



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**OVERCOMING FLAWS IN THE  
MISSION DEPENDENCY INDEX (MDI) WITH  
NETWORK FLOW ANALYSIS**

by

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March 2021

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**OVERCOMING FLAWS IN THE MISSION DEPENDENCY INDEX (MDI)  
WITH NETWORK FLOW ANALYSIS**

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## ABSTRACT

The Mission Dependency Index (MDI) is a metric used by all U.S. military services for guiding operations, management, and funding decisions for facilities at military installations. Despite its broad adoption, several studies on MDI suggest it may have flaws that limit its efficacy. We present the first rigorous technical analysis of MDI as to how its flaws impact decisions and determine ways to overcome them. We develop a formal mathematical definition of MDI based on multilayer networks that supports reproducible models and formal analysis of the MDI calculation process used in the U.S. Navy. Based on our multilayer formalism, we define three technical problems with MDI methods not previously discussed in the literature. We develop a new model for calculating MDI based on network flow analysis that overcomes these problems. We demonstrate our new approach by assessing the vulnerability of a realistic diesel fuel marine mission to facility disruptions. Overall, our work provides clarity on how to interpret and avoid pitfalls in MDI calculation and use.

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## List of Acronyms and Abbreviations

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|                  |                                                                                |
|------------------|--------------------------------------------------------------------------------|
| <b>AD</b>        | Attacker / Defender                                                            |
| <b>C2</b>        | Command and Control                                                            |
| <b>CIKR</b>      | Critical Infrastructure and Key Resources                                      |
| <b>CNIC</b>      | Commander, Navy Installations Command                                          |
| <b>CNICINST</b>  | Command, Navy Installations Command Instructions                               |
| <b>DFM</b>       | Diesel Fuel Marine                                                             |
| <b>DoD</b>       | Department of Defense                                                          |
| <b>DOE</b>       | Department of Energy                                                           |
| <b>EO</b>        | Executive Order                                                                |
| <b>FCI</b>       | Facility Condition Index                                                       |
| <b>FY</b>        | Fiscal Year                                                                    |
| <b>IRR</b>       | Interruptability, Relocateability, and Replaceability                          |
| <b>MDI</b>       | Mission Dependency Index                                                       |
| <b>NASA</b>      | National Aeronautics and Space Administration                                  |
| <b>NFESC</b>     | Naval Facilities Engineering Service Center                                    |
| <b>OPNAVINST</b> | Office of the Chief of Naval Operations Instruction                            |
| <b>ORM</b>       | Operational Risk Management                                                    |
| <b>PESTONI</b>   | Personnel, Equipment, Supply, Training, Ordnance, Networks, and Infrastructure |
| <b>SME</b>       | Subject Matter Expert                                                          |

|             |                     |
|-------------|---------------------|
| <b>USA</b>  | U.S. Army           |
| <b>USAF</b> | U.S. Air Force      |
| <b>USN</b>  | U.S. Navy           |
| <b>USVI</b> | U.S. Virgin Islands |

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## Executive Summary

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The Mission Dependency Index (MDI) is a metric used by U.S. Department of Defense (DoD) military services and U.S. federal agencies to prioritize operations, management, construction, and funding of facilities and infrastructure assets. MDI was originally developed by Naval Facilities Engineering Service Center to evaluate the relative importance of facilities to missions within and across military installations based on the principles of U.S. Navy (USN) Operational Risk Management (ORM). It focuses attention on how installation missions may be negatively impacted if a facility is rendered inoperable. MDI is calculated using factors for the interruptability, relocateability, and replaceability (IRR) of facility functions, where IRR is measured via expert elicitation of installation mission owners answering four ordinal survey questions. Survey responses are transformed into an MDI score normalized from 0 to 100 for each facility using equations defined in USN instructions. The greater the consequence of the facility's loss, the higher perceived criticality of the facility to mission, the higher the MDI score. MDI scores are then converted into prioritization categories that guide DoD and federal government spending. MDI was used to justify nearly \$20 B of Fiscal Year 21 federal funds.

Despite its broad adoption across federal agencies, the efficacy of MDI for facility prioritization is disputed. Previous studies identify general issues with how MDI scores are calculated and used, such as how MDI does not address risk by standard USN ORM procedures. Still, no previous work develops a rigorous technical analysis of how MDI is calculated and applied to show how flaws may lead to sub-optimal decisions. This is partly due to the dubious nature of MDI. Contrary to doctrine and USN instructions, the MDI calculation process is complicated with many nuances, lacks formal definitions of key terms, and leaves installation users to make assumptions about how to interpret final results. Altogether, MDI is widely regarded as a useful, but flawed, tool and there is no study showing what those flaws are or what they mean for the federal government.

The purpose of this work is to develop a rigorous mathematical analysis of MDI that reveals flaws in its implementation and use. The overall goal is to develop new methods to assess facility importance that overcome these flaws. Towards this goal, we develop:

- a formal mathematical definition of MDI based on multilayer networks that provides rigorous technical methods for facilities at military installations;
- an analysis of MDI showing its technical flaws, including flaws in its interpretation and calculation;
- a series of simple, real-world examples showing the implications of these flaws for installation decision-making;
- a new model for how facilities relate to missions via flow network models;
- an analysis of this new model and conclusions on how it improves upon current methods for MDI; and,
- recommendations and next steps for improving MDI within the USN.

Our work relies on established methods for multilayer networks and network flow optimization. We dissect the key elements of the MDI process and create an installation multilayer network formalism that supports MDI calculation for facilities. Our multilayer network methods are the first rigorous explanation for how MDI works and enables formal analysis of the MDI survey and calculation process.

Building upon our formalism, we present a novel critique of MDI not found previously in the literature. First, we identify issues with MDI interpretation and use for decision-making. These issues stem from conflating long-term infrastructure funding decisions with measures for near-term consequences of facility disruption. Misinterpretation of MDI leads to some mission essential facilities (e.g., a water pumping station) receiving lower scores than less critical facilities (e.g., a gymnasium). We provide guidance on how to overcome these issues by clarifying the purpose of MDI scores and categories for survey respondents.

However, we also find three inherent issues with MDI calculation that cannot be overcome with more clarity in instructions. We name these flaws the *mission partitioning problem*, the *interdependency assignment problem*, and the *replaceability problem*. Each of these problems has the potential to raise or lower the MDI score of a facility based on seemingly arbitrary decisions for an installation, such as choosing the number of facilities assigned to each mission, the number of missions on the installation, and the sharing of functions across facilities. We determine that MDI as currently defined in USN instructions cannot overcome these issues.

Instead, we develop a new model for MDI based on network flow optimization. Our new

methods overcome these problems by being insensitive to mission partitioning, supporting more explicit interdependency assignment, and supporting dynamic analysis of functional relocateability and replaceability. We demonstrate our new model for a characteristic mission for distributing diesel fuel marine across an installation. Results show that network flow models do overcome identified flaws in MDI. Moreover, they reveal new issues with MDI that need to be addressed associated with the sourcing and distribution of services like fuel.

Overall, this work helps identify and overcome flaws in a key metric used by all DoD services for installation mission readiness. Results provide clarity on how to interpret MDI and avoid pitfalls in its calculation and use. Still, the work presented here is limited. Future work can build on this assessment to relate our initial model for a single mission to multiple missions at an installation. Moreover, our analysis is based on simulated responses to MDI surveys and would benefit from real-world case studies based on survey responses from USN subject matter experts.

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# CHAPTER 1:

## Introduction

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The Department of Defense (DoD) is split into two chains of command that share a common goal through separate lines of effort. The first is the Operational Command which plans and executes operational and tactical functions. The second is the Administrative Command that oversees and budgets for Personnel, Equipment, Supply, Training, Ordnance, Networks, and Infrastructure (PESTONI). The PESTONI pillars are defined by the DoD Chief Financial Officer, Comptroller (2018) as managing the following functions and needs:

1. Personnel: compensation, medical, and administration;
2. Equipment: sustainment, maintenance, and modernization;
3. Supply: material readiness; spares, repair parts, and consumables;
4. Training: ensuring forces remain proficient and effective;
5. Ordnance: capacity to load and reload naval forces;
6. Networks: cyber security, Command and Control (C2), information, and the systems and networks used to support; and,
7. Infrastructure: systems of facilities, buildings, structures, equipment, or installations required for military purposes.

This thesis focuses on analyzing the efficacy of DoD practices for managing critical infrastructure at military installations. Critical infrastructure is defined by the DoD as, “The infrastructure and assets vital to a nation’s security, governance, public health and safety, economy, and public confidence” (Joint Chiefs of Staff 2020). Critical infrastructure ensures the adequate flow of electricity, fuel, water, communications, supplies, food, and other resources required to complete military missions. The infrastructure pillar is broad and includes diverse activities and decision-makers at installations, including engineering and public works, communication and information technology, physical assets (e.g., runways, ports), and other specialty services.

U.S. military services use two key performance measures to prioritize infrastructure funding and operational needs at installations: the Facility Condition Index (FCI) and Mission Dependency Index (MDI). FCI is a measure used to determine the current condition of

DoD facilities and guides military construction, rehabilitation, and demolition activities (Office of the Assistant Secretary of Defense for Sustainment 2021). MDI is a measure that relates facilities to military missions to help prioritize operations and management efforts for facilities at the installation level.

This thesis focuses on the calculation and implications of MDI for facility funding decisions. For the remainder of this thesis, we refer to assets and systems assessed by MDI as *facilities* to broadly capture the critical infrastructure associated with the PESTONI pillars. For more information on FCI and how facility condition impacts decisions, see Renosto (2019).

## **1.1 The Mission Dependency Index**

The calculation and use of MDI influences operations and protection of facilities at military installations. MDI was developed by Naval Facilities Engineering Service Center (NFESC) to evaluate the relative importance of facilities to each other based on the principles of U.S. Navy (USN) Operational Risk Management (ORM) (Antelman and Miller 2002).

The most common use of MDI is to prioritize operations, management, construction, and funding decisions at an installation alongside FCI. Prior to MDI, facility prioritization was determined qualitatively by the installation Commanding Officer. MDI was adopted to provide a quantitative way that identifies critical facilities and prioritizes their funding. MDI is calculated by converting expert elicitation of mission needs into a normalized score on a scale of 0 to 100 for each facility on an installation. It focuses attention on how installation missions may be negatively impacted if a facility is rendered inoperable. The greater the consequence of the facility's loss, the higher perceived criticality of the facility, and the higher the MDI score.

Notably, MDI is not used for ranking supporting systems such as the roads, power lines, and water distribution pipelines that connect facilities. Instead, the MDI framework implicitly assumes these additional critical infrastructure systems will operate to supply services to high MDI facilities for mission assurance.

Assigning an MDI score for a facility consists of a two-step process involving a survey of installation mission-owners and Subject Matter Experts (SMEs) and then calculating MDI for each facility based on survey results.

### 1.1.1 Step 1: MDI Facility Survey

At the heart of MDI is a survey conducted to relate facility functions to mission. The survey involves four questions with ordinal responses where the “leader(s) directly responsible for the mission or operation [of the facility] are asked to respond” (Antelman and Miller 2002). The questions in the survey are meant to evaluate the importance facility functions to mission using three factors known as Interruptability, Relocateability, and Replaceability (IRR), defined in Commander, Navy Installations Command (2018) as follows:

- *Interruptability* is the length of time a mission can sustain given an interruption of facility functions or the length of time before an interruption in functions affects mission operations;
- *Relocateability* is the difficulty and time required to relocate a facility function required by a mission to another facility; and
- *Replaceability* is the difficulty and time required to replace a facility function required by a mission with another equivalent function.

The first two survey questions assess interruptability and relocateability of a facility, and the answers are used to assess its *intradependency* score. Intradependency is intended to measure the relationship of a facility to the mission and mission-owners that own and operate it. The following intradependency questions and responses are reproduced verbatim from Commander, Navy Installations Command (2018):

**Question 1 (Intradependency / Interruptability):** How long could the functions supported by your infrastructure be stopped without adverse impact to the mission?

N: None (Must be maintained continuously (24/7) (Note: If you select “N” additional information must be provided to support that the mission cannot be interrupted).

B: Brief (minutes or hours not to exceed 24 hours).

S: Short (days not to exceed 7 days or hours).

P: Prolonged (more than a week).

**Question 2 (Intradependency / Relocateability):** If your facility were not functional, could you continue performing your mission by using another facility, or by setting up temporary facilities?

- I: Impossible (an alternate location is not available)
- X: Extremely Difficult (an alternate location exists with minimally acceptable capabilities, but would require either a significant in-house effort (money/man-hours), dislocation of another major occupant or contracting for additional services and no available contract mechanism is in place to replace the services being provided.
- D: Difficult (an alternate location exists with acceptable capabilities and capacity, but relocation would require a measurable and unbudgeted level of effort (money/man-hours), but mission readiness capabilities would not be compromised in the process.
- P: Possible (an alternate location is readily available with sufficient capabilities and capacity; in addition, the level of effort has been budgeted for or can be easily absorbed)

Upon completion of Question 1 and 2, an intradependency score is calculated using the matrix shown in Figure 1.1. The intradependency score is denoted by  $MD_w$ , meaning “Mission Dependency Within,” referring to the importance of facility functions within a mission.

| $MD_w$                |                     | Q1: Interruptability      |                 |               |                   |
|-----------------------|---------------------|---------------------------|-----------------|---------------|-------------------|
|                       |                     | <u>N</u> one              | <u>B</u> riefly | <u>S</u> hort | <u>P</u> rolonged |
|                       |                     | Available<br>24hrs/7 days | ≤ 24 hrs        | 1 – 7 days    | ≤ 7 days          |
| Q2:<br>Relocatability | <u>I</u> mpossible  | 6.00                      | 5.50            | 4.67          | 3.67              |
|                       | <u>X</u> _Difficult | 5.10                      | 4.43            | 3.43          | 2.60              |
|                       | <u>D</u> ifficult   | 4.90                      | 4.23            | 3.23          | 2.40              |
|                       | <u>P</u> ossible    | 4.00                      | 3.00            | 2.00          | 1.00              |

Figure 1.1. Calculation of Mission Intradependency Score. Expert elicitation is used to determine how mission needs supported by a facility are affected by facility interruption and relocatability. Experts responses to Questions 1 and 2 are then input into this matrix to turn elicitation into values for MDI calculation. Figure adapted from Commander, Navy Installations Command (2018).

The second two survey questions assess the interruptability and replaceability of facility functions, and their answers are used to assess its *interdependency* score. Interdependency is intended to measure the relationship of a facility to other facilities in different missions. The following interdependency questions and responses are reproduced verbatim from Commander, Navy Installations Command (2018):

**Question 3 (Interdependency / Interruptability):** How long could the services provided by (named Functional Area) be interrupted before impacting your mission readiness?

- N: None (Must be maintained continuously (24/7)).
- B: Brief (minutes or hours not to exceed 24 hours).
- S: Short (days not to exceed 7 days or hours).
- P: Prolonged (more than a week).

**Question 4 (Interdependency / Replaceability):** How difficult would it be to replace or replicate the services provided by (named Functional Area) with another provider from any source?

- I: Impossible (there are no known redundancies or excess/surge capacities available, or there are no viable commercial alternatives – only this site/command can provide these services).
- X: Extremely Difficult (there are minimally acceptable redundancies or excess/surge capacities available, or there are viable commercial alternatives, but not readily available contract mechanism in place to replace these services).
- D: Difficult (services exist and are available, but the form of delivery is ill defined or will require a measurable and unbudgeted level of effort to obtain (money/man-hours), but mission readiness capabilities would not be compromised in the process)
- P: Possible (services exist, are available, and are well defined).

Upon completion of Question 3 and 4, an interdependency score is calculated using matrix shown in Figure 1.2. The interdependency score is called  $MD_b$ , referring to “Mission Dependency Between” facilities functions across missions.

| $MD_B$                |                    | Q3: Interruptability      |                 |               |                   |
|-----------------------|--------------------|---------------------------|-----------------|---------------|-------------------|
|                       |                    | <u>N</u> one              | <u>B</u> riefly | <u>S</u> hort | <u>P</u> rolonged |
|                       |                    | Available<br>24hrs/7 days | $\leq 24$ hrs   | 1 – 7 days    | $\leq 7$ days     |
| Q4:<br>Replaceability | <u>I</u> mpossible | 6.00                      | 5.50            | 4.67          | 3.67              |
|                       | <u>X</u> Difficult | 5.10                      | 4.43            | 3.43          | 2.60              |
|                       | <u>D</u> ifficult  | 4.90                      | 4.23            | 3.23          | 2.40              |
|                       | <u>P</u> ossible   | 4.00                      | 3.00            | 2.00          | 1.00              |

Figure 1.2. Calculation of Mission Interdependency Score. Interdependency is calculated using a similar process to intradependency. Experts answer Questions 3 and 4 for facilities to determine how interdependent the mission is with other facilities and missions on the installation. Expert responses are then input into this matrix to turn elicitation into values for MDI calculation. Figure adapted from Commander, Navy Installations Command (2018).

Intradependency is calculated only once for a single facility function within a mission. For example, a pump station providing water to an installation will only receive one  $MD_w$  score from the water mission SME. However, that same facility function can be interdependent with multiple other missions and can have many  $MD_b$  scores. Continuing the example, the same pump station can have  $N$   $MD_b$  scores, where  $N$  is the number of facility functions that require water. For this reason, the final score for a facility used for MDI calculation is the mean of all  $MD_b^i$  scores ( $i = 1, \dots, N$ ) it receives during the MDI survey:

$$MD_b^{avg} = \frac{\sum_i^N MD_b^i}{N}. \quad (1.1)$$

### 1.1.2 Step 2: MDI Calculation

After determining intradependency and interdependency, the MDI score for a facility is calculated as a function of  $MD_w$ ,  $MD_b^{avg}$ , and  $N$  with the following equation (Commander, Navy Installations Command 2018):

$$\text{MDI} = 16.5 \times \left[ \text{MD}_w + \frac{\text{MD}_b^{\text{avg}}}{8} + 0.1 \times \ln N \right] - 15.5. \quad (1.2)$$

Once its MDI score is calculated, a facility is then assigned an MDI Category. The MDI categories used in the USN are presented in Figure 1.3. MDI categories are ultimately used to guide infrastructure decision-making and funding prioritization.

| MDI Category       | Score Range   |
|--------------------|---------------|
| <b>CRITICAL</b>    | <b>100-85</b> |
| <b>SIGNIFICANT</b> | <b>84-70</b>  |
| <b>RELEVANT</b>    | <b>69-55</b>  |
| <b>MODERATE</b>    | <b>54-40</b>  |
| <b>LOW</b>         | <b>39-1</b>   |

Figure 1.3. Mission Dependency Index Categories. Once facility intradependency and interdependency scores are calculated, Equation 1.2 is used to calculate MDI. MDI scores on their own are often not used for decision-making. Instead, MDI scores are input into this table to prioritize different facilities and missions. Figure adapted from Commander, Navy Installations Command (2018).

### Example 1: Sample MDI Calculation

We present a realistic example MDI calculation to show the entire process. For this example, we calculate the MDI for a gymnasium that is part of an installation fitness mission. The fitness mission SME determines that for survey Question 1 the gymnasium could be interrupted for less than 24 hours before adverse impact to the fitness mission (B, briefly). The SME then answers Question 2 that it is not possible to move the functions provided by the gymnasium to another facility (I, impossible). Using the table in Figure 1.1 to interpret these responses results, the gym is assigned  $\text{MD}_w = 5.5$ .

Next, we assume only one facility function from the training mission depends on the gymnasium ( $N = 1$ ). Thus, a SME from the training mission provides responses to MDI Questions 3 and 4 for the gym. The training mission determines that the interruption of the gym would have a impact training within 1-7 days (S, short), but it is possible to replace the gym mission (i.e., training outside) (P, possible). Using these responses, the table in

Figure 1.2 results in the gym  $MD_b^{avg} = 2.0$  (with only one interdependent facility, this is the average value).

Once the survey is done, Equation 1.2 is used to calculate for the gymnasium's MDI score. We find:

$$\begin{aligned}
 MDI_{\text{gymnasium}} &= 16.5 \times \left[ MD_w + \frac{MD_b^{avg}}{8} + 0.1 \times \ln N \right] - 15.5 \\
 &= 16.5 \times \left[ 5.5 + \frac{2.0}{8} + 0.1 \times \ln 1 \right] - 15.5 \\
 &= 79.38
 \end{aligned}$$

The MDI score of 79.38 would place the gymnasium into the MDI category of “significant” as per the table in Figure 1.3.

## 1.2 MDI and DoD Infrastructure Decisions

The perceived benefits of MDI are established in DoD doctrine and requirements. For example, the Commander, Navy Installations Command (CNIC) instruction for MDI makes the following claims about its efficacy (Commander, Navy Installations Command 2018):

- “MDI evaluates the installation’s ability to support the Warfare Enterprise’s mission should the infrastructure be damaged or destroyed.”
- “MDI ....captures the operational mission impacts of facility degradation or outage.”
- MDI “ensures limited resources are prioritized and allocated properly.”

MDI also helps DoD services meet requirements set by the Office of the President of the United States for asset management. Executive Order (EO) 13377 entitled “Federal Real Property Asset Management” (2004) was intended to improve the agency asset management planning process that measures life-cycle cost estimations, including costs of acquiring, repairing, maintaining, operating, managing, and disposing assets and facilities. This required agencies to not only use life-cycle cost estimation, but also a method of prioritization (Nichols 2015).

MDI addresses the section of EO 13327 requiring agencies to validate funding through methods of prioritization. As such, MDI gained popularity across the DoD and has since been adopted by several agencies. Some of the larger agencies to date include:

- USN (Commander, Navy Installations Command 2018),
- U.S. Air Force (USAF) (Weniger 2018),
- U.S. Army (USA) (Grussing et al. 2010),
- National Aeronautics and Space Administration (NASA) (National Aeronautics and Space Administration 2010), and
- Department of Energy (DOE) (NNSA Office of Safety, Infrastructure & Operations 2017).

Each of these organizations has made changes to the original MDI concept first proposed by Antelman and Miller (2002). These changes may be in the assigned values, range and depth of ordinal questions, or other aspects of the framework. Even with these changes they all use MDI in essentially the same way: to determine facility importance on mission and thus, how critical it is.

MDI directly assists decision makers in prioritization of funding. Table 1.1 breaks down how much each agency that uses MDI has requested in spending for Fiscal Year (FY) 2021. Taken together, MDI is used to request nearly \$20 billion dollars across the services.

Table 1.1. Fiscal Year 2021 U.S. Infrastructure Budget Using Mission Dependency Index for Justification (\$ in Millions).

| Agency | \$       | Source                                               |
|--------|----------|------------------------------------------------------|
| USN    | 3,523.1  | Chief Financial Officer, Comptroller (2020)          |
| USAF   | 3,388.5  | Chief Financial Officer, Comptroller (2020)          |
| USA    | 3,882.1  | Chief Financial Officer, Comptroller (2020)          |
| NASA   | 539.1    | National Aeronautics and Space Administration (2020) |
| DOE    | 8,613.4  | Office of Chief Financial Officer (2020)             |
| Total  | 19,946.2 | * Figures are based from FY21 projections            |

### 1.3 Challenges with the Mission Dependency Index

Despite broad adoption across the DoD and Federal agencies, the efficacy of MDI for effective prioritization is disputed. Analysis of the MDI process reveals numerous issues with the program. Kujawski and Miller (2009) challenge claims made by the MDI developers. Their challenges include (Kujawski and Miller 2009):

- MDI does not employ ORM techniques as prescribed by Office of the Chief of Naval Operations (2018), which describes risk assessment according to the severity and probability of an event.
- MDI relies on expert elicitation where SMEs are asked ordinal questions pertaining to facilities and structures under their purview. The resultant numbers associated with the questions are then manipulated using multiplication and division, which is not an acceptable use of ordinal numbers.
- MDI is not a simple process that can be used alone to guide decision makers.
- MDI can wrongfully prioritize funding to projects.
- MDI does not link facilities to mission importance.
- The validity of the validation analysis was based more on advocacy than science.

In addition to the examples given by Kujawski and Miller (2009), Command, Navy Installations Command Instructions (CNICINST) 11100.1A states that “The MDI is an operational risk metric describing the relative importance of shore facilities in terms of their mission criticality” (Commander, Navy Installations Command 2018). However relative importance would imply that each facility is considered in relation or in proportion to another facility. Later in the instruction, it states;

The scoring nomenclature is divided into five categories, with 15-point spreads separating the critical, significant, relevant and moderate levels. The MDI equation is weighted to allow Functional Elements with high interdependency scores to move up to the next level of criticality. Facilities within the same MDI Category should receive similar attention. For example, a facility with a 75 score

is of similar significance as a facility with a score of 82 (Commander, Navy Installations Command 2018).

Thus, the facility with a score of 75 is the same in relation to the facility with a score of 82. Therefore, funding could go to a less important facility simply because of the lack of relative importance.

MDI also uses confusing terminology that can mislead readers and decision makers alike. For example, one of the categories MDI may assess a facility is “critical”. However, this does not mean that facility necessarily falls into the DoD definition of Critical Infrastructure and Key Resources (CIKR) which is the infrastructure and assets vital to the nation’s security, governance, public health and safety, economy, and public confidence (Joint Chiefs of Staff 2020).

Despite identifying these flaws with MDI, their implications have never been quantitatively measured, nor has there been analysis that considers the potential for sub-optimal decisions resulting from the use of MDI. One reason these issues have yet to be assessed is because the implications of MDI on missions and related facilities are rarely considered. MDI focuses on expert elicitation of individual SMEs, and its use might be overlooking facility interdependency and mission needs that are difficult to measure on an asset-by-asset basis. In contrast, the operations and protection of the critical infrastructure systems that support these facilities with power, water, fuel, mobility, communications and other services can change dramatically given different distributions of facilities across networks. Moreover, it is unclear how changing MDI scores for facilities at a single installation affects prioritization across multiple installations and regions. In all cases, the implications of MDI scoring is only understood by assessing the network effects on mission operations and regional funding decisions.

## **1.4 Thesis Goals**

The purpose of this thesis is to assess the flaws inherent in MDI with technical rigor and to identify ways to improve MDI calculation for guiding infrastructure decisions.

In this work, we wish to show how the MDI survey and calculation process can lead to sub-optimal decisions. We aim to identify precise mathematical flaws with MDI and generate

reproducible examples that show these flaws.

In addition, our analysis is meant to provide precise ways to overcome these flaws. Specifically, we develop a model that overcomes the flaws by developing a new mathematical formalism for MDI based on network science and building on established methods in operations research related to infrastructure vulnerability analysis. Our work results in one example of a more internally consistent model for MDI that can be easily adopted within the USN and across DoD services.

Overall, this thesis aims to contribute to improving our understanding of a widespread decision-making metric used within the DoD. Providing a single example of how MDI can be misused or lead to sub-optimal decisions can have widespread implications for nearly \$20 B in funding decisions. Providing an example of a new model for MDI that supports more internally consistent results would further benefit all DoD services.

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## CHAPTER 2:

### Literature Review

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MDI was developed based on literature in infrastructure analysis and operations research. In this chapter, we review literature on critical infrastructure risk and vulnerability as a characteristic body of knowledge integrating these fields for the purposes of infrastructure protection. We also review methods for representing critical infrastructure systems as networks and the services they provide to military missions as flows. Related literature on network interdiction informs key methods for measuring the impacts of critical infrastructure failures on missions.

### 2.1 Risk, Vulnerability, and Mission Dependency Index

The development and use of MDI is based on well-established practices for risk analysis found across critical infrastructure sectors and systems (Commander, Navy Installations Command 2018). In general, *risk* is defined in the USN by Office of the Chief of Naval Operations Instruction (OPNAVINST) 3500.39D 2018 as the “Chance of adverse outcome or bad consequence, such as failed or degraded mission, injury, illness, or loss. Risk level is expressed in terms of hazard probability and severity.” Quantitative measures of risk relate this definition by considering the likelihood of threats, asset or system vulnerability, and a measure of failure consequences (Kaplan and Garrick 1981), sometimes called the risk triplet. The risk triplet has been widely applied in critical infrastructure systems to prioritize the protection of assets vulnerable to natural disaster and terrorist attacks and related methods are currently used in frameworks for U.S. homeland security (Willis et al. 2018; Office of the Chief of Naval Operations 2018). For example, Willis (2007) studied terrorism risk for critical infrastructure using the following quantitative definition:

$$Risk = Threat \times Vulnerability \times Consequence \quad (2.1)$$

where;

- Threat =  $p(\text{event occurs})$

- Vulnerability =  $p(\text{event results in damage} \mid \text{event occurs})$
- Consequence =  $E[\text{damage} \mid \text{event occurs and results in damage}]$

For example, consider a military base that is situated in a hurricane-prone area. The threat is the possibility of a hurricane near the installation. Vulnerability can be thought of as the probability a facility is damaged in the storm. The consequence is the average amount of damage to a facility given there is a storm that effects the facility.

Despite the widespread use of quantitative risk methods for infrastructure risk analysis, Cox (2008a, 2009) and Brown and Cox (2011b,a) challenge the application of the risk triplet for terrorism and adversarial risks experienced in military systems. The authors argue that the treatment of terrorist threats via conditional probabilities leads to spurious critical infrastructure protection recommendations and makes assumptions about an adversary's capability and intent to perform an attack. In general, neither the capability nor intent of an attacker can be known, making any probabilistic representation of this information inaccurate. Brown and Cox (2011a) offer a list of possible methods that overcome these issues, with particular focus on interdiction methods for networked infrastructure systems. In response, both Brown and Cox (2011b) (and more recently Alderson et al. (2015)) present how interdiction studies are more appropriate for large-scale terrorism threats because this form of analysis provides decision support for worst-case failures without making assumptions about adversary capability or intent.

Eisenberg (2020) builds upon the distinctions among methods for risk analysis to define multiple perspectives on critical infrastructure vulnerability. In particular, Eisenberg (2020) suggests that methods promoted by Willis (2007) and Cox (2008a) support protection from different disruptions because they focus on different ways infrastructure systems are vulnerable to threats. This distinction is based on different perspectives on threats and consequences. Eisenberg (2020) defines two perspectives on threats:

- **Probable threats** are events that have a frequency of occurrence that can be evaluated. Probable threats generally have significant historical data indicating how likely the disruption will occur, such as floods.
- **Possible threats** are events that do not occur with any assumed frequency or likelihood. In general, adversarial perspectives on probable threats focus on unlikely, worst-case disruptions based on attacker budget. An example of a possible event

would be the combined loss of all backup systems to a mission-critical asset.

Eisenberg (2020) also defines two perspectives on consequences:

- **Known consequences** have a characteristic measure and some known range of outcomes. Known consequences can be measured given either probable or possible threats. For example, the impact in dollars of the loss of an infrastructure asset.
- **Unknown consequences** do not require characteristic measures or do not have a well defined range of outcomes. Here, the implications of probable and possible events are either not considered or not measured. For example, many mission continuity of operations plans are made without full knowledge of how, when, or what impacts occur when assets fail.

Together, these four perspectives relate to four characteristic approaches to measure infrastructure vulnerability referred to as the four horsemen of critical infrastructure vulnerability. Figure 2.1 illustrates how using these sub-categories generates a matrix with 4 types of vulnerability assessments. The itemized list below was adapted from (Eisenberg 2020):

- **Risks:** Risk analysis uses probabilistic measures of threat likelihood and known measures of threat consequences. The combination of this information focuses attention on expected system disruptions and expected vulnerabilities. This case is best represented by insurance, which is meant to invest now for a probable event in the future with a known cost. Risks can be evaluated through probability and statistics.
- **Adversaries:** Adversarial analysis considers possible threats with known measures of threat consequences. This quadrant emphasizes worst-case vulnerabilities identified with game theoretic methods that consider an event or group of events that leads to the worst outcome for an infrastructure systems. Thus, adversarial vulnerabilities focus attention on worst-case disruptions and were originally developed in the U.S. military. These vulnerabilities are often modeled with optimization models.
- **Failures:** Infrastructure will naturally fail if left unattended. Reliability engineering uses probabilistic measures of infrastructure due to design, (mis)operation, and end-of-life. Reliability-based methods focus on making infrastructure and systems that continue to function and ignore the consequences of their failure. Thus, reliability focuses on making fault tolerant and redundant systems and emphasizes engineering. Reliability-related vulnerabilities can be identified using systems modeling.

- **Surprises:** Organizations that operate and manage infrastructure are complex and infrastructure can fail due to the outcomes of decisions across organizations. Importantly, decisions meant to protect systems and users can backfire due to unforeseen and unintended consequences. These unexpected events are referred to as surprises. Surprises are identified using methods for safety and resilience engineering to identify how issues with organizational structure, culture, and decision authority meant to keep systems running can lead to failure. Often surprises are mitigated with emergency plans that are developed without knowing the consequences of threats. Surprise-based vulnerabilities are studied with qualitative research methods and case study analysis of organizations and through exercises and gaming with decision-makers.

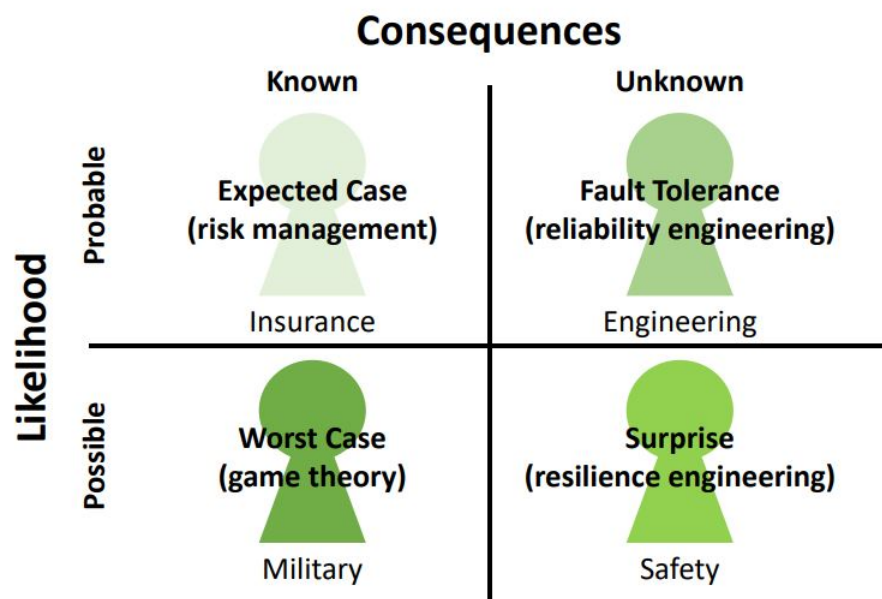


Figure 2.1. Eisenberg (2020) quad chart depicting the four types of vulnerabilities and their relationships with the likelihood and consequence of an event.

The critique of terrorism risk analysis provided by Brown and Cox (2011b) and discussion of critical infrastructure vulnerabilities provided by Eisenberg (2020) informs the methods useful for assessing the efficacy of MDI. The IRR factors embedded in MDI are meant

to quantify the consequences of facility and infrastructure loss. Thus, Eisenberg (2020) would classify MDI as providing either a risk or adversarial perspective on installation vulnerability. Accordingly, MDI claims to be a risk assessment tool modeled from the USN ORM policy (Commander, Navy Installations Command 2018) and employs similar methods for decision prioritization via risk matrices. However, MDI calculation never takes into account the probability of an event happening (Kujawski and Miller 2009), making it not an effective risk measure (Hubbard 2020).

The use of MDI is more akin to a worst-case or adversarial measure of vulnerability and prioritization. MDI as a means to prioritize facilities within an installation against worst-case vulnerabilities aligns with military mission planning because it cares more about mission assurance than expected risks. The IRR factors included in MDI align with adversarial measures by focusing on the consequences facility failures have on mission rather than the reasons the facility fails. Yet, the use of risk matrices diminishes MDI as a means to inform adversarial risks (Cox 2008b) and the implementation of MDI suffers from numerous issues identified by Brown and Cox (2011a).

Taken together, analyzing the efficacy of MDI for facility prioritization decisions is best informed by both risk and adversarial methods. MDI calculation includes elements of both risk and adversarial methods, but employs only partial elements of both. MDI uses risk-based prioritization through expert elicitation and matrix calculations, but does not consider the probability of threats. Assessing the efficacy of MDI as a risk measure would include simulation and statistical analysis of scenarios that threaten infrastructure systems. In contrast, MDI is also based on IRR factors and tries to inform worst-case disruptions. Assessing the efficacy of MDI also requires consideration of methods suggested by Brown and Cox (2011a), including network optimization, network interdiction, and related game theoretic methods for worst-case vulnerability analysis.

## **2.2 Infrastructure Networks and Vulnerabilities**

One of the goals of this thesis is to connect the MDI of facilities to the critical infrastructure systems that support facilities with services like electricity, fuel, water, mobility, and telecommunications among others. There is significant research on risk and adversarial vulnerabilities to infrastructure systems. The majority of these works rely on developing a

network model of critical infrastructure systems to represent their structure and function. We review network science literature for representing missions and infrastructure that informs the connection of facility MDI to supporting systems and related risk and adversarial vulnerability analyses.

### **2.2.1 Network Representations of Infrastructure Systems and Missions**

There are numerous ways in which systems can be represented as networks. A network is a mathematical graph of nodes connected by links representing nodal relationships, such as a social network of people connected by links representing who-knows-whom (Newman 2018). Many complex systems can be represented as networks, such as biological, social, economical, and infrastructure. For example, supporting infrastructure systems like electric power grids (Pagani and Aiello 2013), water systems (Yazdani and Jeffrey 2011), and roads (Ganin et al. 2017) are often modeled and assessed as networks. MDI itself creates a network as the relationship from one facility on another quantifying mission impacts. Specifically, in an MDI network, facilities and mission sets are represented by nodes or vertices and their connections to one another by edges or arcs represent intra- and interdependency.

Linking multiple network models together into multilayer networks (Kivela et al. 2014) supports further understanding across systems and missions. Natural and engineered systems on installations often rely on more than one type of commodity for operation and mission assurance. Military installations are similar to small cities and rely on electricity, water, fuel, communications, and roads. These systems can be studied together using multilayer networks, where each layer may represent a different type of commodity (Kivela et al. 2014).

Multilayer networks related to military infrastructure are often studied as either physical systems and social systems. For example, it is possible to study interdependent facilities without considering missions and still assess how facilities supports civilian and military needs. In his works concerning urban infrastructure, Derrible (2017b,a) explores aspects of urban infrastructure planning. The author assesses centralized-decentralized and integrated-separated methods through complex systems science. Derrible (2017b,a) show the effects of different planning paradigms on the network representation of urban infrastructure.

In addition to informing planning decisions, numerous network models of interdependent

infrastructure systems support advances for MDI. MDI relies heavily on assessing the interdependent relationship between facilities of different mission types. These interdependent relationships introduce new ways in which failures can ripple or cascade from one mission type to another. Ouyang (2014) reviews multiple approaches to model interdependent infrastructure systems and their implications for resilience. The author provides a conceptual basis for understanding interdependency across mission networks.

One key factor affecting MDI is network flows across interdependent systems. Ouyang (2014) identify numerous methods that analyze infrastructure in a static state similar to MDI. Yet, the flow of services across infrastructure systems suggests that a survey conducted at a moment in time does not address multiple realizations of possible interdependencies and their potential for disruptive affects (Goldbeck et al. 2019). These interdependent models may have numerous layers representing different mission or commodities types and have increased in proficiency (Enayaty Ahangar et al. 2020).

Multilayer networks also support models that connect physical and social systems together. Barker et al. (2017) evaluate the relationship between networks and resilience through modeling, quantification, and management. They interpret both cyber-physical and social networks to understand interdependent infrastructure dependence. This work is further forwarded by Sharkey et al. (2020) in which resilience is evaluated with greater detail investigating robustness, rebound, extensibility, and adaptability.

Whereas work by Sharkey et al. (2020) emphasize the function and disruption of physical networks, networks are also used by other authors to study impacts to decision-making and missions. For example, Eisenberg et al. (2018) reviews military and civilian C2 systems though “Network Centric Warfare.” The authors present C2 as a multilayer network involving physical, informational, social, and cognitive systems and how they interrelate with each other. MDI is a direct extension of these types of relationships, and relates to the social and cognitive networks meant to enable missions. MDI also includes facilities that house C2 and the infrastructure required to supply the necessary resources.

Eisenberg et al. (2020, 2017) build on multilayer networks and C2 theory to show the relationships between infrastructure and social networks for large-scale civilian systems. The authors examine power grid resilience in South Korea and how blackouts lead to different decision-making scenarios. Unlike other articles that try to determine system resilience by

metrics placed on a network flow model, they evaluate the power grid as a mission. In other words, they evaluate the interdependence of both the power grid and the social network of those who operate the network, which the authors dub sociotechnical network analysis.

Overall, multilayer networks provide a helpful formalism for representing and analyzing MDI. MDI itself is a network and the supporting facilities on missions that it measures are often studied as networks. Intradependencies can be studied using independent networks for physical and social aspects of MDI. Interdependencies across systems can be assessed via links and flows across network layers. This is possible for systems with both physical and social networks, such as military C2 systems and sociotechnical systems.

Networks are also an important formalism because disruptions to infrastructure and organizations can be measured via the interdiction of nodes and arcs. Multilayer networks support support both risk and adversarial vulnerability analyses. Here, we review aspects of both analyses.

### **2.2.2 Infrastructure Network Risks**

Risks are vulnerabilities that consider probability of a threat occurrence and the severity of the consequences when the system is disrupted. Applying risk analysis to a network model can identify potential hazards to a system and support improving resilience. Common risks include natural disasters that have significant historical precedent to guide measures of likelihood and intensity.

Numerous studies consider natural disaster risks on infrastructure systems at the scale of military installations. For example, studies have assessed the impacts of hurricanes and flooding on critical infrastructure in the U.S. Virgin Islands (USVI) territory, which is comprised of islands roughly the size of military installations. Good (2014) and Routley (2020) analyze disruptions to the road networks and their risk to hurricanes and flooding across the territory. Moeller (2020) and Wine (2020) study impacts to telecommunications infrastructure, including backbone fiber internet and wireless cell phone services. Wille (2019) analyzed the impacts of hurricane winds and storm surge on USVI electric power and water distribution systems. All studies utilize some form of network model for representing systems and their interdependent function.

Risks also relate to human decision-making and networked missions. For example, various authors studied the grouping of optimal personnel and resources for missions tasking while managing the risk of execution cost or work quality (Beavers 2019; Diaz 2019). These scheduling and task networks models can be further broadened to evaluate forms of risk not centered around probability or a specific threat. They can be used to evaluate how surprise, or unforeseeable, disaster can affect systems that were never built to handle such an event (Eisenberg et al. 2019).

At an intersection where network analysis meet risks, the incorporation of MDI elements can be explored. The worst case scenario that IRR factors analyze can be implemented to evaluate risk by connecting the concept of facilities onto infrastructure networks. This analysis can provide insight to determine the impacts of MDI inter-relationships to change and conclude if MDI is truly a measure of facility importance.

### **2.2.3 Network Interdiction and Adversarial Methods**

Adversarial modeling with networks focuses on interdiction of flow networks. Interdiction is the action taken by adversary the with the purpose of blocking or increasing the cost of movement of a commodity that an operator is trying to optimize across a network (Smith and Song 2020). Sometimes described as leader-follower games, for the context of this paper they will be refereed to as Attacker / Defender (AD) models. In this respect the terms defender and operator are synonymous. Below is the reproduction of the key assumptions noted by Smith and Song (2020) when employing AD models.

- 1: All information concerning the network is known to both the attacker and defender.
- 2: The attacker understands optimization and has the resources to employ algorithms quickly. In this sense the attacker fully understands the effect his attack has on the network.
- 3: The attacker is attempting to reverse the objective of the defender. Thus, if the defender is attempting to minimize a system the attacker is attempting to maximize and vice versa.
- 4: In a given round both the attacker and defender make one decision. The attacker would first decide on its attack followed by the defender's response.
- 5: The game consists of one round only.

These types of models are extremely useful in military applications. Network interdiction gained popularity during the Vietnam War where interdiction techniques were employed on enemy supply routes (Steinrauf 1991). Interdiction models were applied to the war on drugs. Using the network models to simulate the flow of both drugs and the precursor chemicals needed to synthesize them through roads and rivers this information could then be used to optimize interdiction efforts (Steinrauf 1991; Wood 1993). These early models were from the reference frame of the attacker. They focused on the best ways to disrupt networks in the forms of supply chains.

Focusing on how to make the most impactful disruption to networks reveals the best ways to protect them. Applying this to defense of facilities, from an MDI perspective may identify bottlenecks or key assets that if you protect will maintain network functionality through possible disruptions (Brown et al. 2006).

The practice and approach to prioritizing how to actually protect facilities become nuanced and not so clear using this method for various reasons. For example, a facility that has a critical MDI score may receive funding that would lower its score, but in doing so you have suddenly made other facilities more likely to be targeted from an attacker perspective as they now have the highest MDI in the network.

Alderson et al. (2014) dismiss the evaluation of a single asset and prefer to think about defense in terms of groups or networks that can provide normal rules for determining how prioritization should occur for the optimal attack or defense of a network contributing to the overall resilience of a system. This argument can be extended to MDI, where MDI focuses only on the facility and those facilities that directly interact with it. Instead, by implementing MDI as a network we can see what the true impacts that interruption may pose to facilities that are further removed from an immediate interaction but could experience cascading effects from interruption.

These models can provide great revelations about a network, but every network is different and unique in its own way. To the end network interdiction does not lend itself to easy rules or simple algorithms that can determine the most essential asset in a system (Alderson et al. 2013). Similar to asking what is the biggest pipe in the network and assuming that it is the most essential link, the data was not informative in determining vulnerability of systems, because these systems are functioning and the operators will direct flow as best they can to

manage disruptions.

Alderson et al. (2015) details a notional fuel network. This particular study evaluated a notional fuel network and showed all the worst case disruptions for various attack budgets, best case defenses, given those attack budgets for using hardening of redundancy kinds of options (Alderson et al. 2015)

To this point all models have been deterministic. This can lead to a misconception in results. For example, the cost to move a commodity across a network may depend on weather. It may be cheaper to send merchandise down southern routes when northern routes are covered in snow. While it may be cold during the winter months in the north, it does not always snow. Therefore, it may be useful to add robustness through stochastic processes (Delage and Iancu 2015).

## **2.3 Contributing to MDI**

We build on broad literature to assess the efficacy of MDI for facility prioritization and funding decision making. First, we closely examine the MDI formula and calculations and identify issues with the way MDI is used in the USN. We will align the MDI process to network science models, specifically multilayer networks. In this process we will formalize definitions associated with MDI. In doing so, we will search for imperfections in the MDI methodology and provide recommendations using mathematical formalism. This critique of MDI can then be used to generate models that are scalable, reproducible, and relates missions to literature on the prioritization of facilities for funding.

Finally, this thesis will evaluate alternative methods of calculating dependency and criticality using IRR factors, intradependencies, and interdependencies.

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## CHAPTER 3:

# Mission Dependency Index: Technical Definition and Analysis

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In this chapter, we dissect the MDI calculation process as defined by Antelman and Miller (2002) and applied in the USN (Commander, Navy Installations Command 2018). MDI is described in CNIC requirements as, “a survey that is an organized process of reviewing all scored facilities to identify the intra- and inter- dependencies between functional/mission areas and the risks associated with interrupting or relocating/replacing the functions that take place in the facilities, from a planned outage perspective. MDI scores are calculated based on survey data submitted during the interviews with installation functional and mission SME” (Commander, Navy Installations Command 2018). Our example in Chapter 1 reproduces these instructions to show how the MDI survey and calculation process is currently implemented across DoD services.

However, this common presentation of MDI does not provide a mathematical formalism rigorous enough to apply MDI and easily reproduce results of previous studies. For example, the MDI process is filled with terms like *infrastructure* and *facility* that are synonymous, ambiguous, and easily misunderstood. MDI calculation also uses new terminology like *intradependency* that is hard to understand. One goal with this chapter is to redefine the MDI process using standardized terminology that enable reproducible models and results. We achieve this by developing a mathematical formalism for MDI based on multilayer networks (Kivela et al. 2014).

Our second goal is to use this mathematical formalism to identify flaws in MDI that can lead to sub-optimal decisions. Our network formalism provides technical rigor that allows us to develop examples that highlight and quantify the impacts of its technical flaws. We demonstrate our critique using hypothetical and real examples relevant to military installations.

Although never described in the literature in this way, MDI calculation is based on thinking of installations as networks. When conducting an MDI survey, mission-owners and SMEs

are asked to consider relationships across installation missions and facilities. This process is very similar to the process used by scientists and researchers to create a network model to assess risk and worst-case disruptions. As a result, the MDI process generates scores for facilities that are similar to centrality scores for nodes in network models. We use this idea to re-imagine MDI as a form of network analysis, rather than a general survey.

In what follows, we build up our network-based perspective on MDI. First, we define all the key terminology and concepts and how they relate to networks. Then, we build on an existing formalism for multilayer networks presented in Kivela et al. (2014) to define a network formalism appropriate for MDI calculation. We further assess the sensitivity of MDI calculation. Together, we provide rigor to the terminology, representation of systems, and mathematical calculation embedded in the MDI survey and process

### 3.1 Redefining the Terminology of MDI

We redefine the following terminology to provide more rigor to MDI calculation via networks: missions, facilities, functions, dependency, disruption intradependency, interdependency, and installations:

**Mission.** We start our new vision of MDI by defining the term *mission*. Missions are a fundamental component of military systems and MDI calculation — something cannot be mission-dependent without a definition of the term mission. However, while the word itself is very common, the term mission is never explicitly defined in MDI literature. For this reason, we define a *mission* as a specified goal completed for a military purpose.

There are at least two kinds of missions relevant for MDI calculation, each related to a chain of command in the DoD. As described in Chapter 1, the DoD is split into two chain of commands. The chain of command involved with infrastructure is the administrative command that oversees the PESTONI pillars. In addition, there is the operational command which plans and executes mission functions. In this fashion, MDI observes two types of missions: *administrative missions*, referred to as *A-missions*, and *operational missions*, referred to as *O-missions*.

In general, both A-missions and O-missions are conceptual in nature and can be comprised of anything related to their predefined goal. For our purposes, we visually represent both

mission types as clouds, such as A-mission Red shown in Figure 3.1.



Figure 3.1. Mission Representation. An MDI administrative mission, mission red, represented by a cloud. Examples of administrative missions may include providing potable water to a certain area or group of facilities, providing housing for military personnel, establishing and maintaining C2, etc. Operational missions are derived by operational commands. For the scope of this paper and MDI and operational command is synonymous with operational mission. For example a helicopter squadron would be an operational mission in terms of MDI.

**Facility.** The next key components of MDI are facilities. A *facility* is synonymous with, and includes, any type of building or structure. For the purposes of MDI, the term facility also means the portions of buildings that serve a single purpose (e.g., a sensitive compartmentalized information facility within a larger structure) and individual infrastructure assets or equipment (e.g., a utility control panel on the side of a building). This means the term facility is broad to include buildings, critical infrastructure (e.g., radar towers, substations, etc.), and assets (e.g., a wind sock).

Overall, the only common defining factor across facilities is that they are tangible objects geolocated in physical space. For our purposes, we visually represent facilities as cubes. We show an example of this representation for a facility in A-mission Red in Figure 3.2.

**Function.** In addition to the concept of facility, there needs to be reason to relate a mission, which is conceptual, and a facility, which is tangible — a facility has to “do” something in order to support missions or interact with other facilities. To this point, we introduce the concept of a function. We define a *function* as a service provided by or housed within a facility. A mission is a concept that depends on functions to achieve the mission’s goal. In

other words, functions are actions (e.g., pumping potable water, sheltering personnel, transmitting communications, entertaining, etc.). Figure 3.2 represents function as a lightning bolt.

It is the synergy between the facility and a function that allows us to understand the interactions between facilities and missions. Combining the concepts of facilities and functions produces the notion of a *facility function*. Like the term facility, facility functions are also broad and vary from physical services (e.g., shelter) to social services (e.g., personnel management) or even weapons platforms (e.g., a ship). A single facility may provide multiple functions to the same mission and/or across multiple missions. We represent the combination of function and facility together as a circle or node as shown in Figure 3.2 for A-mission Red.

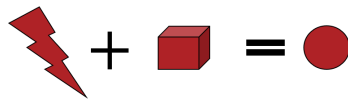


Figure 3.2. Facility Function Representation. The facility function (node) is the combination of a function (lightning bolt) and a facility (cube). A single facility can produce or house multiple functions, such that facility function nodes can include multiple functions.

**Dependency.** MDI calculation is based on the relationships among facility functions and missions. We call these relationships dependencies. We define a *dependency* as a both the relationship between a facility function (node) and its mission (cloud) and as its relationship to another facility function (node). Since dependencies relate multiple distinct MDI building blocks (i.e., nodes to clouds *and* nodes to nodes), there is not single way to visually represent a dependency.

**Disruption.** The goal of MDI is to assess the importance of facility function(s) to missions. This importance is measured by the potential impacts across missions and facilities if a facility function is lost. We define a *disruption* as the event, attack, or otherwise intervention that interdicts or stops a facility function from supporting its mission or other facility functions.

As described in Chapter 1, disruptions are considered in MDI calculation via IRR factors. For the purposes of our MDI formalism, we adopt the definitions of interruptability,

relocatability, and replaceability as in Chapter 1.

With these definitions of mission, facility, function, dependency, and disruption, we can now show the MDI process for ranking facilities by importance as a network analysis.

**Intradependency.** As described in Chapter 1, *intradependency* is one of the two key measures used to calculate MDI. The intradependency score,  $MD_w$ , is the result of a survey on facility function interruptability (Question 1) and relocateability (Question 2) (see: Section 1.1.1). Survey responses are converted to  $MD_w$  scores using Figure 1.1.

We base our definition of intradependency in networks on this process used in the USN. We define *intradependency* as a measure that indicates the dependency of a mission (cloud) on a facility function (node). Intradependency is a two-fold concept involving both the the assignment of facility function to a mission and the scoring of the importance of that facility function to its mission.

The first part of our definition is that interdependency involves the assignment of a facility function to a mission. Facility functions are only assigned to a single mission. This assignment implies that the mission owns the facility function and is in charge of its management. It also implies that the mission *depends* on the facility function. Figure 3.3 illustrates the assignment of facility functions (nodes) to A-Mission Red (cloud).

The second part of our definition of intradependency involves scoring the importance of a facility function to its assigned mission — in other words, scoring *how much the mission depends on the facility function*. This part of intradependency involves the IRR questions and  $MD_w$  score. IRR questions are answered by SMEs. When we refer to a *SME*, we mean a person that is considered significantly knowledgeable on a mission’s goal and its dependence on facility functions. By answering Question 1 and 2 of the MDI survey for a given facility function, the SME effectively scores the importance of the facility function with  $MD_w$ . We consider these scores as weights on facility function nodes representing the intradependency of each facility function on its mission. Figure 3.3 demonstrates this second part of intradependency for A-mission Red via the  $MD_w$  weights shown to the left of each facility function node.

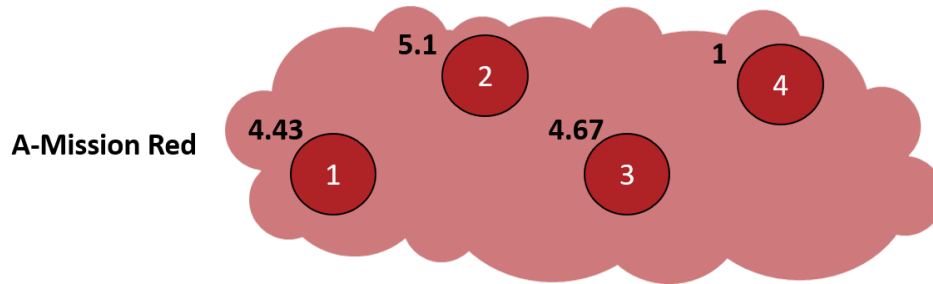


Figure 3.3. Intradependency Representation. Facility functions (nodes 1-4) have been assigned to A-Mission Red and therefore are represented as part of the red cloud. A SME for A-Mission Red then answers Question 1 and Question 2 of the MDI survey for each facility function. After the survey, each facility function is assigned a weight (shown to the left of each node). These weights are  $MD_w$  scores from Figure 1.1. Each weight is on a scale from 1 to 6, where 6 has the most extreme impact to the mission.

Thus, intradependency is both an *assignment* of facility functions to missions and a *weight* that correlates to the significance an interruption of facility function would have on its mission. Intradependency weights are scaled between 1 and 6, where  $MD_w = 6$  implies complete dependency of a mission on a facility function (Figure 1.1). In Figure 3.3, A-Mission Red has the highest dependency on the facility function represented by node 2 and has the lowest dependency on the facility function represented by node 4.

For a single mission, the MDI story might stop here. However, most missions do not exist on their own. Normally, at a military installation, there are many missions, each dependent on their respective facility functions. Picturing each mission as its own grouping of facility functions, we can designate different missions by color (e.g., A-mission Red, A-mission Blue, etc.). Figure 3.4 depicts four missions differentiated by color. We refer to each individual mission as a mission layer. Three of the mission layers are A-missions and the fourth is an O-mission. Additionally, each mission layer comprises intradependent facility functions with their intradependency weights shown.

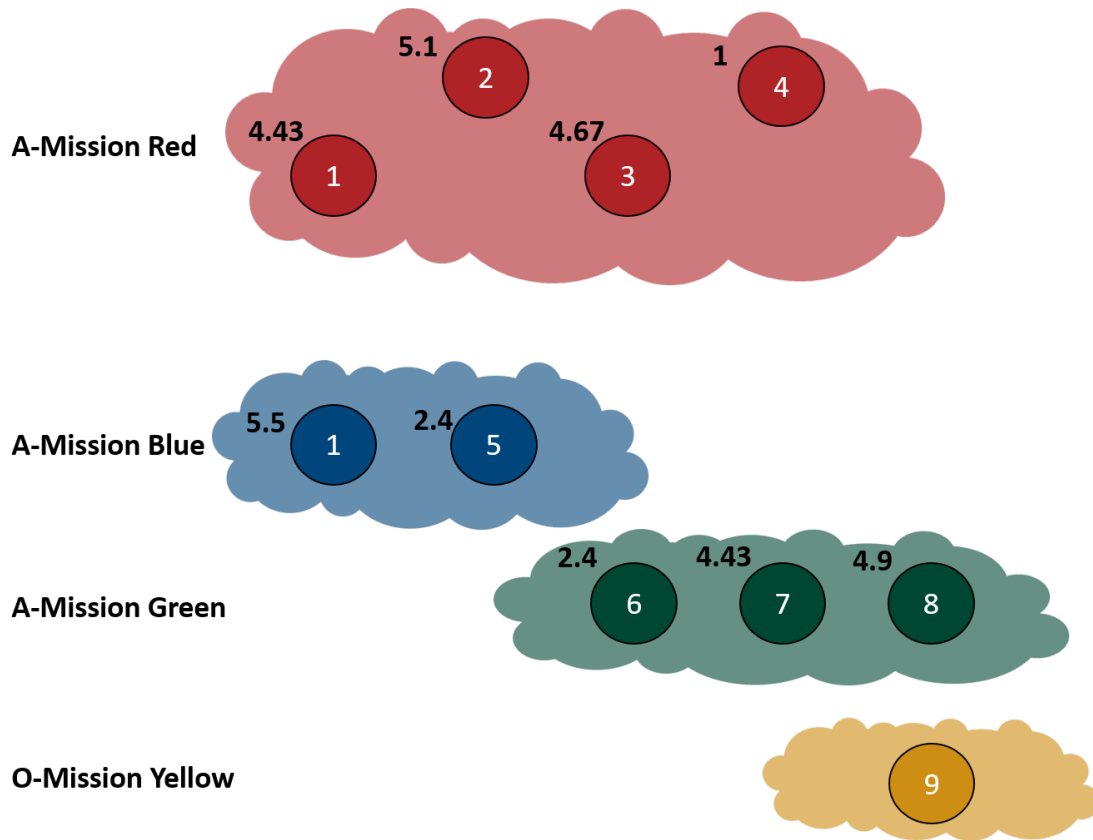


Figure 3.4. Representing Multiple Missions at an Installation. An installation often comprises multiple missions. Each mission can be considered a layer and designated as a colored cloud. Mission clouds can be either A-missions (i.e., Red, Blue, and Green) and O-missions (i.e., Yellow). Facility function nodes assigned to each mission are colored to match their intradependent mission. A SME for each A-mission determines intradependency scores  $MD_w$  for each facility function within their cloud. This is done via MDI survey and answering Questions 1 and 2 (see Section 1.1.1). Facility functions in O-missions do not receive intradependency scores (e.g., node 9).

Considering multiple missions at the same installation reveals several important aspects of the way MDI is calculated based on facility functions and intradependencies. First, some facility functions *do not have an intradependency score*. Specifically, facility functions in operational missions do not receive intradependency scores (e.g., Facility Function 9 in O-mission Yellow). O-mission facility functions are comprised of operational units such as helicopter squadrons or naval ships. These operational units do not fall under the purview of the PESTONI pillars nor do they receive funding under the context of infrastructure. Therefore, they do not receive an intradependency score nor an MDI score. With this exception, operational missions and their respective facility functions handled just like their administrative counterparts.

Figure 3.4 also shows how it is possible for a single facility to house multiple facility functions. Both A-mission Red and A-mission Blue are dependent on node 1. This means that there are at least two different functional capabilities housed in Facility 1. The distinction between missions lies in the actual functions performed at facility 1. To differentiate, we name the facility function that lies in A-mission Red, “Facility Function 1, Red” and the facility function in A-mission Blue mission as “Facility Function 1, Blue”.

For example, take two different A-missions, such as the port operations mission and the potable water mission, that are located in the same part of an installation. For these two missions, there may be a single facility that houses offices for the port ops mission and a large water pump for the potable water mission. Neither function is the same — the water pump supports the potable water mission and offices support the port ops mission. However, both missions being co-located in the same facility means SMEs from both missions may assign an intradependency score to Facility 1. If we assume the port operations mission is A-mission Red and the potable water mission is A-mission Blue, we find that A-mission Red is less dependent on Facility 1 ( $MD_w = 4.43$ ) than the potable water mission ( $MD_w = 5.5$ ).

The choice of using both values separately, or only choosing the higher, lower, or average value of these intradependency scores for Facility 1 can be at the discretion of the installation commander. This choice has practical significance, as the higher an intradependency score, the more likely a facility will receive prioritized funding. For example, if we assume an installation commander concerned with the interruption of all functions equally at a given facility, they might choose to give Facility 1 an MDI score based on  $MD_w = 5.5$ .

The most common practice in the DoD and NASA is to calculate MDI for each facility function separately, then assign the facility the highest MDI score of these values (National Aeronautics and Space Administration 2010). We follow this guidance, and assume when multiple functions are located in the same facility, the highest MDI is chosen for final calculation.

**Interdependency.** Also described in Chapter 1, *interdependency* is the second key measure used to calculate MDI. The interdependency score,  $MD_b$ , is the result of a survey on facility function interruptability (Question 3) and replaceability (Question 4) (see: Section 1.1.1). Survey responses are converted to  $MD_b$  scores using Figure 1.2.

Interdependency is also a two-fold concept that incorporates facility function relationships and weighting together. Specifically, we define *interdependency* as a measure that indicates the dependency of a facility function (node) on another facility function (node).

The definition and use of interdependency involves three parts.

The first part of interdependency is the assignment of a dependency of one facility function on another facility function. Our definition of interdependency broadly includes any dependency between any two facility functions (nodes). However, an important restriction on MDI calculation is it only considers interdependencies *between* mission layers. Figure 3.5 illustrates examples of MDI interdependencies as dotted arrows connecting facility functions (nodes) in different mission layers. Here, a facility function depends on another if the arrow is pointing to it. For example, in Figure 3.5 Facility Function 5, Blue depends on Facility Function 1, Red.

Figure 3.5 demonstrates that a key feature of interdependencies is their directionality. In practice, a facility function in one mission (e.g., Facility Function 5, Blue) may depend on another (e.g., Facility Function 1, Red), but the inverse may not be true (i.e., Facility Function 1, Red may not depend on Facility Function 5, Blue). For this reason, all interdependencies are represented as directional arcs.

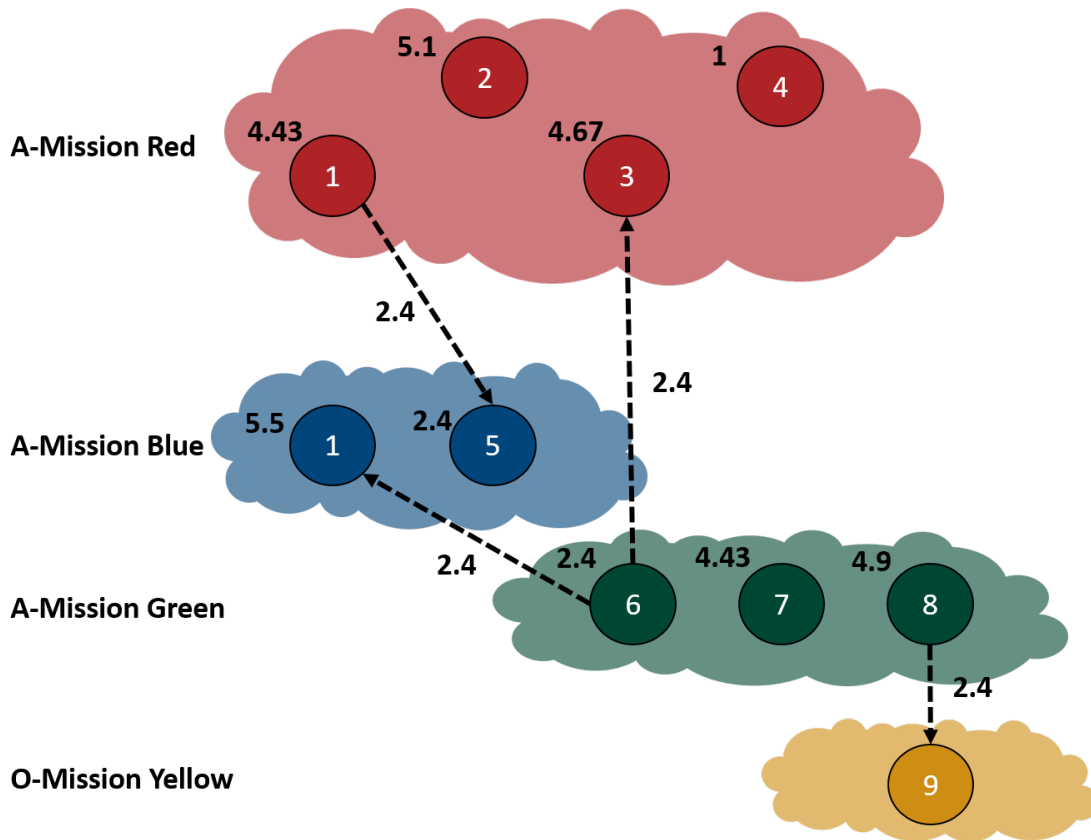


Figure 3.5. Representing MDI Interdependencies. Interdependencies are best represented as directed arcs between facility functions (nodes), where arcs point towards the dependent facility function (e.g., Facility Function 5, Blue depends on Facility Function 1, Red). MDI calculation as defined in the USN is only concerned with interdependencies between mission layers. Interdependency also refers to the importance score (weight) assigned next to each arc. This value is an  $MD_b$  score resulting from a SME answering MDI survey Questions 3 (interruptability) and 4 (replaceability).  $MD_b$  scores are normalized between 1 and 6, where 6 indicates the strongest level of interdependency (see Figure 1.2). Interdependency also refers to a nodal weight  $MD_b^{avg}$  that is mean  $MD_b$  score for all interdependencies  $N$  for a facility function (i.e., mean weighted out-degree). We do not show these nodal weights as they are easily calculated based on interdependencies shown.

The second part of interdependency involves the scoring of the importance of facility function dependencies — in other words, scoring *how much the facility functions in one mission depend on facility functions in another*. This part of interdependency involves the

IRR questions and  $MD_b$  score. Similar to intradependency, IRR questions are answered by SMEs. Presumably, the same SME knowledgeable about intradependencies within a mission is also knowledgeable about interdependencies between missions. By answering Question 3 and 4 of the MDI survey for a given facility function, the SME effectively scores the importance of the facility function on another with an  $MD_b$  score. We consider these scores as weights on arcs representing the strength of interdependency between facility functions. Figure 3.5 demonstrates this second part of interdependency for via the weights shown next to each interdependency arc.

The third part of interdependency is assigning a score to each facility function as a nodal weight  $MD_b^{avg}$ .  $MD_b^{avg}$  is a function of arc weights, specifically, it is the mean of the  $MD_b$  weights for all facility functions that depend on it (see Equation 1.1). For example, in Figure 3.5 both Facility Function 1, Red and Facility Function 6, Green would receive an  $MD_b^{avg} = 2.4$ . This happens even though Facility Function 1, Red has only one interdependency and Facility Function 6, Green has two. This discrepancy is dealt with in MDI calculation by also assigning each node a value  $N$  equal to its out-degree (e.g.,  $N_{1,Red} = 1$  whereas  $N_{6,Green} = 2$ ).  $N$  is used both in  $MD_b^{avg}$  and MDI calculations (i.e., Equation 1.1 and 1.2, respectively). Because both  $N$  and  $MD_b^{avg}$  are functions of the interdependencies shown and easily calculated, we do not label facility function nodes with their  $N$  and  $MD_b^{avg}$  values in Figure 3.5.

Figure 3.5 also shows that only some facility functions will be given  $MD_b$  scores. For example, for A-mission Red, Facility Functions 2 and 4 do not receive any  $MD_b$  scores. This is common and the MDI calculation process and dealt with explicitly in USN instructions (Commander, Navy Installations Command 2018). Specifically, facility functions without interdependencies are assigned and  $MD_b^{avg} = 0$  and  $N = 1$  for final MDI calculation.

**Installation.** Figure 3.5 presents all necessary concepts for MDI calculation. From this simple image, we can now define what an installation is. We define an *installation* as one set of all facility functions that physically reside inside a US base, camp, or fort organized into missions. The existence of an installation is justified by one or more of the missions it contains.

### 3.2 Viewing MDI with a Multilayer Networks

Given our definition of an installation, we present a formal definition of an installation as a multilayer network using notation adapted from Kivela et al. (2014). This formalism supports MDI calculation as conducted in the USN:

- An *installation* is a multilayer network graph  $G$  such that  $G = (V_M, E_M, M, \chi)$ . Here,  $M$  is the set of layers in the multilayer network each representing a mission at the installation,  $V_M$  is the set of facility functions at the installation,  $E_M$  is the set of interdependencies connecting facility functions, and  $\chi$  is a mapping function assigning facility functions to missions.
- A *mission* is a network layer comprised of the set of facility function nodes  $V_M$  and interdependency arcs  $E_M$ . Setting  $M$  to  $m$  yields a mission network layer that is a graph  $G(V_m, E_m)$ .
- The two types of missions — administrative and operational — are subsets of  $M$ , such that A-missions are in  $M^A \subseteq M$ , O-missions are in  $M^O \subseteq M$ ,  $M^A \cup M^O = M$ , and  $M^A \cap M^O = \emptyset$ .
- A *facility function* is a node  $i \in V_M$  representing a tuple  $(f, s)$ , where  $f$  is the physical facility and  $s$  is the function it houses or produces. A single facility can house or produce multiple functions, such that two nodes  $i$  and  $j$  can have the same  $f$ . Similarly, two different facilities can house or produce the same function  $s$ , such that  $i$  and  $j$  can have the same  $s$ . However, all facility function tuples are unique, such that  $i \neq j, \forall f \in F, \forall s \in S$ .
- $\chi$  is a mapping function assigning a facility function node  $i$  to a mission layer:  $\chi : i \rightarrow V_M$ .  $\chi$  also assigns a SME to conduct the MDI survey for the given facility function.
- An *interdependency* is a directed arc, denoted  $(i, j)$ , linking one facility function node  $i$  to another facility function node  $j$ , where  $i \neq j$ . The set  $E_M$  is the set of all interdependencies in the multilayer network.
- *MDI interdependencies* are the arcs  $(i, j)$  used for MDI calculation, such that  $E_M^{MDI} \subseteq E_M$ . Here, an arc  $(i, j)$  is in  $E_M^{MDI}$  if assigned nodes  $\chi : i \rightarrow V_m$  and  $\chi : j \rightarrow V_n$  are in different mission layers ( $m \neq n$ ).
- A *node intradependency score* ( $MD_w$ ) is a node weight assigned by a SME associated with the dependency of an A-mission network layer on a facility function node.  $MD_w$

are only assigned for nodes with the following:  $\chi : i \rightarrow V_m, \forall m \in M^A$ .  $MD_w$  is calculated using the USN MDI process.

- An *arc interdependency score* ( $MD_b$ ) is an arc weight assigned by a SME associated with the dependency of one facility function on another.  $MD_b$  are only assigned for arcs  $(i, j) \in E_M^{MDI}$ .  $MD_b$  is calculated using the USN MDI process.
- A *node interdependency score* ( $MD_b^{avg}$ ) is an node weight calculated as the mean weighted out-degree of a facility function node.
- The value  $N$  is the out-degree of a facility function node.

Taken together, we can use this network formalism to redefine MDI scores as a multilayer network centrality. Specifically, an *MDI score* is a centrality score assigned to facility  $f$  given the surveyed dependencies of all mission layers  $M$  in an installation multilayer network  $G(V_M, E_M, M, \chi)$  on facility functions  $i \in V_m$ . MDI scores are determined using intradependency and interdependency node weights ( $MD_w$  and  $MD_b^{avg}$ , respectively), and node out-degree  $N$  (for  $(i, j) \in E_M^{MDI}$ ). The MDI for each facility function  $i$  is calculated with Equation 1.2. A facility  $f$  is assigned  $MDI = \max\{MDI_1, \dots, MDI_k\}$  for  $k$  nodes with tuples  $(f, s), \forall s \in S$ . MDI is normalized between 0 to 100. A facility with  $MDI = 0$  means its functions in its assigned A-mission(s) have no impact on any mission if disrupted and a facility with  $MDI = 100$  means its functions in its A-mission(s) have the highest possible impact on missions if disrupted.

Figure 3.6 presents a example of a installation multilayer network using this formalism. Our definition of an installation multilayer network is an adapted version of the node-colored network and interdependent network-of-networks formalism in Kivela et al. (2014). Specifically, in a installation multilayer network, missions are equivalent to colors (layers) and facility functions are equivalent to nodes mapped to a color. The additional elements unique to installation multilayer networks include the inclusion of two mission layer aspects (administrative and operational), the relationship between the mapping function  $\chi$  and MDI survey, the possibility for a facility to exist in multiple mission layers, the restriction to only use directional arcs, the specialized subsets necessary for MDI calculation, and the methods for node and arc weighting. We refer the reader to Kivela et al. (2014) for other applications of node-colored networks and to compare our installation multilayer network with other multilayer networks.

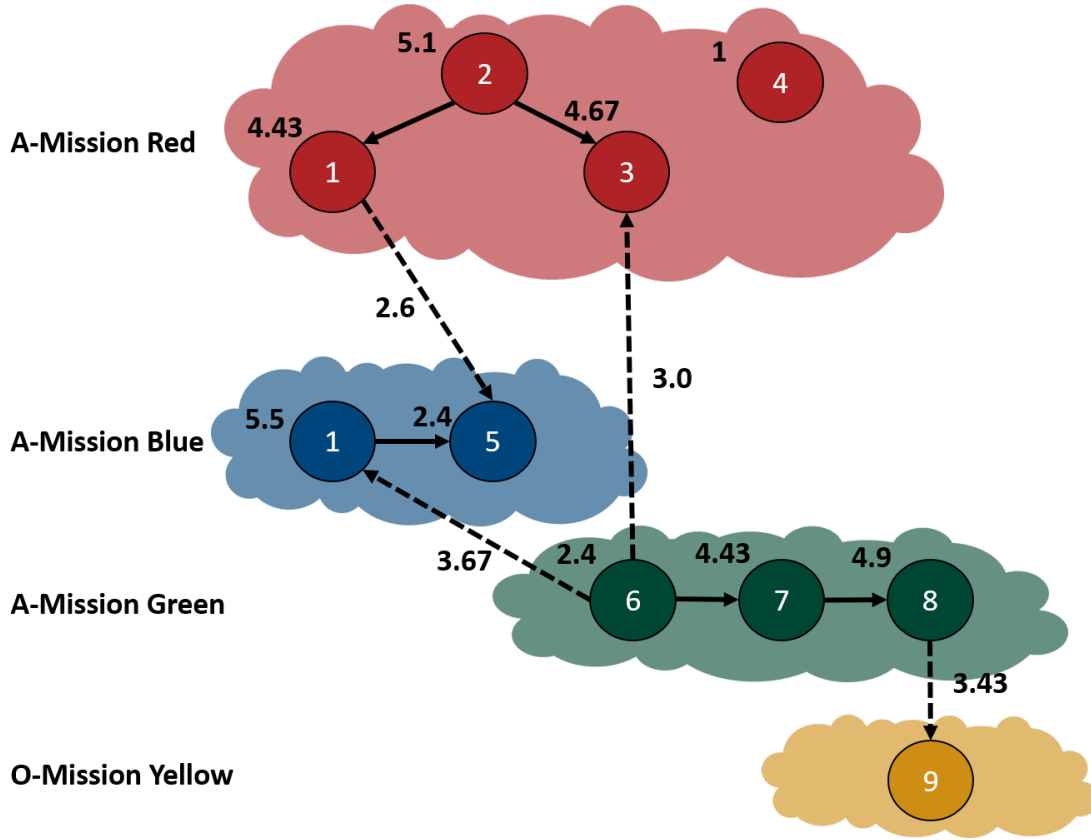


Figure 3.6. A Complete Installation Multilayer Network for MDI Calculation. Our installation multilayer network formalism can be used to mathematically represent the network visualized in this figure. The network  $G(V_M, E_M, M, \chi)$  consists of  $|M| = 4$ , where  $|M^A| = 3$  (Red, Blue, and Green), and  $|M^O| = 1$  (Yellow).  $|V_m| = 10$ , where facilities 2 to 9 only have one representative facility function node, and facility 1 has two (Red and Blue). The mapping function  $\chi$  assigns facility functions to mission layers, such as  $\chi : 1 \rightarrow \{V_{Red}, V_{Blue}\}$ .  $|E_M| = 9$  where only arcs shown with dotted lines are in  $E_M^{MDI}$ . Node intradependency scores and arc interdependency scores are shown. The MDI for each facility 2 to 8 can be calculated directly using the  $MD_w$ ,  $MD_b$ , and out-degree  $N$  of their respective facility function nodes. In contrast, the MDI of facility 1 would be  $\max\{MDI_{1,Red}, MDI_{1,Blue}\}$  and facility function 9 does not receive an MDI score for being in an O-mission. While MDI has never been conceived in this way prior, we find this implementation has several benefits for understanding issues with MDI calculation. For example, there are elements within our formalism that currently do not affect MDI calculations, such as interdependency arcs within mission layers (solid arcs).

### 3.3 MDI Concepts Revealed by Networks

Our mathematical formalism and Figure 3.6 demonstrate that there are several complicated aspects of MDI calculation that can lead to misunderstandings.

First, MDI scores are attributed to a facility, not a facility function. However, all the values used to calculate MDI— $MD_w$ ,  $MD_b$ , and  $N$ —are all attributed to facility functions. We have discussed that multiple functions can be located in the same facility. When this event occurs every facility function determines what its overall MDI score would be if no other function was located at the facility. The MDI scores for all the functions are then compared and the highest MDI score is chosen to represent the facility as a whole. This score is then used to assign a MDI category based on a range of values. *This process of assessing facility functions and scoring facilities is easily misunderstood and may be implemented differently across missions and installations.*

Second, *MDI ignores interdependencies among facilities that are within the same mission.* As shown in Figure 3.6, intradependency scores do not consider interdependencies among facility functions within the same mission (shown with solid arrows). Moreover, interdependency scores only consider dependencies between mission layers (shown with dashed arrows). This oversight may miss the importance of facility functions on each other for mission assurance after interruptions.

For example, in Figure 3.6, we show that there are relationships between some facility functions within A-mission Red. Using our network formalism, we can evaluate the consequence of interruption within a mission layer qualitatively by considering the entire set of interdependency arcs  $E_M$ , rather than only the subset  $E_M^{MDI}$ . Considering these additional arcs, we can estimate that the disruption of Facility Function 1, Red does not affect Facility Function 2, Red. In contrast, disruption of Facility Function 2, Red may impact both Facility Function 1, Red and Facility Function 3, Red.

Our network formalism also exposes new types of facility functions helpful to understand the MDI process. For example, we define ***lone facility functions*** as facility function nodes that only support a single mission layer and no other mission or facility function and do not depend on other facility functions. An example of a lone facility function in Figure 3.6 is Facility Function 4, Red. The existence of these lone facility functions emphasize the

importance of the intradependency score. Whereas many network measures disregard nodes that are in the network but have no connectivity (i.e., degree = 0), an installation multilayer network may depend on these nodes more than others. In fact, an installation may have a good reason to rank them with higher MDI centrality values than other well-connected facility functions. An example of this may be an airstrip used for aircraft landing and takeoff.

Another facility function worth highlighting we call a *source facility function*. We define a ***source facility function*** as a facility function node that is depended on by other facility functions (either in its own mission layer or a different mission layer), but itself does not depend on other facility functions. An example of a source facility function in our multilayer network is A-mission Red, 1. A real-world example of a source facility function may be large fuel tank located on an installation. The fuel tank is part of an aviation mission and the tank delivers fuel to several other refueling facilities located across the installation. There is no facility function at the installation that refills the fuel tank. Thus, at the installation level the fuel tank appears to be a source facility function. While our example tank may depend on facilities outside the installation to first fill it, MDI analysis at the scale of an installation ignore these dependencies that exist across and outside the fence line.

We build on these insights to critique MDI. Overall our network formalism for MDI is necessarily complicated because the MDI calculation process is not as straightforward as presented to stakeholders. Without our network representation of MDI, it is difficult for any SME, mission-owner, or installation commander to understand how their responses influence facility scores and ranking. We use our multilayer network perspective to develop simple examples and quantify issues with MDI.

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## CHAPTER 4:

### Mission Dependency Index: Critique

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The MDI calculation process is intended to be easy to follow, but there are many facets in application that are either subjective or ambiguous. As presented in Ch. 1, there are several known critiques of MDI already identified by Kujawski and Miller (2009) (see Chapter 1, Section 1.3). However, there are key issues with MDI that have yet to be addressed that result from greater investigation of its use and calculation. It is only through examples that these nuances can be investigated.

#### 4.1 Measuring the Sensitivity of MDI Calculation

As a start, we assess the sensitivity of the MDI equation to  $MD_w$ ,  $MD_b$ , and  $N$  factors. This requires understanding how the MDI equation (Equation 1.2) works. This equation is complicated and includes normalization factors and non-linear relationships. MDI was purposefully designed to normalize  $MD_w$ ,  $MD_b^{avg}$ , and  $N$  into a single metric from 0 to 100. Commander, Navy Installations Command (2018) states how the variables,  $MD_w$ ,  $MD_b^{avg}$ , and  $N$  are weighted, where each has a contribution to final MDI score with the following percentages:

- $MD_w = 84\%$
- $MD_b^{avg} = 12\%$
- $N = 4\%$

These percentages can be seen directly from Equation 1.2: MDI scales linearly at approximately 16 times its  $MD_w$  value, approximately two times its  $MD_b^{avg}$  value, and as  $1.65 \cdot \ln N$ . This leads to our first critique of MDI.

**Critique 1: The relative weighting of  $MD_w$ ,  $MD_b$ , and  $N$  means MDI scores are dominated by subjective interpretation of intradependency, rather than relationships among facilities to work as networks and support mission.**

We build on this understanding of weighting to see how these input variables influence MDI categories. Figure 4.1 presents a 3-D scatterplot representing the 256 possible combinations

of  $MD_w$  and  $MD_b^{avg}$  scores in the case where  $N = 1$ . Each combination is colored according to their respective MDI categories. Due to the weighting of  $MD_w$  in the equation, small increases in  $MD_w$  can lead to large changes in MDI category. In contrast, there are only a few specific  $MD_b^{avg}$  scores that can lead to switching categories. For example, when  $MD_w$  is 5.1, there is no  $MD_b^{avg}$  score that would lead to a change in facility MDI category.

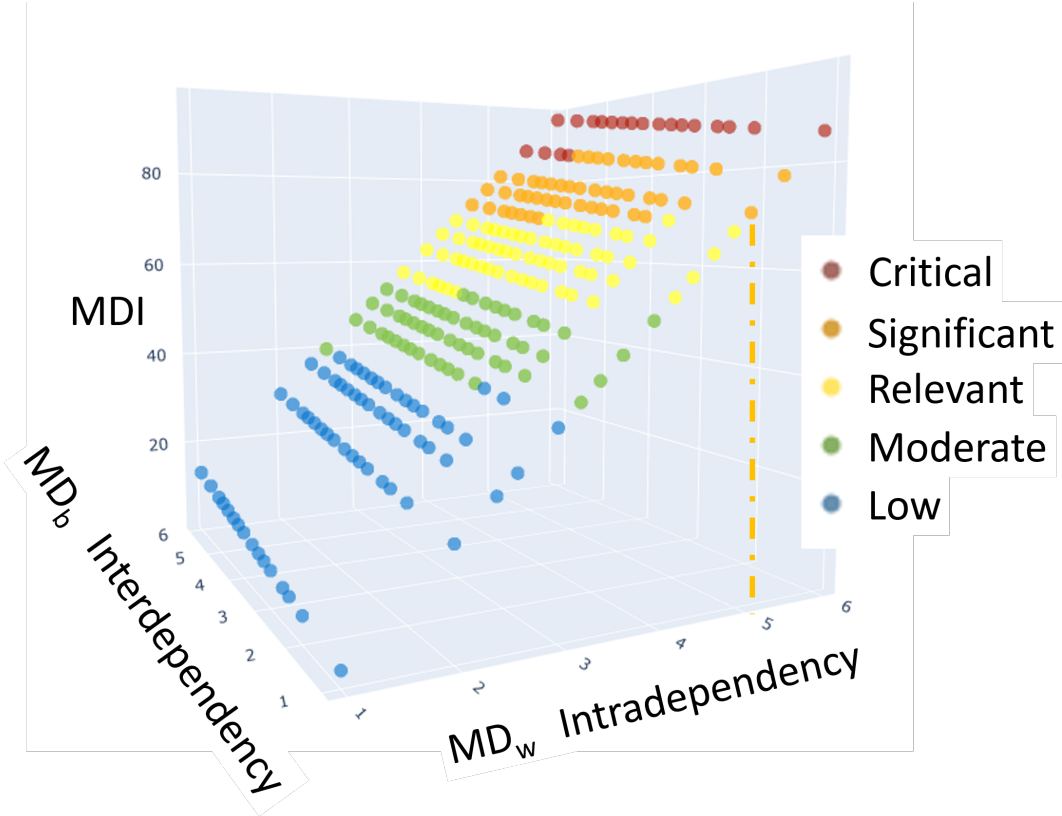


Figure 4.1. MDI Response Surface when  $N = 1$ . A dotted line extends up to  $MD_w = 5.1$ . At at this value, the MDI category of a facility will not change regardless of its  $MD_b^{avg}$  value.

Figure 4.1 was generated for  $N = 1$ . As the value  $N$  increases, MDI grows as  $1.65 \cdot \ln N$ , which tends to be small. For values  $N = 10$  and  $N = 100$ , MDI grows by only 3.8 and 7.6 respectively, which could potentially increase the MDI category by one level but is more likely to have no effect at all.

So the MDI score for a facility is dominated by its  $MD_w$  value, which is assigned subjectively

according to the lookup table in Figure 1.1. Yet, MDI scoring is veiled as being quantitative. This leads to considerable misinterpretation and misuse.

## **4.2 Issues with MDI Interpretation and Use**

MDI is concerned with rating the overall importance of facilities, with the goal of providing a prioritized list of the facilities of greatest importance for an installation. MDI scores and categories are used by individuals tasked with executing funding across an installation. MDI is particularly important because every mission type is treated equally during analysis and categorization.

While many DoD services and federal agencies have adopted MDI for these reasons, each installation and organization varies in the way it employs MDI scores to guide decisions. For example, NASA uses a three-factor model for facility prioritization (Figure 4.2). In this framework, NASA uses MDI as a measure both to decide where funds go and to determine which facilities may qualify for disposal or divestiture. In general, this is a common interpretation and use of MDI across the DoD, such as in the U.S. Marine Corps (Renosto 2019).

This use of MDI suggests that answers to Survey Questions 1-4 relate to long-term infrastructure planning that involves new construction, recapitalization, and demolition projects. This perspective does make sense for some responses to Survey Questions 1-4, such as for facility functions that are impossible to relocate even in the far future. However, Survey Questions 1-4 also emphasize the impacts of near-term and immediate loss of function, rather than long-term planning. This suggests that there is another interpretation of MDI related to its calculation — MDI is the expected near-term impact to mission when a facility function is lost. This perspective emphasizes how MDI attempts to evaluate the severity of consequences, which is estimated via IRR measures used in intradependency and interdependency scores.

With at least two perspectives on MDI — one for long-term planning and one for near-term impacts — it is unclear what an MDI score represents to a decision-maker. For example, one facility manager or SME might understand a high MDI score as a chance for greater funding, but another might understand the same score as identifying a facility that is sensitive to

## Mission Dependency Index and Asset Condition

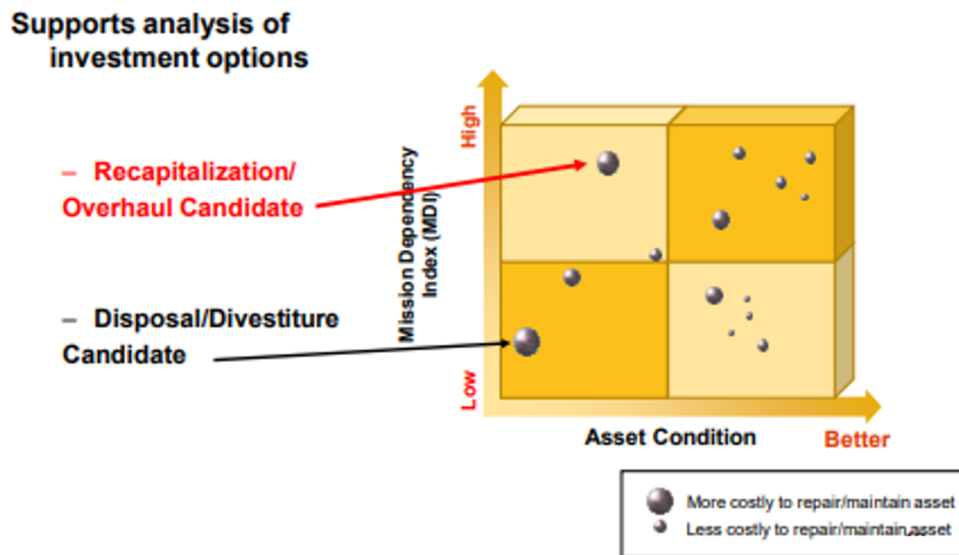


Figure 4.2. NASA's use of MDI, adapted from National Aeronautics and Space Administration (2010). This quad chart evaluates MDI score versus Asset condition. It adds a third variable, namely cost to repair, represented by the size of each point.

interruption. In contrast, a facility with a low MDI score could be interpreted as a facility that does not affect mission when lost, or as a facility that will receive very little funding.

### **Critique 2: Conflicting long-term and near-term perspectives on MDI create incentives to give facilities that are less important to mission higher MDI scores.**

Since MDI scores are a result of expert elicitation and survey, these conflicting perspectives create an incentive to assign MDI scores in ways that might undermine its intent. For example, SMEs may give high MDI scores to facilities that do not have any direct mission impacts, but rather to those the SME or installation commander wants to maintain or overhaul. Moreover, the SME may be incentivized to give a low MDI score to facilities that are deemed unnecessary or unwanted in order to speed up facility disposal, even if some mission-essential functions might be housed there. Together, these conflicting perspectives can lead different SMEs on the same installation or across multiple installations to answer

Survey Questions 1-4 with different intent.

We provide a hypothetical example for how this conflict can occur using our example calculation from Section 1.1.2, involving the base gymnasium ( $MDI = 79.38$ ). This MDI score is in the significant category and is relatively high compared to many other missions. The reason the gym may have such a high score is that the SME scoring it decided it requires an overhaul. The SME justifies this score by saying the fitness mission would be unable to reestablish mission needs if the facility were shutdown. In an attempt to receive, or qualify for funding, the SME answers MDI Survey Questions 1 and 2 to maximize the  $MD_w$  score.

At the same installation, infrastructure that appears more critical to mission needs may receive lower scores than the gym. For example, there may also be a potable water mission that contains a water distribution system. Rather than scoring the water distribution system based on a need for overhaul, the water mission SME scores Survey Questions 1 and 2 from the perspective of immediate consequence. The potable water mission SME considers the backup water systems and water storage on base during this calculation. As such, there is some ability to interrupt and relocate water services if the water distribution system is disrupted.

In this situation, the gymnasium may receive a higher MDI score than the water distribution system. The fitness mission SME is incentivized to give an  $MD_w$  score based on funding, where the water mission is incentivized to give a score based on mission consequence. While physical fitness is very important, a disruption in the gymnasium would probably lead to staff exercising outside, while the loss of potable water could shut down large portions of an installation. This hypothetical example can be demonstrated using real data.

Figure 4.3 shows actual MDI scores for a gymnasium and water distribution system — two facilities taken from the Antelman and Miller (2002). In their work, Antelman and Miller (2002) use different intradependency and interdependency matrices, leading to different MDI scores, but the impact of differing decision incentives on prioritization occurs nonetheless. Not only does the water distribution system facility receive a lower MDI score, it is also in a lower MDI category (relevant). This almost guarantees less funding for the water distribution system in future decision-making.

The limited effect of  $MD_b^{avg}$  on MDI score is also pronounced in this example. Figure 4.3

shows that there are 32 dependencies on the water distribution system, almost three times that of the dependency on the gymnasium. Furthermore, those facility functions dependent on the water distribution system have determined that interruption of potable water has greater consequence their missions, than an interruption to the gymnasium on its interdependent missions. This is shown by the larger  $MD_b^{avg}$  for the water distribution system of 3.98 compared to the gymnasium  $MD_b^{avg} = 2.46$ .

| Facility                  | $MD_w$ | $MD_b$ | n  | MDI  |
|---------------------------|--------|--------|----|------|
| Water Distribution System | 4.33   | 3.98   | 32 | 68.3 |
| Gymnasium                 | 5.5    | 2.46   | 12 | 84.4 |

Figure 4.3. MDI Scores for a Water Distribution System Compared to Gymnasium. Adapted from Antelman and Miller (2002).

**Critique 3: Conflicting long-term and near-term perspectives on MDI can make it more difficult to make DoD administrative decisions (e.g., determining the best installation to locate a new mission).**

MDI also creates an opportunity to confuse operational decisions related to missions that depend on installation infrastructure, but are not housed at a single installation. For example, in the situation where the USN creates a new class of ship, the ship community manager will need to select an installation from which to home port. If the community manager was only given MDI scores for each installation, what should they look for? An installation with many high MDI scores may mean a higher risk for interruption to mission, yet that higher risk equates to better funding and thus better facilities. Likewise, an installation with low MDI scores may mean stability in operational support, but less funding for upkeep and the potential for some services to be divested in the near future.

A similar hypothetical situation occurs when a USN Captain is choosing which of two new bases he/she wants to take command of next. Here, the Captain may prefer an installation

where MDI scores are predominately high, indicating higher risk and greater consequences to mission sets, but with greater budget and more attention by their service community. Whereas an installation with mostly low MDI scores would appear more stable with less risk, thus receiving less funding and attention when problems arise.

One might also conclude that the best MDI scores for an installation should lie somewhere in between the two extremes. For example, imagine an installation that balanced all MDI scores such that each facility had a score near some mean value (e.g., MDI= 50). This balancing prevents adversaries from identifying critical facilities as targets and may deter an attack on the installation. Yet, this balance would also make it difficult to manage funds. Similar to deterring an attacker, an installation with balanced scores does not help decision-makers prioritize which facilities need funding.

Overall, these hypothetical examples demonstrate the true difficulty of the MDI process: the ultimate use of MDI does not necessarily relate to its interpretation. MDI Survey Questions 1-4, IRR responses, and intradependency and interdependency scores can be interpreted in at least two ways. This makes it difficult to know how MDI scores were assigned within and among installations. This also creates situations where using MDI to guide decisions may only complicate the decision-making process.

### **4.3 Issues with MDI Calculation**

Even if all facility SMEs and decision-makers across the DoD were able to agree on MDI interpretation and use, there are inherent issues with measuring intradependency and interdependency scores that may lead to ineffective ranking and prioritization with MDI. For example, past studies critiquing MDI suggest that the use of risk matrices for calculating  $MD_w$  and  $MD_b$  may be ineffective for asset prioritization (see Kujawski and Miller 2009). In addition to these known issues, we identify additional issues that derive from MDI calculation generating a *multilayer network* of military missions and facility functions without being explicit about this process.

Specifically, assessing intradependency for a mission essentially means generating a network that links mission needs to facility functions. Then, when assessing interdependency, a second network is generated linking facilities across missions. This two-step process

has at least three problems that lead to significant sources of error among missions and installations:

- **The Mission Partitioning Problem:** The number of missions at an installation has a direct impact on the MDI score for *all* facilities at the installation.
- **The Interdependency Assignment Problem:** There are multiple ways to assign dependencies across facilities and missions, where methods that assign more dependencies lead to increased MDI scores over methods that assign fewer dependencies.
- **The Replaceability Problem:** Replaceability is only measured for a single facility-facility dependency that is currently in use (one-to-one, static). However, replaceability involves multiple interactions representing where a facility may access services when functions are disrupted (one-to-many, dynamic).

We consider each of these in additional detail.

### 4.3.1 The Mission Partitioning Problem

As described above, MDI scores do not consider interdependencies among facilities within the same mission. Instead, the the only way to include facility-to-facility dependencies is when these facilities are managed by different missions. Using our notation from Chapter 3, MDI only considers arcs  $(i, j) \in E_M^{MDI} \subseteq E_M$ . This leads to what we term a *mission partitioning problem*, where increasing the number of missions on an installation may increase the number of the interdependencies used for MDI calculation. Specifically, the more missions on the installation, the more likely that interdependencies within a mission become interdependencies across missions and are included in MDI calculation (i.e., the more likely an arc  $(i, j)$  changes from  $(i, j) \notin E_M^{MDI}$  to  $(i, j) \in E_M^{MDI}$ ). The extreme situation would be each facility function is its own mission, which would consider all interdependencies in MDI calculation (i.e.,  $E_M^{MDI} = E_M$ ).

We motivate the mission partitioning problem with a hypothetical, but realistic example. Consider a Diesel Fuel Marine (DFM) mission that is comprised of seven separate facilities (Figure 4.4). The DFM mission is established to provide fuel to ships at a pier. There are two storage tanks that house the fuel, a pumping station that flows fuel from the tanks to the pier pumps, three fuel pumps that service separate locations at a pier, and one motor control center that controls all pump speeds and fuel flow rates.

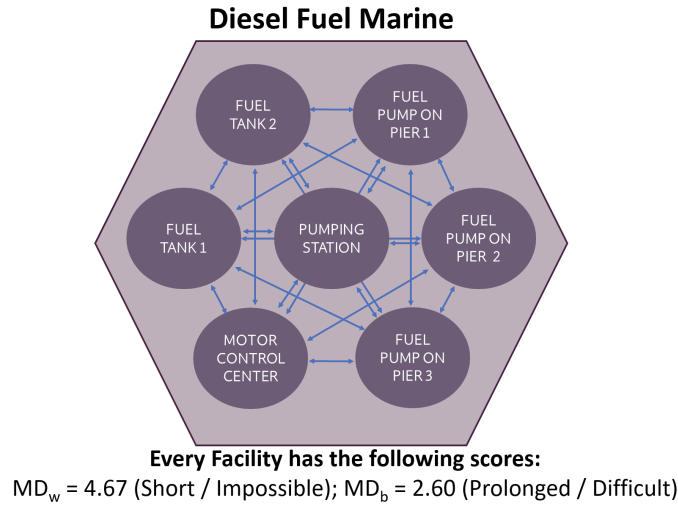


Figure 4.4. Example Diesel Fuel Marine Mission. The DFM mission is comprised of seven facilities. Each facility function is dependent on each other to function (shown with blue arrows).  $MD_w$  and  $MD_b$  values for all facility functions are the same.

For simplicity, let us assume that every facility function within the DFM mission is dependent on every other facility (i.e., dependencies within the DFM mission form a fully connected network). Figure 4.4 illustrates how this would look for the seven facilities and their functional dependencies within the DFM mission. Here, the blue arrows represent the dependence of one facility function on another facility function.

We also assume that each facility function within the DFM mission is assigned the same  $MD_w$  and  $MD_b$  scores. Figure 4.4 sets every  $MD_w$  score to 4.67, which equates to MDI Survey Questions 1 and 2 responses as short and impossible, respectively. Likewise, every  $MD_b$  score is 2.6, which results from responses to Survey Questions 3 and 4 as prolonged and difficult, respectively.

Grouping all facilities into the DFM mission affects their final MDI scores. We refer to this situation as all seven facilities being assigned into the same mission layer. Here, only  $MD_w$  scores are used for MDI calculation. Even though the facility functions in Figure 4.4 have dependency amongst themselves (shown in blue), they are not considered because all facilities support the DFM mission. Since all facility functions have the same  $MD_w$  scores, all facilities have the same MDI. Specifically, each facility function in the DFM mission has

an MDI = 65.55 (Relevant).

An important questions is: *what would happen if the DFM facilities were partitioned into separate missions, and what happens when the same facilities and dependencies are spread across more missions?* Figure 4.5 shows several ways to partition the DFM into two missions  $M1$  and  $M2$  that are reasonable to capture some of the sub-mission functions and their relationships. For example, an installation commander may separate the controls system from the DFM mission if its primarily operated by the utility mission ( $P1$ ). The tanks may be considered their own mission related to storage and emergency management ( $P2$ ). The pumping station may be combined with the tanks as the storage and pumping mission ( $P3$ ). The control system can be included with the storage and pumping mission to consider the docking and pier infrastructure as its own mission ( $P4$ ).

Although each grouping of facilities and missions across Figures 4.4 and 4.5 appears reasonable, the choice of chosen partitioning changes the MDI scores and categories assigned to each facility function. When the DFM mission is partitioned into  $M1$  and  $M2$ , the blue arcs representing dependencies are now included in MDI calculation as interdependencies. Only blue arcs that cross these partitions are included in calculation (intradependencies are still ignored). This can have drastic effect on results even when  $MD_w$  and  $MD_b$  do not change.

Table 4.1 presents the MDI scores and categories for DFM facilities given different mission partitions. Partition  $P0$  represents the original DFM mission where all facilities are in  $M2$ . We can see that once the DFM mission is partitioned into two sub-missions, all facilities receive a higher MDI score than the  $P0$  instance. Additionally, facility functions that lie within the smaller sub-mission group have higher MDI scores than those in the larger sub-mission group. For example, in Partition  $P3$ , the facilities in  $M1$  receive a higher score than those in  $M2$  since there are only 3 facilities in  $M1$  and 4 facilities in  $M2$ . The MDI scores for these facilities are exchanged once  $M1$  becomes the larger mission partition.

While more mission partitions automatically raise MDI scores, the most important effect is on MDI categories. Given the  $MD_w$  and  $MD_b$  scores for the DFM mission, facilities in each mission partition are assigned different MDI categories. For example, in Partition  $P1$  the controls mission ( $M1$ ) is placed in the MDI category significant, where the rest of the DFM mission remains in the category relevant. Simply by setting a sub-mission partition,

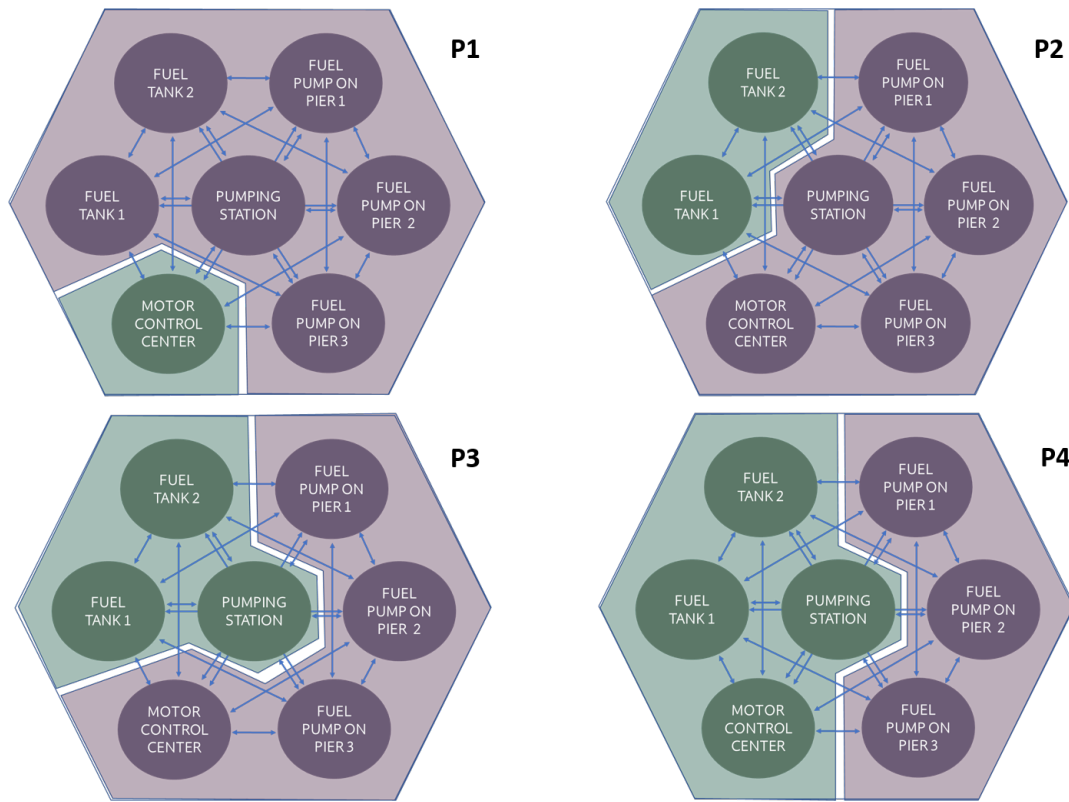


Figure 4.5. Partitioning Possibilities of the Diesel Fuel Marine Mission. The two new sub-mission types are  $M1$  (green) and  $M2$  (purple). There are four different partition patterns represented by  $P1 - P4$ . Notice that some arrows that represent facility function dependencies now connect across missions, which means they now constitute an interdependencies according to MDI calculation. Only these interdependency arrows are used for MDI calculation.

one can both raise MDI scores *and* change their categories used for decision-making.

This realistic example shows that the number of mission partitions on an installation affects the MDI score of all facilities on an installation. If each facility function was part of one big installation mission, they would only be ranked by  $MD_w$  scores, which minimizes each facility's possible MDI score and category. In contrast, if each facility function was assigned its own mission, it would maximize each facility's MDI score and category by including as many  $MD_b$  interactions as possible (Max  $N$ ).

Taking this concept of partitioning to the extreme, imagine if every facility function was its own mission. In this situation, every facility-facility interaction is an interdependency.

Table 4.1. Effect of Mission Partitioning on MDI. Partition  $P_0$  is the base case presented in Figure 4.4. Partitions  $P_1 - P_4$  are from Figure 4.5.  $|M_1|$  and  $|M_2|$  refers to the number of facility functions in each mission. The last two columns are the MDI scores for each facility function within the given partition. Color relates to MDI category, where yellow represents relevant and orange represents significant (rounded up).

| Partition | $ M_1 $ | $ M_2 $ | $M_1$ MDI | $M_2$ MDI |
|-----------|---------|---------|-----------|-----------|
| $P_0$     | 0       | 7       | n/a       | 65.55     |
| $P_1$     | 1       | 6       | 69.8      | 66.9      |
| $P_2$     | 2       | 5       | 69.3      | 68.0      |
| $P_3$     | 3       | 4       | 69.2      | 68.7      |
| $P_4$     | 4       | 3       | 68.7      | 69.2      |

This removes the partitioning problem, but maximizes MDI scores. Figure 4.6 depicts this representation for the DFM mission. In this example, every facility increases their respective MDI score from 65.55 to 69.2 and their category from relevant to significant.

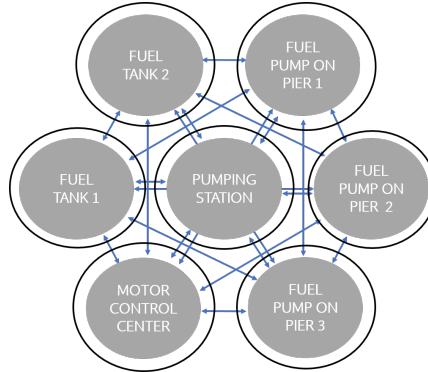


Figure 4.6. Full partitioning of the Diesel Fuel Marine Mission. The facility's color is not an attributing any mission type, but rather to show the facilities edge. Each black circle would represent each facility's unique mission type. Notice that now every arrow that represents dependency is cut by the black unique mission circles.

**Critique 4: The existence of the mission partitioning problem enables misuse by allowing the arbitrary choice of the number of missions and facility functions at an installation to change all facility MDI scores.**

The existence of the mission partitioning problem can lead to shifts in MDI scores as missions are assigned to an installation. Knowing this enables misuse of MDI within the U.S. government. For example, a SME, base commander, or manager who decides mission partitions can choose partitions that best suit their funding needs. For example, a base commander within the USN trying to receive additional funding for infrastructure would want to increase the number of mission partitions on their installation. Within the DoD, it is unknown how missions and facilities are partitioned in this way.

The ability to “game” the scoring system in this way is not as bad as it gets, in the sense that gaming the system means that its users understand its rules and can make use of them to achieve some subjective desired outcome. Given the convoluted and obscure nature of the MDI scoring system, a more likely scenario is that users are following it blindly, unaware how their arbitrary but well-intended decisions about mission partitioning are artificially influencing the outcome of their analysis.

### 4.3.2 The Interdependency Assignment Problem

The initial determination of interactions between facility functions, termed here *the interdependency assignment problem*, has its own issues. The MDI process considers interdependencies based on answers to Survey Questions 3 and 4. However, there are multiple ways a SME may answer these questions, which in turn can change the number of interdependencies considered in final calculation. In other words, the number of interdependencies among facility functions,  $|E_M|$ , is a function of SME interpretation. As explained above, situations where more interdependencies are considered tend to lead to higher MDI scores.

Again, we motivate this problem with a hypothetical, but realistic scenario. Recall that there are both administrative A-missions, and operational O-missions. Consider an O-mission answering Survey Questions 3 and 4 for the example DFM mission defined in Figure 4.4 (e.g., a ship that needs fuel). Figure 4.7 shows that interdependency assigned from the O-mission to the DFM mission can occur in at least two different ways. The first method we call *blanket assignment*, where the a facility function (e.g., ship) attributes its interdependency to every facility function in the DFM mission. The second method we call *direct assignment*, where a facility function attributes its interdependency to only a single facility function that it directly depends on (e.g., fuel pump on pier). Whereas blanket assignment assumes each

facility function within the DFM mission supports refueling, direct assignment assumes interdependency only matters for the facility that actually provides the desired service or commodity.

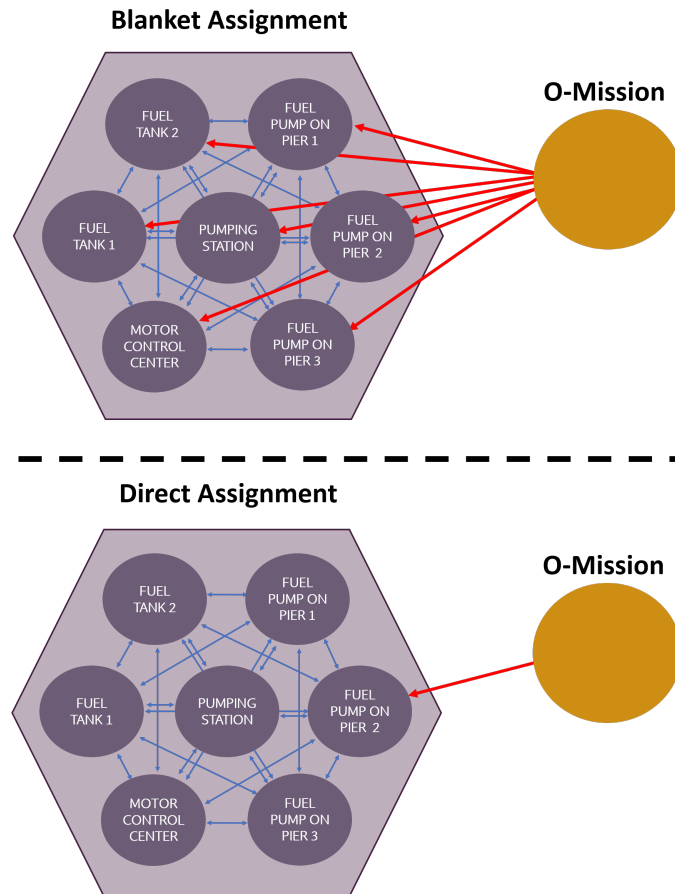


Figure 4.7. While not solely specific to only O-missions, blanket assignment is when an interdependent O-mission or a facility function from another mission type attributes its dependency to every facility function within the interdependent mission type. In contrast to blanket assignment, direct assignment only assigns interdependency to those facility functions which directly provide service or commodity.

To emphasize the interdependency problem, we present real examples of using both blanket and direct assignment. Figure 4.8 presents a situation where blanket assignment was used to determine MDI scores for an fuel-aviation mission. This example is from the MDI validation report of Antelman and Miller (2002), adapted to emphasize the interdependency

assignment problem. Here, the report shows all facility functions within the fuel-aviation mission. On the far right is the column labelled  $N$ , which is the number of facility functions from other missions that report interdependency on the fuel-aviation mission. In this scoring, almost every facility function has an  $N$  reported as seven.

| <i>Mission</i>              | <i>MDI</i> | <i>Facility No.</i> | <i>Facility Name</i>              | <i>Investment Code</i> | <i>Critical System</i> | <i>MDw</i> | <i>MDbAvg</i> | <i>n</i> |
|-----------------------------|------------|---------------------|-----------------------------------|------------------------|------------------------|------------|---------------|----------|
| <b>FISC JACKSONVILLE FL</b> |            |                     | <b>FUEL - AVIATION</b>            |                        |                        |            |               |          |
| 87.07                       | 0111       |                     | FUELING WHARF & DOLPHINS          | 3                      |                        | 5.5        | 4.33          | 7        |
| 87.07                       | MDI-00254  |                     | POL PIPELINE                      | 4                      |                        | 5.5        | 4.33          | 7        |
| 87.07                       | MDI-00255  |                     | POLLUTION CONTROL EQUIP SYS       | 17                     |                        | 5.5        | 4.33          | 7        |
| 87.07                       | MDI-00287  |                     | TK FARM DIST SYS                  | 4                      |                        | 5.5        | 4.33          | 7        |
| 74.74                       | 0046       |                     | TANK 8                            | 10                     |                        | 4.67       | 4.59          | 9        |
| 73.38                       | 0004TK     |                     | TK 31 DIESEL FUEL MARINE          | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0039       |                     | TANK 1 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0040       |                     | TANK 2 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0041       |                     | TANK 3 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0042       |                     | TANK 4 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0043       |                     | TANK 5 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0044       |                     | TANK 6 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0045       |                     | TANK 7 FLOATING ROOF TYPE         | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0047       |                     | TANK 9                            | 10                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0051       |                     | WATER PUMPHOUSE - Fire Protection | 17                     |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0105       |                     | PUMPING STATION J88               | 4                      |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0106       |                     | TRUCK LOADING STAND F76           | 4                      |                        | 4.67       | 4.33          | 7        |
| 73.38                       | 0471B      |                     | MOTOR CONTROL CENTER              | 17                     |                        | 4.67       | 4.33          | 7        |
| 67.77                       | 0037       |                     | FIRE EQUIP SEHD W/GEN 200124      | 16                     |                        | 4.33       | 4.33          | 7        |
| 67.77                       | 0071C      |                     | BACKUP GENERATOR #1               | 17                     |                        | 4.33       | 4.33          | 7        |
| 67.77                       | 0072C      |                     | BACKUP GENERATOR #2               | 17                     |                        | 4.33       | 4.33          | 7        |
| 67.77                       | 0119       |                     | RIVER WTR PUMPSTA@PIER 111        | 17                     |                        | 4.33       | 4.33          | 7        |
| 67.77                       | 0120       |                     | BACK-UP GENERATOR                 | 17                     |                        | 4.33       | 4.33          | 7        |
| 67.77                       | MDI-00202  |                     | ALARM SYSTEM                      | 17                     |                        | 4.33       | 4.33          | 7        |

Figure 4.8. Blanket assignment interdependency excerpt taken from Antelman and Miller (2002). Depicts the Fuel-Aviation and a number of its associated facility functions. On the right hand side is the  $MD_b$  average and  $N$  value for each one of the facility functions. In all but one case both values are exactly the same.

Upon further analysis, we find that these  $N$  values are a result of blanket assignment. Figure 4.9 presents an example of where these interdependency scores are originate from. Specifically, “POL PIPELIN” (a facility in the fuel-aviation mission) is scored by missions “AIMD Mayport”, “NAVAIRDEPOT JACKSONVILLE FL”, and “NAVSTA MAYPORT FL - Supply.” We find each of these mission’s facility functions reported their interdependency the same way for every facility within the fuel-aviation mission type (i.e., blanket assignment). This is not a stand alone result. Within Antelman and Miller (2002) and other reports showing MDI calculation, many facility functions used blanket assignment to determine  $MD_b$  scores.

| Facility No.                    | Facility Name | IC        | Critical System | Q1       | Q2 | MDw      | MDbAvg   | n | MDI   |
|---------------------------------|---------------|-----------|-----------------|----------|----|----------|----------|---|-------|
| MDI-00254                       | POL PIPELINE  | 4         |                 | B        | I  | 5.5      | 4.33     | 7 | 87.07 |
| Other Mission(s)<br>Interdep-en |               | Facility  | Facility Name   | Question |    | Question | Question |   |       |
|                                 |               | Number    |                 | 4        | 5  |          | dency    |   |       |
| AIMD Mayport                    |               | MDI-00254 | POL PIPELINE    | B        | D  |          | 4.33     |   |       |
| AIMD Mayport                    |               | MDI-00254 | POL PIPELINE    | B        | I  |          | 5.5      |   |       |
| AIMD Mayport                    |               | MDI-00254 | POL PIPELINE    | B        | D  |          | 4.33     |   |       |
| AIMD Mayport                    |               | MDI-00254 | POL PIPELINE    | S        | p  |          | 2        |   |       |
| AIMD Mayport                    |               | MDI-00254 | POL PIPELINE    | B        | D  |          | 4.33     |   |       |
| NAVAIRDEPOT JACKSONVILLE FL     |               | MDI-00254 | POL PIPELINE    | B        | I  |          | 5.5      |   |       |
| NAVSTA MAYPORT FL - Supply      |               | MDI-00254 | POL PIPELINE    | B        | D  |          | 4.33     |   |       |

Figure 4.9. Interdependency reporting taken from Antelman and Miller (2002). This image highlights the facility function “POL PIPELINE” from the Fuel-Aviation mission. It also highlights the other missions that assign interdependency to the “POL PIPELINE” function.

In contrast, Figure 4.10 shows facility functions that belong within the electrical mission with  $MD_b$  scores that result from direct assignment. The column to the far right,  $N$ , shows a different number of interdependent facilities for every single facility function within the electrical mission. In fact the “Step-Down Transformer” listed at the bottom has no interdependencies. The MDI values for the electrical mission are result of direct assignment.

| Mission             | MDI      | Facility No. | Facility Name            | Investment Code | Critical System | MDw | MDbAvg | n  |
|---------------------|----------|--------------|--------------------------|-----------------|-----------------|-----|--------|----|
| PWC JACKSONVILLE FL |          |              | Electrical               |                 |                 |     |        |    |
| 98.44               | 1566     |              | SWITCHING STATION        | 17              | Specialties     | 6   | 5.24   | 19 |
| 98.19               | 0496     |              | SUB-STATION              | 17              | Specialties     | 6   | 5.12   | 16 |
| 98.14               | 1317     |              | SWITCHING STATION        | 17              | Specialties     | 6   | 5.10   | 15 |
| 98.05               | 0493     |              | MAIN SUB-STATION         | 14              | Specialties     | 6   | 5.05   | 37 |
| 97.56               | 1434A    |              | SUB-STATION - MORAL WEST | 17              | Specialties     | 6   | 4.82   | 10 |
| 94.47               | 1434B    |              | SUB-STATION - MORAL EAST | 17              | Specialties     | 6   | 4.72   | 3  |
| 79.65               | BD       |              | SWITCHING STATION        | 17              | Specialties     | 5   | 5.33   | 4  |
| 77.96               | TT       |              | SWITCHING STATION        | 17              | Specialties     | 5   | 4.91   | 2  |
| 76.34               | BC       |              | SWITCHING STATION        | 17              | Specialties     | 5   | 4.33   | 1  |
| 67.00               | 329 Main |              | Step-Down Transformer    | 17              | Specialties     | 5   | 0.00   | 0  |

Figure 4.10. Direct assignment interdependency excerpt taken from Antelman and Miller (2002). The electrical mission is highlighted at the top. To the right the  $MD_b$  average and  $N$  values are highlighted. Notice that none of these values are the same per facility function

**Critique 5: The interdependency assignment problem enables misuse as the best choice of how to assign interdependencies among facility functions is unclear, and methods that increase the number of interdependencies will raise MDI scores.**

These inconsistencies in attributing interdependency lead to unfair MDI comparisons, which in turn will lead to ill-advised funding decisions. Facility functions that are scored based on blanket interdependency assignment will receive higher MDI scores on average than those using direct assignment. In turn, more funding will be directed to blanket assignment missions than those with facility functions using direct interdependency assignment. It is important to emphasize that the interdependency problem occurs across all missions considered in MDI calculation. We present our example using an O-mission to simplify explanation. The effect of the interdependency assignment problem becomes more pronounced and difficult to measure when missions with multiple facilities and MDI scores are related to each other.

The interdependency assignment problem also leads to other unintended consequences. In particular, it artificially raises scores for missions housed within the same building.

Figure 4.11 shows how two different missions may share the same building. Here facility number 0002 is shared by both the “DESRON 24” mission and the “NAVSTA MAYPORT FL - HARBOR OPS” mission. As previously discussed, we have one facility that co-locates two functions. Other missions that depend on destroyer squadron 24 and harbor ops only select facility number 0002 when answering Survey Questions 3 and 4, rather than specifying which facility function they are dependent on. As a result, these two distinct facility functions receive the same  $N$  values and  $MD_b$  scores, despite serving different missions.

| <i>Mission</i>                        | <i>MDI</i> | <i>Facility No.</i> | <i>Facility Name</i>      | <i>Investment Code</i> | <i>Critical System</i> | <i>MDw</i> | <i>MDbAvg</i> | <i>n</i> |
|---------------------------------------|------------|---------------------|---------------------------|------------------------|------------------------|------------|---------------|----------|
| <b>DESRON 24</b>                      |            |                     |                           |                        |                        |            |               |          |
|                                       | 47.12      | 0002                | FLEET STAFF/PORT SERVICES | 14                     | Electrical             | 3          | 4.36          | 11       |
| <b>NAVSTA MAYPORT FL - HARBOR OPS</b> |            |                     |                           |                        |                        |            |               |          |
|                                       | 80.12      | 0002                | FLEET STAFF/PORT SERVICES | 14                     | Electrical             | 5          | 4.36          | 11       |

Figure 4.11. Shared facility between two functions of different missions excerpt taken from Antelman and Miller (2002). Highlighted in blue is the facility number, 0002. Highlighted in red are the two different functions that reside in that facility. Highlighted on the right are the  $MD_b$  average and  $N$  values. We see that both functions share the facility benefit from the interdependencies of the other.

This form of assignment means the more facility functions that are housed in the same facility, the greater chance of receiving funding (similar to the mission partitioning problem). This self-referential issue is shown in Figure 4.12. Here, facility number A-2 is a berth which is owned by the harbor ops mission. This berth also houses a water hook-up that is owned by the water distribution mission. The “Berth” then reports its mission is interdependent on the water distribution mission located at the same facility. Thus, it could be interpreted that the harbor ops mission facility is interdependent on itself, creating an unfair representation of dependence that would lead to increased MDI scores.

| Mission: NAVSTA MAYPORT FL - HARBOR OPS |               |          |                         |    | Location: Mayport |          |          |       |       |
|-----------------------------------------|---------------|----------|-------------------------|----|-------------------|----------|----------|-------|-------|
| Facility No.                            | Facility Name | IC       | Critical System         | Q1 | Q2                | MDw      | MDbAvg   | n     | MDI   |
| A-2                                     | Berth         | 3        | Structural              | B  | I                 | 5.5      | 3.72     | 13    | 87.04 |
| Other Mission(s)<br>Interdep-en         |               | Facility | Facility Name           |    |                   | Question | Question |       |       |
|                                         |               | Number   |                         |    |                   | 4        | 5        | dency |       |
| NAVSTA MAYPORT FL - HARBOR OPS          |               | A-2      | Water Hook-Ups @ Berths | N  | I                 |          |          | 6     |       |
| NAVSTA MAYPORT FL - Homeport - CG       |               | A-2      | Water Hook-Ups @ Berths | N  | D                 |          |          | 5     |       |
| NAVSTA MAYPORT FL - Homeport - CG       |               | A-2      | Water Hook-Ups @ Berths | N  | D                 |          |          | 5     |       |
| NAVSTA MAYPORT FL - Homeport - CG       |               | A-2      | Water Hook-Ups @ Berths | N  | D                 |          |          | 5     |       |
| NAVSTA MAYPORT FL - Homeport - CG       |               | A-2      | Berth                   | S  | p                 |          |          | 2     |       |
| NAVSTA MAYPORT FL - Homeport - CG       |               | A-2      | Water Hook-Ups @ Berths | N  | D                 |          |          | 5     |       |
| NAVSTA MAYPORT FL - Homeport - DD       |               | A-2      | Berth                   | S  | p                 |          |          | 2     |       |
| NAVSTA MAYPORT FL - Homeport - DD       |               | A-2      | Berth                   | S  | p                 |          |          | 2     |       |
| NAVSTA MAYPORT FL - Homeport - DD       |               | A-2      | Berth                   | S  | p                 |          |          | 2     |       |
| NAVSUFGP2                               |               | A-2      | Berth                   | B  | I                 |          |          | 5.5   |       |
| SIMA MAYPORT FL                         |               | A-2      | Berth                   | P  | D                 |          |          | 2.5   |       |

Figure 4.12. Shared facility between two functions of different missions with interdependency between the functions excerpt taken from Antelman and Miller (2002). Highlighted at the top is a mission Harbor Ops. The same mission is highlighted again in the other mission interdependency section. This is caused because the potable water mission has a water hook up that shares the facility A-2, creating what appears to be a facility function depending on itself.

### 4.3.3 The Replaceability Problem

The assignment problems exist due to the networks formed during MDI calculation. In both cases, MDI calculation assumes a static network structure underlying mission-facility and facility-facility dependencies. However, many aspects of IRR factors relate to network dynamics that should include network reconfiguration. Notwithstanding issues with representing interruptability and relocatability with a static network, we focus attention on how a static network representation fails to capture the effects of replaceability.

There are many instances where redundancies and alternate sources of facility function are built into real systems. An example may be the three piers in our DFM example, where a ship can refuel at any one pier and the other two act as redundant backups. Using a network representation, we may consider these additional sources of facility function as arcs that exist but are not necessarily active (Figure4.13).

Figure 4.13 shows an O-mission facility function who is dependent on the DFM mission and could attribute interdependency to three different pier fuel pump functions. Currently,

neither intradependency nor interdependency considers these arcs associated with replaceability and MDI lacks the capability to evaluate circumstances when the O-mission facility function switches between facilities. In many cases, facilities that are installed as redundancies or backups will have lower MDI scores than their “in use” counterpart. These redundant facility functions receive less funding and may be threatened by disposal and divestiture.

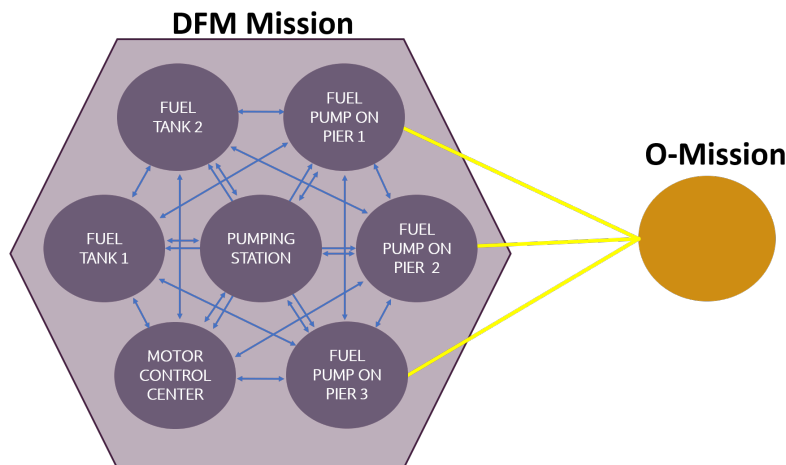


Figure 4.13. Replaceability and Redundancy in the Diesel Fuel Marine Mission. We assume an O-mission that needs a pier to function. Normally, MDI only considers the pier the O-mission facility function is located at via direct assignment. However, the O-mission facility function can receive refueling functions at any pier connected by yellow arcs. These represent possible assignments and replaceability of function. Should any of the three pier fuel pumps become interrupted there are two other possible facility functions that can be used instead. MDI does not consider these functional replacements in calculation.

MDI Survey Questions 1-4 consider only how difficult it is to replace a facility function, not where the new function would be acquired. Thus, MDI scoring may lead one to believe that the loss of any facility function would eventually interrupt a mission need as a whole. This is unrealistic and introduces additional issues when considering how MDI calculation changes over time.

**Critique 6: The replaceability problem enables misuse as interdependencies to backup facilities and redundant functions meant to enable mission assurance are not considered in MDI calculation.**

Compare Figures 4.13 with Figure 4.14. Given current MDI calculation in Figure 4.13, if there is only a single O-mission facility function, a single pier may receive a higher MDI score (assuming direct assignment). Moreover, the answer to MDI Survey Question 4 would suggest easy functional replacement. If at a later time there were ships located at each pier (Figure 4.14) the vulnerability of the new system would not be considered in MDI scores. Here, each pier has a ship, and each pier should have a higher MDI score. There is also no additional capacity for functional replacement, leading to higher  $MD_b$  scores overall.

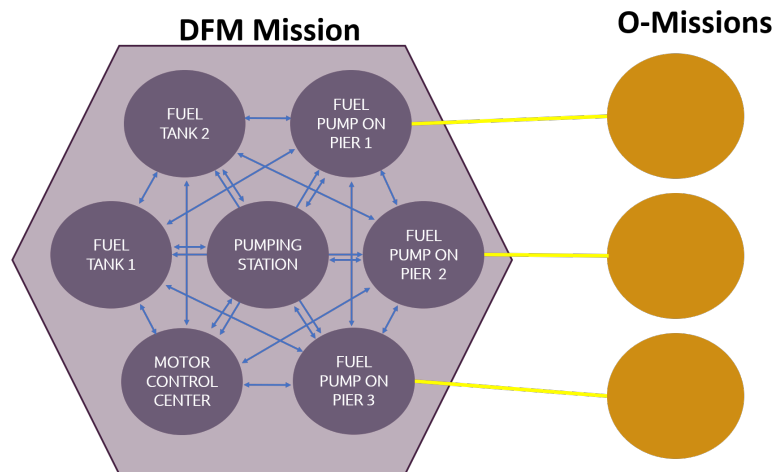


Figure 4.14. Functional Replaceability Given More O-mission facility functions. When all piers have O-mission facility functions assigned to them, there is no capacity for the DFM mission to replace the fuel pump functions. Each pier will have a higher  $MD_b$  score than in Figure 4.13 as each pier has an O-mission facility function and functional replaceability is more difficult.

Overall, there is no effective way to consider facilities that perform similar or interchangeable functions without considering network dynamics. In one situation, where the O-mission facility function moving from one pier to another should lower the score of the original pier, and raise the MDI of the new pier. In another situation, when the number of O-mission facility functions on an installation changes, MDI should be reassessed as the availability and difficulty of functional replacement will also change.

## 4.4 Summary

This chapter takes a deep dive into the application and nuances of MDI. We present an in-depth explanation of MDI calculation not previously found in the literature. In doing so, we expose several new issues with MDI interpretation and calculation.

Issues with MDI interpretation and use stem from conflicting perspectives on long-term infrastructure funding decisions with perspectives on near-term consequences of infrastructure failure. This may lead a SME to answer the same MDI questions differently based on perspective. This leads to inconsistent and possibly erroneous results, such as a gymnasium receiving a higher MDI score and category than a water distribution system.

One way to overcome this issue is to include weighting across missions. MDI is mission agnostic and assumes that every mission is equal. While the issues associated with conflicting funding and operational incentives may never go away, weighing the scores of one mission to another could help alleviate issues with inflated  $MD_w$  scores. In the case of the gymnasium versus the water distribution system, if there existed a way to weight the utility mission as more important than the fitness mission based on the goals of the installation, more appropriate ranking for funding prioritization would occur.

We recommend developing an internally consistent manner for installation commanders to rank and weight missions on their installation. One way to do this is with multi-criteria decision analysis (Kiker et al. 2005). This weighting should be included directly in the MDI score calculation and categorization of facilities (Commander, Navy Installations Command 2018). These weightings should also consider the needs of both SMEs, and high-level decision-makers within each service. Achieving this would require developing a way to survey and generate consensus among SME within each DoD service.

To manage the mission partitioning problem, the interdependency assignment problem, and the replaceability problem, MDI methods need to change. We develop a new network-based model for MDI in an attempt to overcome these issues.

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## CHAPTER 5:

### An Improved Network Model for MDI

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We build on our multilayer network model and critique of MDI to develop new methods for measuring mission dependency across facilities. Our new methods start by considering MDI via a network flow model. Specifically, we develop a flow network model for a single mission layer and assess how disruptions to facility functions impact MDI scores.

#### **5.1 Mission Network Flow Model**

We choose to develop our improved model for MDI using network flow methods for several important reasons. First, as shown in our literature review in Chapter 2, network flow models have been extensively used for network vulnerability analysis for many infrastructure missions assessed by MDI. They also easily build upon our infrastructure multilayer network formalism presented in Section 3.2, by setting modeling restrictions for single-layer networks (Alderson et al. 2015) and interdependent networks (Enayaty Ahangar et al. 2020). Thus, we can relate the function of a flow network to an installation multilayer network for MDI calculation.

##### **5.1.1 A Diesel Fuel Marine (DFM) Mission Network**

We start with a sample flow network introduced by Alderson et al. (2015) and presented in Figure 5.1. For our purposes, this network model represents a DFM mission at the scale of a military installation. It is comprised of 16 facility function nodes. Nodes n08 and n10 represent source facility functions which supply diesel fuel to the rest of DFM mission. Source nodes are assumed to have a supply of 10 units of fuel (i.e., the commodity) such that neither source node has enough commodity to support the entire network. Thus, it is important that those source nodes remain functional. The rest of the nodes are distribution and demand nodes. All nodes are connected by edges representing pipes that can support fuel flow in either direction. Nodes n03, n04, and n16 are linked to the network with parallel, redundant pipes to ensure reliable delivery of fuel even after a network disruption of any single pipe. In other words, there would need to be two simultaneous pipe breaks to sever the linkage. The sample flow network assumes 1 cost unit per item of flow across any arc.

The penalty to cross a damaged arc and the penalty for not getting enough resources to an arc are both assumed to be 10 cost units. The overall objective is to minimize the cost to flow fuel over a pipeline connecting source facility functions to facility functions that either deliver and/or demand fuel, including any penalties for non-delivery. Mathematical details of the underlying optimization model are available in the Appendix.

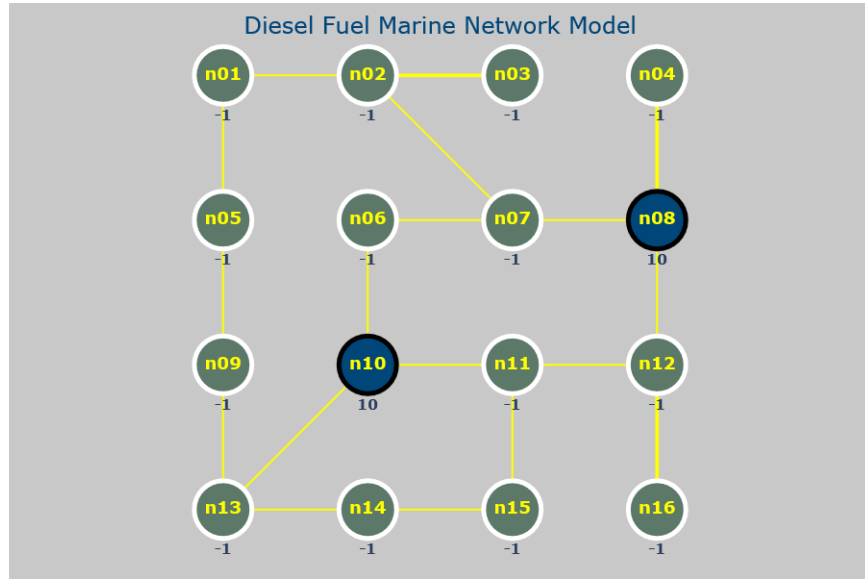


Figure 5.1. Diesel Fuel Marine Network Model. We adapt a fuel network model from Alderson et al. (2015) as the start to our mission network model. Below each node is the supply of fuel currently stored at the facility ( $d_n > 0$ ) or the demand the node requires to continue functioning ( $d_n < 0$ ). The DFM network has two source facility functions (black outlines) and 14 distribution and demand facility functions (white outlines). Blue color indicates the node is functioning properly and does not have unmet demand, whereas nodes that are colored green are in demand of fuel and/or are interrupted. All arcs (yellow) represent pipes and are modeled as bidirectional edges until our mission network flow problem is solved.

Figure 5.1 was recreated using the Plotly library (Plotly Technologies Inc. 2015) in the Python Programming Language (Van Rossum and Drake Jr 1995). Source nodes n08 and n10 are denoted with an outer black ring while the other nodes have a white ring. Additionally, nodes that have a supply of commodity greater than or equal to zero will be blue on the

interior. This would indicate that the node has the resources necessary to perform its function. Nodes with green centers have supplies less than zero and are considered interrupted, thus and not able to perform its function. The supply levels for each node are annotated below each node.

This network flow problem has been well-studied in the literature (Alderson et al. 2015; Ruether 2015; Barrow III 2019; Flinn 2020; Kuc 2020), and our implementation uses the same problem data and assumptions as previous studies. Building on the literature, we provide a model description using terminology developed for installation multilayer networks to explain how this problem formulation relates to MDI.

All facility function nodes are able to reroute and deliver fuel from source facilities to other facilities, similar to pumping stations and control facilities in a pipeline. As a result, each facility function node can be interdependent on each adjacent facility depending on commodity flow direction. Given sources, demands, and possible flow paths over edges, solving the network flow problem minimizes the cost to move commodities from sources to demands and determines flow direction. The resulting minimum cost solution determines the directionality of network interdependencies.

We solve the optimization problem detailed in the Appendix to determine the minimum cost flow of fuel over this DFM mission. We use the Pyomo optimization library (Hart et al. 2011) to represent the mathematics in a laptop computer and use the CPLEX solver (IBM 2017) to obtain the solution, which represents a steady state snapshot of fuel flows and network interdependencies. Figure 5.2 presents the resulting solution in terms of the quantity of commodity and direction of flow across the arcs of the network given the minimum cost objective value and no network disruptions.

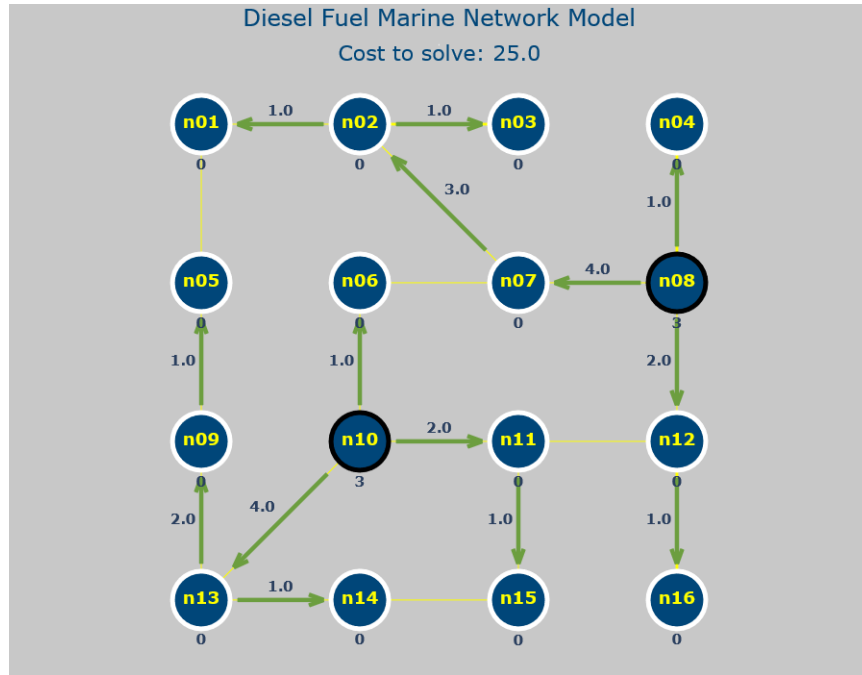


Figure 5.2. Diesel Fuel Marine Network with Flows. Green arcs show the flow of fuel over the DFM network to achieve the minimum cost for a network operator using our mission network flow problem. The quantity of fuel moved across each arc is shown beside each arc. All the nodes are now blue indicating that every node received enough fuel to function properly. The cost to the operator to solve the system is 25 units.

### 5.1.2 Realistic Mission Network Model

To use our network flow problem for mission dependency analysis, we need to define a mission network model. Considering our realistic DFM network, we apply MDI scoring methods presented in Chapter 1 and several additional model assumptions.

#### Model Assumptions for MDI

We make several assumptions about the MDI survey and calculation process that are intended to overcome flaws identified in Chapter 3.

First, we assume that all interdependencies within a mission are known. Our network flow problem is only for a single network layer and models interdependencies among

facility functions as edges and arcs. The MDI survey process does not consider these interdependencies within a mission layer in normal calculation. We assume that the mission owner or SME who answer questions for an MDI survey knows these interdependencies prior to analysis. This assumption is reasonable for the DFM mission and similar missions as SMEs would know the connectivity and operation of their facility functions and the direction and use of their commodity flows. This assumption overcomes aspects of the Mission Partitioning Problem by including all arcs within a mission layer in analysis.

We also assume that *possible* interdependencies within a mission are known. Possible interdependencies are modeled in our network flow problem as edges instead of directed arcs. This is done to identify flows and interdependencies as an output from identifying an optimal flow solution. This assumes that the location facility functions would relocate to or be replaced from are predefined given a disruption to the mission network. This assumption is also reasonable as this knowledge is known by SMEs, especially those involved in continuity of operations planning. This assumption overcomes aspects of the Interdependency Assignment Problem by assuming direct assignment, but allowing for multiple possible assignments prior to model solve.

We assume that  $MD_b^{avg}$  scores for facility functions are assigned after a network flow problem is solved. Accordingly, we assume all  $MD_b$  scores for arcs are assigned prior to knowing the facility that is providing the interdependent function.  $MD_b$  scores are the output of answering MDI Survey Questions 3 and 4. Normally this is done for the facility already providing the required function. However, we assume that Survey Questions 3 and 4 can be answered for the function, rather than the facility. For example, a SME can determine how interruptable and replaceable pumping and re-routing of fuel flows is within the DFM without knowing where the fuel is coming from. We assume SMEs are capable to answer MDI survey questions in this way. The assumption overcomes aspects of the Relocatability Problem by allowing for functional relocation via network edges.

### **MDI Scores for the Diesel Fuel Marine Mission**

We develop notional MDI scores for our sample DFM mission network. Although our DFM mission network is a recreation of the network developed in (Alderson et al. 2015), this network has never had  $MD_w$ ,  $MD_b$ , and  $N$  values assigned to it. Following our network flow assumptions, prior to solving our flow problem, we assign  $MD_w$  only to nodes and  $MD_b$

to possible arcs. We generate these scores by creating notional responses to MDI survey questions.

Table 5.1 presents hypothetical MDI survey responses for each node in the DFM mission. From these responses that the mission network flow model can evaluate each node's  $MD_w$ ,  $MD_b$ , and  $N$  values from Equation 1.2. The attribution of  $MD_b$  and  $N$  values are directly associated with how the sample flow network moves material through the network. This provides the basis for how the mission network flow model interprets interdependencies.

Table 5.1. Example MDI Survey Responses for Diesel Fuel Marine Mission Network.

| node | Q1 | Q2 | Q3 | Q4 |
|------|----|----|----|----|
| n01  | P  | P  | P  | P  |
| n02  | P  | D  | P  | D  |
| n03  | N  | I  | B  | X  |
| n04  | N  | I  | N  | I  |
| n05  | S  | P  | P  | P  |
| n06  | S  | D  | S  | X  |
| n07  | S  | X  | S  | D  |
| n08  | S  | D  | P  | D  |
| n09  | S  | D  | P  | D  |
| n10  | S  | D  | P  | D  |
| n11  | B  | P  | S  | D  |
| n12  | S  | X  | S  | X  |
| n13  | S  | X  | S  | D  |
| n14  | B  | X  | B  | X  |
| n15  | B  | X  | B  | X  |
| n16  | N  | I  | N  | I  |

**Note:** Q1 and Q3 Responses: N: None; B: Brief; S: Short; P: Prolonged. Q2 and Q4 Responses: I: Impossible, X: Extremely Difficult; D: Difficult; P: Possible. See Section 1.1.1 for more detail.

We use the values from Table 5.1 to compute the  $MD_w$  value for each node in the DFM network. We use the direction of fuel flow in the DFM network to identify interdependencies between nodes. This allows for attribution of interdependency and assignment of  $MD_b$  scores, which are calculated from responses in Table 5.1 interpreted through Figures 1.1 and 1.2. We count the number of dependencies each node has in terms of the number of arcs originating from a node and use it as that node's  $N$  value. The mission network flow model will then calculate  $MD_b^{avg}$  for each node as determined by the number of  $MD_b$  values attributed to that node. Thus, this assignment allows us to calculate  $N$  for each node as the out-degree of interdependency arcs.

Figure 5.3 illustrates the mapping between the original DFM pipeline network and a corresponding mission network annotated with MDI calculations. Figure 5.3A repeats the optimal minimum-cost flows from Figure 5.2 for ease of comparison. Figure 5.3B shows the resulting mission network, which requires some explanation.

Each node in Figure 5.3B is annotated with all three MDI variables used as input to calculate the overall MDI score for the entire system using Equation 1.2. The MDI scores for each facility function are shown centered on top of each node. On the top of Figure 5.3B the average MDI value and the sum of all MDI values also shown.

We observe that this calculation of MDI from a relatively simple fuel network is neither transparent or intuitive. It is not apparent how the survey responses in Table 5.1 affect the MDI scores or how the operational resilience of the original fuel network is captured, if at all, in MDI scores.

We explore this in additional detail by considering the way this mission network can be used to inform vulnerability assessment.

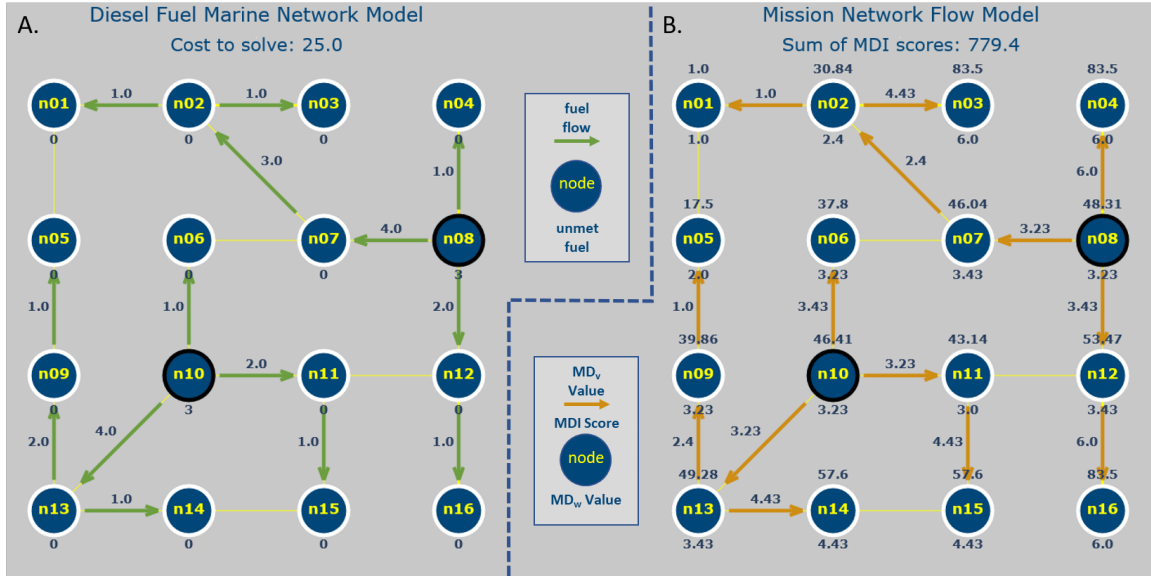


Figure 5.3. Mission Network Flow Model at Steady State. Panel B represents the mission network flow model at steady state.  $MD_w$  values are displayed below the nodes,  $MD_b$  values are center point on the orange arcs, and the node's MDI score is depicted on top of the node. The sum of all the MDI scores in the network is annotated at the top. Panel A represents the underlying Diesel Fuel Marine network that, once in steady state, provides the basis for how dependence is established in Panel B. Therefore, Panel B is conditional on the outcome of Panel A. It is important to note that only the location and direction of arcs is transferred from Panel A to Panel B. No other information is required to generate Panel B from Panel A. For instance, the flow volume shown over arcs in Panel A has no correlation to the  $MD_b$  values shown by arcs in Panel B.

## 5.2 Mission Vulnerability based on Network Function

With the network and synthetic MDI scores, we can calculate MDI for a single set of survey responses. Two key measures for a single network realization are the flow cost (via the objective value of the underlying optimization problem), representing the difficulty of completing the DFM mission, and the sum of the MDI scores across facilities, representing the amount of mission essential facilities in the mission. When disruptions lead to changes in flow direction and active interdependencies, we can then use these new results to calculate a new flow costs and a new MDI for each facility function. How these measures relate to

each other provides a glimpse at the relationship between relocatability and replaceability and MDI.

Accordingly, we can couple our mission network flow model with different vulnerability analysis methods to assess this cost-mission relationship. The literature on network vulnerability has many methods for guiding the analysis of many different failure scenarios. In particular, there are at least two ways to consider vulnerability of flow networks with the goal of maximizing the cost to operate the mission: worst-case and exhaustive enumeration. Worst-case vulnerability utilizes an additional game theoretic model to determine the single worst-case failure of edges or nodes that interdict network flows, maximizing the minimum cost objective value. Exhaustive enumeration studies every single combination of failures to determine each of their effects. Due to the relatively small size of our model, we use exhaustive enumeration to study the cost-mission relationship in the DFM mission.

### **5.2.1 Mission Vulnerability via Edge Interdictions**

We assess mission vulnerability via edge interdictions on the original DFM network. We start with one interdiction, that is to say that the simulated scenario involves the loss of flow over a single pipeline in the DFM mission. Figure 5.4B presents an example of a single edge interdiction for the worst-case failure of an edge from a network function perspective. Interdiction of edge (n10, n13) raises the flow cost of the objective value more than any other single edge interdiction. We interpret this as worst-case for relocatability and replacement of facility functions. However, it is unclear if this causes the greatest interruption to mission facility functions. We estimate interruption to facility functions via the summation of MDI scores for each active node in the mission network after interdiction. Thus, it is necessary to compare flow cost to the sum of MDI scores remaining in the mission.

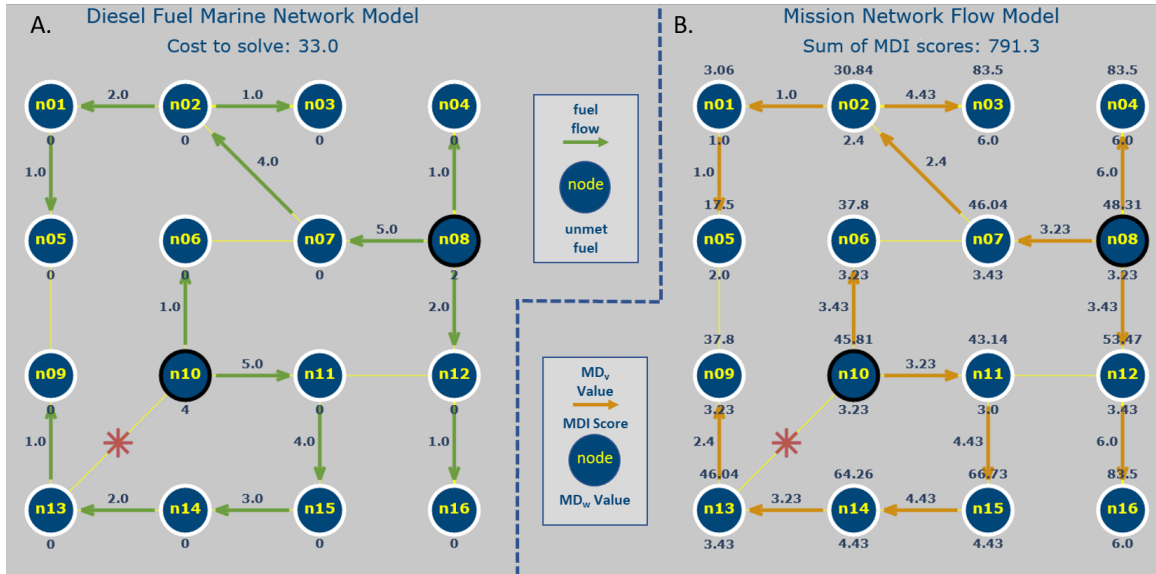


Figure 5.4. Worst-case One Edge Interdiction. The edge between n10 and n13 is the single worst-case failure of a pipe based on the literature (Alderson et al. 2015), as it raises the network flow cost the most as shown in Panel A. In Panel B, the mission network flow model is conditional on how flow was rerouted in Panel A. The interdiction of this edge may lead to the greatest disruption to cost in Panel A, it does not lead to the greatest disruption to Panel B. However, this network disruption may not lead to the greatest interruption to sum of MDI facility function in Panel B

We now consider an experiment to assess systematically the relationship between system operation (i.e., cost of rerouting fuel) and the associated MDI scores. We repeat the calculation explained in Figure 5.4 for *every possible break of a single pipe segment*. For each simulated pipe break, we compute the resulting operating cost (after fuel flow has been rerouted) and the resulting MDI calculation for the corresponding mission network.

The scatterplot in Figure 5.5 displays the results for this experiment. The vertical axis shows the overall system operating cost when flows have been rerouted after a pipe break (as in Figure 5.4A). The horizontal axis shows the aggregate MDI score across all nodes in the corresponding mission network (as in Figure 5.4B). In this figure, each point represents the combination of operating cost and MDI aggregate score for each possible single pipe break. The original network (no breaks) has a low cost and low MDI score, as indicated by the green marker. The worst-case single pipe break (from Figure 5.4) has the highest possible

operating cost and also the highest aggregate MDI score.

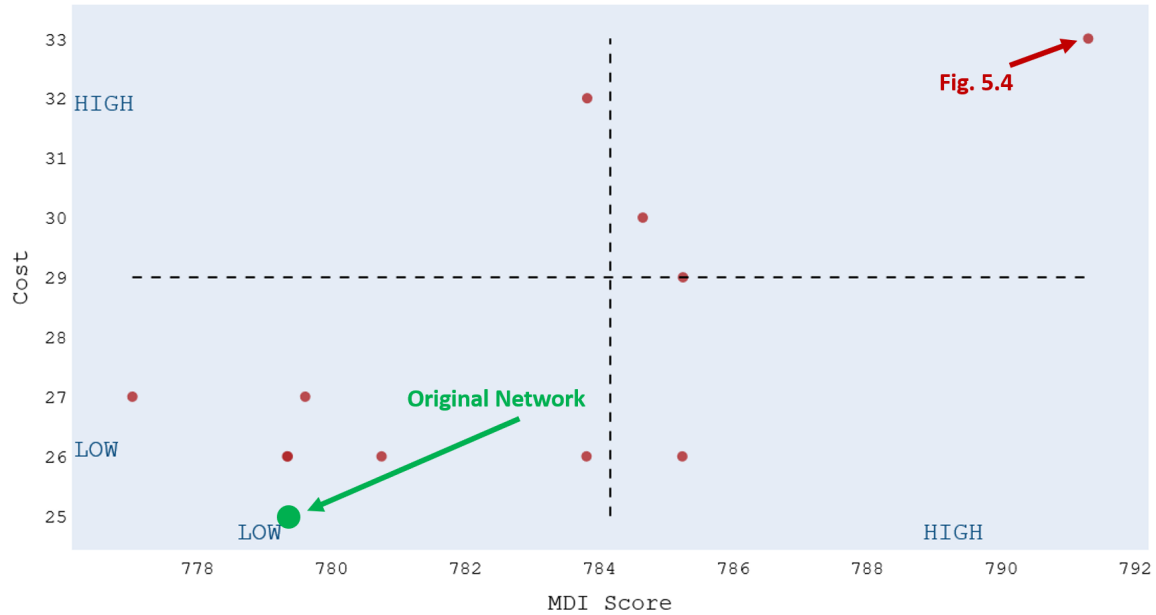


Figure 5.5. Comparison of Flow Cost vs. MDI for Single Edge Interdiction. Each point in this figure represents the operating cost from the underlying fuel network and the aggregate MDI score for facility functions in the corresponding DFM mission. The green marker in the bottom left is for the original DFM mission (no interdictions) and the red points are for all single edge interdictions. The point labeled Fig. 5.4 represents the worst-case single edge interdiction shown in Figure 5.4.

Figure 5.5 is subdivided into four quadrants for readability. On the MDI Score axis, network flow solutions in the HIGH region have more critical facility functions online. In general, we find these network states to be less interrupted. However, they also tend to have high volatility and greater risks to missions, especially if value is greater than our network flow solution without interdictions (green marker). In contrast, network flow solutions in the LOW MDI region represent situations where many facilities may be interrupted and/or are stable to further interruption.

Figure 5.5 helps to explain whether a high cost of functional relocation and replacement corresponds to a large interruption of facilities. In particular, we find many single pipe break situations to cost more and therefore require functional relocation and replacement,

but few single pipe break situations to result in significant drop in facility MDI scores. In fact, many single edge interdictions only raise the MDI scores for DFM facility functions, rather than reduce or interrupt them. This is emphasized with the worst-case interdiction result from Figure 5.4 labelled in Figure 5.5. Here, the worst-case situation for relocatability and replaceability leads to the greatest increase in overall MDI score.

The observed increase in MDI is the result of a change in flow that leads to a change in how  $MD_b$  values are attributed across the network. The interdiction of edge (n10, n13) leads to facility functions n09 and n13 MDI values dropping due flow redistribution. However, the MDI scores of facility functions n01, n14, and n15 increase. The overall decrease is smaller than overall increase, and thus we see that total MDI has increased. Overall, the system has become *more* critical from an MDI perspective, even though nothing has been interrupted.

Our analysis for a single edge interdiction suggests that having redundancy in a network can have an effect on the interpretation of MDI values. Specifically, including redundancies in initial MDI calculation can reduce facility function scores. When redundancies are removed (or interdicted), facilities may receive higher MDI scores by becoming more critical. This simple result has many implications for MDI survey and calculation. Namely, a facility that receives a high MDI score, may appear extremely vital, but may easily be routed around after disruption. And if MDI is used as a tool to used to allocate limited resources, then a facility with a high MDI score that has redundancy would receive funding when it may not as critical as it appears.

Figure 5.6A presents the worst-case interdiction of two edges based on flow cost from Alderson et al. (2015). In this case, the corresponding mission network in Figure 5.6B reveals many facility functions are removed from the network, suggesting a large impact on network MDI score. Although this is the worst interdiction from an operating cost perspective, it is unclear if this is the worst for mission interruption without measuring the sum of MDI scores for the remaining facilities. Moreover, we need to compare this situation to all possible cases involving two edge interdictions.



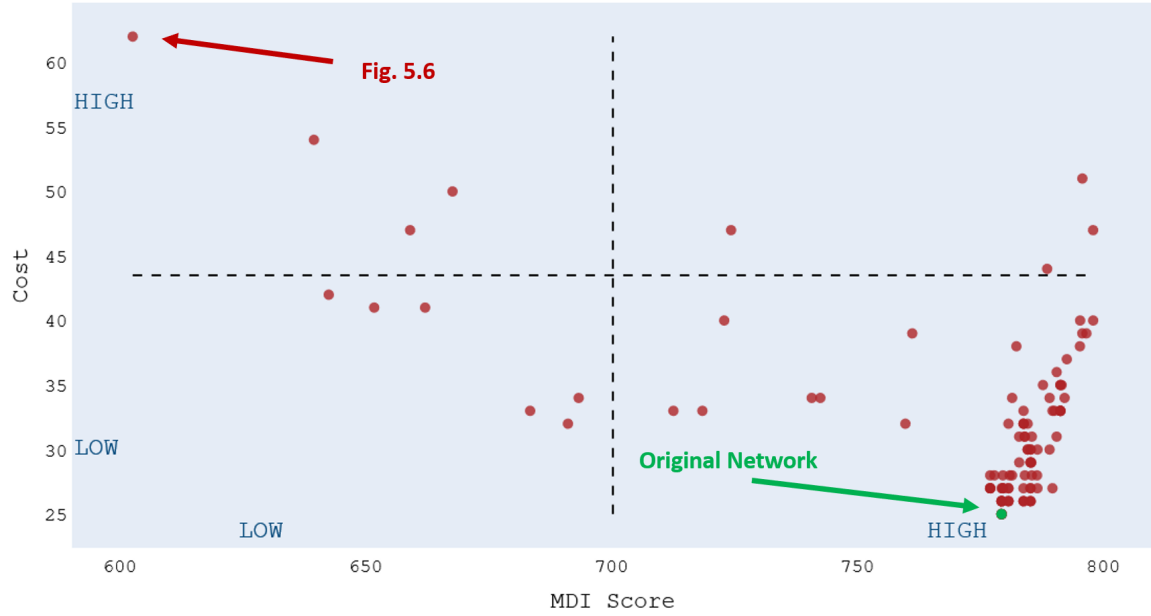


Figure 5.7. Comparison of Flow Cost vs. MDI for Double Edge Interdiction. Each point in this figure represents a network flow solution and MDI scores for facility functions in the DFM mission. The green point in the bottom right is for the DFM mission without interdictions and the red points are for all double edge interdictions. Additionally, we add a red arrow showing the point associated with Figure 5.6

Figure 5.7 shows that when there are two simultaneous pipe breaks in the DFM system, we find many situations where the MDI score for the network increases. Most of the scenarios that lead to higher MDI scores are due to breaks that do not disconnect facility functions from the larger network. In contrast, edge interdictions that disconnect facility functions lead to situations with increased replacement and relocation costs alongside facility interruption. In many cases, facility interruptions have a lower relocation and replaceability cost than cases without interruptions. Since MDI calculation is heavily weighted towards  $MD_w$ , it is worse from a mission perspective to disconnect facilities from the network rather than force significant rerouting of fuel.

## 5.2.2 Mission Vulnerability via Node Interdictions

We shift focus to address how facility function interruptions (i.e., the loss of nodes) in our DFM system changes the mission network. We begin by studying how the loss of

a single node can impact flow costs and MDI scores. Figure 5.8A presents an example of a single node interdiction, along with the resulting rerouted flows. Figure 5.8B shows the corresponding changes to the mission network. Because node interruption will always remove at least one facility function from the mission network, one might assume the summed MDI scores always decrease. However, this is not the case. As shown in Figure 5.8, removal of a facility function with low MDI score can lead enough redistribution of  $MD_b$  values that the total score for the network increases.

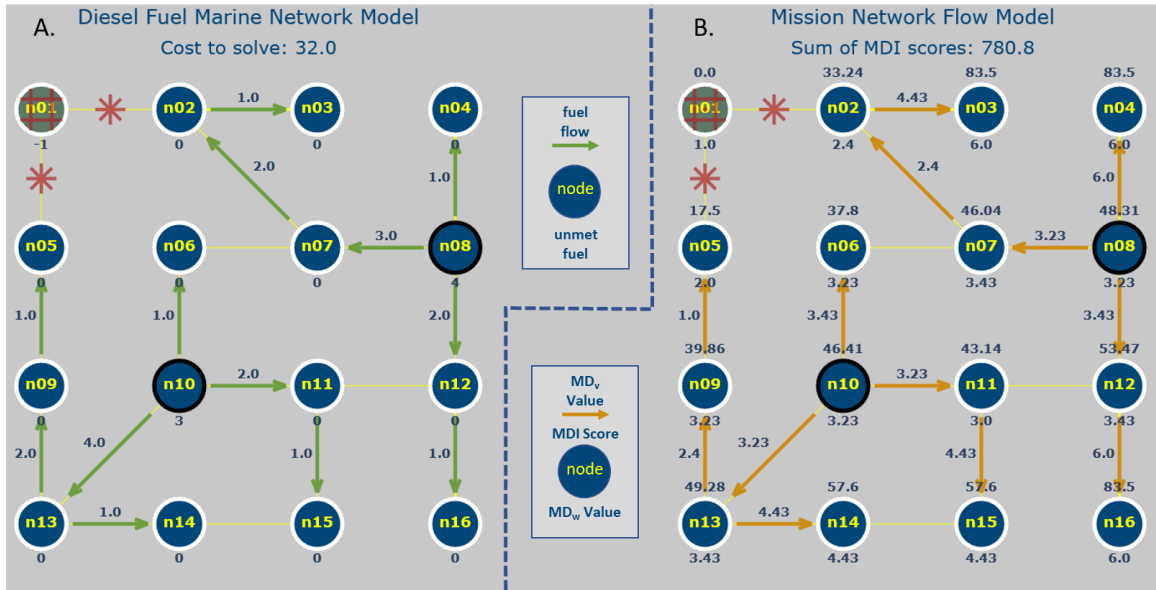


Figure 5.8. Example Single Node Interdiction. Panel A: the loss of node n01 requires re-routing of flow and a change in flow cost. Panel B: The resulting mission network receives higher a summed MDI score.

We consider all possible cases involving the loss of a single node to assess the possible increase or decrease in MDI versus flow cost. Figure 5.9 shows the results for each resulting case, where the scenario from Figure 5.9 is explicitly labelled. We find situations where a facility interruption leads to increased MDI scores are rare, as this is the only scenario that causes this effect.

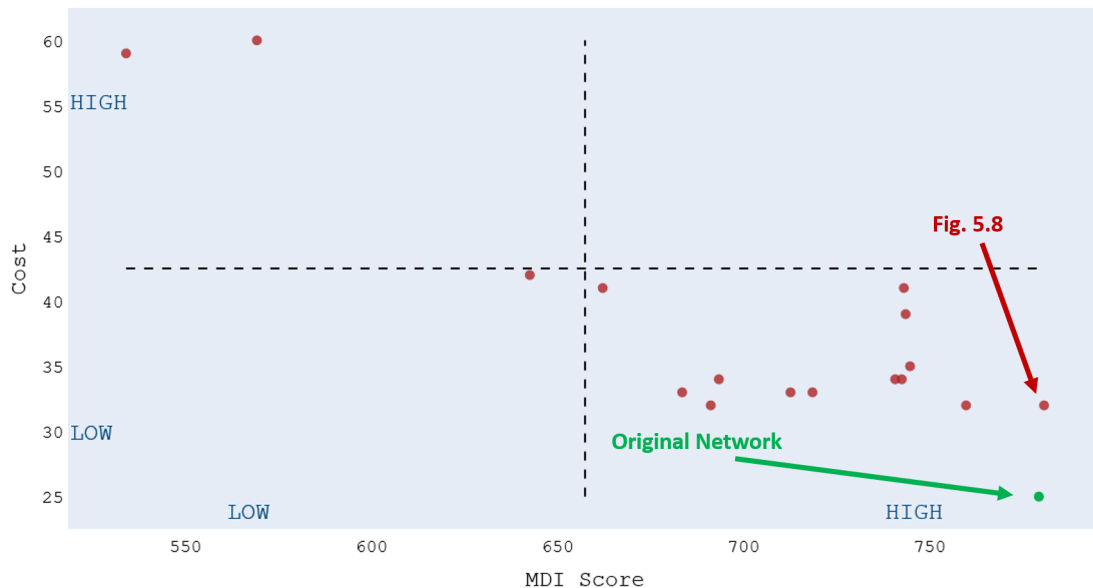


Figure 5.9. Comparison of Flow Cost vs. MDI for Single Node Interdiction. Each point in this figure represents a network flow solution and MDI scores for facility functions in the DFM mission. The green point in the bottom right is for the DFM mission without interdictions and the red points are for all single node interdictions. Lastly, we add a red arrow showing the point associated with Figure 5.8.

Figure 5.10 shows the worst-case interdiction of two nodes (source facility functions n08 and n10) which results in the greatest impact on mission and flow cost. With the loss of two nodes, it is possible to completely disrupt the mission by removing both source facility functions. From an mission assurance perspective, these source facility functions should receive much higher MDI scores and/or prioritization based on this result. Notably, this interdiction of the source facility function produces the highest flow cost, but it does not produce the lowest MDI.

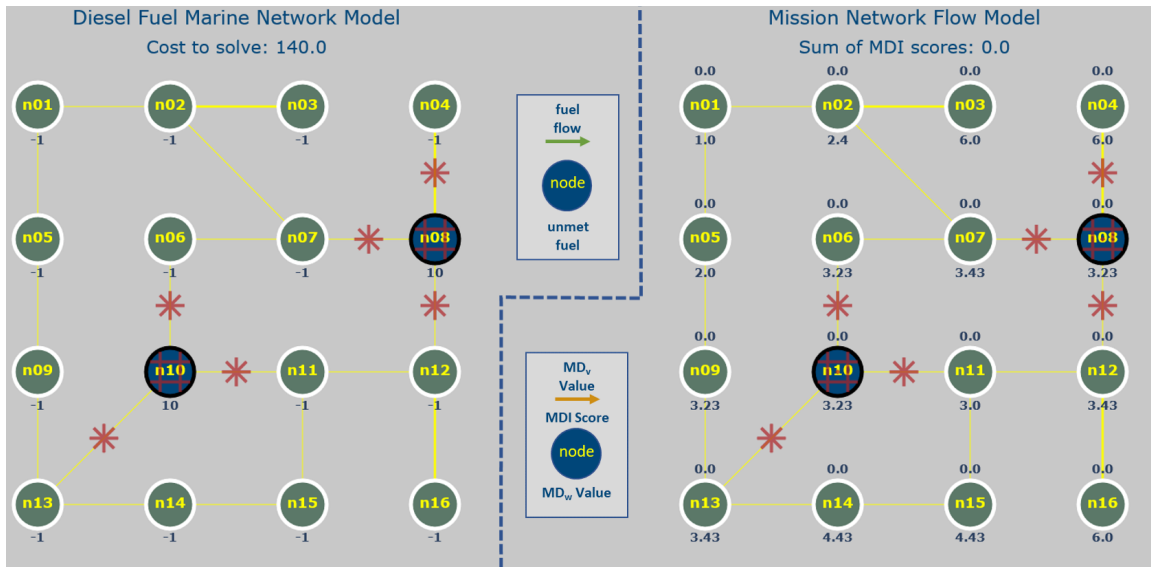


Figure 5.10. Example Two Consecutive Node Interdictions. In this specific scenario, source nodes n08 and n10 are selected for interdiction in Panel A. This action translates over to Panel B where every node is interrupted due to either direct interdiction or lack of fuel required to function. This dual attack maximizes the cost in Panel A and reduces MDI scores to zero for every node in Panel B.

We also all possible cases involving two node interdictions. Figure 5.11 presents the summed MDI value versus flow cost. The worst-case loss from Figure 5.10 is explicitly labelled. We also see a correlation between increase in cost and decrease in total MDI score. This implies that loss of other facility functions when combined with an interdiction of a source facility function have roughly the same impact of overall mission.

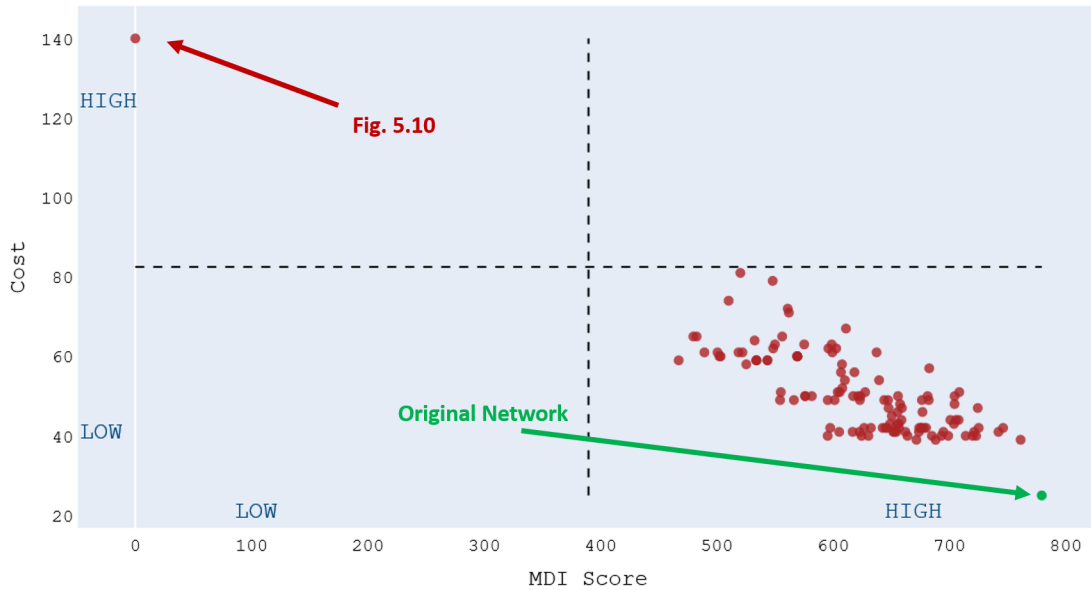


Figure 5.11. Comparison of Flow Cost vs. MDI for Two Consecutive Node Interdictions. Each point in this figure represents a network flow solution and MDI scores for facility functions in the DFM mission. The green point in the bottom right is for the DFM mission without interdictions and the red points are for all double node interdictions. A red arrow points to the worst-case interdiction where both source facility functions n08 and n10 are disrupted as discussed in Figure 5.10 .

### 5.2.3 Implications for MDI

Overall, our analysis of mission vulnerability based on network function provides useful insights for understanding and improving MDI. First, while MDI tries to gauge network redundancy through SME elicitation on relocatability and replaceability, in practice this effort is subjective and unable to measure these factors quantitatively. Evaluating redundancy through the network model using flow cost and an objective function provides quantitative measures that can lend itself to trend analysis. Furthermore, the mission network flow model can capture the effects of interdicting multiple edges and nodes, whereas MDI survey focuses entirely on individual arcs and facility functions.

We find that MDI scores for a mission network can both increase and decrease after interdiction. Disruption of edges and nodes lead to functional relocation and replacement

that may increase the MDI scores of remaining nodes. This can lead to facilities receiving higher MDI scores than when the system experiences no interdictions. This result means that the maximum (or minimum) possible MDI score for a facility is unknown given initial network conditions. We can only find this via vulnerability analysis with network disruptions and flow redistribution. This result strengthens our argument that including edges representing possible flows in mission networks provides a useful basis for understanding the mission dependency of a single facility. It further emphasizes the need for vulnerability analysis to understand the importance of relocation and replacement of facility function.

Managing flow redistribution after an interdiction also suggests new ways to protect missions from facility interruptions. In general, source facility functions are vulnerable nodes that need to be protected. However, loss of distribution and demand functions can have a large impact on overall mission depending on their location within the network. In both cases, some facility functions and interdependencies appear to be more important than others for mission assurance. Hardening these edges and nodes in the network can protect missions. This is a similar result to that of Alderson et al. (2015) for optimal defense given network interdiction. However, the objective in this work would be to minimize both the impact on flow cost *and* mission, which highlights the need to defend facility functions as much as the interdependencies between them.

Our model also emphasizes protection measures that alter the mission network itself. In some situations, investment in an entirely new facility (e.g., adding a new node to the network) could provide redundancy in the system that is more advantageous to flow cost and mission than fortifying existing nodes facilities. This result also emphasizes the results of Alderson et al. (2015) for rerouting flows, but with the addition of facility functions in addition to flow paths.

MDI scores should also reflect the importance of facility functions on the network function. MDI calculation is heavily weighted towards  $MD_w$ , which allows many facility functions to have high MDI scores even if they have no impact on network function. In contrast, facilities with low  $MD_w$  may have a large impact on network function if disrupted, such as source facility functions n08 and n10. We would expect in future advances in MDI that their scores would be the largest overall and/or their scores to be much larger than some other facilities in the same mission.

One way to address this issue is to weight  $MD_w$  based on the facility's impact on mission after disruption. This would heavily weight source facility functions to receive high MDI scores even though they have few direct connections. This would also weight distribution and demand functions relative to each other based on their impacts on mission.

Another way to address this may be to increase the importance of  $MD_b$  to final MDI score and to relate the MDI score of a facility to all of its interdependent facility functions. Our model mimics MDI calculation by only attributing  $MD_b$  from the out-degree of the node itself. However, in the DFM, source facility functions are providing fuel to all other nodes, making these distribution and demand facility functions interdependent on their source. Here, it may make sense to use a blanket assignment procedure to emphasize the fact that the entire network is disrupted if the source is lost.

### **5.3 Mission Vulnerability based on MDI Scoring**

We also investigate how different synthetic MDI scores affect mission vulnerability based on facility function attacks. As described in Chapter 3, there are multiple competing ways that a SME can answer MDI survey questions for the same DFM mission. This means that no single set of MDI responses we create for our mission model (even if set by a real installation SME) will inform all relevant operational perspectives. Moreover, our DFM mission model does not consider other missions at the installation or military priorities. We explore this in more detail.

#### **5.3.1 Simulating MDI Scoring**

We consider an experiment in which we generate many synthetic MDI scores for our DFM mission model and assess the MDI scores of the mission. Specifically, we repeat the survey of MDI Survey Questions for the DFM mission network as in Table 5.1, but we select responses at random (uniformly from the possible choices) for each node. That is, all four responses to Survey Questions 1-4 have a 0.25 likelihood of being chosen. For each simulated survey response, we then calculate the associated MDI score for each node.

Figure 5.12 show the frequency with which each node in the DFM mission network receives the highest MDI score. Nodes with higher connectivity tend to have higher MDI scores, but any single node can receive the highest score in this subjective process.

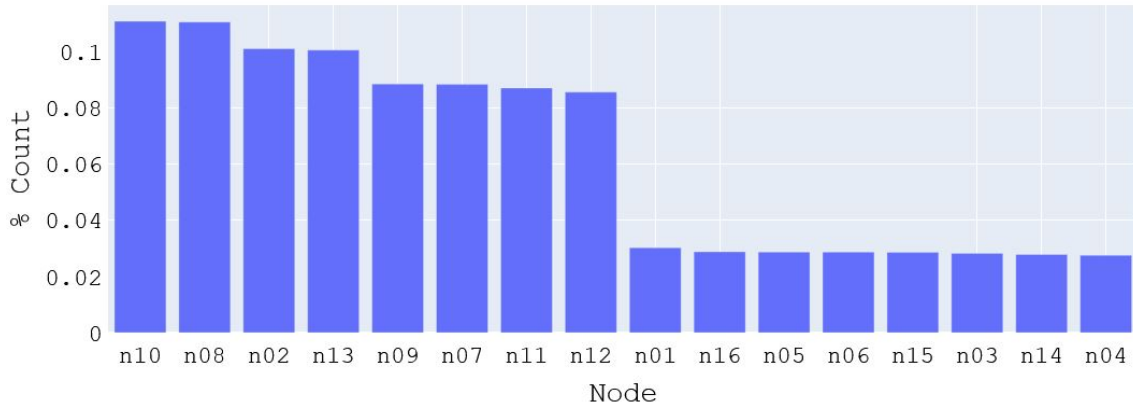


Figure 5.12. Likelihood each Facility Function Receives the Highest MDI Score. While MDI scores are assigned using uniform distributions, some nodes are still more likely to receive the highest scores. Specifically nodes with a larger number of edges and a high out-degree and high  $MD_b$  get higher scores on average. This occurs even though  $MD_w$  accounts for 84% of the MDI score.

### 5.3.2 Calculating MDI Impacts on Mission Vulnerability

Consider a situation where an adversary has access to the MDI values of all nodes and uses it as a basis for selecting nodes to target in an attack. We assume the adversary will interdict facility functions based on MDI values, interdicting the node with the highest MDI value. In the event that two or more facilities share the highest MDI value, we assume the attacker will choose one facility function from that group.

If we consider this hypothetical attack process for each simulated MDI survey assessment from in Figure 5.12, then MDI scores will now vary facility to facility for every trial. To adequately compare MDI scores from one model to another, we normalize scores using Equation 5.1.

$$x_{\text{Normalized}} = \frac{x_{\text{avg}} - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}} \quad (5.1)$$

$x_{\text{max}}$  represents the starting average MDI score prior to any attack, steady state. Any node who is attacked or does not receive enough commodity such that the commodity at the node

is less than zero, will have a MDI score is zero as it is not contributing to any mission. Hence,  $X_{min}$  represents the system when completely compromised, and thus will be zero. The calculated  $X_{avg}$  is the average MDI score after an attack and will be interpreted using two different methods.

$$X_{\text{Static Average}} = \frac{\sum_{i=1}^n MDI_i}{\text{Number of nodes available prior to attack}} \quad (5.2)$$

Equation 5.2 evaluates the average MDI of all nodes divided by the number of nodes prior to any attack and will be called the static average. We use this measures to determine the vulnerability of a mission network when high MDI facility functions are targeted. Collectively, this allows us to assess the vulnerability of the DFM mission to attacks based on network and facility function.

### 5.3.3 Analysis of MDI Scores on Mission Vulnerability

We now investigate how different synthetic MDI scores affect mission vulnerability. We use our Monte Carlo simulation methods described in Section 5.3.1 to generate 40,000 sets of MDI scores for the DFM mission network. Given each set of MDI scores, we recalculate the impacts on normalized network MDI.

We then simulate the impact of an attack on the highest MDI score. We then adjust the flow in the underlying DFM network and recalculate MDI scores.

We consider the case where the attacker can choose 1, 2, or 3 targets. In the case of more than one target, we assume the attacker has access to the adjusted MDI scores after each attack. Our goal is to investigate the relationship between MDI scores and network function on expected MDI for all facilities.

Figure 5.13 presents histograms for the percent change in normalized MDI using Equation 5.2 for three consecutive interdictions interdiction budget = 1, 2, and 3 for all 40,000 simulated sets of scores. Results show bimodality of the distribution of how much average MDI scores will drop after the first interdiction, centered around MDI = 68% and MDI = 90%. This bimodality holds for the second interdiction, but the higher peak is reduced to MDI = 80%. A small percent of simulations with two interdictions have no

average MDI score. These simulations are when source nodes n08 and n10 are removed from the network. After three interdictions we see the bimodality disappear, the tail of the distribution stretching the entire range of scores between 0 and 80%, and a significant peak of simulations with MDI = 0.

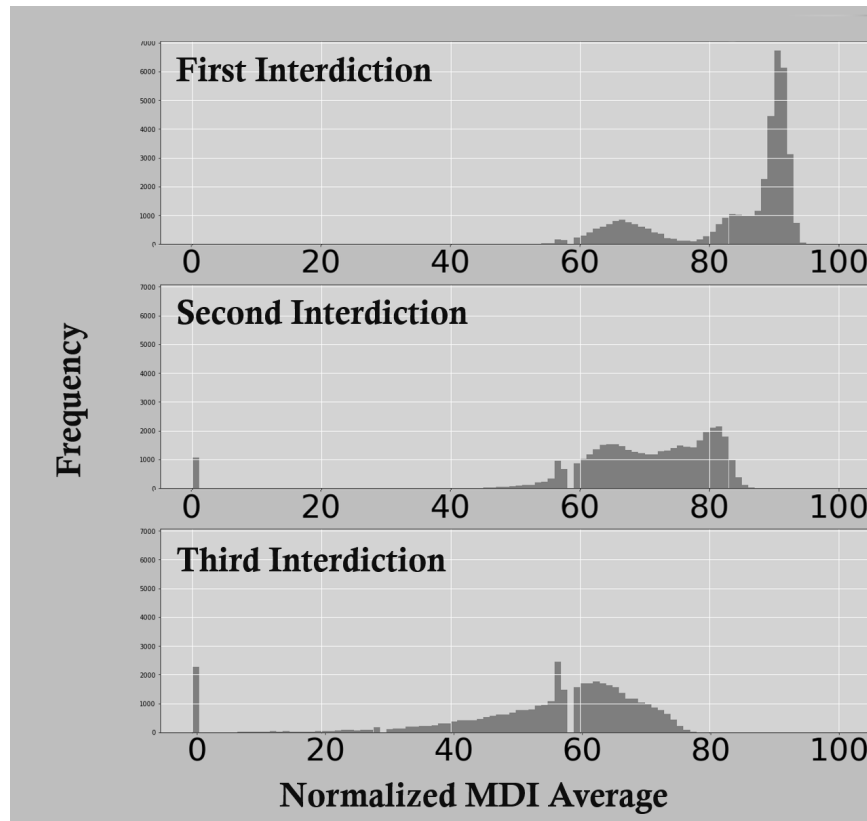


Figure 5.13. Histogram of Normalized MDI Static Average for Three Interdictions. We show the change of average MDI as the DFM network experiences interdiction of the highest MDI node. After the first interdiction, the average MDI score is bimodal with peaks at MDI = 90% and 68% of its original score, meaning the network MDI dropped by 10% and 32%, respectively. After the second interdiction, the average MDI remains bimodal centered with peaks at 82% and 65%, with some scenarios at 0%. At the third interdiction we see a more normal type distribution centered around 62%.

Results show that the choice of MDI values across simulations are less important than network function and structure when determining the impact of node interdiction. If choice of MDI answers had a strong effect on mission vulnerability, we would expect the uniform

sample distributions for Survey Questions 1-4 would produce uniform distribution for change in MDI after interdiction. Instead, we find clear peaks and lower variance for each distribution in Figure 5.13, indicating that the structure and function of the network is a strong indicator of resulting MDI score after attack. We determine that there are three factors involved: 1) source nodes, 2) level of interdependency, 3) difference in value between the highest MDI score and the average MDI score for a single simulation.

The existence of source facility functions impact final distributions and average scores. Figure 5.13 shows that the second interdiction results in the entire mission interrupted. The function source nodes serve to the mission skews their impact on overall MDI. For example, after the third interdiction, 5.6% of the scenarios are completely interrupted. If these nodes were randomly selected we would expect that scenario to occur 2.5% of the time.

When randomizing the values, we find intradependency has a lower impact on vulnerability than interdependency and node degree. Figure 5.12 are three histograms showing which nodes were chosen for interdiction based on highest MDI score. In all three cases the source nodes, n08 and n10 were in the top three positions. Given random assignment of MDI,  $MD_w$  scores cannot explain this. On average, all nodes receive the same  $MD_w$  values, so this cannot explain this phenomena. Instead, this is because they are the only two nodes with three edges are n08 and n10, such that they can have higher  $MD_b$  and  $N$  values than other facility functions.

In contrast, in scenarios where specific facilities receive very high MDI scores, they obfuscate the vulnerability to loss of source functions. In general, large loss in average MDI occurs when source functions or nodes near source functions are interdicted. However, in situations where enough facilities far from source nodes (near the corners of the network) receive high MDI scores, the mission from protected from nodal interdiction. As a result, protecting the network from direct attacks that interdict source facility functions is possible by separating them from other critical functions. In other words, co-locating mission essential functions (that would normally receive high MDI scores) and source functions (that are important for network function) in the same facilities is vulnerable to few interdictions.

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## CHAPTER 6:

### Conclusions

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MDI is a key performance index used across DoD services and the federal government for guiding infrastructure operations and planning decisions. MDI is widely adopted and its use is generally presented as a straightforward process to calculate and categorize mission-essential infrastructure by considering IRR factors, answering survey questions, and inputting results into simple equations. This ranking is meant to assist decision makers prioritize nearly \$20 B of annual government funds. However, several criticisms of its efficacy exist in the literature that suggest it has technical and practical issues in application. Still, these criticisms have never developed a mathematical basis for their critique or provide examples that demonstrate flaws in MDI.

The purpose of this thesis is to assess the flaws inherent in MDI with technical rigor and identify ways to improve MDI calculation for infrastructure decisions. We do this by developing a mathematical formalism that captures how MDI currently works, identify flaws in this process, present a model that overcomes these flaws, and studying the vulnerability of missions using our model.

### 6.1 Summary

We develop a mathematical formalism for assessing the MDI of an installation based on multilayer networks. We provide more effective definitions of key terms for MDI calculation, including mission, facility, function, dependency, intradependency, interdependency, and installation. We use these definitions to relate their meaning and purpose to existing multilayer network models based on node-colored network or interdependent networks-of-networks. Our formal definition and model provide a basis for identifying the flaws in MDI and developing simple examples demonstrating the flaws.

We identify flaws in MDI interpretation and calculation. Issues with interpretation and use stem from conflicting perspectives on long-term infrastructure funding decisions with perspectives on near-term consequences of infrastructure failure. The result is some mission essential facilities, like a water distribution pump station, can receive significantly lower

scores than other facilities that might be less critical to mission, like a gymnasium. Issues with interpretation and use can be overcome if the SMEs who conduct surveys for these assessments and decision-makers agree on how MDI should be used to guide decisions.

We also identify three mathematical issues with MDI that lead to erroneous results even if consensus is decided among SMEs and decision-makers. We refer to these issues as the mission partitioning problem, the interdependency assignment problem, and replaceability problem.

The mission partitioning problem relates to the way facilities are sub-divided or partitioned into missions. Here, the size of each mission partition artificially lowers or raises MDI scores for facilities. The key reason this problem exists is because dependencies among facilities within a single mission are ignored in MDI calculation. To address this issue, we recommend acknowledging and evaluating interdependency at the intra-mission level and argue this will extinguish the partition problem altogether.

The interdependency assignment problem is the result of the way both blanket assignment and direct assignment of missions are being used within the DoD. We show that blanket assignment leads to higher overall MDI scores, but in doing so actual dependencies among facilities are lost. This also occurs when multiple missions are within the same building and dependencies are blanket assigned to the facilities rather than the missions themselves. In both cases, blanket assignment seems to contradict the fundamental goal of MDI and leads to issues when answering Survey Questions 1-4. For this reason, we recommend using direct assignment when calculating MDI. Direct assignment shows actual dependency and avoids artificially raising scores for related facilities and missions. However, this approach only works given our solution to the mission partitioning problem — direct assignment works best when facility interactions are considered within missions. Therefore, one cannot solve the interdependency assignment problem and the mission partitioning problem separately. Solutions to one affect the other.

However, the final problem we identify — the replaceability problem — suggests that neither of these solutions will be sufficient. Even with all dependencies accounted for and direct assignment, MDI fails to capture the dynamics of replaceability as network redundancy or the effect of changes in O-mission facility functions and needs. Simply put, MDI is a static network measure that is trying to assess dynamic network properties (e.g., reconfiguration,

flows, etc.). Instead, possible, but unrealized network replacements should be modeled and considered in MDI calculation. This is especially important given disruptions to the network and the need to replace facility functions.

One way to consider dynamics is to treat the networks generated during MDI calculation as flow networks. Flow networks are one way to consider dynamics, where the dependencies among facilities would be measured as the flow over arcs. This can be determined by an optimization model or network flow algorithm depending on the installation or mission. Whereas structural networks only measure facility-facility connectivity, flow networks also enable the measurement of mission functional state. For example, given disruptions to a flow network representing facilities and missions, an analyst can measure the difficulty for replacing a facility function via the cost to meet new flow demands. Moreover, the possible flows over the mission network can be represented explicitly in the model, yet need not influence MDI calculation when not in use.

We develop a mission network flow model to understand how this new perspective relates MDI and mission vulnerability. We find that including redundancies in MDI calculations can reduce facility function scores. When redundancies are not employed facilities may appear extremely vital to a mission even though they are easily routed around. Additionally, MDI scores should also reflect the importance of the facility function to the network function. MDI calculation is heavily weighted towards  $MD_w$ , which allows many facility functions to have high MDI scores even if they have no impact on network function.

As a form of sensitivity analysis, we also assess the effect of assigning synthetic MDI scores on mission vulnerability. We find that when MDI values are randomized,  $MD_w$  scores become less important. Instead,  $MD_b$  and  $N$ , now take the spotlight. Finally, we saw that having maximum MDI values either very close or very far away from the average MDI score obfuscated attacks on the source nodes.

In summary, MDI is not a straightforward process that can objectively or accurately determine facility importance based on consequences to mission performance, and thus use of MDI to support funding decisions is not justified. We find that the process is still based on advocacy rather than data-driven analysis.

## 6.2 Limitations and Future Work

There are several limitations of our current work. While our analysis provides a new view of MDI and a model that can overcome some of its flaws, we have yet to determine a better way to measure MDI scores themselves. Moreover, our mission network flow model is simplified and possibly unrealistic. The results of our model are only helpful in real systems if flow cost relates to actual cost in dollars. However, our measures of MDI follow the current evaluation process, so our interpretation of interruptability may be accurate to similar missions.

Another limitation with this work is the focus on network flow models. There are other ways to study dynamics and overcome MDI flaws. For example, simulation models could evaluate MDI to include discrete events that determine how facility relocation and replacement occurs. This type of model could also bridge MDI critiques to provide a better method for determine relative importance of facilities. Additionally, our example focuses on a DFM mission that lends itself nicely to flow networks. Other model types may provide deeper insight into missions that are not physically linked by wire, pipes, etc.

A key issue with our analysis is we only study a single mission layer, when MDI is meant to prioritize decisions across many missions at the same installation. Before considering the efficacy of using network flow models, we should assess multilayer network flows to recognize how to make sense of MDI scores across mission layers. We identify several studies in Chapter 2 that consider multilayer and interdependent networks that provide a basis for this analysis. Future work should implement MDI in one of these models and analyze the effect of multilayer interdependencies on MDI scores.

Although our analysis provides understanding in IRR in the DFM mission, we only generate MDI scores synthetically for a single mission type. Our synthetic MDI scores may not represent how real SMEs would rank the importance of facilities. Moreover, not all missions at military installations have similar flows and function to the DFM mission. Future work should consider a broader set of mission types with real data from SME elicitation to validate our conclusions.

Finally, our network flow study of MDI currently doesn't consider related measures like FCI and/or the final decision-making context in which MDI is used. While we provide technical rigor to MDI calculation and analysis, final conclusions on which model to use should be

done with respect to their impact on real decisions in this broader context.

Based on the limitations addressed, future studies should include a direct case study. This study could continue to build on our established model formalisms to include multilayers and other related measures. Lastly, our model used cost as a proxy for MDI scores. MDI is about consequence. To build a better model, rather than evaluate the output of MDI scores we would suggest a model that could determine a different measure of effectiveness, like time duration a facility function or mission is interrupted.

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## APPENDIX: Mathematical Formulation for Min-Cost Network Flow Problem

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This minimum-cost network flow model is reproduced from Alderson et al. (2015) for convenience.

### Indices and Sets

|     |                                                                          |
|-----|--------------------------------------------------------------------------|
| $N$ | the set of nodes $i \in N, j \in N$                                      |
| $E$ | undirected edge between nodes $[i, j] \in E \subseteq N \times N, i < j$ |
| $A$ | directed arc $(i, j) \in A \subseteq N \times N$                         |

### Parameters [units]

|                |                                                           |
|----------------|-----------------------------------------------------------|
| $u_{ij}$       | the flow capacity on arc $(i, j) \in E$                   |
| $c_{ij}$       | the cost per unit flow of commodity on arc $(i, j) \in A$ |
| $\hat{x}_{ij}$ | 1 if $[i, j] \in E$ is damaged, 0 otherwise               |
| $q_{ij}$       | penalty cost to traverse arc $[i, j] \in A$               |
| $d_n$          | supply at node $n \in N$<br>(-demand for $d_n < 0$ )      |
| $p_n$          | per unit penalty for demand shortfall $n \in N$           |

### Decision Variables [units]

|          |                                  |
|----------|----------------------------------|
| $Y_{ij}$ | the flow on arc $(i, j) \in A$   |
| $S_n$    | fuel shortfall at node $n \in N$ |

## Formulation

$$\min_{Y, S} \sum_{[i,j] \in E} [(c_{ij} + q_{ij}\hat{x}_{ij}) Y_{ij} + (c_{ji} + q_{ji}\hat{x}_{ij}) Y_{ji}] + \sum_{n \in N} p_n S_n \quad (\text{A.1})$$

$$\text{s.t} \quad \sum_{(n,j) \in A} Y_{nj} - \sum_{(i,n) \in A} Y_{in} - S_n \leq d_n \quad \forall n \in N \quad (\text{A.2})$$

$$0 \leq Y_{ij} + Y_{ji} \leq u_{ij} \geq 0 \quad \forall [i, j] \in E \quad (\text{A.3})$$

$$S_n \geq 0 \quad \forall n \in N \quad (\text{A.4})$$

Our development of a mission network starts by constructing a network model of facility function nodes  $N$  connected by undirected edges  $E$  representing *possible* interdependencies. Each edge represents a physical connection between facility functions (e.g., pipe) with a capacity  $u_{ij}$  to flow a commodity (e.g., fuel) and cost to flow the commodity  $c_{ij}$ . Some nodes are *source facility functions* (e.g., fuel tanks) with  $d_n > 0$  that provide commodities to facility functions that demand fuel with  $d_n < 0$ .

All facility function nodes are able to reroute and deliver fuel from source facilities to other facilities, similar to pumping stations and control facilities in a pipeline. As a result, each facility function node can be interdependent on each adjacent facility depending on commodity flow direction. Given sources, demands, and possible flow paths over edges, solving the network flow problem with objective function (Constraint A.1) minimizes the cost to move commodities from sources to demands and determines flow direction. The resulting minimum cost solution determines the directionality of network interdependencies.

This network flow problem also includes parameters and constraints to minimize penalty costs and shortfalls when serving demands. These are necessary to capture DFM mission flows when the system is disrupted. Following realistic contracts and mission operations, there is a penalty cost  $p_n$  for any unserved demand at a facility function. Moreover, there is a penalty cost  $q_{ij}$  applied to interdependencies that are disrupted or difficult to use. Minimizing these penalties requires the mission to reroute commodity flows over possibly more difficult paths. While this is may be costly to the mission network operator, it is less costly than having a mission disruption due to loss of facility functions.

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