (please see end of paper) shows a partial resilience map with some subset of the total disruptions and a subset of potential mitigation measures. This map explores the state of SoS resilience when certain modes or lines of transportation are disrupted and how well the remaining transit services handle the spillover ridership. Darker shades of red indicate disruptions that are highly unmitigated, while darker shades of green indicate disruptions that are currently handled well. We assume here that the SoS here does not provide any explicit means (e.g., shuttle buses) to transport stranded passengers to other links. Hence, the only factors driving the effectiveness of the mitigation strategies are proximity to the disrupted line and ability of alternate modes to handle the extra passenger traffic.

For example, when the Orange Line (south) is disrupted, three alternative modes of transit (Silver Line, buses in Zone 3, and the commuter rail in Zone 3) are able to partially mitigate the impact. The commuter rail is quite effective in handling spillover traffic from the Orange Line (as indicated by the dark green cell) since it runs parallel to the disrupted line and has several stations collocated with those of the Orange Line. Thus, the passengers who intended to travel on the disrupted Orange line have relatively easy access to an alternate mode of transportation. However, the other two mitigation modes of transport (Silver Line and the bus service in Zone 3) are less effective in mitigating the impact of the disrupted subway line as (1) they do not run the length of the Orange Line and hence do not serve the same locations, meaning passengers would be delayed or inconvenienced with respect to getting to their final locations, and/or (2) they do not have sufficient capacity to handle the extra demand from the Orange Line.

How does the resilience map guide decision-making in the context of the urban transportation SoS? We list key observations, describe the problems or opportunities
they indicate, and point to potential design principles (see Uday and Marais (2015)***)
to address them.

**First**, we identify the disruptions that are being adequately managed, that is, the green
cells in the final column. In this case, disruptions of Green Lines B or E are adequately
mitigated using buses and commuter rail, or transferring E line traffic to the B line.
Although we do not consider simultaneous disruption of the B and E lines here, the E
line’s role as backup for the B line suggests that the next round of disruption analysis
should consider this possibility.

**Second**, we identify disruptions that are mitigated, but not adequately, that is, the red
numbered cells in the final column. In this case, our hypothetical analysis indicates that
most disruption mitigations are inadequately mitigated, because they have insufficient
capacity and passengers have limited access to the alternative modes.

- **Specific problem (a):** The mitigation measures (i.e., alternate transportation
  modes) have insufficient capacity to handle the spillover demand.
- **Potential solutions:**
  - One way to realize physical redundancy is to maintain spare subways and buses,
    which can be called in to service when there is a disruption on the respective
    lines.
  - Functional redundancy for disrupted subway lines can be realized by using “bus
    bridges” [Kepaptsoglou and Karlaftis, 2009]. Bus bridges provide short-term bus
    routes between rail (subway or commuter) stations in the event of a disruption.
    Buses can be mobilized from depots (spare buses) or retracted from existing
    routes to establish the bus bridges.
  - An opportunity that arises from considering both principles together (physical
    and functional redundancy) is the ability to combine mitigations across multiple
    transportation modes. For instance, investment in spare buses (a relatively
    cheaper option than investing in spare trains) is useful to address bus
    disruptions (deploy the spare bus when a primary bus is disrupted – physical


redundancy) as well as rail disruptions (deploy spare buses to establish bus bridges between subway stations – functional redundancy).

• **Specific problem (b):** Passengers have limited access to these alternate modes.
• **Potential solutions:**
  o *Improved communication at the organizational level* can improve access to the mitigation measures. Well-established emergency plans that clearly facilitate timely and effective sharing of information between regulatory authorities, operators, and passengers can help minimize performance impacts on the transportation network. Thus, passengers can be evacuated safely and re-directed to other modes of transport efficiently.
  o *Inter-node interaction* can improve access to the mitigation measures. This principle can be realized by providing shuttle services to the nearest alternate mode of transportation (e.g., from the disrupted subway stations to the nearest bus or commuter rail facilities). Another method to increase inter-node interaction is to improve bicycle infrastructure. Suitably located bicycle stations can allow some passengers to cycle to the nearest alternate mode.

The presence of red and green cells in columns *Commuter Rail Zone 1* and *Commuter Rail Zone 2* indicate that commuter rail services in both these zones provide adequate mitigations in some instances and inadequate mitigation in other instances. For example, the commuter rail line in Zone 2 provides effective partial recovery when the Orange Line (North) is disrupted but not when the Blue Line is disrupted.

• **Specific problem:** The alternate modes are unable to provide adequate mitigation because passengers have limited access to them.
• **Potential solutions:**
  o One way to realize this principle in Zone 1 is to maintain bus stops within walking distance of commuter stations. However, making this change would require a redesign of existing bus routes so that the stops are co-located with rail stations. A relatively cheaper option is to provide shuttle services between bus stops and the commuter rail stations. However, this option needs pre-planning
in terms of personnel co-ordination and the availability of shuttles to be deployed in a timely manner.

- The principle of inter-node interaction can be realized in Zone 2 by co-locating subway and rail stations. In fact, this design is already seen on the Orange Line (North) where several transfer facilities are provided between commuter rail service and subway stations. Such a provision allows passengers to switch modes relatively easily. Again, since this might be a challenging change to make in the SoS design (extensive structural and procedural modifications of the transit services are required), operating shuttle buses between the stations of the two modes may be a more cost-effective option.

- Bus Zone 1 mitigates disruptions to Green Line (B) well, but does less well for disruptions to the Red Line (North). This finding suggests that Bus Zone 1 performance for Red Line disruptions could be improved by increasing its accessibility to Red Line passenger, for example, by using temporary shuttle services.

The presence of multiple red cells in column Ferry indicates that this service contributes inadequately to mitigating the impacts of multiple disruptions.

- **Specific problem:** While it seems that this mode can be leveraged to mitigate disruptive impacts across several (more than three) adverse events, the passenger capacity of the Ferry service is insufficient.

- **Potential solution:**
  - *Physical redundancy* can improve the passenger ridership capacity of the mitigation measures. One way to realize this principle in this instance is to maintain spare ferries, which are called in to service when there is a disruption. For example, in the aftermath of Hurricane Sandy in New York, an extra ferry was introduced between Manhattan and Staten Island to compensate for the railway disruption [Kaufman et al., 2012].
Third, we identify disruptions that have no mitigations and a high SDI, that is, the grey cell in the last column. None of the mitigation measures address the disruption of Green Line (D).

- **Specific problem:** Passengers affected by the disruption are unable to access alternative transit modes.
- **Potential solutions:** Since there are several modes with green SDMIs, we should look for ways to provide access to these modes if Green Line D is disrupted.

Figure 19 (please see end of paper) shows another example of a partial resilience map for the Boston urban transportation SoS. This map reflects a more resilient SoS with better mitigation measures that have been realized, for example, by implementing the functional redundancy and inter-node interaction suggestions from the previous discussion. Here, we focus on the green cells and describe the opportunities they suggest for resilience improvement.

The light green cells in the mitigation columns for bus service (Zones 1, 2, and 3) and commuter rail (Zones 1, 2, and 3) indicate that these two modes are reasonably well equipped to provide mitigation when disruptions occur, but there is room for further improvement. One way to improve the resilience further is to focus on delaying or reducing the impact of the disruption.

- **Potential solutions:** *System-level properties* and *drift correction* can improve the capacity of the mitigation measures.
  - One way to leverage system-level properties is to improve the robustness of the subway by for example deploying inflatable flood barriers in subway tunnels or constructing raised entrances at flood-prone stations.
  - One way to realize drift-correction is to deploy sensors in subway tunnels to detect rising water levels and automatically activate water pumps. Thus, preemptive initiation of mitigation allows subway services to continue for a longer duration of time before being halted than would otherwise be possible.
When considered together, the bus service (Bus Zone 1, Bus Zone 2, and Bus Zone 3) and commuter rail (Commuter Rail Zone 1, Commuter Rail Zone 2, and Commuter Rail Zone 3) are able to adequately mitigate all the disruptions in identified set. A useful next step would therefore be to assess what minimum combination of these six mitigation strategies could be the most effective. For instance, the bus service and commuter rail in Zone 3 sufficiently address the same disruptions. Decision-makers can now explore if either of these can be downgraded slightly in order to allocate resources to transportation facilities in other zones.

5 Model Improvement: Automated design principle

The basic SIM approach for SOS resilience design lacks further comparison to distinct different design changes. Specifically, though suggestions of categories of changes are provided, detailed comparison measures are not provided in this approach. To fulfill this need and improve model's usability, an improved model is proposed, as shown in Figure 17. This improved model is the focus of our current work.

![Figure 17. Automated Design Principle Model](image)

The automated design principle model answers the following questions: 1) Among the design principles, which one improves the SOS resilience more and thus the most helpful? 2) For users with cost or design constraints, which design change is more preferable?
To answer these questions, a quantitative analysis is performed on the proposed design changes, derived from design principles. This quantitative analysis compares the most direct SOS resilience metric, $SDCI$, and for every design change, $\Delta SDCI$ is generated specifically for each disruption-recovery pair. Based on a $\Delta SDCI$ table that details resilience effects on all disruption-recovery pair and the average $\Delta SDCI$ for each design change, comparison without cost factor among these changes is performed.

With the given $\Delta SDCI$ table and an extra dimension of comparison, cost, the model further develops cost-benefit analysis which assists designers with cost and design constraints in decision-making process. The main idea behind cost-benefit analysis is to present designers most efficient pairs of cost-$\Delta SDCI$ so that limited resources can be allocated properly. To arrive at this goal, Pareto efficiency is employed to generate Pareto frontier based on pairs of cost-$\Delta SDCI$ and therefore designers can visualize that at each cost, what is the maximum $\Delta SDCI$ can be achieved.

The above improvements essentially differentiate different design changes and therefore respond to designers which one is most appropriate for their specific requirements.

6 Conclusions

We have developed a set of System Importance Measures (SIMs) that can be used to assess and improve resilience. We then showed how they can be used for resilience design in the context of Systems of Systems (SoS). We showed that SIM-based design provides a structured approach to resilience management. Using the design framework, decision-makers are guided through the analysis of SoS resilience in a systematic way, starting from the identification of disruptions to iterating in a group setting to improve SoS resilience. The resilience map presents both high-level and detailed information about SoS resilience. The visual nature of the resilience map provides a useful way to summarize the current resilience of the SoS as well as point to key systems of concern. Finally, it provides a platform for multiple analysts and decision-makers to study,
modify, discuss and document options for SoS, for example as part of a cost-benefit analysis.

The four steps of the design process can be used to study the resilience of both existing (fielded) SoSs and new (un-deployed) SoSs. In the case of the former, the resilience map highlights how well or how badly the current SoS structure can handle disruptions and points to inadequacies that need to be addressed. For the latter type of SoS, resilience map helps evaluate the resilience of potential SoS architectures.

Currently, we are making several refinements and additions to the SIM framework. In particular, we are incorporating the SIM analysis into a cost-benefit framework, as shown in step 5.

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