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Development and analysis of system and human architectures for critical infrastructure vulnerability assessment

By

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Development and analysis of system and human architectures for critical infrastructure vulnerability assessment

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The need to secure critical infrastructure (CI) systems against attacks is a topic that has been discussed recently in literature. Many examples of attacks against CI exist, such as the physical attack on the Pacific Gas and Electric Metcalf substation in 2013 that caused millions of dollars in damage or the Stuxnet cyber-attack which was identified in 2010 that caused damage to Iran's nuclear program and alerted the world to the existence of cyber weapons. As a result of these types of events in which vulnerabilities in CI are exploited, it is important to have a comprehensive systems approach for assessing the vulnerabilities in CI systems. This dissertation seeks to provide a method for engineers to use system and human architectures to perform vulnerability assessment (VA) and decision analysis to enable decision makers to make tradeoffs on how to use their resources to protect CI against attacks.

There are several gaps in literature in how to use system and human architectures to perform VA to protect CI from damage. First, no method exists that uses a model based approach and human and system architectures to perform a comprehensive analysis of CI to develop decision analysis models to aid decision makers in determining the most effective use of security resources to secure their CI systems. It is important that such models be comprehensive by including industry standards, system and human architectures, attack scenarios, subject matter expert opinion and models for analysis to help decision makers determine the best security investments. Second, there is not an established method to develop detailed mathematical models from an operational activity diagram that represents an attack scenario. This is important because the translation from architecture to high fidelity models will enable CI asset owners to make tradeoffs on security resource use. Finally, there is no method to evaluate the role of humans in a CI VA based on human views of the system. This dissertation provides an approach to use human and system architectures to perform VA and decision analysis to fill these gaps.

Keywords: Systems engineering, system architecture, human architecture, critical infrastructure, vulnerability assessment

DEDICATION

To my lovely wife who has supported me without fail throughout this journey.

ACKNOWLEDGEMENTS

First, I would like to thank my wife, Tameka, my sons, Ethan and Gavin, and the little one on the way for sharing their time with me so I could do this research. Tameka has been so encouraging throughout this process and has taken the kids to school and picked them up more than her fair share so I could work nights and weekends on this research. Next, I would like to thank my parents, Raymond and Melissa, for always being there and letting me know that I could achieve anything.

Next, I would like to thank my advisor, Dr. Medal, for his support. When I first started my Ph.D. journey, I spoke with Dr. James Malcolm, my dorm mate and a good friend from my freshman year in college. I asked him what was most important about the journey that is the Ph.D., and he said that I needed to pick a great advisor and that my advisor would make all the difference in the journey. I spent an entire year interviewing advisors and students from various universities, and Dr. Medal stood out as the person who could help me accomplish my life-long goal of acquiring a Ph.D. Dr. Medal has been a fantastic mentor throughout this process, and I appreciate his understanding of the challenges of seeking a Ph.D. while having a family. I thank his wife and children for welcoming me into their home for dinner while I was doing my research intensives at Mississippi State.

I would also like to thank Dr. Griendling, whom I called after about a year or two of study and asked to help me with my research on human and system architectures. After just one phone call, she agreed to serve on my committee, and she has helped me tremendously throughout this journey.

Dr. Hamilton has been great – I appreciate his insights and bringing his experience to our discussions. Whenever he was in Albuquerque, he made sure to call me up for lunch, and that really helped me stay connected to the campus and feel like a real student.

Dr. Smith, thank you for agreeing to be a co-advisor as the research became more systems engineering-based. I appreciate you helping me to understand the nuances of systems engineering. Thanks for helping with techniques to summarize the contributions of my journal articles; I still remember that time you recorded me describing the main points of my research.

I would also like to thank the undergraduate students that have worked with me, Will Leonard and Ryan Stallcup. Will, I appreciate that weekend you spent with me in Starkville working all weekend to make sure that I would graduate; you did not have to do it, but you did, and I am grateful.

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Finally, I want to thank God for His grace during this process. There were many nights and weekends when I did not think I had the strength to write one more line of code or one more sentence, and He gave me the strength to fulfill this lifelong dream. Without Him, this would not have been possible.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Critical Infrastructure (CI) is categorized into 16 sectors of physical or virtual assets that are so important that their damage or destruction would have a devastating effect on national economic security, public health, safety or security [DHS, 2016]. Because of the importance of CI, securing these assets against adversaries is imperative. The primary contribution of this research is developing an approach that allows the vulnerabilities of these assets to be identified so they can be secured against attack. In this dissertation, a model based approach to perform vulnerability assessment (VA) on system and human architectures of CI systems is developed. The human and system architectures can result in executable architectures, which will be shown in the human analysis portion of the case study, or in data that can be used for other types of modeling and analysis. In general, the approach results in data that can be analyzed to aid decision makers in making tradeoffs on how to use security resources. In addition, the approach allows the architectures developed to be analyzed using various analysis techniques. While operations research (OR) methodologies (Integer Linear Program (ILP) and Bi-level Mixed Integer Program (BLMIP)), social network analysis (SNA) and time to compromise (TTC) analysis is used in the case study in this research, other modeling and simulation tools such as discrete event simulation could be used for the analysis portion of the approach presented. These methods will help decision makers to determine the best investments to mitigate security risks in CI. This is the first research that links model based systems engineering concepts and human and system architectures to CI VA in a methodical way that leads to a quantitative analysis.

The approach developed in this research also provides a method for systems engineers to use common tools and approaches to contribute to CI VA at the architecture level without having detailed data. This will provide more engineers that can contribute to assessing and mitigating vulnerabilities in CI.

Figure 1.1 provides an overview of the scope of this research, showing how the CI VA uses human and system architectures and the types of quantitative analysis that can be performed on each.

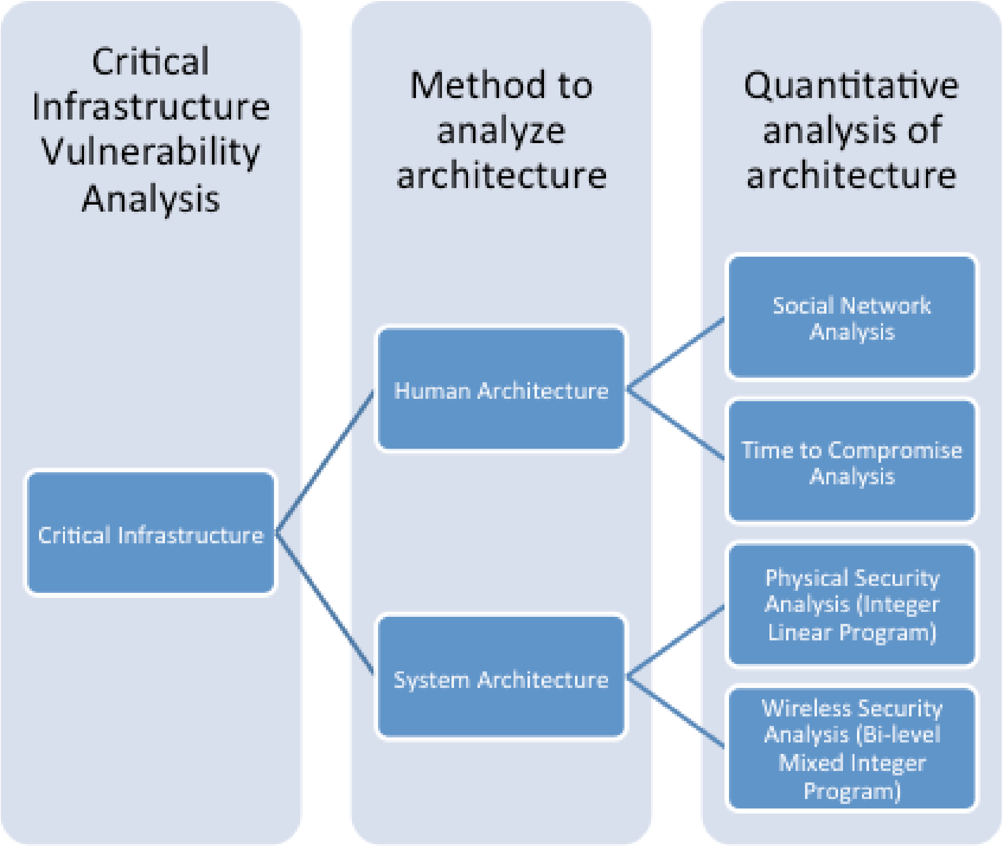

Critical Infrastructure Vulnerability Analysis
Method to analyze architecture
Quantitative analysis of architecture
Critical Infrastructure
Human Architecture
System Architecture
Social Network Analysis
Time to Compromise Analysis
Physical Security Analysis (Integer Linear Program)
Wireless Security Analysis (Bi-level Mixed Integer Program)

Figure 1.1 Dissertation overview

This research develops approaches to analyze system and human architectures of CI. Once the analysis of these approaches is developed, the data in the architecture that is collected is used to create models to perform quantitative analysis, which allows decision makers determine how to invest security resources. The quantitative analysis methods represent the type of analysis that can be performed once the architecture is fully developed.

1.1.1 Background and motivation

There have been many examples of both cyber and physical attacks on CI systems. Two examples of such attacks that impact both the human and systems components of CI are the Metcalf electrical substation attack in 2013 and the Stuxnet cyber-attack that was discovered in 2010.

Securing electrical substations has become an increasingly important topic since the Metcalf attack in 2013. The attack occurred in April 2013 at the Pacific Gas and Electric Corporation Metcalf substation; gunmen fired bullets at the substation, damaging 17 transformers and 6 circuit breakers and causing an estimated $15.4 million in damage [Brinkman et al., 2015]. Although this attack was not catastrophic, a potential exists for a major impact to national security if there is a coordinated attack on substations. The Wall Street Journal reported that the "U.S. could suffer a coast-to-coast blackout if saboteurs knocked out just nine of the country's 55,000 electric transmission substations on a scorching summer day, according to a previously unreported federal analysis" [Smith, "US Risks" 2014]. These numbers have not been confirmed by the federal government, but the then-chairman of the Federal Energy Regulatory Commission (FERC) noted that "there are probably less than 100 critical high voltage substations on our grid in this country that need to be protected from physical attack" [Smith, "US Risks" 2014]. This substation example demonstrates clear human to system interaction, which shows that both system and human aspects would need to be evaluated to determine all of the system's vulnerabilities.

In addition to the physical security aspects in the substation case study, cyber security is another area of concern in human-system integration. The discovery of

Stuxnet, a highly publicized cyber weapon, changed the conversation about cybersecurity; it highlighted the vulnerabilities in human-system integration points because it was spread via USB and local networks [Langer, 2011] by humans connecting USB devices to systems. The malware infected any Windows PC with which it came in contact, but its targets were specific programmable logic controllers (PLCs) manufactured by Siemens [Langer, 2011]. A PLC is used in industrial control systems to control devices such as pumps, valves and motors. Once the code had found a target controller, it would cause damage to physical equipment; one example of the code's effect is the sabotage of centrifuges at the Natanz uranium enrichment plant in Iran [Langer, 2011; Zetter, 2014]. This is just one example of vulnerabilities that can be exploited in human to system interfaces, such as USB.

In these attacks, both the systems and human-system interfaces were vulnerable. These vulnerabilities, if exploited, can have levels of severity from damaged equipment to loss of life in the case of loss of electrical power. As new infrastructure is built and existing infrastructure is maintained, a method to evaluate vulnerabilities and allow decision makers to determine the best use of security resources is needed. The approach presented in this research will allow system architects and decision makers to construct a comprehensive model for evaluating CI systems.

1.1.2 Method for evaluating CI systems

The goal of this research is to provide a new method for using system and human architectures to perform VA for CI systems; the data from the VA will be used by decision makers to determine how to invest security resources. The method for evaluating systems developed in this research targets a general class of systems that have operations and cyber-physical system of systems components. The operations component consists of humans who operate the system and the system of systems component is the hardware and software parts of the CI. Examples of these types of systems include electrical power systems that include both electric system control centers and the cyber-physical grid, aviation systems that include both air traffic control and aircraft, and mass transportation systems that include transportation command centers and rail transportation, buses and trolleys. While there are many systems that can be analyzed using the proposed method, systems that this method would not be suitable for are systems that cannot be analyzed using a high level architecture. For example, firmware VA, a VA of a circuit or other subsystems would not be good candidates for using this method. The research performed can help answer the following sample list of questions about these systems. Note that other questions could be answered by the method as well and these are only meant to provide an illustrative set of questions.

- What vulnerabilities do employees introduce based on their skill level at performing certain tasks?
- How long would it take for an employee with a certain skill level to damage the system if they became a malicious insider?
- What employees should receive more extensive background checks based on their level of influence within the organization?
- How should a decision maker invest security resources based on the cost of the resources and the level of risk associated with the mitigated vulnerability?
- Does my system meet regulatory requirements and industry recommendations for security?
- Where do subject matter experts believe that my primary security investments should be made and what is the optimal selection of those investments based on my budget?

The specific approach for evaluating CI developed in this research is shown in Figure 1.2. The type of analysis is denoted by numbers on the boxes. The boxes with a 1, indicating analysis path 1, shows the evaluation of the human view of the CI system. Within the system view, two paths exist to perform analysis; analysis path 2 is at the system level and analysis path 3 is at the subsystem level. These path references will be used throughout the dissertation as a reference for the type of analysis being performed. The analysis performed in each of these paths will be detailed in Chapter 3 and applied to an electric power system in Chapter 4, but the general approach for each of these paths can be applied in multiple domains. The human path can be applied to the operations part of the system where humans send commands and receive status from the system and the system and subsystem paths can be applied to the cyber-physical system of systems component of the system where the core hardware and software components are captured in the architecture.

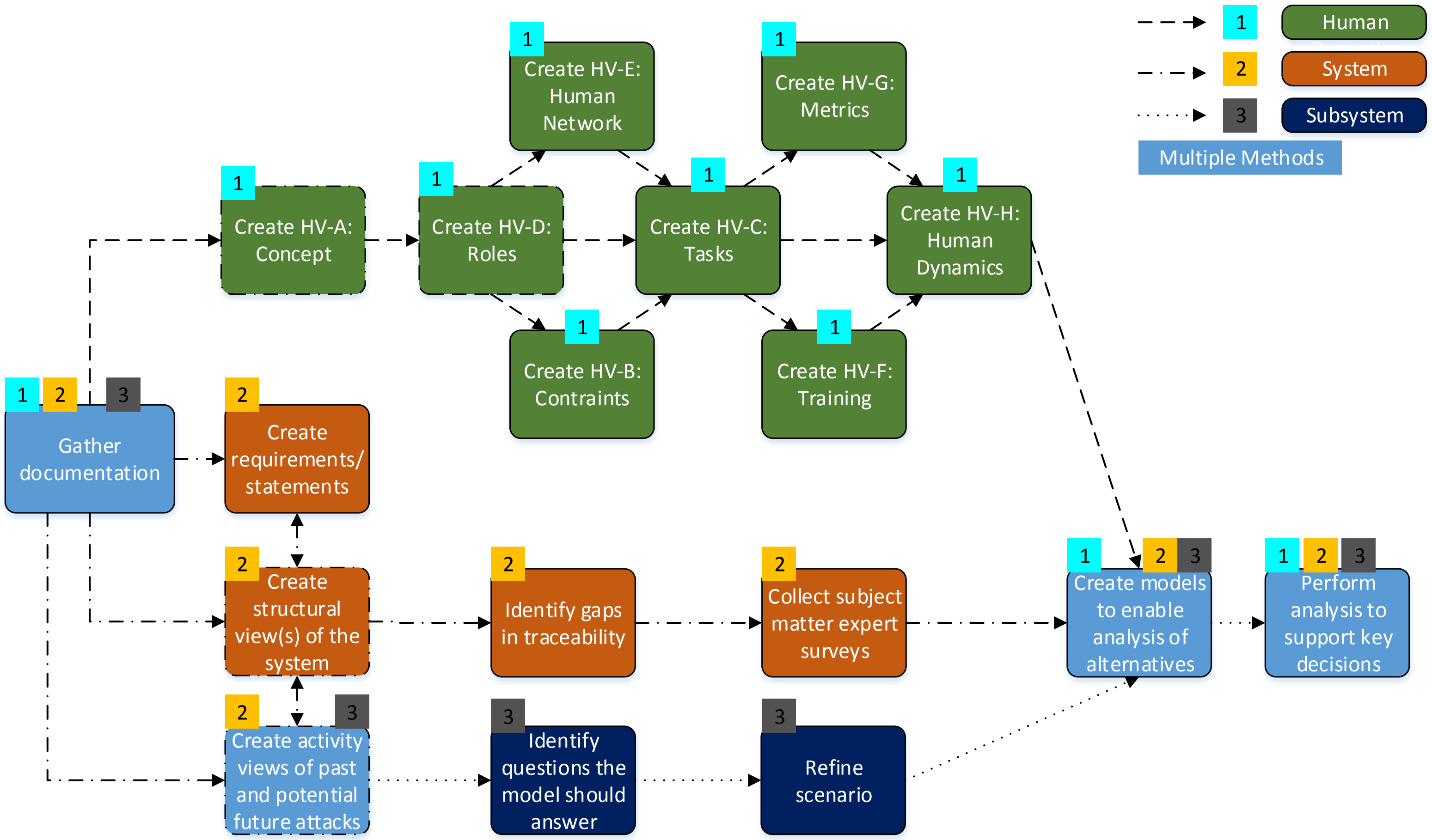

1
2
3
Gather documentation
1
Create HV-A: Concept
1
Create HV-D: Roles
1
Create HV-E: Human Network
1
Create HV-B: Contraints
1
Create HV-C: Tasks
1
Create HV-G: Metrics
1
Create HV-F: Training
1
Create HV-H: Human Dynamics
2
Create requirements/ statements
2
Create structural view(s) of the system
2
3
Create activity views of past and potential future attacks
2
Identify gaps in traceability
3
Identify questions the model should answer
2
Collect subject matter expert surveys
3
Refine scenario
1
2
3
Create models to enable analysis of alternatives
1
2
3
Perform analysis to support key decisions
1
2
3
Human
System
Subsystem
Multiple Methods

Figure 1.2 CI VA approach

In the first component of this research, indicated by path 1 in Figure 1.2, a VA of the human component of the system will be performed using the NATO Human View to address the problem of determining what security risks humans introduce to CI and how to mitigate those risks. While the NATO Human View is used as an example for this research because the NATO Human View was designed to supplement DoDAF, another human view framework could be used in the method as long as the views allow the collection of data to answer the questions needed by the decision maker. This research develops an analysis approach that allows decision makers to determine where to make CI investments in training, physical security, cyber security and other areas to mitigate vulnerabilities that can be exploited by human actors. SNA and TTC analysis will be used to demonstrate the value of the NATO Human View in CI analysis. The SNA demonstrates how an architecture can be executed directly for analysis, which is the executable architecture component of this research. In the case study, the human views with organizational structures are used to determine key influencers that could be serious threats if they became malicious insiders. Note that these analysis methods are used to demonstrate the utility of the approach developed in this research, but other approaches such as discrete event simulation could also be used depending on the question the decision maker wants answered.

Whereas in the first component of this research, the human view is evaluated, the next step is to evaluate the hardware and software of the system. In the second part of this research, indicated by path 2 in Figure 1.2, a VA of the system architecture is performed to address the problem of determining vulnerabilities in CI. Once the vulnerabilities are identified, a model is developed to enable decision makers to answer questions about the optimal use of security resources. While there are many types of models that can be developed based on the decision maker interests, in the case study presented in this research, a model is developed to minimize cost while maintaining a desired level of security effectiveness against adversaries who would exploit those vulnerabilities. To accomplish this analysis, the general approach presented develops a comprehensive model based approach that allows architects to link regulatory requirements, subject matter expert opinion, system architecture, and attack vectors to an model that allows decision makers to determine alternatives to securing their systems. The DoDAF is used for the architecture framework and an ILP is used for the analysis, but these are used as examples of approaches that can be used and can be replaced with other frameworks and analysis methods as needed to answer the decision maker's questions.

In the third component of this research, indicated by subsystem analysis path 3 in Figure 1.2, the past and future attack scenarios developed are used to develop a detailed mathematical model. This provides an alternative to the approach developed in the system path that does not require subject matter expert opinion surveys. In addition, the subsystem path allows attack scenarios to be used to develop detailed models at the subsystem level that aid decision makers and engineers in determining where to invest security resources during the design and development of CI systems.

Overall, the result of using each of these paths to analyze a system results in a VA of the system at the architecture level that allows decision makers to understand the security investments that need to be made based on their budget to mitigate vulnerabilities. The NATO Human View and DoDAF are used in this research because the NATO Human View was designed to augment the DoDAF views [NATO, 2010], but other human and system views or architecture frameworks could be used to accomplish the VA goals. To demonstrate the general method that could be applied to CI systems with operations and cyber-physical system of system components as previously described, an illustrative case study of a VA of an electric power system will demonstrate how the method can be used.

1.1.3 Illustrative case study: Electric power system VA

The case study that is used to illustrate the method developed will be an electric power system. The electric power system was selected because it not only has operations and cyber-physical components, but as discussed in earlier in the introduction, is a key component of our everyday lives. Figure 1.3 shows how the power system maps to the generic system that this method targets. The human architecture will be used to analyze the operations component of the system which is the electrical power operations center denoted by a one in Figure 1.3. The system architecture will be used to analyze the cyber-physical system of systems portion of the system, which is shown as the electrical substations (dotted purple) and the wireless video surveillance subsystem.

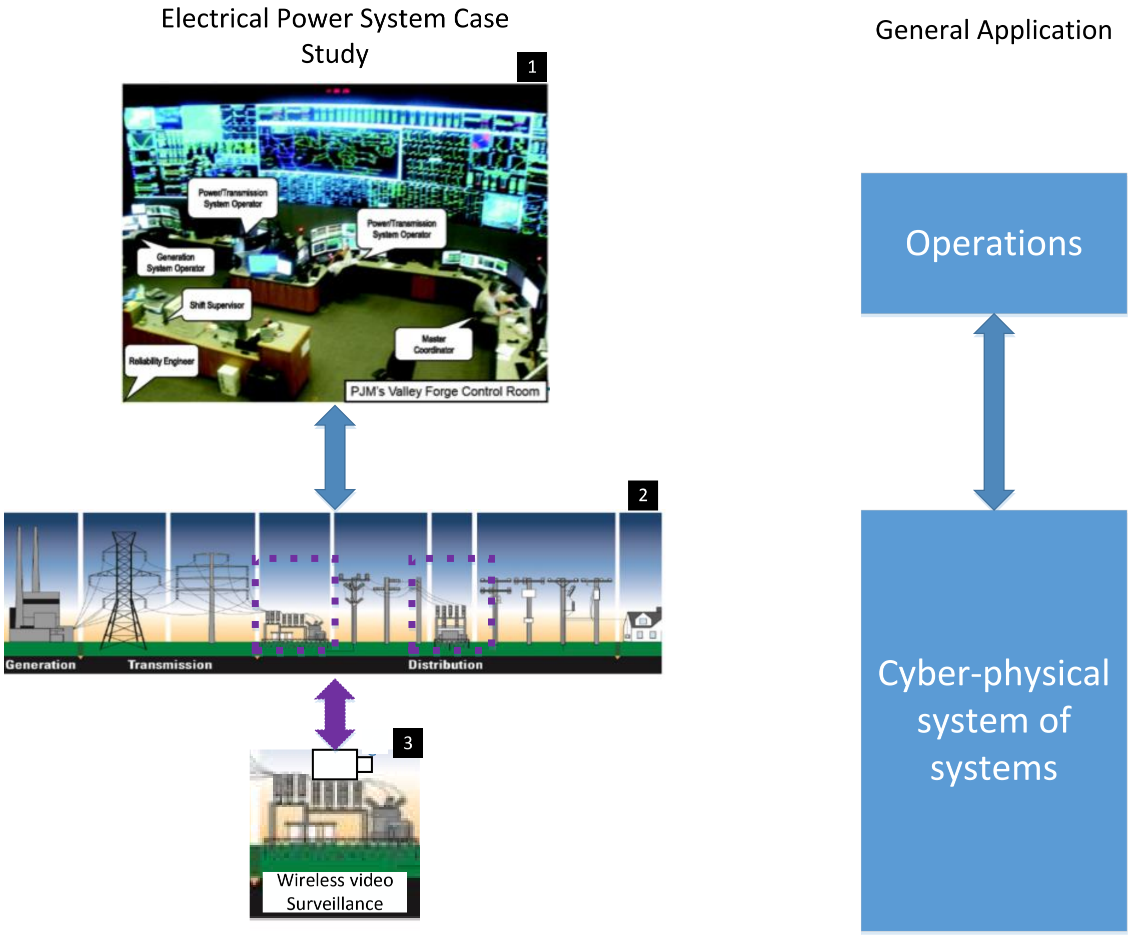

Electrical Power System Case Study
1
Power/Transmission System Operator
Power/Transmission System Operator
Generation System Operator
Shift Supervisor
Master Coordinator
Reliability Engineer
PJM's Valley Forge Control Room
2
Generation
Transmission
Distribution
3
Wireless video Surveillance
General Application
Operations
Cyber-physical system of systems

Figure 1.3 Case study overview

The labels on each part of the electrical power system in Figure 1.3 indicate the path that the analysis corresponds to in Figure 1.2. For example, the operation center figure is labeled with a one and will be analyzed using path 1 in Figure 1.2. Once the case study analysis is complete, it demonstrates how the method developed in this research can be used for an analysis of a real system.

The remainder of the dissertation is organized as follows. Chapter 2 presents a literature review of the work that has been done and how this work fills gaps in current research. Chapter 3 presents the details of the methodology for evaluating CI as shown in Figure 1.2. Chapter 4 presents the use of the CI VA approach to evaluate an electric power system. Finally, Chapter 5 contains the conclusions of the research and potential areas for future work.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This literature review explores the following major topics of this research: Security analysis of human architecture, security analysis of system architecture, optimal placement of jammers in ad hoc wireless networks, and the integration of DoDAF and OR. Human architectures, represented by the NATO Human view are used to evaluate the operations side of CI. System Architectures, represented by the DoDAF are integrated with OR to evaluate the system of systems side of CI. Lastly, since an optimal jammer placement model is extended as part the illustrative case study, the gap in literature to support that extension is included here. All of these areas are reviewed to understand the current literature, where the gaps are and how this research fills those gaps.

2.2 Security analysis of human architecture

Although a review of scholarly literature reveals little discussion of human roles in the context of CI systems' security, there exists a wide variety of information related to the analysis of human beings in systems in general. Human architectures and human-system integration, as discussed in other literature, have proven useful when applied in various contexts outside of the security domain.

In 2008, the NATO Research and Technology Panel on Human Factors and Medicine Human View workshop convened to develop an architectural view that captures the human aspects of a system [Handley and Smillie]. While there were many efforts in other architecture frameworks such as the DoDAF and the Ministry of Defence Architecture Framework (MoDAF), there was a need to develop a standard approach to represent the human view of a system [Handley and Smillie, 2008]. The NATO Human View products that were developed provide the following: a link from the engineering to the human factors community, a way to integrate human system integration early into the systems engineering processes, and an approach for the coordination of task analysis by systems engineering and human factors teams [Handley and Smillie, 2008]. The purpose of the NATO Human View is to "define the role of the human in the system and to capture the human operator activities, tasks, communications and collaborations required to accomplish mission operations and support operational requirements" [Handley and Smillie, 2008]. The Human View products are as follows in Table 2.1. While the views are used for comprehensive general human behavior analysis, they do not include a method to perform VA, which is critical for the threat employees and employers face in the workplace today.

Table 2.1 NATO Human View products [Handley and Smillie, 2008]

View	Description
HV-A Concept	A high level representation of the human component of the system
HV-B Human Factors Constraint	Operator capabilities and limitations under various conditions
HV-C Task Decomposition and Interdependencies	Generation of the network diagram composed of tasks and subtasks; Assignment of system interfaces to tasks
HV-D Roles	List of roles and assigned task responsibilities
HV-E Human Network	Role groupings or teams formed; interaction types between roles and teams
HV-F Training	Training required to obtain the necessary knowledge, skills and abilities to perform assigned tasks.
HV-G Metrics	Performance parameters and standards
HV-H Human Dynamics	Uses information from the other human views to provide the basis for developing executable models

As a follow-on to Handley and Smillie's [2008] work, the NATO Human View coupled with the U.S. Army Research Laboratory Improved Performance Research Integration Tool (IMPRINT) was used to create a simulation model and capture task performance results that ultimately can show the impact of high workload, poor training, and inadequate communications on system performance [Handley and Smillie, 2008].

Colombi et al. [2012] continued the use of IMPRINT by using the MoDAF Handbook of Human Views to represent remotely piloted aircraft operations. The operations were simulated using the professional version of IMPRINT (IMPRINT PRO) to evaluate the mental workload of operators. The model proved successful in providing insight into mental workload of the operator during system operation. In another use of IMPRINT for human analysis, Goodman et al. [2015] used SysML activity diagrams and

IMPRINT to determine how human workload is impacted by reliance on automation. The researchers used SysML to provide the basis for task networks within IMPRINT showing that re-allocating tasks from humans to machines results in additional tasks for which workload modeling must account so as to be truly accurate. Although this research shows that human architectures can be executable, no previous research accounts for the vulnerabilities humans introduce into the system and how to evaluate those vulnerabilities.

In addition to using IMPRINT to execute human architectures of the system, researchers have recognized the need for system views that represent human-system integration points and proposed methods to create executable architectures from these views of the system. Bodenhamer [2012] used the case study of a handheld mine detector to demonstrate that not including the system architecture with human system integration elements in place can result in missed requirements which will negatively impact system performance. Bodenhamer [2012] also proposed using genetic algorithms to optimize the Manpower, Personnel, Training, Safety, Health Hazards, Human Factors and Survivability factors of the overall system architecture. Following this work, Handley and Knapp [2014] discussed human views being used to evaluate multi-sensor systems operations. Intelligence crews that support these systems were evaluated based on their roles, tasks, and work processes. A simulation model was used to demonstrate their effectiveness.

In summary, while parameters such as mental workload, training, and communications have been considered in the analysis and simulation of human views of systems, no work has been done to examine how these views can create architectures that allow architects and decision makers to evaluate human system integration risks related to system security vulnerabilities.

2.3 Security analysis of system architecture

In addition to the NATO Human View, the DoDAF is also used to represent CI systems in the model based systems engineering approach presented in this research. The ability to execute architecture and use the architecture meta-data for analysis has been researched in the literature. The DoDAF has been used extensively to develop architectures for analysis and its relationship to MSBE has been studied [Piaszczyk, 2011]. Research has been conducted in the area of DoDAF executable architectures [Griendling et al., 2008; Griendling and Mavris, 2011; Mittal, 2006], which provide links from DoDAF architectures to various simulation and modeling tools.

Griendling and Mavris [2011] use DoDAF to create Markov chains, petri nets, systems dynamics models and mathematical graphs. The use of a stochastic petri net to implement discrete event simulation is also discussed. Other literature has proposed using colored petri nets [AbuSharekh et al., 2007; Wagenhals and Levis, 2009], hierarchical colored petri nets [Griendling and Mavris, 2011], and SysML colored petri net transformation [Wang and Dagli, 2008] for characterization and execution of DoDAF products. Griendling et al. [2008] also used a modeling process that selects the DoDAF architecture that best meets mission needs by using agent-based modeling and simulation, artificial neural networks and optimization and decision support.

Mittal [2006] proposes to add two new Operational Views to DoDAF, version 1.0 in order to model and simulate DoDAF architectures within a development environment based on Discrete Event System Specification (DEVS). Xia et al. [2013] propose using

Simulink models to evaluate a command, control, communications, computers, intelligence, surveillance and reconnaissance architecture. Recently, researchers have proposed using the DoDAF DM2 data model for creating executable architectures [Ge et al., "Novel" 2013; "Data-centric" 2013]. The DoDAF DM2 is a push towards a more data-centric approach to the analysis. While the research discussed provides various ways to create executable architectures, the methods do not provide a way to link resources identified in system architectures to an OR model for determining the best use of those scarce resources. This type of analysis is useful to CI asset owners who seek to minimize cost while providing as much security as possible for their assets.

In addition to the execution of DoDAF products, using DoDAF to aid in the evaluation of the security level of a system has also been an area of increasing interest because the inclusion of DoDAF architectures as part of new system developments is mandated in Department of Defense (DoD) acquisition regulations [Hamilton, 2006]. Hamilton [2006] and O'Farrell et al. [2010] proposed methods to add information assurance data to DoDAF architectures to support security analysis.

Building on this previous work, Hamilton [2013] later discusses using architecture-based network simulation for visualization of security requirements and auto generation of network architecture artifacts. Farroha and Farroha [2011] present several concepts utilizing DoDAF to achieve a higher level of security in information sharing systems. The focus is on adding agility and assurance to current enterprise systems engineering processes. As the volume of research has increased in the representation of security measures in DoDAF architectures, one of the gaps in this research is a method to represent past and future attacks that can be used in a model for traceability to the system architecture to ensure that the system contains the appropriate security resources to protect or mitigate against attacks. As attacks on CI happen more often, the ability to identify the lack of traceability will help in VA.

While DoDAF is used to represent the system in this research, the final product is a complete model that can be used to evaluate the system for vulnerabilities and help decision makers determine the best use of security resources. This work most closely builds on the work by Shin et al. [2015] and Kerzhner et al. [2015]. Shin et al. [2015] developed a reference model for CI protection using SysML. A nuclear power plant protection system's operations are analyzed to determine which model would meet constraints such as accuracy of detection, object recognition, and cost. Models were then analyzed to see which models met the requirements for protecting the power plant in the event of an attack. In their approach to developing a reference model, Shin et al. [2015] do not discuss incorporating subject matter expert opinion in their analysis of protection schemes and do not consider the mapping of the system being protected to the CI regulations, policy or requirements. The use of subject matter expert opinion and mapping to regulations, policy or requirements is one of the contributions of this research, however. This is important because such requirements, regulations and recommendations change to accommodate newly identified threats, and asset owners would want to know if their current system is protected from those threats.

Kerzhner et al. [2015] extend this work by creating a tool for analysis of cyber-physical systems; the tool includes physical elements, network, topology, software applications, system functions and usage scenarios [Kerzhner et al., 2015]. To capture vulnerabilities and possible attacks, an algorithm in the tool works from a starting point to the attacker goal and outputs if the attacker will be successful and what vulnerabilities could be exploited [Kerzhner et al., 2015]. The focus of Kerzhner et al. [2015] is analysis of potential attacks based on an existing system model, but their work does not consider the analysis of the use of specific security resources based on cost or how the system meets regulatory requirements and policies. The analysis of the use of security resources based on cost is demonstrated in this research and would be important to CI asset owners who need to determine the best use of potentially limited funds to invest in security.

2.3.1 Using an OV-5b to develop an OR model

At the subsystem level, this work covers the intersection of two major areas of research: systems architecture and wireless network jamming. In the approach developed, the DoDAF OV-5b Operational activity model is used to represent a future attack scenario and a decision analysis model is developed based on this scenario. As a case study, an attack scenario is used to create a wireless network jamming decision analysis model.

While research has been conducted on executing and implementing security in DoDAF architectures, there has not been a case study that demonstrates how a DoDAF OV-5b can be used to develop a detailed OR model. Specifically, in the illustrative case study, the subject will be a wireless network subject to jamming.

Wireless networks have been researched extensively for use in both civilian and military applications. For example, with respect to CI, researchers have explored using wireless sensor networks for substation monitoring and control [Matta et al., 2012], and they have researched the various design challenges associated with hardening the network architecture that supports CI to prevent exploits such as traffic analysis and jamming attacks [Buttyan et al., 2010]. Wireless networks have also been used for structural health monitoring on the Golden gate bridge [Kim et al., 2007]. In military applications, wireless networks have been researched for use for communication of tanks in hostile environments [Halvardsson and Lindberg, 2004], and there has been work performed to connect independent mobile ad-hoc networks that are used for military tactical operations both on the ground and in the air [Wang et al., 2015]. The security of these ad hoc networks using secure routing, key management and intrusion detection has also been explored [Zhou and Haas, 1999; Zhang and Lee, 2000]. Specifically, some literature has examined how to respond to jamming attacks [Jiang and Xue, 2009; Ma et al., 2005] and how to determine the location of a jammer during an attack [Pelechrinis et al., 2009].

While there have been studies on how an attacker allocates their resources [Tague et al., 2008] and the struggle between operators and attackers [Li et al., 2007], only Commander et al. [2008], Commander et al. [2007] and Noubir [2004] have examined the placement of jammers. The jammer location problem is a perfect application for the field of network interdiction, in which device placement to disrupt a network has been researched extensively. Wood [1993] introduced interdicting networks to minimize the maximum flow, Israeli and Wood [2002] maximized the shortest path, and Arulselvan et al. [2009] minimized the network connectivity. Researchers have continued this work by studying networks with multiple commodities [Lim and Smith, 2007], time periods [Malaviya and Sharkey, 2012], changing attacker-defender relationships [Lunday and Sherali, 2010], as well as random interdiction [Cormican et al., 1998], network topology

[Held and Woodruff, “Decomposition” 2005; “Heuristics” 2005], and attacker attributes [Morton et al., 2007; Pan and Morton, 2008].

Medal [2016] expanded on previous work that minimized connectivity by optimally placing jammers [Commander et al., 2008; Commander et al., 2007; Noubir, 2004] by contributing a mixed-integer programming formulation that showed how to design a network to be secure against jamming attacks and how to place nodes to increase the interruptions caused by a jamming attack. In Medal’s [2016] work, omnidirectional antennas were used for the target and the jamming attack nodes. Based on the field test of an ad hoc network performed by Ramanathan et al. [2005], in which the authors found that directional antennas offer improved capacity and connectivity improvement in an ad hoc network, Medal’s [2016] work should be extended to include directional antennas. This will allow network designers more fidelity when using the model to evaluate key parameters to make a network robust against jamming attacks. Although the work by Gao et al. [2007] uses slices to simulate the directional radiation pattern, Ramanathan et al. [2005] found in their field test that real antenna patterns were more complex than slices or cone models; therefore, this work will use data that is representative of real radiation patterns. Finally, the extended model will also consider the energy consumed by the nodes and how that impacts both the communications and jamming capabilities.

2.3.2 Integration of DoDAF and OR

In the approach developed, DoDAF is used for the structural and behavioral views of the system, and OR, specifically integer linear programming, is used for the system analysis. In light of this, it is important to understand the intersection between DoDAF and OR.

The DoDAF Version 2.0 is used by the DoD to enable DoD managers at all levels to make decisions more effectively by using this standard of information sharing [DoDAFBG, 2014]. The focus of DoDAF 2.0 is on architectural "data that can be collected and organized using commercial tools" [DoDAFBG, 2014]. Because it is data centric, the content can be "Fit-for-Purpose," which means the architecture can be developed to address specific applications to support a specific decision [DoDAFBG, 2014].

OR is a "scientific approach to decision making that seeks to best design and operate a system, usually under conditions requiring the allocation of scarce resources. This scientific approach to decision making usually involves the use of one or more mathematical models" [Winston and Goldberg, 2004]. A mathematical model is a "mathematical representation of an actual situation that may be used to make better decisions or simply to understand the actual situation better" [Winston and Goldberg, 2004]. The first formal OR activity occurred during World War II when a team of scientists in England were called upon to determine the most effective use of limited military resources [Taha, 1971]. Due to the success of the OR team in World War II, OR has continued to be used in various military and industrial applications. In the methodology presented, the scarce resources will be security related – such as lights, motion sensors, and manned patrols.

Since DoDAF Version 2.0 is data centric and OR is based on building mathematical models, it follows that OR may be a good fit for analysis of the data produced from the DoDAF architecture development process. Next, the development process for DoDAF and OR will be discussed to show how they integrate.

2.3.2.1 DoDAF architecture development process

A summary of the steps in the DoDAF Architecture Development Process is shown in Table 2.2. These steps are performed by the process owner, architect and development team. Note that the first step in the process is to determine the intended use of the architecture. In applying DoDAF to VA, we use the ability to make DoDAF "Fit-for-Purpose" in assigning the use of the OV-5b to describe attack scenarios and modifying the development process to fit the analysis needs.

Table 2.2 Summary of DoDAF development process [DoDAF202, 2014]

Step Number	Name	Description
1	Determine intended use of architecture	Defines the purpose ("Fit-for-Purpose") and intended use of the architecture. It includes the data needed, the impact of the system on others, and the process by which the success of the effort will be measured. Information typically provided by the process owner.
2	Determine scope of architecture	Make sure there is clarity of scope for the effort defined for the nature of the project that enables an expected result. Define and describe the data to be used in the proposed architectural description in advance of the creation of view(s) that present desired data in a format useful to managers.
3	Determine data required to support architecture development	The level of detail of data required is determined by the scope established in step 2. This data could be data previously collected or new data. This step is completed in conjunction with step 4. Organized data collection and architecture development iterate over these two steps.
4	Collect, organize, correlate and store architecture data	Architects typically collect and organize data in the best way to present it to decision makers. Architecture data should be stored in a recognized commercial or government architecture tool.
5	Conduct analyses in support of architecture objectives	Validates that the architecture meets the requirements established by the process owner.
6	Document results in accordance with decision maker needs	Transform architectural data into presentations that meet the decision maker needs.

2.3.2.2 Operations research seven step model building process

The next step is to understand the OR model development process as shown in Table 2.3. As the problem is formulated there is an iterative relationship with the architecture and this problem formulation. As the architecture develops and more information is gathered, the problem formulation and the fidelity of the mathematical model can increase to more closely match the question that a decision maker would like to answer.

Table 2.3 Summary of OR model building process [DoDAF202, 2014]

Step Number	Name	Description
1	Formulate the problem	Define the organization's problem. This includes specifying the organization's objectives and the parts of the organization that must be studied before the problem is solved.
2	Observe the system	Collect data to estimate the parameter values that affect the organizations problem.
3	Formulate a mathematical model of the problem	Develop a mathematical model of the problem (e.g., linear program).
4	Verify the model and use the model for prediction	Is the mathematical model developed an accurate representation of reality?
5	Select a suitable alternative	Based on the model and set of alternatives, the best alternative is selected.
6	Present the results and conclusion of the study to the organization	Present the model and recommendations to the decision making individual or group.
7	Implement and evaluate recommendations	The recommendations are implemented and the system is monitored to ensure the organization meets its objectives.

2.3.2.3 Mapping OR model to DoDAF model

The mapping of the two processes is shown below in Figure 2.1. While the architecture team is determining the intended use of the architecture, the OR team members are starting to formulate the problem based on the intended use. As the scope becomes more clear and data is collected, OR is used to formulate a mathematical model of the system. Once the model is developed, the model is solved and the results are documented based on the decision maker's needs.

This research does not change the fundamentals of the current DoDAF process as just described; rather, it includes OR modeling in the analysis in a tailored way to meet the VA and decision analysis objective. OR (specifically, an integer linear program) will be used to determine the best use of security resources while minimizing cost.

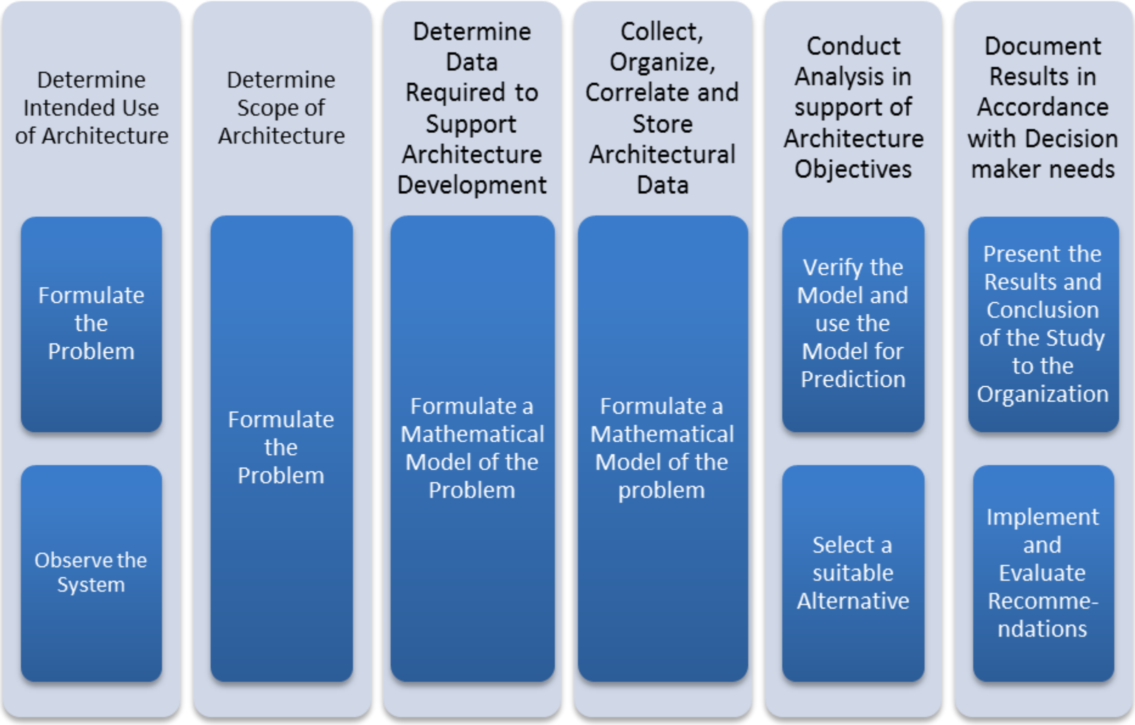

Determine Intended Use of Architecture
Formulate the Problem
Observe the System
Determine Scope of Architecture
Formulate the Problem
Determine Data Required to Support Architecture Development
Formulate a Mathematical Model of the Problem
Collect, Organize, Correlate and Store Architectural Data
Formulate a Mathematical Model of the problem
Conduct Analysis in support of Architecture Objectives
Verify the Model and use the Model for Prediction
Select a suitable Alternative
Document Results in Accordance with Decision maker needs
Present the Results and Conclusion of the Study to the Organization
Implement and Evaluate Recomme-ndations

Figure 2.1 Integrated DoDAF and OR processes

2.4 Contributions

The primary contribution to the literature made by this dissertation is a model based approach for the VA of CI human and system architectures. By using common tools and framework, this research allows systems engineers to contribute to CI VA efforts at the architecture level. The analysis of the architectures provides results to aid decision makers in making tradeoffs between security resource investments. This type of analysis is needed because of the importance of CI systems to our everyday lives. If these systems are not adequately protected and are damaged, the impacts could range from complete electric power system outage to causing financial markets to close. An electrical system outage could result in loss of life and markets closing unexpectedly for long periods of time could cause a meltdown of the financial system. These are unacceptable consequences and therefore continuous VA of CI systems is needed to ensure that they are robust against attacks.

This research extends the application of the simulation of human processes by adapting the NATO Human View to create NATO Human View executable architectures for SNA and to provide inputs for TTC analysis. The human views are used directly for the SNA, making the architecture created executable. The multi-sensor systems example discussed by Handley and Knapp [2014] is expanded upon by using SNA to understand the interaction between roles. The work of Handley and Smillie [2010] on Human View dynamics is expanded because task performance is based on skills, and, in this research, skill levels are used to determine how long it would take an insider to compromise the system. Past research has not used human views for security analysis.

Furthermore, this research applies human views to CI systems for the first time. These systems have complex human interactions across a large footprint of infrastructure, so the analysis of these systems should include not only hardware and software but also people within the system. By performing SNA and TTC analysis, which is straightforward to accomplish with information provided in standards documents and other documentation readily available to the asset owners, system architects will be able to identify the interfaces where human vulnerabilities can have the most impact.

This research also extends the application of system architectures by directly using the resources identified in a DoDAF SV-1 System Interface Description in the objective function of an integer linear program to minimize the cost of allocating security resources. This is important because the funds available to support security are limited, and, therefore, the best mix of security resources based on cost and effectiveness would allow asset owners to understand what level of security effectiveness they can afford based on their budgets. Additionally, Hamilton's work on the intersection of information assurance and DoDAF is expanded in this research by using the DoDAF OV-5b Operational Activity Model to model historical and potential future attacks on CI; past research has not used an OV-5b for this purpose. By using the OV-5b to describe attacks, it provides a method to trace parts of an attack back to the system architecture and industry regulations, recommendations and policies, which ensures that the security of CI is always based on the latest standards or identifies areas in which it is not.

Finally, this research extends the model based analysis of CI protection systems by considering the requirements that not only involve protection from potential threats but also industry standards and recommendations. CI is heavily regulations and standards-driven, so capturing what the standards are and how they apply to the system is an important facet that is not discussed in previous models. In addition, activity diagrams are modeled from the view of the attacker, not the protection system. Doing so allows a model user to easily evaluate specific nuances to various attacks when they occur and make changes to the architecture as vulnerabilities are exploited.

At the subsystem level, this research shows how activity diagrams can be linked to detailed OR models and provides decision makers with critical information for determining the best use of security resources. Another contribution is the expansion of the bi-level model by Medal [2016] to include directional antennas and power to provide more fidelity in the model for our application. The original work by Medal [2016] used omnidirectional antennas to represent both the communication and jammer nodes in an ad hoc wireless network and did not consider the power available for each node. In this work, directional antennas are used for the communication nodes, which allows for a reduced chance of jamming within the network. Also, the battery capacity available for each node is considered for the communication nodes. This is an important extension to make because it allows network designers a more realistic model for determining network parameters that make their designs more robust against jamming attacks.

In summary, the primary contribution to the literature is an approach for VA of human and system CI architectures that can be used by decision makers to determine the best use of security resources. In addition, by using standard systems engineering frameworks and tools, this method allows systems engineers to do CI VA at the architecture level. The next chapter explains the generic approach in detail.

CHAPTER III

METHOD FOR CRITICAL INFRASTRUCTURE VULNERABILITY ASSESSMENT

3.1 Introduction

This chapter explains the new step by step approach for CI VA developed in this research. Once the method is described in this chapter, it will be executed in chapter 4 with an illustrative example. The process for VA begins with a decision maker determining that a VA needs to be done and the questions that they would like answered. After that is determined, the method developed is used to for CI VA. The complete approach is shown in Figure 1.2. Each of the paths in Figure 1.2, when executed and the result obtained, provide data for decision makers to make tradeoffs between multiple options for security resource investments. In this section, path 1(human) is presented in section 3.2, path 2 (system) is presented in section 3.3, path 3 (subsystem) is presented in section 3.4, and the summary of how all the data is aggregated for decision making is discussed in section 3.5.

3.2 Path 1: Human architecture analysis method

Using the NATO Human View for security analysis is a new research area that has not been explored in spite of the fact that human threats such as insiders (e.g., malicious employees) and external actors (e.g., terrorists) have been active in exploiting security vulnerabilities. As a result of these risks, the development of a general approach to understanding how each NATO Human View product can be used for security analysis is warranted to enable early evaluation of the security aspects of the system by system architects and decision makers. Architects and decision makers should note that analysis of these views is only one indicator of a potential insider, and other indicators should be used to understand an individual’s potential for malicious activity.

The NATO Human View is a means for analyzing the interactions, responsibilities, and other attributes of human beings within a system [NATO, 2010]. The approach presented in this section provides security analysts, architects, decision makers and others a view into the functions that are performed and skills that are present in an organization. This overview does not repeat the overviews and examples presented by Handley and Smillie [2008] and the NATO Research and Technology Organisation [2010]; rather, it presents a method for how to expand on the views to include the descriptions appropriate for security analysis. Although the content of the views presented by Handley and Smillie [2008] and NATO [2010] is the same, some of the numbers of the views differ, a distinction that will be noted in the applicable sections. The security features each view provides are summarized in Table 3.1.

Table 3.1 Summary of analysis of the NATO Human View and its products

Human View Product	Description	Security Features
HV-A: Concept	Conceptual view that shows a "high-level representation of the human component" of the system [NATO, 2010; 4]	Identification of human system interfaces and initial questions about vulnerabilities based on high level architectural view
HV-B1: Manpower projections	Personnel-related view that determines the needed number of individuals to be present at the organization at a specific time for the organization to function [NATO, 2010]	Times during the day, week, month or year that the system is most vulnerable based on the number of employees present in the work place
HV-B2: Career progression	Personnel-related view that indicates the competencies necessary for members of an organization to perform their jobs and advance in the job hierarchy [NATO, 2010]	Skills employees gain that can be used to exploit the system
HV-B3: Establishment inventory	Shows the current and future number of employees expected to be needed in a specific job category [NATO, 2010]	The number of employees in a specific job category that will be needed in the future coupled with outside information can help determine how employees will react to layoffs
HV-B4: Personnel policy	Enables the user to determine the rules, policies, and procedures that each employee is subject to during their time in the workplace [NATO, 2010]	Which personnel policies (e.g., security clearances) apply to particular employees to find potential hazards

Table 3.1 (continued)

Human View Product	Description	Security Features
HV-B5: Health Hazards	Captures potential health hazards toward humans [NATO, 2010]	Identification of hazards that could affect individuals' lives, health, and ability to complete required work. Overexertion could cause mental fatigue that terrorists could exploit through social engineering and exposing employees to health hazards could play a psychological role in causing resentment among employees to cause sabotage
HV-B6: Human characteristics	Product related to human factors and ergonomics that consider what an operator is able to accomplish in various settings under various operating conditions [NATO, 2010]	The proportion of jobs subject to security requirements (e.g., security clearances)
HV-C: Tasks	Illustrates the tasks and activities that humans fulfill within a system [NATO, 2010]	Identification of available competencies of employees and the relative security threat of knowledge of each one
HV-D: Roles	Demonstrates the relationships of authority between tasks and roles in a system [NATO, 2010]	Hierarchy of responsibility for completion of tasks, with which one can determine the tasks that a job positions affects if the holder of that positions acts maliciously
HV-E: Human Network	"Human Network" that investigates the interactions among humans within a system [NATO, 2010; 35]	The listing of individuals to whom an employee reports, so that one can determine those affected if an employee is determined to have spread dangerous material (e.g., malicious computer code)
HV-F: Training	Considers training, including requirements, risks, and the role of career progression for training [NATO, 2010]	Identification of the minimum level of training needed for an employee (with malicious intent) to affect a given facet of the system

Table 3.1 (continued)

Human View Product	Description	Security Features
HV-G: Metrics	Provides a method of measuring human performance based on the completion of tasks, courses and pre-set objectives for a particular job category [NATO, 2010].	A straightforward, metrical (pass/fail) determination of how to meet standards required to work in the system, which can show whether or not employees have shown competencies needed to affect a given part of the system, which is useful if that part is subject to malicious actions
HV-H: Human Dynamics	This view "provides the basis for human behavior and executable models that may be supported by simulation tools" [Handley and Smillie; 2008].	A comprehensive view that (1) in the case of SNA, shows the interrelationships among positions and tasks to indicate measures of centrality and identify the most important jobs, and (2) in the case of TTC analysis, shows the correlation between increased skill level and decreased TTC the functioning of the system

The HV-A starts the security analysis at a high level by showing the security analysts the key system interfaces and allowing identification of key questions or observations about the security of the human system interfaces. At a more detailed level, the HV-B products allow the identification of specific times of the day when the system is most vulnerable based on employee work schedules and the skill sets of the employees. Questions such as "which personnel need security clearances?" or "which employees are risks for malicious activity due to a future layoff?" are also answered by the HV-B.

After looking at employees and their job categories, the next step is to evaluate the security risks based on an employee's specific competency (HV-C), and, based on this level of competency, to determine the minimum training an employee needs to affect the system (HV-D, F). The employee's impact on the system is not only impacted by what the employee knows, but also by who the employee interacts with on the job or his or her human network (HV-E). One question that might be posed is the following: does an employee have access to people with more influence in the company or a higher level of permissions on the CI system? This information from the previous views can be used to develop a metric that can determine whether or not employees should be able to work on the system based on the security risk they impose (HV-G). Finally, all the previous products discussed can be used to create simulations and do analysis (HV-H). In the illustrative example in the next section, the HV-H will be used for social network and TTC analysis, but it can also be used for other analysis such as discrete event simulation. The outcome of this view is focused on answering the questions that architects need to answer for a decision maker, and that determines what modeling and simulation is done.

In the context of SNA, an HV-H diagram should fulfill the dual purposes of showing which people are responsible for fulfilling which tasks and providing additional information relevant to the social network that cannot be discerned from just one Human View. For example, a software program involving SNA, such as NodeXL, Gephi, or UCINET, could be used to organize the data in the form of nodes and edges [Choudhary and Singh, 2015]. Nodes could include positions or tasks that are subject to linkages that could be represented by edges. After identifying these nodes and edges, the analyst can run an analysis on the available data to gather information relevant for insider threat analysis. Such information might include centrality, so that the user could discover which positions are the most well-connected and have the easiest access to others in the organization.

Another application is time to compromise (TTC) analysis. TTC analysis determines how long it would take an individual with certain skillsets, training, and abilities to exploit a vulnerability. TTC information is relevant because it is another metric for how susceptible an organization's systematic layout might be to internal and external malicious actors. SNA and TTC analysis are merely two forms of analysis, but there are other forms of analysis that can use the data in the Human Views, such as discrete event simulation.

In the next section, the approach for systems analysis will be discussed.

3.3 Path 2: System architecture analysis method

In the approach to system architecture VA and decision analysis, a combination of DoDAF and OR will be used. DoDAF will form the basis of a model that includes industry standards and best practices, attack scenarios, and expert opinion. By using a model based approach, users of this approach can easily understand the traceability between vulnerabilities, system components and industry standards. Ultimately, a model is developed that allows decision makers to make tradeoffs between cost and the level of security effectiveness desired.

Figure 1.2, path 2 shows the overall approach. First, standards and requirements are gathered for the system. Next, reference documents and subject matter expert opinion are used to create a structural view of the system that is being evaluated. This can be an existing system ("as-is") or future system ("to-be"). Then, case studies of previous security incidents and potential future security vulnerabilities are used to create activity views. All this data is entered into a model based systems engineering tool so that traceability is established between all artifacts. This model can now be used to identify key security resources and gaps in security resources based on the traceability between the system, industry standards, and past and possible future attack scenarios. Based on this information and their experience, subject matter experts can determine the importance of various security resources. The expert opinion determined in this step is used to develop individual security effectiveness scores (ISES) for each security resource. The total security effectiveness (TSE) of the system can be selected by the decision maker and is used to develop a model for performing tradeoffs between a combination of security resources.

The approach is detailed in the sections below. Separate sections consider the approach for an existing system versus a system being built. If an architecture was not originally developed for an existing system, this process would be used to document the as-is system.

3.3.1 Step 1: Gather documentation

If there is a system that is in the planning stages ("to-be") and has not yet been built, this step will be used to gather all the information required to develop the architecture and attack scenarios. Sources such as subject matter experts, industry standards, textbooks and news articles can be used. For an existing system, one can gather all the technical documentation available and any reports of system attacks or vulnerabilities that have been identified.

The gathering of attack scenarios should not only focus on scenarios that are directly related to the specific system that is being analyzed, but it should also focus on systems that have common traits. For example, one can consider a case involving the security of a chemical plant that uses wireless cameras. If there are no reported incidents with the cameras, but there was an incident at an electrical substation where the same type of camera's wireless signal was jammed, then this scenario should be captured because of the core similarity in the attack vector. One should note that the step of gathering documentation will be revisited throughout this methodology because, as a better understanding of the system is gained, more documentation may be needed.

3.3.2 Step 2: Create list of requirements or statements

After gathering the documentation, the lists of requirements or statements are derived from what is collected. The reason that requirements or statements are used is because there may be a general recommendation that will be referenced in the architecture or specific requirements. CI documentation can contain recommendations that are general. For example, a recommendation may say that there should be a lighting system at an electrical substation, but it may not quantify how much coverage those lights should have. That information may be in another document, or the asset owner may be given the freedom to decide.

For each document, the list created at this step needs to be decomposed into distinct units so that they can be referenced in the structural view of the architecture. For example, if a standard includes an entire section on cyber security, that section will have to be decomposed into a referenceable list so that the different elements of the system can be mapped to the relevant sections.

3.3.3 Step 3: Create a structural view of the system

After the requirements are decomposed, a block diagram of the system should be created using an architecture framework or modeling language such as DoDAF or SysML. While only one structural view is identified for use, it is possible that multiple views would be created during this step as needed to support answering the decision maker's questions. CI systems can be very complex systems of systems, so it will be important to capture the system at the appropriate level for the questions that need to be answered. In addition, the meta-data descriptions for the blocks and flows should be filled in as completely as possible. This will aid in the evaluation of the architecture immediately and in the use of the architecture by other system architects in the future. Resources that are used should be identified clearly in the structural view; this will allow a seamless transition from this view to the analysis in step 8. During the current step, one should trace the resources identified in the architecture to the list of statements or requirements in step 2.

3.3.4 Step 4: create activity views of past and potential future attacks

Now that there is a baseline structure of the system, this step begins with reviewing the past attacks that were identified in the initial data gathering step. One should determine the following: has all the information on relevant attacks been gathered now that the structure of the system is understood? Once the team is comfortable that the data has been gathered, the first step is to create activity views of past attacks. These attacks will represent attacks not only on the exact system but also on systems that are fundamentally similar. For example, an industrial control system and information technology system are not exact matches, but there are enough similarities that there may be similar attack vectors used by an adversary.

Once previous attacks have been diagrammed, the next step is for the team to develop activity diagrams based on potential future attacks. For this step, subject matter experts should be used to review the architecture developed and identify other scenarios. In both the past and potential cases, these diagrams should capture all activities associated with the attacks they describe. The activities should capture who performed the action, what standards or methods were used, and the relevant inputs and outputs based on actions. During this step, one ought to trace the activities to the resources identified in the structural block diagram.

3.3.5 Step 5: Identify gaps in traceability

Now the requirements, structural and activity views are linked. The next step is to evaluate the traceability between these elements. A traceability diagram can be used to determine where there is no traceability between elements. The lack of traceability from a requirement to a structural block or from an attack activity to a structural block could be a gap that indicates a vulnerability. For example, if a recommended standard is that a substation should have lighting, but there is no lighting system in the architecture as a resource, then that could be a potential vulnerability. In addition, if an activity diagram shows that an attacker came at night and was not stopped because there was no security guard, and there is not a manned security resource in the structural diagram, then that could be a potential vulnerability based on past events.

3.3.6 Step 6: Collect subject matter expert surveys

At this stage, the complete architecture model has been built and evaluated for traceability between elements. The next step is for subject matter experts to evaluate the model and determine what security resources provide the most security effectiveness against the identified vulnerabilities. The security resources used here should be those identified in the structural view of the system. The vulnerabilities will be those identified in the activity diagrams.

The scores in this step can be derived through many means. One option is to have the subject matter experts rank the security resources individually as either not effective, somewhat effective, or very effective in terms of security effectiveness. The percent of subject matter experts that vote for a particular security resource can then be used to determine the effectiveness scores that will be used for modeling and analysis.

These effectiveness scores can vary based on different environments. For example, if someone has a system that is in a military facility, the effectiveness of an additional fence around the system may be less than a system that is in a rural area. This analysis will address how to compare such security scores in the last step.

3.3.7 Step 7: Create a model to enable analysis of alternatives

Now that the security effectiveness scores are determined for the security resources, the next step is to use the effectiveness scores and the cost of the resources to determine the cost required to meet the security effectiveness desired by a decision maker. The model developed in this step should seek to establish an effectiveness score that can be adjusted so that decision makers can select a lower security effectiveness if they need to lower their costs.

As an example, in the illustrative case study in Chapter 4, an OR model is used, but other models could be used. For the OR model, the assumptions, objective function, decision variables and constants in the model are major considerations. The assumptions should capture any information that the decision maker needs to know about the model. For example, for a new system ("to-be") with an intrusion detection system, does the cost capture the implementation and maintenance of the system or just the cost of the device? These costs must be as accurate as possible to get useful information out of the model. Next, the objective function of the model should use the identified resources (e.g., video surveillance) in the structural diagram as the decision variables. The constants for the costs and other parameters are very important to making the model useful for decision makers; if these costs are not properly defined, the result of the model will not be correct. This data can be obtained from vendor quotes or Internet searches for representative hardware or software. Sometimes, vendor quotes are proprietary, so that fact needs to be a consideration when determining when or how such data is shared outside of the entity that obtained the quote. Once the data obtained has been verified and the model is complete, the next step is to execute the model so the results can inform decision makers of their options.

3.3.8 Step 8: Perform analysis to support key decisions

The model should then be executed at various levels of security effectiveness. For the comparison of alternatives with different benefit scales, the model results can be compared by establishing a maximum security effectiveness, minimum security effectiveness, and percentages of effectiveness (e.g., 25%, 50%) based on model constraints. This will allow a comparison among the models for various sets of benefit scores, which is illustrated in the case study in the next chapter.

Once the analysis is complete, the results should be presented to the decision maker and the subject matter experts to determine what security investments should be made. The results should include the total security effectiveness (TSE) scores, the security resources, options for security effectiveness solution percentages, and the ISES originally derived from the subject matter experts. Chapter 4 demonstrates how to apply the methodology presented here to an electrical substation VA and decision analysis.

3.4 Path 3: Subsystem analysis method

The first step in this approach for deriving a subsystem level decision analysis model is to develop or use an existing OV-5b operational activity diagram of an attack scenario from system analysis path 2. Once an OV-5b has been derived from an attack scenario, the next step is to identify the list of questions that a decision maker or designer would like to be answered, which can be the questions identified in system analysis path 2 or they can be new questions. Then, the scenario is refined based on the questions that need to be answered, and, finally, a decision model is developed and analyzed. Figure 1.2, path 3 shows the sequence of these steps, which will be discussed in detail.

3.4.1 Step 1: Develop an OV-5b from an attack scenario

The first step in this process is the same as step 4 in Figure 1.2, path 2. The architecture development team should develop an OV-5b based on a previous or future attack scenario. In the case of a future scenario, the scenario should be reviewed by subject matter experts to evaluate the validity of the scenario. Once the validity of the scenario is established, the team should begin to work with decision makers and system designers to identify a list of questions that they would like to know about the scenario.

3.4.2 Step 2: Identify list of questions

Based on the attack scenario identified in step 1, decision makers and system designers will identify specific questions that they would like answered about the system. These questions could range from system configuration questions to design questions about how particular attack scenarios could be used to exploit their systems.

3.4.3 Step 3: Refine the scenario

Once the questions have been developed, the next step is to refine the scenario to answer the questions. This may include developing a diagram of a detailed attack to determine the parameters that will be needed for the decision model or interviewing subject matter experts for more detailed information about the particular behavior of hardware, software, people, policies or other attributes in the system. This step may not need to be performed if it is determined that the diagram developed in step 1 is sufficient for everyone to understand the scenario in sufficient detail to answer the questions. There will be a feedback loop between step 3 and 4, since it might be necessary to continue to refine the scenario as the assumptions of the decision model are better understood.

3.4.4 Step 4: Develop decision model

Once a refined scenario is developed, the next step is to develop a decision model to attempt to answer the questions presented in step 2. Some of the questions presented in step 2 may not be appropriate for the type of analysis presented here, and it may be determined what analysis is appropriate to answer those questions. The decision model step will identify assumptions and further details needed to develop a decision model that will be useful for decision makers and designers. While in the illustrative example, a BLMIP is used, network simulation tools such as OPNET, Network Simulator 2, and OMNet++ could also be used. . It is expected that subject matter experts may need to be queried during this step to determine the best path forward for selecting parameters and reasonable assumptions.

3.5 Aggregating the results for analysis

After all three paths are complete, the analysis results for each path allow the decision maker to determine the security investments of the overall system based on available resources. For example, the decision maker could choose to invest all their funds in background checks or some in additional sensors and some in additional wireless network nodes. This aggregation step is currently executed manually by the decision maker and potentially a team that they choose. In the next section, the approach is applied to an electric power system as a case study.

CHAPTER IV

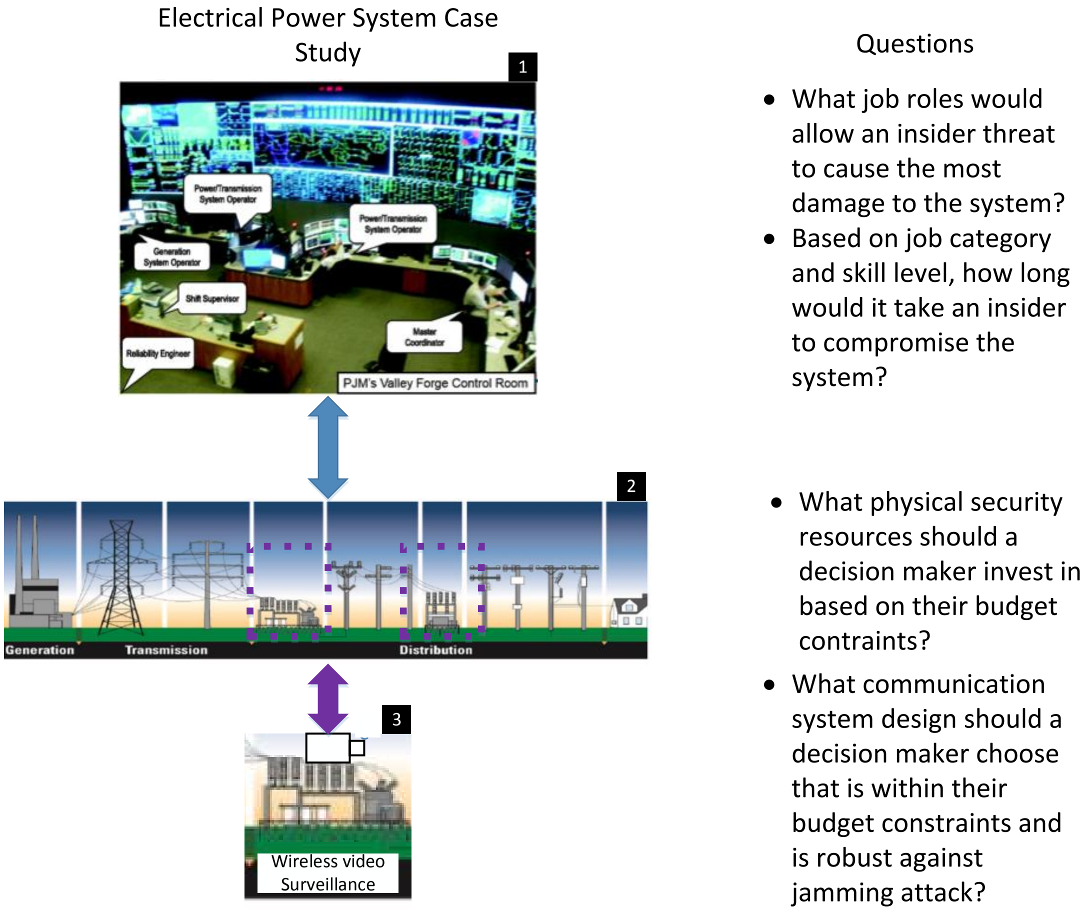
ILLUSTRATIVE CASE STUDY: ELECTRIC POWER SYSTEM VULNERABILTITY ASSESSEMENT

4.1 Introduction

The method presented in Figure 1.2 and explained in chapter 3 is illustrated in this chapter through an electric power system case study. The case study begins with a decision maker determining the purpose of the VA. The scenario is as follows.

> A decision maker at an electric utility has $1,000,000 to invest in security. The decision maker requests that the engineers on the team do an architecture level VA with a focus on operations, substations and wireless video monitoring. For the operations (path 1 in Figure 1.2), the decision maker wants to know which roles and job skill levels could cause the most damage to the system. For the system level (path 2 in Figure 1.2), the decision maker wants to know which security resources would be the most effective to mitigate vulnerabilities in an electrical substation. For the subsystem level (path 3 in Figure 1.2) the decision maker wants to know how to make the wireless network design robust against a jamming attack. Where should the decision maker invest the funds?

The case study will cover the each of the paths presented in Figure 1.2 and in each section (human, system, and subsystem) the questions shown in Figure 4.1 will be answered. The numbers in Figure 4.1 correlate to the analysis path that will be followed from Figure 1.2. The case study begins with an analysis of the human architecture in section 4.2, then the system architecture in section 4.3, and finally the subsystem architecture in section 4.4. All the results are used to help the decision maker determine how to invest the $1M in section 4.5.



Electrical Power System Case Study

1
Power/Transmission System Operator
Power/Transmission System Operator
Generation System Operator
Shift Supervisor
Master Coordinator
Reliability Engineer
PJM's Valley Forge Control Room
2
Generation
Transmission
Distribution
3
Wireless video Surveillance

Questions

- What job roles would allow an insider threat to cause the most damage to the system?
- Based on job category and skill level, how long would it take an insider to compromise the system?

- What physical security resources should a decision maker invest in based on their budget contraints?
- What communication system design should a decision maker choose that is within their budget constraints and is robust against jamming attack?

Figure 4.1 Case study questions

4.2 Illustrative case study: Human architecture assessment (path 1)

4.2.1 Introduction to electrical utility operations and security

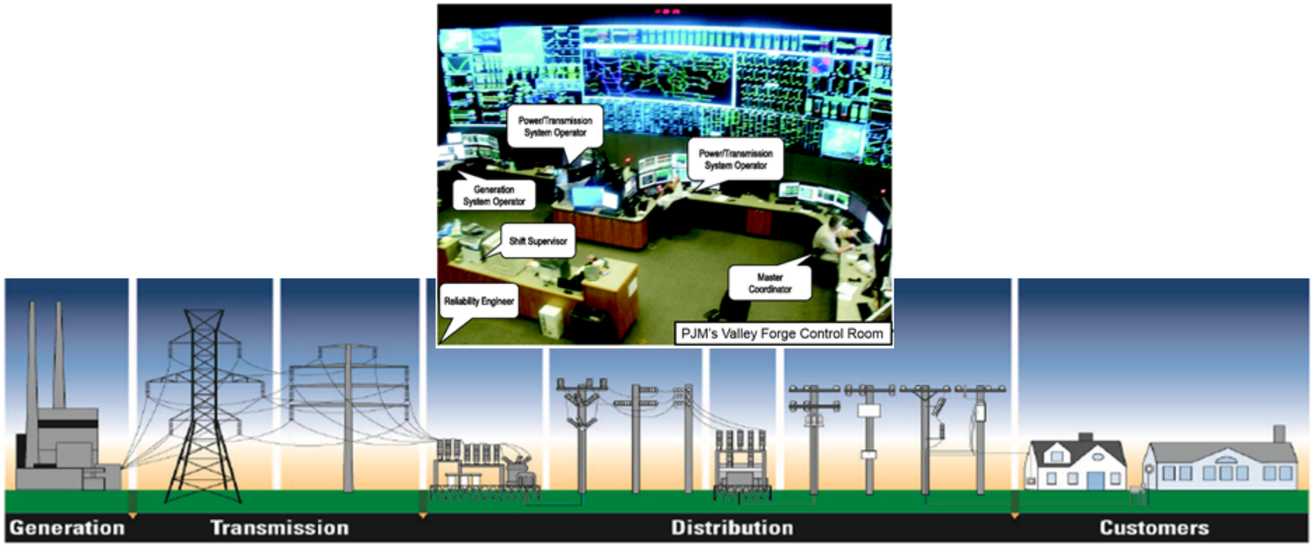
The energy sector of CI utilizes both human beings and technology for the completion of tasks critical for the function of electrical generation, transmission and distribution. Because electrical utilities' operations are so integral to the well-being of society, it is imperative to consider the areas in which they could be vulnerable. For this case study, identifying insider threats will be the focus of the analysis, since insiders have been identified as a means to exploit vulnerabilities within electrical utilities [Luallen, 2011]. Luallen describes an insider as "anyone who has approved access, privileges or knowledge of information systems, information services and missions" [2011: 2]. The unique value of these human views is to provide a systems-level view of human organizations' functionality on a day-to-day basis, in areas ranging widely from training requirements to safety hazards. For this chapter, the NATO Human View was constructed based on job descriptions for the San Diego Gas and Electric Company (SDG&E) [2016] and Apprenticeship Guidelines from Pacific Gas and Electric Company [2011]. Many of the human views in this case study are partial views, and the complete views are available upon request. The purpose of this case study is to show how the Human Views can be used with the most realistic data openly available. Thus, to use the methods discussed in practice, organizations would have to substitute their real data for the data used here.

4.2.2 HV-A: Concept

The HV-A for electrical utility operations is shown below in Figure 4.2. The top of the figure shows an operations center and the physical equipment that is used in the flow of power from its generation to consumer's homes and businesses. The bottom of the figure has text that discusses the roles of humans as well as some questions relative to vulnerabilities that may be relevant for utility operations.

The generation section of the electrical grid relies on employees in the plants to work together to maintain equipment that generates electricity to provide to consumers. The primary question is as follows: how easily can employees or people outside the plant tamper with generation equipment and computer systems? This subject could lead to follow-on questions such as the following: are badges required to get access to the facility? Also, transmission and distribution are the next sections of the system where various roles that employees fill are identified. In that context, the following questions are raised: Can any of the employees in these areas or terrorists gain access to the systems for malicious purposes? At a high level, what are the controls in place to prevent such an occurrence? Finally, on the consumer side, are there systems that consumers can access that would potentially damage the entire system?

The initial discussions when developing and evaluating the HV-A prepare the team for the high-level security issues with the system. These issues will be explored in more detail in views B through H.


Power/Transmission System Operator
Power/Transmission System Operator
Generation System Operator
Shift Supervisor
Reliability Engineer
Master Coordinator
PJM's Valley Forge Control Room
Generation
Transmission
Distribution
Customers

Human Roles: Requires involvement of staff members to supervise and execute the production of electricity using fuel. **Vulnerabilities:** Can employees tamper with generation equipment and control systems?	**Human Roles:** Requires involvement of staff members in various areas such as grid control, grid operations, technical support, engineering general support and analysis, transmission systems, EMS operations, control systems, compliance, software, outage coordination, training, business systems, document control, hardware, project management, etc. **Vulnerabilities:** Are transmission systems vulnerable to attacks by maintenance personnel (insiders) or terrorists?	**Human Roles:** Requires involvement of staff members in various areas such as grid control, grid operations, technical support, engineering general support and analysis, distribution systems, EMS operations, control systems, compliance, software, outage coordination, training, business systems, document control, hardware, project management, etc. **Vulnerabilities:** Are distribution systems vulnerable to attacks by maintenance personnel (insiders) or terrorists?	**Human Roles:** Requires involvement of customers willing to utilize and pay for service. **Vulnerabilities:** Can customers tamper with meters and impact overall system operation?

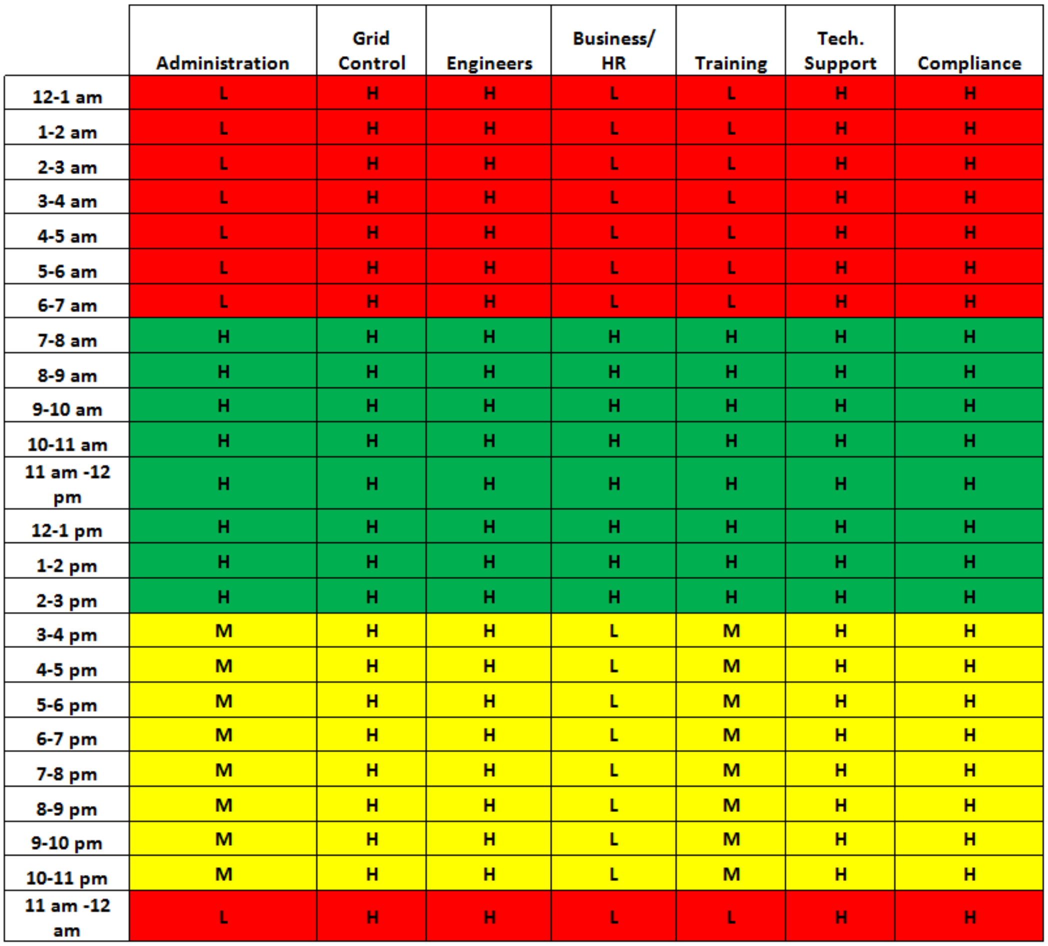
Figure 4.2 Human View A for electrical utility operations [San Diego, 2016; Hiskens, 2013]

4.2.3 HV-B1: Manpower projections

The HV-B1 for electrical utility operations shown in Table 4.1 is based on several assumptions: 1) The job divisions within the company are those identified in Table 4.1, which have been deemed to be necessary for the proper functioning of the company; 2) Since electrical utilities operate 24 hours a day, employees must be present at all times; 3) The workday is divided into three distinct shifts in which the system is maintained, similar to the workday for many workplaces in the real world, with eight-hour shifts beginning at 7:00 am, 3:00 pm, and 11:00 pm; and 4) The likelihood of a worker in a certain job division being present is based on the perceived need for members in each job division to be present, with all workers being present during the day shift (7:00 am to 3:00 pm) and only critical, safety-related employees and possibly trainees and managers being present at other times.

The model, including these perceived likelihoods and categories of job divisions, is included in Table 4.1. In Table 4.1, on the vertical axis, the hours of the workday are shown beginning at midnight and ending at the following midnight. The HV-B1 helps analysts to determine whether there is a high (H), medium (M), or low (L) likelihood that a specific group of employees will be present during any one of the three shifts. For instance, among the types of employees listed on the horizontal axis at top, engineers are shown as having a “high” likelihood of being present during all three shifts; this is the case because engineers’ presence is critical at all times for the safe functioning of the system. On the other hand, employees related to business and human resources (HR) are more likely to be present during the daytime (regular hours), but they are less likely to be present at night simply because they are not integral for the functioning of the system at that time. In other words, they can accomplish necessary tasks such as hiring and disbursing payroll during the day shift, but they are not needed for such tasks at night.

Table 4.1 Human View B1 for job divisions and shifts of the electrical utility system



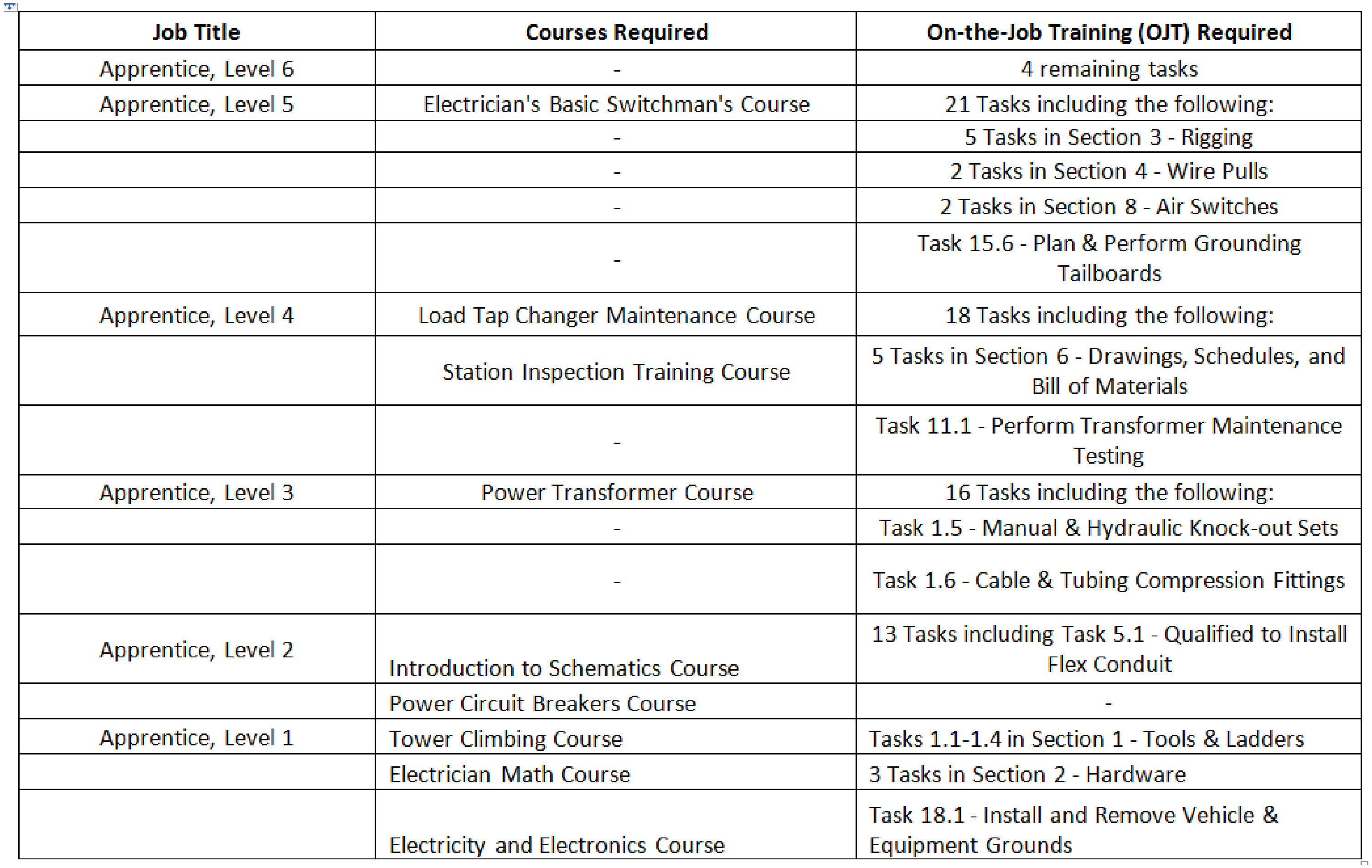
	Administration	Grid Control	Engineers	Business/ HR	Training	Tech. Support	Compliance
12-1 am	L	H	H	L	L	H	H
1-2 am	L	H	H	L	L	H	H
2-3 am	L	H	H	L	L	H	H
3-4 am	L	H	H	L	L	H	H
4-5 am	L	H	H	L	L	H	H
5-6 am	L	H	H	L	L	H	H
6-7 am	L	H	H	L	L	H	H
7-8 am	H	H	H	H	H	H	H
8-9 am	H	H	H	H	H	H	H
9-10 am	H	H	H	H	H	H	H
10-11 am	H	H	H	H	H	H	H
11 am -12 pm	H	H	H	H	H	H	H
12-1 pm	H	H	H	H	H	H	H
1-2 pm	H	H	H	H	H	H	H
2-3 pm	H	H	H	H	H	H	H
3-4 pm	M	H	H	L	M	H	H
4-5 pm	M	H	H	L	M	H	H
5-6 pm	M	H	H	L	M	H	H
6-7 pm	M	H	H	L	M	H	H
7-8 pm	M	H	H	L	M	H	H
8-9 pm	M	H	H	L	M	H	H
9-10 pm	M	H	H	L	M	H	H
10-11 pm	M	H	H	L	M	H	H
11 am -12 am	L	H	H	L	L	H	H

In terms of predicting at which time of a day an insider threat is most likely to be successful, this view indicates when particular employees are most likely to be present without supervision. As previously discussed, engineers are highly likely to be present during all three shifts, but business and HR workers are probably present only during the main day shift (7:00 am to 3:00 pm). If someone is intending to perpetrate a malicious action, it is probably easier to do so when fewer employees are present to watch their actions and practice surveillance [Brass et al., 1998]. The evidence from the HV-B1 indicates that the day shift has a greater likelihood of many employees being present to practice surveillance. A color-coded range of times is used to indicate the relative supervision level for a given time of day, with red denoting the least-supervised shift, yellow denoting the shift with a moderate level of supervision, and green denoting the most-supervised shift. Since the day shift (7:00 am to 3:00 pm) had already been identified as the shift where people are most likely to be present, its hourly ranges were color-coded with green. The next shift, 3:00 pm to 11:00 pm, includes employee categories such as training and administrative staff that may be present but are not guaranteed to be so, so its hourly time ranges were made to be yellow. Finally, the last shift, 11:00 pm to 7:00 am, is believed to represent the time of day when only critical safety-related employees like engineers would probably be present; for that reason, it is color-coded with red. HV-B1 thus provides a clear picture of the manpower requirements for a given time of day and illustrates when workers are more and less likely to be present to practice surveillance against other employees that might pose an insider threat.

4.2.4 HV-B2: Career progression

The HV-B2 for electrical utility operations shown in Table 4.2 is used to indicate the skills and competency requirements for substation maintenance electricians. This data is from PG&E’s substation maintenance electrician apprenticeship guidelines [Pacific, 2011]. The HV-B2 only captures one job category, so one of these views will need to be developed for each job category when a utility uses this method. For the given apprenticeship, the employee must complete the courses listed in the center column and the on-the-job training indicated in the right-hand column. For instance, during level 2 of career advancement, an apprentice must complete the following classes: Introduction to Schematics and Power Circuit Breakers. According to the HV-B2, the apprentice must also successfully complete 13 tasks including Task 5.1 – Qualified to Install Flex Conduit to advance to the next stage of the apprenticeship, level 3. This view's significance is that it provides a clear indication of what requirements are necessary to advance into higher positions within the employment hierarchy, which provides an obvious pass-fail metric for career advancement and for the analyst to see what skills employees at a specific level have.

Table 4.2 Human View B2 for electrical utility system’s apprenticeship job level advancement requirements [Pacific, 2011]



Job Title	Courses Required	On-the-Job Training (OJT) Required
Apprentice, Level 6	-	4 remaining tasks
Apprentice, Level 5	Electrician's Basic Switchman's Course	21 Tasks including the following:
	-	5 Tasks in Section 3 - Rigging
	-	2 Tasks in Section 4 - Wire Pulls
	-	2 Tasks in Section 8 - Air Switches
	-	Task 15.6 - Plan & Perform Grounding Tailboards
Apprentice, Level 4	Load Tap Changer Maintenance Course	18 Tasks including the following:
	Station Inspection Training Course	5 Tasks in Section 6 - Drawings, Schedules, and Bill of Materials
	-	Task 11.1 - Perform Transformer Maintenance Testing
Apprentice, Level 3	Power Transformer Course	16 Tasks including the following:
	-	Task 1.5 - Manual & Hydraulic Knock-out Sets
	-	Task 1.6 - Cable & Tubing Compression Fittings
Apprentice, Level 2	Introduction to Schematics Course	13 Tasks including Task 5.1 - Qualified to Install Flex Conduit
	Power Circuit Breakers Course	-
Apprentice, Level 1	Tower Climbing Course	Tasks 1.1-1.4 in Section 1 - Tools & Ladders
	Electrician Math Course	3 Tasks in Section 2 - Hardware
	Electricity and Electronics Course	Task 18.1 - Install and Remove Vehicle & Equipment Grounds

In terms of insider threat analysis, the architects can determine which workers have the given skills to perform certain malicious actions against the electrical transmission and distribution system. For instance, if the analyst wants to see which employees have the capability to exploit power transformers because they are vulnerable to attack, they would evaluate the record of level 3 apprentices and above since those individuals have power transformer knowledge and skills. Because insider threat analysis may be lengthy and time sensitive, the use of HV-B2 can provide assistance with a relatively fast and easy metric to see which workers meet the minimum knowledge standard necessary to exploit a particular vulnerability.

4.2.5 HV-B3: Establishment inventory

In electrical utility operations, it is important to understand the manpower required to maintain operations. The HV-B3 shown in Table 4.3 uses data from the federal Bureau of Labor Statistics to forecast the number of workers needed in specific job categories in the electrical transmission and distribution sector with information collected for 2014 and projected to 2024 [Bureau, “221100” 2015; Bureau, “17-2070” 2015]. This view shows the relative number of employees expected to be needed in a category of workers and the growth prospects of a particular type of job in the economy over the next several years. For instance, Table 4.3 indicates that the number of needed electrical and electronics engineers for utilities involved in electric power generation, transmission, and distribution will experience a net shrinkage of approximately 1,900 jobs over the decade following 2014.

Table 4.3 Human View B3 data [Bureau, “221100” 2015; Bureau, “17-2070” 2015]

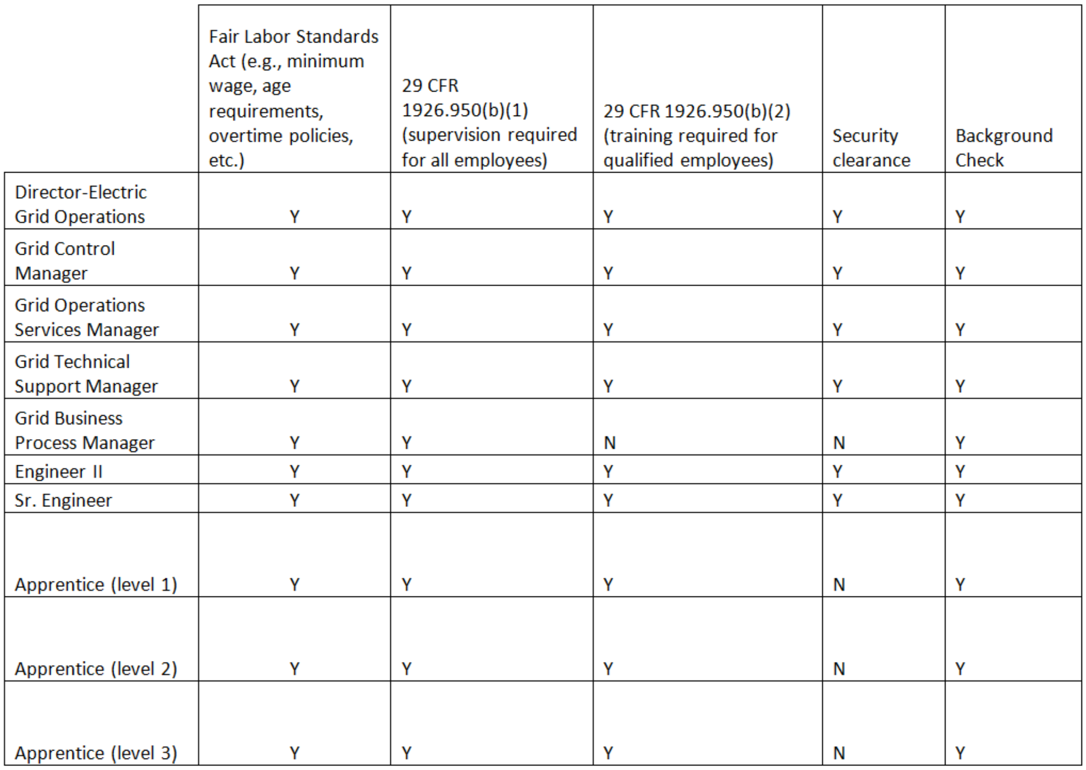
	Years for Employment (in thousands)	
Type of Manpower	2014	2024 (projected)
Electrical and electronic equipment mechanics, installers, and repairers for utilities involved in electric power generation, transmission, and distribution	15.8	14.2
Electrical and electronics repairers, powerhouse, substation, and relay for utilities involved in electric power generation, transmission, and distribution	14.5	13.0
Electrical and electronics engineers for utilities involved in electric power generation, transmission, and distribution	17.9	16.0

From a security vulnerability perspective, the HV-B3 assists in determining, if crudely, the likelihood that a particular type of worker might be needed in the coming years, and it can be coupled with other analysis of specific employee behavior to determine if they would potentially be malicious if laid off. If particular kinds of employees are not as likely to be needed or feel that they are becoming “expendable” because their skills are not needed as much as they were needed previously, those employees might be more likely to pose a threat to the organization for which they work because of resentment. This view would have to be coupled with other psychological factors, but could be an initial flag to an organization to begin to review specific employee records based on upcoming workforce projections.

4.2.6 HV-B4: Personnel policy

The HV-B4 in Table 4.4 describes a subset of the regulations, laws, and policies applied to particular positions at the SDG&E [2016]. One policy that is likely applicable to at least some of the employees would be 29 CFR 1926.950(b)(2), which details the requirements for training qualified employees for constructing new and altering existing electrical transmission and distribution lines [Occupational, 2015]. This requirement is indicated as being applicable or not applicable to a particular job title by using a "Y" for "yes" or an "N" for "no" in the applicable box in Table VI. For instance, the training required by 29 CFR 1925.950(b)(2) for qualified employees appears to be more applicable to persons having a direct interaction with the electrical grid, such as the Sr. Engineer; on the other hand, the Grid Business Process Manager, who is responsible for tasks such as contracting and invoicing, probably does not do direct work on the electrical grid system itself, so her job has an "N" listed, evidencing that the requirement is not applicable to her job responsibilities [San Diego, 2016].

Table 4.4 Personnel policies applicable to senior level employees [Pacific, 2011; San Diego, 2016]



	Fair Labor Standards Act (e.g., minimum wage, age requirements, overtime policies, etc.)	29 CFR 1926.950(b)(1) (supervision required for all employees)	29 CFR 1926.950(b)(2) (training required for qualified employees)	Security clearance	Background Check
Director-Electric Grid Operations	Y	Y	Y	Y	Y
Grid Control Manager	Y	Y	Y	Y	Y
Grid Operations Services Manager	Y	Y	Y	Y	Y
Grid Technical Support Manager	Y	Y	Y	Y	Y
Grid Business Process Manager	Y	Y	N	N	Y
Engineer II	Y	Y	Y	Y	Y
Sr. Engineer	Y	Y	Y	Y	Y
Apprentice (level 1)	Y	Y	Y	N	Y
Apprentice (level 2)	Y	Y	Y	N	Y
Apprentice (level 3)	Y	Y	Y	N	Y

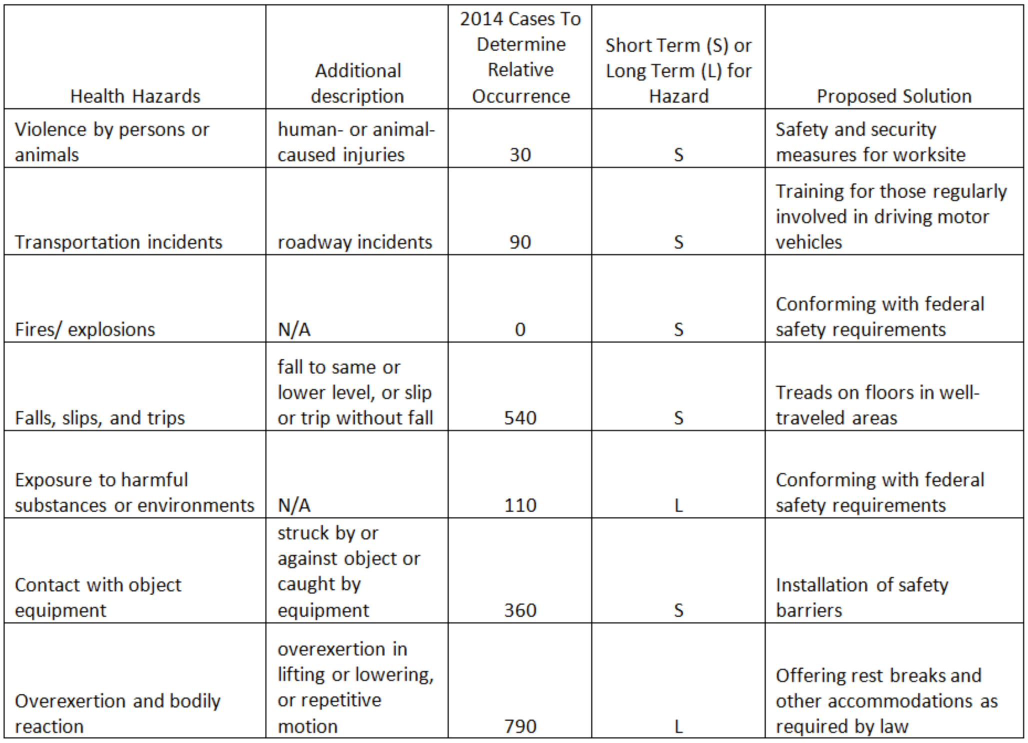
The HV-B4 is useful for VA because analysts can determine which employees are more prone to engaging in threatening behavior by detecting which of them are subject to certain types of regulations (e.g., supervisory regulations). It is possible that those persons' subject to more supervised training would have more time to be evaluated by others as malicious or not and may have been more likely to have been identified already as constituting potential insider threats. In contrast, those not subject to supervisory regulations, such as the Grid Business Process Manager, may be more likely not to have been identified as insiders. While this example is very situation-dependent, it gives an idea how this information can be used.

In addition, some security clearance and background check requirements can help determine which employees seem more prone to questionable behavior than others. For example, the Document Coordinator, because his business-related job is the least closely connected to the electrical grid operations, may be a lower priority to require a special security clearance among all of the relatively senior officials listed in Table 4.4. Although the Document Coordinator is also less likely to be exposed to sensitive information, it does indicate that he or she is less likely to be detected if he or she chooses to act maliciously and tries to steal sensitive information that is known to employees with whom the Document Coordinator interacts daily. In such a case, insider threat analysts can have a means with which to determine which employees might be the most dangerous – by detecting which ones are not subject to additional security checks like background checks and by seeing which ones are subject to supervision (even indirect supervision) while learning to perform their jobs. Some of the available information from HV-B4, as applied here, can help to detect such individuals.

4.2.7 HV-B5: Health hazards

HV-B5 is a view related to Human Factors and Ergonomics (HFE) that considers the characteristics of a system that could injure its users or participants [NATO, 2010]. As shown in Table 4.5 below, various health hazards can be determined and are listed together at the left side of the table with their relative occurrence rates and proposed solutions as categories. Whether the hazard is short-term or long-term is also noted in the figure in the fourth column. An example of a potentially dangerous characteristic is falls, slips, and trips, which caused 540 accidents in 2014 in the electrical transmission and distribution utilities sector. A proposed solution, listed on the right of the row for that hazard, is putting treads on floors in certain areas to minimize slippage. Additionally, the hazard is marked with an "S," meaning that it is a short-term hazard, because generally a fall, slip, or trip takes place almost instantly and does not require much time to cause serious damage.

Table 4.5 Listing of potential health hazards for employees



Health Hazards	Additional description	2014 Cases To Determine Relative Occurrence	Short Term (S) or Long Term (L) for Hazard	Proposed Solution
Violence by persons or animals	human- or animal-caused injuries	30	S	Safety and security measures for worksite
Transportation incidents	roadway incidents	90	S	Training for those regularly involved in driving motor vehicles
Fires/ explosions	N/A	0	S	Conforming with federal safety requirements
Falls, slips, and trips	fall to same or lower level, or slip or trip without fall	540	S	Treads on floors in well-traveled areas
Exposure to harmful substances or environments	N/A	110	L	Conforming with federal safety requirements
Contact with object equipment	struck by or against object or caught by equipment	360	S	Installation of safety barriers
Overexertion and bodily reaction	overexertion in lifting or lowering, or repetitive motion	790	L	Offering rest breaks and other accommodations as required by law

From the perspective of an insider threat analyst, HV-B5 can give an idea of how an insider could potentially cause damage to those around him so as to decrease supervision and act maliciously with a decreased fear of being discovered. For instance, one health hazard listed is "violence by persons or animals." In that context, someone could expose his or her co-workers to the possibility of violence, whether by physical means (e.g., bringing a handgun to the workplace) or by cyber means (e.g., sabotaging a computer system such that safety warning messages are not shown when hazards are present). A pattern in these types of safety issues coupled with a specific individual's involvement several times might be a red flag. Constructing a model for HV-B5 can assist analysts with identifying methods of potential threats. Furthermore, the category including overexertion has a relative occurrence of 790 injuries in 2014. Although overexertion might be thought of as just a personal, physical problem, it could also pose a threat because overexertion can cause cognitive fatigue and decreased vigilance – the perfect elements that an insider could use to act with a lessened worry of discovery [Gawron, 2015]. These are the type of vulnerabilities that may not be exposed in a traditional VA but are brought to the forefront when analyzing with the NATO Human View.

4.2.8 HV-B6: Human characteristics

The Human View B6 (HV-B6) shown in Table 4.6 is based on assumptions that will be explained further below and is another view properly placed in the HFE category. In the HV-B6, the architects can consider the characteristics required for an employee to complete the tasks required for his or her position in the organization: for example, the ability to lift up to 25 pounds [NATO, 2010]. This particular case study considers the multitude of people employed at the organization and determines the number of workers that must satisfy a given requirement. The assumptions required for the data include the following: 1) The various categories of attributes needed for employees within the organization include physical, sensory (e.g., visual and auditory), cognitive, and security-related attributes, as an example, and 2) based on the perceived need for a given attribute within the organization, the number of jobs to which the characteristic seems applicable has been chosen as all, most, many, some, or none, to more easily illustrate the data in Table 4.6. As an example, some engineers may need to lift large weights if they deal with machines with heavy parts, but HR employees probably do not have to lift large weights because they deal with business- and human-related tasks; consequently, such a characteristic would seem to apply to "some" workers in the organization.

Table 4.6 Listing of required attributes for employees

Category	Characteristic	Further description of characteristic	Number of jobs to which the characteristic seems applicable
Physical	Sit	N/A	All
	Walk	N/A	Most
	Operate equipment with hands	N/A	Most
	Reach with hands and arms	N/A	Most
	Lift and move up to 25 lbs of weight	N/A	Some
Visual, Auditory, Etc.	Walk, talk, and hear (at the same time)	N/A	Most
	Hear (DOT hearing standards)	N/A	Most
	Close vision	N/A	Most
	Distance vision	N/A	Most
	Color vision	N/A	Most
	Peripheral vision	N/A	Most
	Depth perception	N/A	Most
	Ability to adjust focus	N/A	Most
Cognitive	Critical thinking	N/A	Most
	Understanding of language	English as well as other languages, if needed	All
Security	Social engineering	Pretexting, phishing, etc., by electronic or other means.	All
	Safeguarding of confidential or proprietary information	Any company-related or security risk-protected information	Many

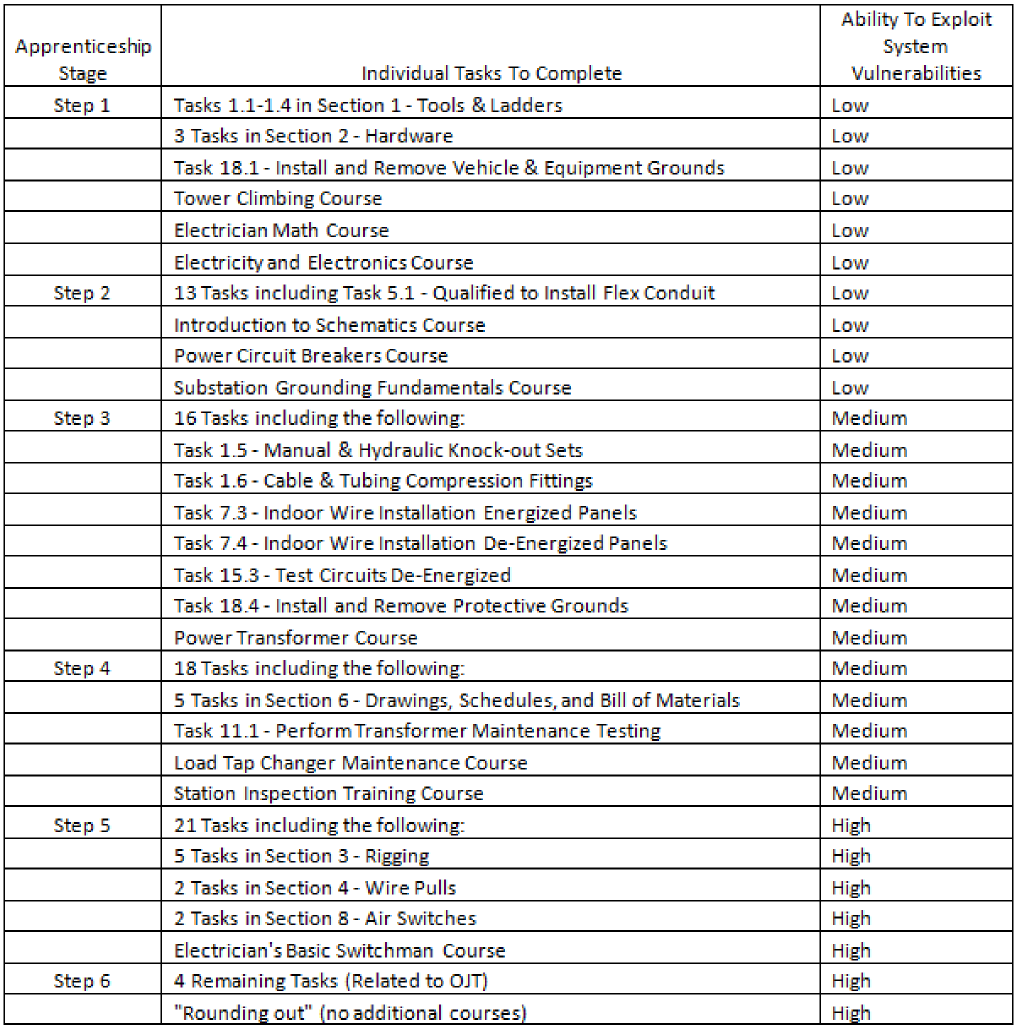
This type of NATO Human View product can help insider threat analysts by informing them about which employees need security-related abilities and competencies to perform their job duties. For example, the security category includes the ability to safeguard confidential or proprietary information. Electrical utility employees have access to information that should be safeguarded. This information can be useful if insider threat analysts are concerned about the potential disclosure of confidential or proprietary information by employees. They can tell that many employees are given at least some amount of access to either confidential or proprietary information and can exclude the fraction of workers that are not subject to the requirement from surveillance, which could save time and money.

Table 4.6 contains high level data, but, depending on the risk of this threat to an organization, this view can be further detailed to show the specific proprietary information mapped to specific employees that have access. Such pre-work could reduce the time needed to determine possible insiders if there was ever a security issue.

4.2.9 HV-C: Tasks

An HV-C for electrical utility operations is shown in Table 4.7. The HV-C indicates the order of the tasks required for apprenticeship candidates to complete in order to advance to a higher stage, which constitutes a higher skill level. Additionally, the table shows the relative ability of an apprentice at each stage of apprenticeship to exploit system vulnerabilities. For this case study, the levels of apprenticeship are defined as "low", "medium," and "high" in terms of the ability to exploit vulnerabilities. In other words, the apprentice will have the capability to perform much more complex exploits of vulnerabilities once she has attained one of the top two levels of apprenticeship by undergoing extensive training. As the apprentice proceeds to higher levels, she has the means to act maliciously in a way that she did not at a lower level of training. For example, once the apprentice at stage 5 has completed tasks related to substation inspections, the apprentice may be more knowledgeable about the vulnerabilities of the overall system and better able to exploit such vulnerabilities from within the system.

Table 4.7 Listing of tasks required for apprenticeship advancement and ability to exploit system vulnerabilities



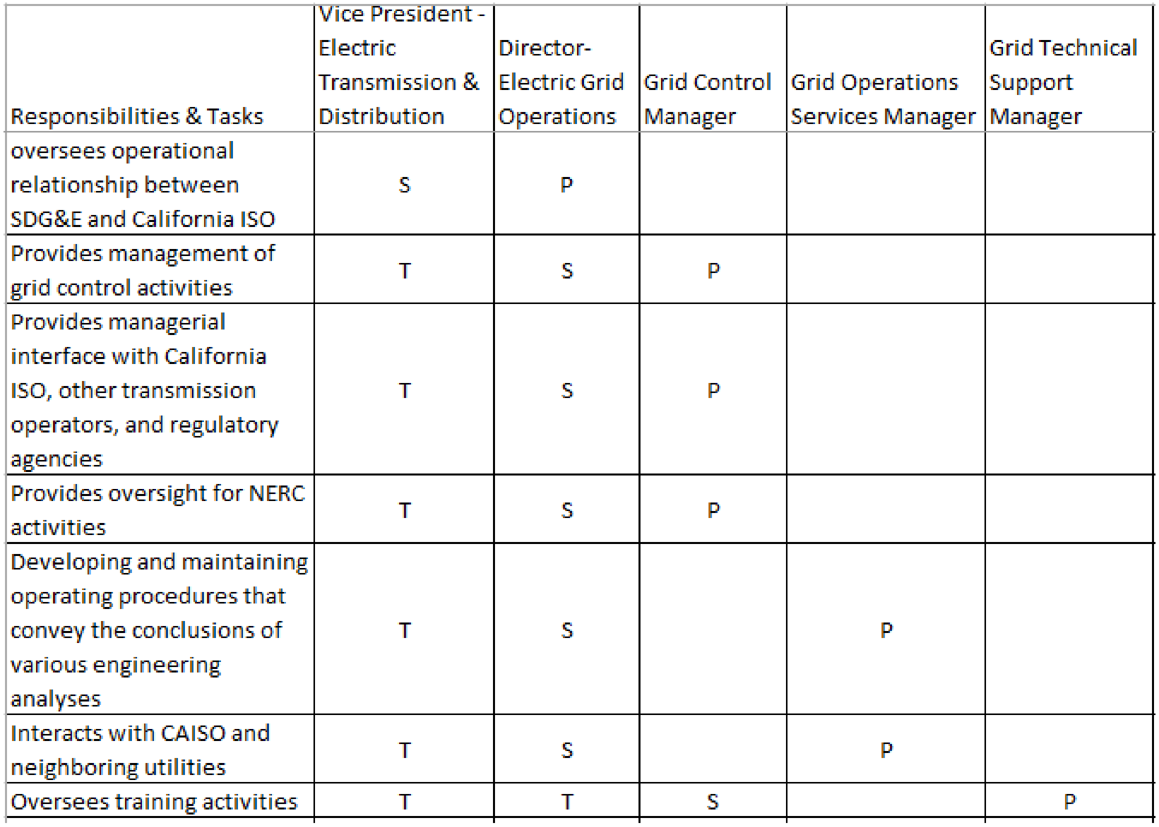
Apprenticeship Stage	Individual Tasks To Complete	Ability To Exploit System Vulnerabilities
Step 1	Tasks 1.1-1.4 in Section 1 - Tools & Ladders	Low
	3 Tasks in Section 2 - Hardware	Low
	Task 18.1 - Install and Remove Vehicle & Equipment Grounds	Low
	Tower Climbing Course	Low
	Electrician Math Course	Low
	Electricity and Electronics Course	Low
Step 2	13 Tasks including Task 5.1 - Qualified to Install Flex Conduit	Low
	Introduction to Schematics Course	Low
	Power Circuit Breakers Course	Low
	Substation Grounding Fundamentals Course	Low
Step 3	16 Tasks including the following:	Medium
	Task 1.5 - Manual & Hydraulic Knock-out Sets	Medium
	Task 1.6 - Cable & Tubing Compression Fittings	Medium
	Task 7.3 - Indoor Wire Installation Energized Panels	Medium
	Task 7.4 - Indoor Wire Installation De-Energized Panels	Medium
	Task 15.3 - Test Circuits De-Energized	Medium
	Task 18.4 - Install and Remove Protective Grounds	Medium
	Power Transformer Course	Medium
Step 4	18 Tasks including the following:	Medium
	5 Tasks in Section 6 - Drawings, Schedules, and Bill of Materials	Medium
	Task 11.1 - Perform Transformer Maintenance Testing	Medium
	Load Tap Changer Maintenance Course	Medium
	Station Inspection Training Course	Medium
Step 5	21 Tasks including the following:	High
	5 Tasks in Section 3 - Rigging	High
	2 Tasks in Section 4 - Wire Pulls	High
	2 Tasks in Section 8 - Air Switches	High
	Electrician's Basic Switchman Course	High
Step 6	4 Remaining Tasks (Related to OJT)	High
	"Rounding out" (no additional courses)	High

In terms of indicating an insider threat, this category of NATO Human View product can demonstrate the interdependencies of various tasks and allows the analyst to determine which employees have the unique combination of tasks and skills required to participate in specific exploitation activities. As an example, once the apprentice has reached stage 4 and can perform transformer maintenance testing, the apprentice would have some knowledge of transformers. If, at that time, insider threat analysts are concerned about the vulnerability of transformers to sabotage or some other threat, they can determine that only apprentices that have reached step 4 and completed the class related to transformer maintenance testing have the means to act as insider threats. Furthermore, if analysts are concerned about substation distribution equipment in conjunction with transformers, they can determine that only level 5 apprentices that have completed substation distribution switching tasks and that have previously passed the necessary transformer-related tasks during stage 4 have the ability to pose a threat to the system from within. Accordingly, HV-C assists with defining the human-related abilities of a given system and can help with determining which humans have the means to act maliciously against a given electrical distribution and transmission system. In the HV-H discussion, such skill level information will be used for TTC analysis.

4.2.10 HV-D: Roles

The HV-D shown in Table 4.8 consists of individuals’ job descriptions from PG&E, including responsibilities, tasks, and the immediate superior to whom each individual reports. In the table, positions within the organization are listed along the horizontal axis, while responsibilities and tasks are listed along the vertical axis. The hierarchy of accountability for the proper execution of these responsibilities and tasks is indicated as primary accountability (P), secondary accountability (S), or tertiary accountability (T). The primary case typifies those individuals whose job descriptions specifically include execution of the indicated responsibility or task, the secondary case indicates individuals who are direct supervisors of the primary individuals, and the tertiary case includes individuals who are direct supervisors of the direct supervisors of the primary individuals.

Table 4.8 Listing of responsibilities and tasks applicable to jobs [San Diego, 2016]

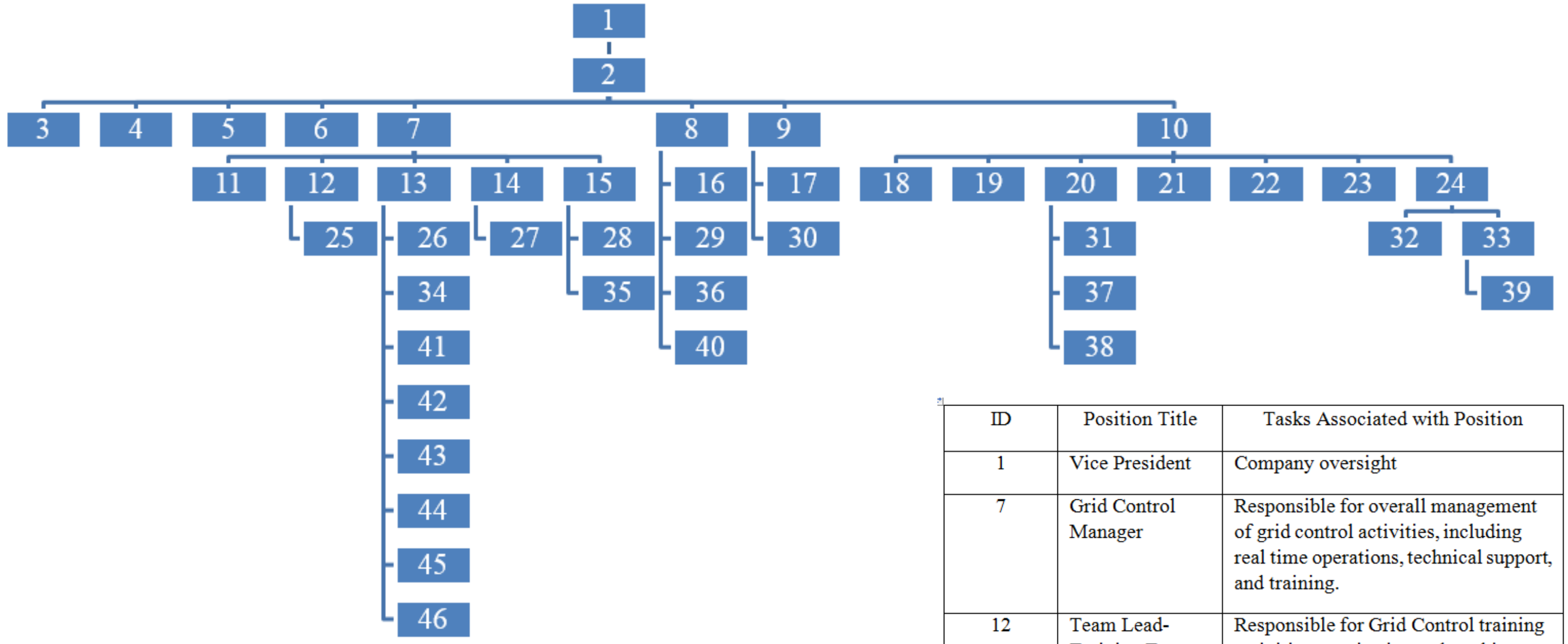


Responsibilities & Tasks	Vice President - Electric Transmission & Distribution	Director- Electric Grid Operations	Grid Control Manager	Grid Operations Services Manager	Grid Technical Support Manager
oversees operational relationship between SDG&E and California ISO	S	P			
Provides management of grid control activities	T	S	P		
Provides managerial interface with California ISO, other transmission operators, and regulatory agencies	T	S	P		
Provides oversight for NERC activities	T	S	P		
Developing and maintaining operating procedures that convey the conclusions of various engineering analyses	T	S		P	
Interacts with CAISO and neighboring utilities	T	S		P	
Oversees training activities	T	T	S		P

The HV-D is an important NATO Human View product for recognition of security threats and helps analysts recognize threats by identifying the individuals that are most responsible for completion of a given task. If a particular task is compromised, it can easily be determined which people are the closest to the task in terms of both carrying out and supervising the task. An insider threat analyst, with the assistance of an HV-D model, may ultimately find out who is responsible for an activity to prevent or diminish damage caused by an insider threat. An example would be an analyst's concern, based on an anonymous tip, about if any of the company's electrical transmission or regulatory activities related to the North American Electric Reliability Corporation (NERC) have been compromised. As the table indicates, the primary (P) responsibility for NERC activities is vested in the Grid Control Manager. The Grid Control Manager position thus seems to be the most obvious place to begin an investigation into a potential threat involving compromised activities related to NERC compliance or otherwise. However, with the aid of the HV-D, the analyst can see that the person holding the Director – Electric Grid Operations post has secondary (S) responsibility for the Grid Control Manager's tasks; that is, the Director is the official to whom the Grid Control Manager reports. If the NERC activities are actually compromised, then not only the Grid Control Manager but also the person holding the job of Director – Electric Grid Operations might be engaging in malicious activities. In any event, the HV-D provides the user with a very simple guideline about who is responsible for a task – in this case, at the primary, secondary, and tertiary levels. However, the idea is portable to any occupational situation in which the hierarchy of job roles and tasks is available. The HV-D model presented here shows that, with the input of job roles and tasks, one can determine who is responsible both directly and indirectly for a task, and one can, using this method, provide greater security by quickly figuring out who is responsible for an area that may be compromised. Because of its natural representation as a graph, the HV-D shown here supports the SNA accomplished with the HV-H product.

4.2.11 HV-E: Human network

The HV-E shown in Figure 4.3 details the interactions among human beings that are necessary for activities in a system to occur [NATO, 2010]. For a subset of the numbers in Figure 4.3, there is a corresponding reference number in the legend that contains the referenced job role and associated tasks.



ID	Position Title	Tasks Associated with Position
1	Vice President	Company oversight
7	Grid Control Manager	Responsible for overall management of grid control activities, including real time operations, technical support, and training.
12	Team Lead-Training Team	Responsible for Grid Control training activities, monitoring and tracking individual training progress.

Figure 4.3 Human View E diagram showing connected job roles [San Diego, 2016]

The overall purpose of the HV-E is to provide to the viewer a comprehensive look at all of the positions available in the organization and the employment hierarchy, so that the employee's day-to-day interactions with others may be determined. In addition, because HV-E also includes the tasks each employee is responsible for, the analyst only needs to determine who is responsible for a task and may then determine the immediate and higher-level supervisors of the person responsible for performing that task. For example, the person holding the Team Lead – Training Team position (position #12 in Figure 4.3) is directly responsible for grid control training activities, but his job is likely affected by instruction and supervision by the Team Lead's immediate supervisor, the Grid Control Manager (position #7). In this way, the entire chain of responsibility that affects a given task may be viewed easily by constructing a HV-E diagram.

This kind of Human View is potentially useful for dealing with insider threats because it shows not only the person responsible for a given task but also the individuals to whom the person reports. If someone within the chain of command of a given employee attempts to affect that employee, or vice versa, it can be said that social contagion is occurring. This means that, to a great degree, how the employee acts is affected by how the employee perceives others around the employee to behave [Brass et al., 1998]. If one employee is discovered to have been acting maliciously, analysts can look at the other employees with whom the insider interacts on a regular basis and determine if those other employees have also been acting maliciously. For instance, if the Grid Control Manager position is compromised, an insider threat analyst can determine if the positions that report to the Grid Control Manager (e.g., Team Lead – Training Team) have also been compromised. One should note that a position could even be compromised inadvertently – for example, if the Team Lead – Training Team has acted in good faith on instructions from the Grid Control Manager that turn out to have been given maliciously. More ominously, if the Grid Control Manager were to be merely lax in his or her following of security protocols, his or her poor judgment could make it easier for subordinates to act maliciously. Regardless of the context, an HV-E diagram can provide myriad benefits by ensuring that the system's chain of command for employees and for employees' tasks is clearly defined.

4.2.12 HV-F: Training

The HV-F shown in Table 4.9 illustrates the training needed for an employee to glean the necessary competency required to advance further in an organization's job position hierarchy [NATO, 2010]. For example, the tower climbing course is a prerequisite for a stage 1 apprentice to advance to the next level of his or her apprenticeship. In a similar but distinct manner to HV-C, HV-F shows the tasks required for advancement to a higher skill level and competency standard; the distinguishing characteristic between HV-C and HV-F is that the former includes the general interconnectedness of how tasks are apportioned to and completed by human beings during a given amount of time, while the latter considers the specific effects that tasks involved in training have on various employees. In any case, HV-F can provide a clear picture of the training that employees undertake and, therefore, to a great extent, the abilities that they have earned from their training.

Table 4.9 Portion of Human View F [Pacific, 2011]

	Tasks	Courses
Stage 6	4 Remaining Tasks (Related to OJT)	None
Stage 5	21 Tasks including the following: 5 Tasks in Section 3 - Rigging 2 Tasks in Section 4 - Wire Pulls 2 Tasks in Section 8 - Air Switches 6 Tasks (with 14 subtasks) in Section 9 - Power Circuit Breakers 2 Tasks (with 3 subtasks) in Section 10 - Circuit Switchers 3 Tasks in Section 12 - Substation Inspections 3 Tasks in Section 13 - Capacitor Banks 5 Tasks in Section 14 - Insulator Washing 1 Task in Section 16- Ground Grid Repair 1 Task in Section 17 - Circuit Breaker Removal 1 Task in Section 18 - Substation Distribution Switching Task 7.1 - Perform Control Wire Marking Task 7.2 - Perform Outdoor Wire Installation Task 11.2 (with 7 subtasks) - Regulator/ LTC Maintenance Testing Task 11.3 (with 4 subtasks) - Current Transformer & Relay Testing Task 15.5 - Perform as a Grounding Observer Task 15.6 - Plan & Perform Grounding Tailboards	Electrician's Basic Switchman Course
Stage 4	18 Tasks including the following: 5 Tasks in Section 6 - Drawings, Schedules, and Bill of Materials Task 11.1 - Perform Transformer Maintenance Testing	Load Tap Changer Maintenance Course Station Inspection Training Course
Stage 3	16 Tasks including the following: Task 1.5 - Manual & Hydraulic Knock-out Sets Task 1.6 - Cable & Tubing Compression Fittings Task 7.3 - Indoor Wire Installation Energized Panels Task 7.4 - Indoor Wire Installation De-Energized Panels Task 15.3 - Test Circuits De-Energized Task 18.4 - Install and Remove Protective Grounds	Power Transformer Course
Stage 2	13 Tasks including Task 5.1 - Qualified to Install Flex Conduit	Introduction to Schematics Course Power Circuit Breakers Course Substation Grounding Fundamentals Course
Stage 1	Tasks 1.1-1.4 in Section 1 - Tools & Ladders 3 Tasks in Section 2 - Hardware Task 18.1 - Install and Remove Vehicle & Equipment Grounds	Tower Climbing Course Electrician Math Course Electricity and Electronics Course

Journeyman

Apprentice

4.2.13 HV-G: Metrics

Insider threat analysis can consider the abilities required to cause damage to the organization and, using HV-G, determine the minimum level of employee that is capable of causing such damage. For instance, maintaining load tap changers is part of a course for training stage 4 apprentices. If, therefore, only apprentices at stage 4 and higher can deal with issues related to load tap changers, and if load tap changers are a particularly vulnerable area of the electrical transmission and distribution system, it might be prudent to have extra surveillance and additional security checks performed for the apprentices at stage 4 and higher. The training requirements very clearly indicate which people have the ability to affect (i.e., sabotage or damage) load tap changers so they are the ones that should be subject to additional security protocols to protect load tap changers. A determination of the minimum training required to cause damage to a given area of the system could assist the analyst in excluding those not at a level high enough to cause a particular sort of problem within the organization. In terms of combatting an insider threat, HV-G illustrates particularly sensitive job categories and levels that should be evaluated based on vulnerabilities.

4.2.14 HV-H: Human dynamics

The HV-H, a compilation of all of the other products of the NATO Human View, will be used to show how SNA and TTC analysis can be used to analyze electrical utility system operations.

4.2.14.1 Social network analysis

In this section, various SNA metrics will be collected to determine the positions in the organization most likely to cause the most damage if an individual in a specific job were to decide to become a malicious insider. The data used was derived from the HV-D and HV-E. The HV-E requires no additional modifications for data analysis and is an executable architecture component. HV-D is translated into a graph and then analysis is performed.

The accountability for the execution of various responsibilities and tasks is a useful metric to determine which positions within the organization are the most well-connected and thus would probably be in the most productive position to perpetrate an insider exploit. This attribute of "well-connectedness" for an individual is his or her position's centrality, of which there are various types. In this investigation of insider threats, the most relevant are closeness centrality, betweenness centrality, and eigenvector centrality. Other measures that could be used for analysis are degree centrality, which can help identify the number of people that can be reached from a particular person, and PageRank, which can be used to determine the overall important of a person based on their position in the network [Choudhary and Singh, 2015]. Using the Gephi [2016] open source visualization software, a web of various nodes and edges was constructed to illustrate the relationships (links) between all members of the organization and is shown in Figure 4.4.

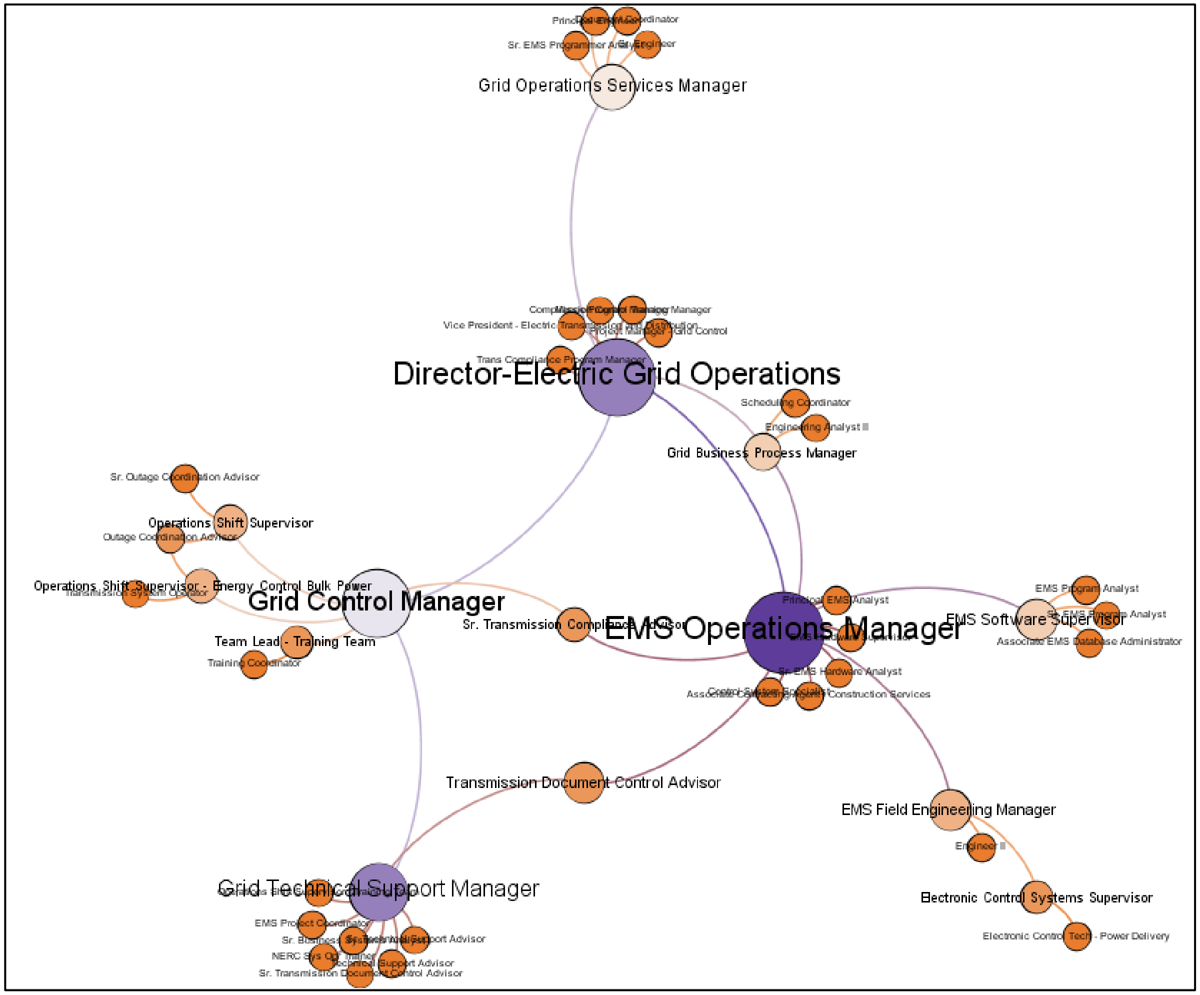

Sr. EMS Programmer Analyst
Sr. Engineer
Grid Operations Services Manager
Vice President - Electric Transmission and Distribution
Project Manager - Grid Control
Trans Compliance Program Manager
Director-Electric Grid Operations
Scheduling Coordinator
Engineering Analyst II
Grid Business Process Manager
Sr. Outage Coordination Advisor
Operations Shift Supervisor
Outage Coordination Advisor
Operations Shift Supervisor - Energy Control Bulk Power
Transmission System Operator
Grid Control Manager
Team Lead - Training Team
Training Coordinator
Sr. Transmission Compliance Advisor
EMS Operations Manager
Principal EMS Analyst
Sr. EMS Hardware Analyst
Construction Services
EMS Program Analyst
EMS Software Supervisor
Sr. EMS Program Analyst
Associate EMS Database Administrator
Transmission Document Control Advisor
EMS Field Engineering Manager
Engineer II
Electronic Control Systems Supervisor
Electronic Control Tech - Power Delivery
Grid Technical Support Manager
EMS Project Coordinator
Sr. Business Systems Analyst
NERC Sys Opr Trainer
Technical Support Advisor
Sr. Technical Support Advisor
Sr. Transmission Document Control Advisor

Figure 4.4 Listing of interrelationships among SDG&E positions [San Diego, 2016]

This graphic demonstrates a position's centrality proportionally to text size and node size. Each node represents a different, unique position within the organization, while each edge represents the "tie" between each employee and his or her supervisor or supervisors. According to this graphic, the Director – Electric Grid Operations and EMS Operations Manager positions are some of the most well-connected (having the highest centrality), because they are the largest on the diagram. The centrality values for these positions are shown in Table 4.10.

Table 4.10 Top three centrality values among SDG&E job positions

Position	Closeness Centrality	Betweenness Centrality	Normalized Eigenvector Centrality
Director – Electric Grid Operations	0.45	477.0	8.47%
EMS Operations Manager	0.44	517.5	9.55%
Grid Control Manager	0.41	391.5	5.89%

Closeness centrality simply refers to "the extent to which an individual can reach all others in the network in the fewest number of direct and indirect links" [Brass et al., 1998:21]. The closeness centrality of positions in the organization ranged from approximately 0.20 to 0.45, for which the highest value corresponded to the Director – Electric Grid Operations position. Closeness centrality can assist with determining which people have the easiest, fastest access to other members of the organization. Based on Figure 4.4 above, the Director, EMS Operations Manager, and Grid Control Manager have direct access to the other members of the organization.

Betweenness centrality refers to the “number of shortest paths between any pair that pass through a node” [Choudhary and Singh, 2015:26]. Betweenness centrality values ranged from 0 to 517.5. Betweenness centrality’s usefulness would be its indication of the positions that provide the greatest linkage between other positions, which Choudhary and Singh refer to as “brokers” [2015:26]. In fact, Figure 4.4 shows that the Director, EMS Operations Manager, and Grid Control Manager provide a significant amount linkage between all of the others in the organization.

Eigenvector centrality refers to the “relative importance in terms of influence of a node to its neighboring nodes in the network” [Choudhary and Singh, 2015:26]. The normalized eigenvector centrality values spanned approximately 0.26% to 9.55%. Eigenvector centrality can help to detect nodes (positions) that have great influence over other nodes (positions), by pinpointing which individuals are “well connected to other well connected persons” [Choudhary and Singh, 2015:26]. Since the Director, EMS Operations Manager, and Grid Control Manager are well-connected to many others in the organization, it follows that they are connected to other well-connected individuals.

The greatest benefit of using a variety of centrality measures is that each can provide a clearer picture of the positions that are the most influential and well-connected: an attribute that provides clear advantages for those intending to commit crimes against the organization. The data from these metrics shows that the Director – Electrical Grid Operations, EMS Operations Manager, and the Grid Control Manager hold positions that need extensive background checks because of their potential to negatively influence personnel, systems and procedures of the organization, should any one of them become a malcontent. Additionally, by investigating the job roles that link multiple individuals with higher centrality measures (e.g., the Transmission Document Control Advisor that interacts with both the Grid Technical Support Manager and the EMS Operations Manager), one could determine additional job roles that could pose a threat because of the small number of high-level persons with whom they interact, rather than a high number of lower-level persons with whom they interact. Furthermore, although the quality of relationships for high-ranking officials may tend to increase as they move higher in the company hierarchy, the number of direct, primary relationships may decrease simply because they do not interact much from day to day with many individuals. As a consequence, it may be the case that some individuals lower-down in the company hierarchy may actually have greater centrality despite having only a medium-ranking job. For example, one can see that the Transmission Document Control Advisor, who reports to the EMS Operations Manager, has higher centrality than some of the other officials that report directly to the Director, which is likely due to such a scenario.

The second analysis performed with Gephi [2016] included roles in the organization, job responsibilities and tasks (from HV-D) as nodes and the supervisory relationships (i.e., to whom each employee reports) as edges. P, S, and T classifications were used to represent job responsibilities and served as the weights of edges connecting the responsibilities to the job category. Individuals directly responsible for tasks would be linked more strongly to those tasks than their immediate supervisors would be. Primary classifications received a relative weight of 3, secondary classifications a relative weight of 2, and tertiary classifications a relative weight of 1. The diagram produced that shows all of these relationships is shown in Figure 4.5.

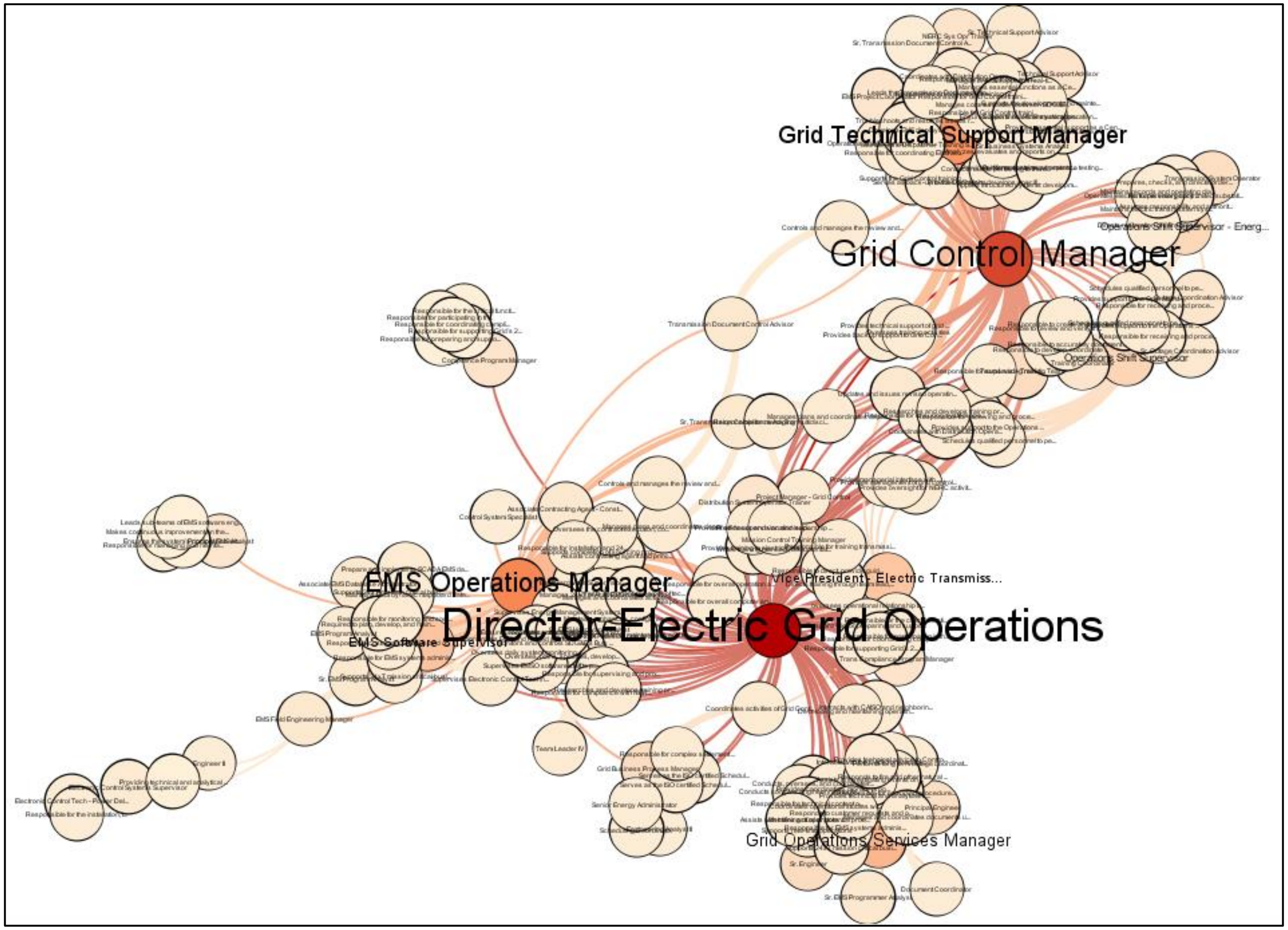

Grid Technical Support Manager
Grid Control Manager
Operations Shift Supervisor - Energ...
Operations Shift Supervisor
Vice President, Electric Transmiss...
EMS Operations Manager
Director-Electric Grid Operations
EMS Software Supervisor
Grid Operations Services Manager

Figure 4.5 Listing of interrelationships among SDG&E positions and tasks [San Diego, 2016]

The diagram in Figure 4.5 indicates that the top three positions in San Diego Gas & Electric Company that are the most well-connected in terms of overall centrality are the following: Director – Electric Grid Operations, Grid Control Manager, and EMS Operations Manager. The centrality values for these positions may be seen in Table 4.11.

Table 4.11 Top three centrality values among SDG&E job positions and tasks [San Diego, 2016]

Position	Closeness Centrality	Betweenness Centrality	Normalized Eigenvector Centrality
Director – Electric Grid Operations	0.60	11830.73	4.89%
Grid Control Manager	0.51	7782.92	3.37%
EMS Operations Manager	0.47	4178.76	2.40%

The closeness centrality of positions in the organization, indicating “quick connectedness,” ranged from approximately 0.20 to 0.60, for which the highest value corresponded to the Director – Electric Grid Operations position. Additionally, betweenness centrality values, indicating the best “brokers,” ranged from 0 to 11830.73. Finally, eigenvector centrality values, indicating an overall measurement of well-connectedness, spanned approximately 0.01% to 4.89%. Each of these types of centrality provides its own clear advantages in trying to pinpoint the positions that provide the most advantage if compromised by an insider.

Another major advantage of this analysis via Gephi [2016] is that, in the event that a compromised position is found, one can easily find the tasks and persons most influenced by the position that may be also be compromised; this is similar to determining the impacts of an infection. With the knowledge of what each position does on a regular basis, including not only tasks but also supervisory responsibilities and influences on other individuals and others' tasks, it is possible that this form of analysis can minimize the danger by attempting to limit the spread of damage after an insider threat is detected – mainly, by "containing the infection." For example, if the EMS Operations Manager is found to have been acting maliciously, the SNA allows the analyst to quickly determine the tasks and people under that position in the chain of command that are under the highest risk of being influenced by the manager's malicious actions. If an analyst is looking for accomplices of a malicious individual, this may be a good place to start looking. The analysis provided with the NATO Human View data and SNA metrics is a straightforward way to measure the linked nature of roles and tasks in a company. Insider threat detection measures would benefit from the use of this analysis to detect and minimize the threat of insiders.

4.2.14.2 Time to compromise analysis

An additional form of analysis useful to insider threat analysts is a model involving a concept called time to compromise (TTC). This model involves "estimating the time to compromise a system component that is visible to an attacker" [McQueen et al., 2006: 2].

The model includes the TTC for an attacker that fits into one of four skill levels: novice, beginner, intermediate, and expert. The data provided in the HV-C is used for this analysis. The HV-C previously discussed indicates the tasks required to advance in each stage of apprenticeship, and it demonstrates that the vulnerability of the company to potential damage (low, medium, and high) caused by the apprentice as she advances in skill level. The skill level for an attacker in this case is roughly analogous to the relative threat level of an apprentice or other employee. In fact, the following equation from McQueen et al. [2006] was used to find the value for the time to compromise *T*:

$$T = t_1 P_1 + t_2(1 - P_1)(1 - u) + t_3 u(1 - P_1) \tag{4.1}$$

where

T is the time-to-compromise

t_1 is the mean time estimation for Process 1

t_2 is the mean time estimation for Process 2

t_3 is the mean time estimation for Process 3

u is the probability that Process 2 is unsuccessful

V is the number of system component vulnerabilities

This model depends on whether or not the system considered is in one of two processes. Process 1 (P_1) is the case in which a given attacker has an exploit available for a known susceptibility, while Process 2 (P_2) is the case in which a given attacker does not have an exploit available for a known susceptibility (the opposite of P_1) [McQueen et al., 2006]. Finally, Process 3 (P_3) is the "identification of new vulnerabilities and exploits" [McQueen et al., 2006: 4]. The reason that these are necessary to distinguish is that the relative risk level of a known vulnerability depends on whether or not it is easily susceptible to an attacker.

To perform the needed calculations to find *T*, all of the unknown variables (namely, t_1, t_2, P_1, u, and t_3) must be determined. The variable t_1, which is the mean (expected) value for completion of Process 1, is considered to be 1 working day by McQueen et al. [2006]. The variable P_1 may be found by using the following equation [McQueen et al., 2006]:

$$P_1 = 1 - e^{-vm/k} \tag{4.2}$$

where

P_1 is the probability that an attacker is in Process 1

e is Euler's number

v is the number of vulnerabilities on the component of interest

m is the number of exploits that an attacker can use

k is 9447 vulnerabilities

This analysis will rely on an assumed value of 100 vulnerabilities (*V*), while the *m* value depends on skill level as determined by McQueen et al. [2006] and represented in Table 4.12.

Table 4.12 TTC Calculations’ data [McQueen et al., 2006]

Level of Skill	HV-C - Ability to Exploit Vulnerabilities	m value	P1 value	AM/V ratio	t2 value	u value	t3 value	TTC (T) (days)
Novice	L	50	0.41	0.15	36.61	$8.75 * 10^{-8}$	193.39	22.0
Beginner	M	150	0.80	0.30	18.90	$3.23 * 10^{-16}$	91.99	4.7
Intermediate	M	250	0.93	0.55	10.46	$2.10 * 10^{-35}$	45.90	1.7
Expert	H	450	0.99	1.00	5.8	0	21.01	1.0

After applying equation 4.2 referenced above, the P_1 values for each skill level were determined as shown in Table 4.14. Also, the variable t_2, the mean (expected) value for the completion of Process 2, is related to the expected time (*ET*) for Process 2 and is given by 5.8**ET*, where *ET* is given by the following equation [McQueen et al., 2006] :

$$ET = \frac{AM}{V} * (1 + \sum_{r=2}^{V-AM+1} [r * \prod_{i=2}^{r} ((NM - i + 2)/(V - i + 1))] \tag{4.3}$$

where

AM is the average number of vulnerabilities for which an exploit can be found

NM is the number of vulnerabilities not able to be used (*NM*=*V*-*AM*)

V is the number of vulnerabilities on the component of interest

r is the number of tries

Equation 4.3 should be evaluated using a *V* value of 100 vulnerabilities and with *AM/V* ratios referenced in Table 4.12 above, as provided by McQueen et al. [2006]. A spreadsheet analysis tool has been constructed which utilizes the model available from McQueen et al. [2006], and the analysis process is shown in Figure 4.6.

Human View
Data Input
Spreadsheet
Analysis Tool
Time to
Compromise

Figure 4.6 Method of analysis of Human View data for TTC model

Next, the *u* variable, which represents the probability that Process 2 is not successful, is calculated using equation 4.4 [McQueen et al., 2006].

$$u = (1 - \left(\frac{AM}{V}\right))^{V} \tag{4.4}$$

Next, *t₃* is calculated to be able to solve for the time to compromise (*T*). The *t₃* value represents the mean (expected) value of Process 3 to complete successfully. It is found using equation 4.5 [McQueen et al., 2006].

$$t_3 = \left(\left(\frac{V}{AM}\right) - 0.5\right) * 30.42 + 5.8 \tag{4.5}$$

Finally, the overall time to compromise (*T*) can be calculated via equation 4.1. To demonstrate the quantitative nature of the TTC model and the aforementioned negative correlation between skill level and TTC, an additional analysis was conducted for 75, 150, and 250 vulnerabilities within a system, in addition to the model already discussed that assumes 100 vulnerabilities within the system. The following overall times to compromise were determined:

Table 4.13 TTC (in days) for a given number of vulnerabilities

Skill Level	75 Vulnerabilities	100 Vulnerabilities	150 Vulnerabilities	250 Vulnerabilities
Novice	25.0	22.0	17.8	10.9
Beginner	6.5	4.7	2.7	1.3
Intermediate	2.3	1.7	1.2	1.0
Expert	1.1	1.0	1.0	1.0

The data compiled were graphed as shown in Figure 4.7 below. The graph demonstrates that, as skill level increases from novice to expert, the TTC for a given number of vulnerabilities decreases. The data produced reiterate the previous conclusion that, as skill level increases from novice to expert, the danger posed by a would-be insider threat increases (as shown in this case study), because the TTC decreases greatly as skill level increases.

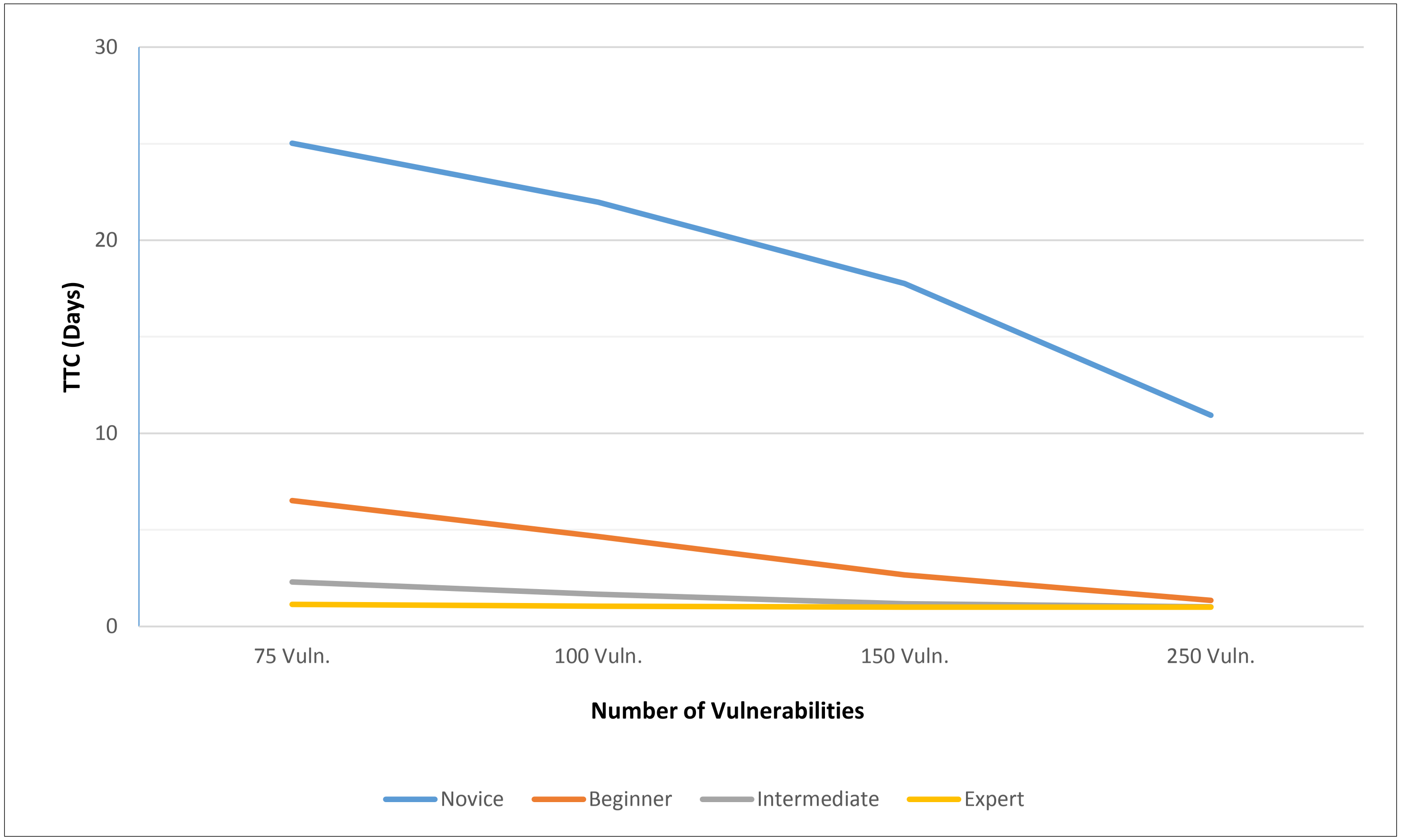


Figure 4.7 Line graph of TTC data (in days) for given skill levels

The TTC values provided illustrate that, as competency increases, the ability of an attacker to compromise the system increases as well (since the time until the system is compromised decreases). The information presented about the HV-C demonstrates that competency increases as skill level increases – that is, with the passing of classes to reach a higher level, one gains more abilities that could be used to attack an electrical transmission and distribution system. The use of TTC data shows this fact very clearly. In the context of preventing insider threats, an analyst could divide up the workers in a facility into categories similar to those used by McQueen et al. [2006] (e.g., beginner or intermediate) to determine which employees have the unique combination of tasks and skills required to participate in specific exploitation activities. The analyst could focus on those with higher skill levels because the analyst would be aware that those with higher skill levels generally pose a greater threat, and, consequently, the analyst could use resources more efficiently by focusing mostly just on those posing the greatest threat to the system, as judged by skill level. Since the vulnerabilities introduced by humans in the electric power system have been identified, the next step is to identify the system vulnerabilities.

4.3 Illustrative case study: System architecture assessment (path 2)

4.3.1 Introduction

While the human architecture assessment produced results about the operations of the electrical power system, this section will assess a component of the physical system, the electrical substation. This is an important problem because recent attacks on electrical substations, specifically the Pacific Gas and Electric Metcalf substation attack, have driven the Federal Energy Regulation Commission (FERC) to approve requirements for substation protection. In the next section, a background of electrical substation security will be given to provide context to this portion of the case study. Then, the method developed will be used to provide decision makers with security alternatives based on their cost and risk constraints.

4.3.2 Background on substation security

Several attacks on electrical substations have taken place over the past few years. One such attack occurred in April 2013 at the Pacific Gas and Electric Corporation Metcalf substation, where gunmen fired bullets at the substation and caused millions of dollars in damage [Brinkman et al., 2015]. As the concern about physical security of substations increased, the FERC directed the North American Electric Reliability Corporation (NERC) to do the following:

> Submit for approval one or more Reliability Standards that will require certain registered entities to take steps or demonstrate that they have taken steps to address physical security risks and vulnerabilities related to the reliable operation of the Bulk-Power System. The proposed Reliability Standards should require owners or operators of the Bulk-Power System, as appropriate, to identify facilities on the Bulk-Power System that are critical to the reliable operation of the Bulk-Power System. Then, owners or operators of those identified critical facilities should develop, validate and implement plans to protect against physical attacks that may compromise the operability or recovery of such facilities [NERC2014-04, 2016].

This resulted in the approval of the Critical Infrastructure Protection (CIP) standard for physical security measures (CIP-04-01) on November 20, 2014 [NERCPSSI, 2016].

The primary purpose of CIP-014-01 is to "identify and protect Transmission stations and Transmission substations, and their associated primary control centers, that if rendered inoperable or damaged as a result of physical attack could result in widespread instability, uncontrolled operation, or cascading with an interconnection" [2016]. The six requirements that transmission owners must meet to comply with this standard are listed in Table 4.14.

Table 4.14 Summary of OR model building process [DoDAF202, 2014]

Requirement ID	Summary
R1	Initial Risk Assessment
R2	Third party verification
R3	Notice to operators of control centers
R4	Evaluation of threats and vulnerabilities of physical attack
R5	Security Plan
R6	Third party review of evaluation and security plan(s)

The approach developed can be used throughout this process, but it would likely be most beneficial in helping with the evaluation in requirement R4. One of the factors recommended for the evaluation of threats and vulnerabilities is the past history of attack [CIP-014-01, 2016], which will be represented as an activity diagram in the method presented in the case study.

4.3.3 System VA approach

In this section, the system VA approach is demonstrated. A distribution substation is shown in Figure 4.8. The substation used in this example is assumed to be a 280 foot by 280 foot fenced or walled area. The analysis will focus on physical security parameters such as lighting, manned patrols, fences and walls. The "to-be" architecture for a substation is explored, but the analysis can also be applied to an "as-is" architecture for evaluation.

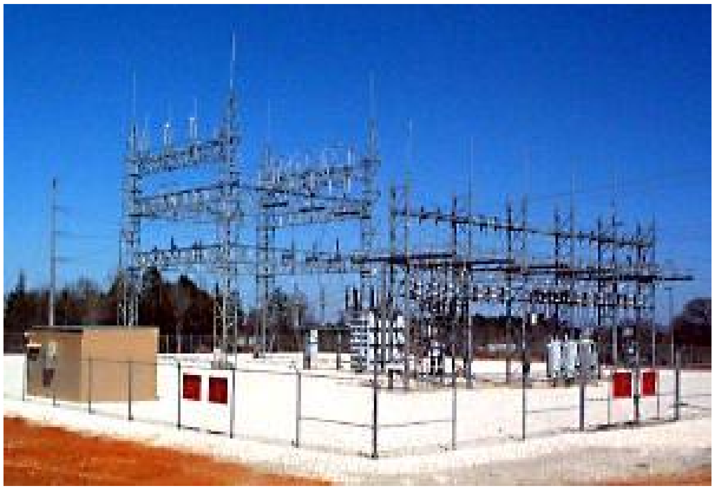


Figure 4.8 Distribution substation [OSHA, 2016]

For this approach, we use the Innoslate [2016] tool by SPEC Innovations for the model development. This tool was selected because it supports model based systems engineering and DoDAF.

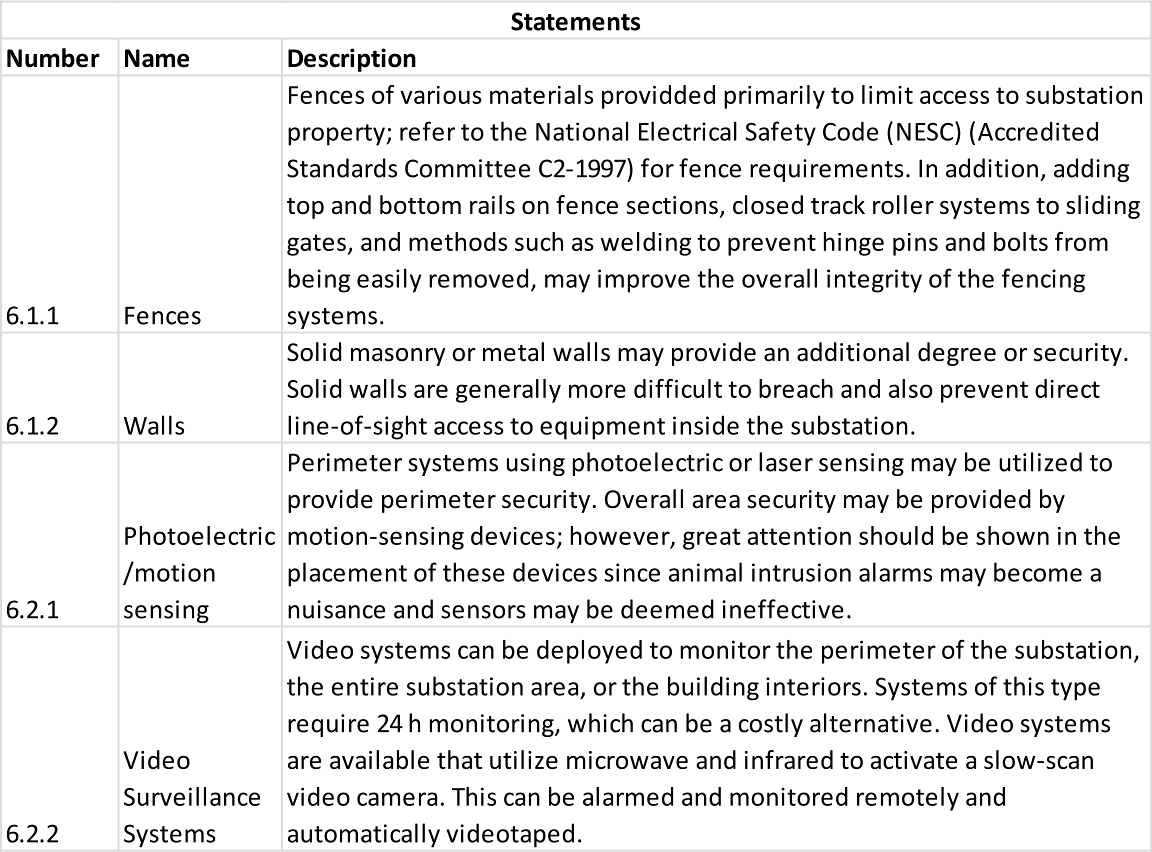
4.3.3.1 Gather documentation

Three major references are used in this example. The first reference is the IEEE Guide for Electrical Substation Physical and Electronic Security (IEEE Std 1402™ - 2000). This guide was written to present methods and techniques to prevent human intrusions into substations [IEEE, 2008]. There are many other guides or standards that can be used, but we selected that one for this example. McDonald [2012] and Blume [2007] provided the basis for the system description meta-data in the structural diagram. Additionally, the activity diagram documentation for the historical attack scenario was derived from Brinkman et al. [2015] and Smith [“Assault” 2014].

4.3.3.2 Create list of requirements or statements

The statements that are used are shown in Table 4.15. These are directly from IEEE Std 1402™ -2000 [2008] and only a subset of the security recommendations are shown below.

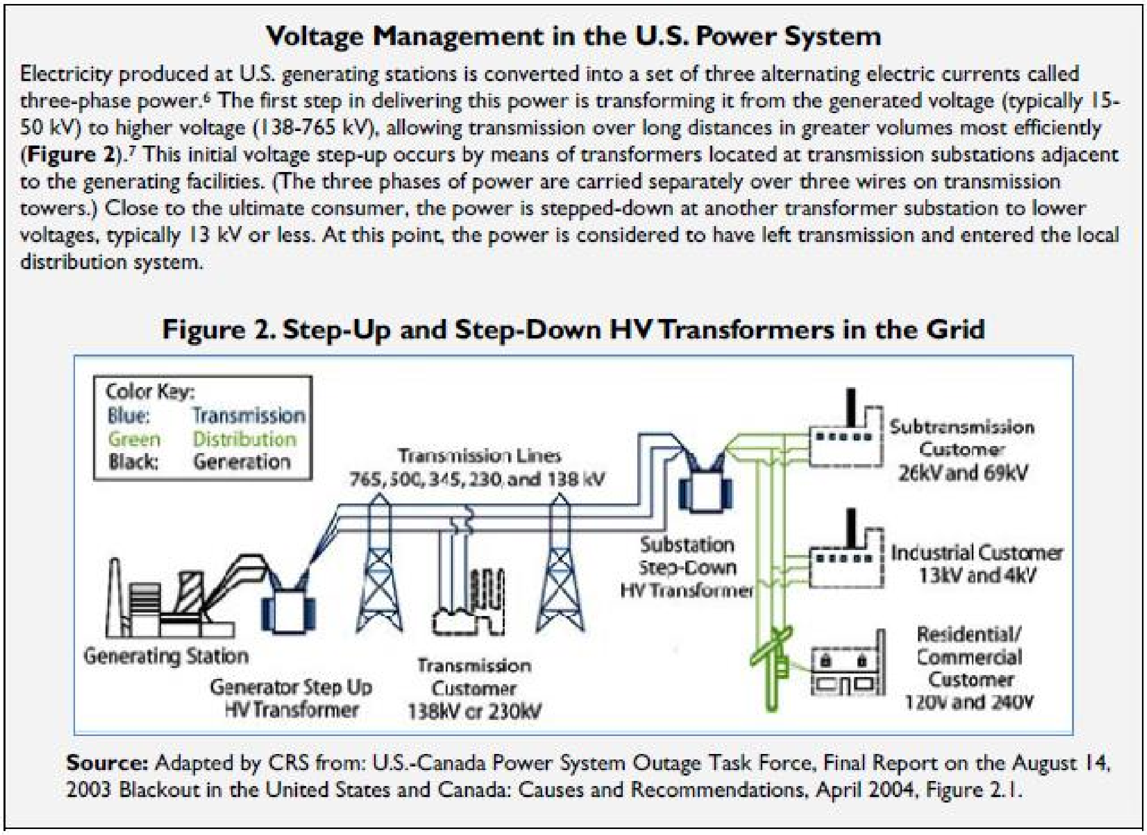
Table 4.15 Partial Innoslate export of statements from IEEE Std 1402™-2000 [2008]



Statements		
Number	**Name**	**Description**
6.1.1	Fences	Fences of various materials providded primarily to limit access to substation property; refer to the National Electrical Safety Code (NESC) (Accredited Standards Committee C2-1997) for fence requirements. In addition, adding top and bottom rails on fence sections, closed track roller systems to sliding gates, and methods such as welding to prevent hinge pins and bolts from being easily removed, may improve the overall integrity of the fencing systems.
6.1.2	Walls	Solid masonry or metal walls may provide an additional degree or security. Solid walls are generally more difficult to breach and also prevent direct line-of-sight access to equipment inside the substation.
6.2.1	Photoelectric /motion sensing	Perimeter systems using photoelectric or laser sensing may be utilized to provide perimeter security. Overall area security may be provided by motion-sensing devices; however, great attention should be shown in the placement of these devices since animal intrusion alarms may become a nuisance and sensors may be deemed ineffective.
6.2.2	Video Surveillance Systems	Video systems can be deployed to monitor the perimeter of the substation, the entire substation area, or the building interiors. Systems of this type require 24 h monitoring, which can be a costly alternative. Video systems are available that utilize microwave and infrared to activate a slow-scan video camera. This can be alarmed and monitored remotely and automatically videotaped.

4.3.3.3 Create a structural view of the system

The structural view of the system is based on Figure 4.9. A DoDAF SV-1 Systems Interface Description is used for the structural view. For this example, none of the blocks are linked to a lower level of detail, such as showing the connection of actual transformers within the transmission and distribution substation blocks.



Voltage Management in the U.S. Power System

Electricity produced at U.S. generating stations is converted into a set of three alternating electric currents called three-phase power.[6] The first step in delivering this power is transforming it from the generated voltage (typically 15-50 kV) to higher voltage (138-765 kV), allowing transmission over long distances in greater volumes most efficiently (**Figure 2**).[7] This initial voltage step-up occurs by means of transformers located at transmission substations adjacent to the generating facilities. (The three phases of power are carried separately over three wires on transmission towers.) Close to the ultimate consumer, the power is stepped-down at another transformer substation to lower voltages, typically 13 kV or less. At this point, the power is considered to have left transmission and entered the local distribution system.

Figure 2. Step-Up and Step-Down HV Transformers in the Grid

Source: Adapted by CRS from: U.S.-Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations, April 2004, Figure 2.1.

Figure 4.9 Overview of power grid [Parfomak, 2014]

In the SV-1 in Figure 4.10, each block in the tool has meta-data associated with it. Blocks are identified as assets or resources for this view. For identification purposes, ‘(Resource)’ was added to the blocks that are resources for assets in the architecture. In the figure below, communications infrastructure and video surveillance are just two examples of identified resources. Each of the resource blocks is linked to the appropriate statements from IEEE Std 1402™-2000 [2008] as defined above. This ensures that the initial architecture meets recommended standards. For example, ‘video surveillance (Resource)’ was ‘traced from statement’ 6.2.2 Video Surveillance Systems (see Figure 4.13) in the Innoslate [2016] tool. If there is no traceability from the recommendation to a security resource in the system, this may be a gap in the architecture that needs to be evaluated. In this analysis, we will allocate these resources to obtain the selected security effectiveness.

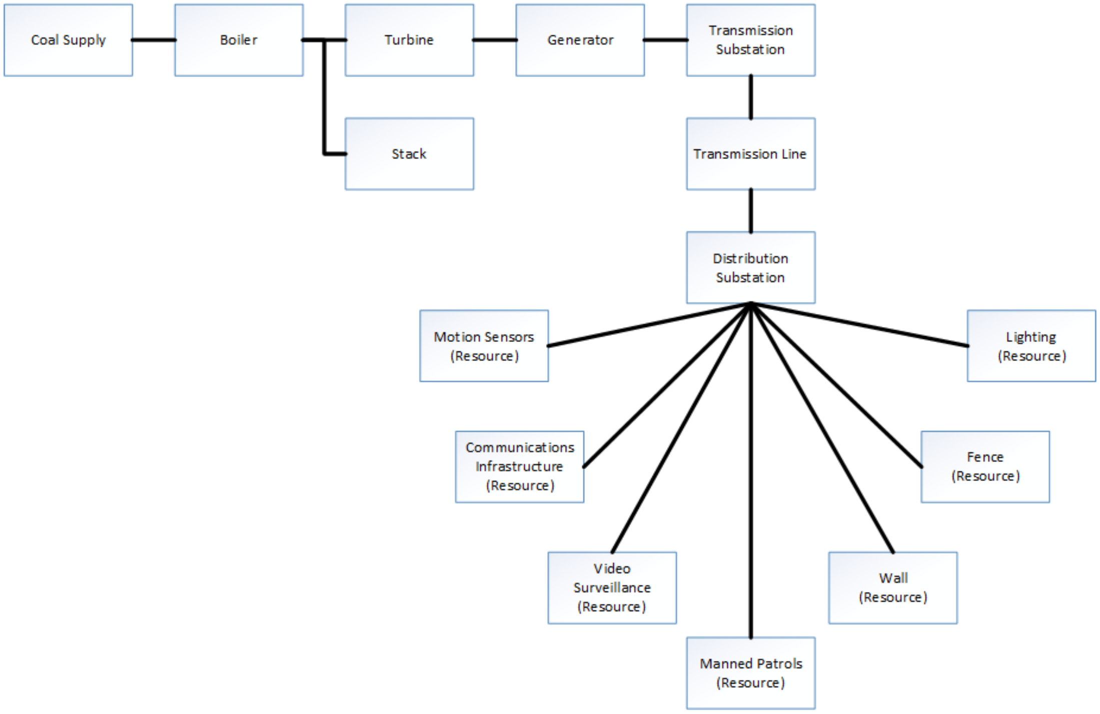


Figure 4.10 SV-1 System interface description

4.3.3.4 Create activity views of past and potential future attacks

4.3.3.4.1 Historical substation attack

Now that there are standards and a structural diagram of the system is in the tool, the next step is to describe the historical attacks on the system or similar system in an activity diagram. For this example, we will use a DoDAF OV-5b Operational Activity Model. There are several historical attack scenarios that could be used, as detailed in Brinkman et al. [2015], but, for this example, we will only use one historical scenario.

The attack scenario used will be the Metcalf substation attack that occurred on April 16, 2013, in which snipers attacked the Pacific Gas and Electric Metcalf substation near San Jose, California [Brinkman et al., 2015; Smith, “Assault” 2014]. The result of the attack was that 17 transformers were damaged [Smith, “Assault” 2014], and repair costs approached $15.4 million [Brinkman et al., 2015]. The detailed series of events was captured by Smith [“Assault” 2014] and are listed in Table 4.16.

Table 4.16 Timeline of Metcalf attack [Smith, “Assault” 2014]

Time	Description of Event
12:58 a.m.	AT&T fiber-optic telecommunications cables were cut—in a way that made them hard to repair—in an underground vault near the substation, not far from U.S. Highway 101 just outside of south San Jose.
1:07 a.m.	Some customers of Level 3 Communications, an Internet service provider, lost service. Cables in its vault near the Metcalf substation were also cut.
1:31 a.m.	A surveillance camera pointed along a chain-link fence around the substation recorded a streak of light that investigators from the Santa Clara County Sheriff's office think was a signal from a waved flashlight. It was followed by the muzzle flash of rifles and sparks from bullets hitting the fence. The substation's cameras weren't aimed outside its perimeter, where the attackers were.
Approximately 1:37 a.m.	PG&E confirms it got an alarm from motion sensors at the substation, possibly from bullets grazing the fence, which is shown on video.
1:41 a.m.	The sheriff's department received a 911 call about gunfire, sent by an engineer at a nearby power plant that still had phone service.
1:45 a.m.	Riddled with bullet holes, the transformers leaked 52,000 gallons of oil, and then overheated. The first bank of transformers crashed and PG&E’s control center about 90 miles north received an equipment failure alarm.
1:50 a.m.	Another apparent flashlight signal, caught on film, marked the end of the attack.
1:51 a.m.	Law-enforcement officers arrived, but found everything quiet. Unable to get past the locked fence and seeing nothing suspicious, they left.
2:03 a.m.	PG&E’s control center called a worker to go to the Metcalf site.
3:15 a.m.	A PG&E worker arrived at Metcalf to survey the damage.

The events in the timeline are described in the OV-5b in Figure 4.11. The process begins with the AT&T and Level-3 Communications lines being cut. Note that 'communications infrastructure' is identified as a mechanism in the diagram for these two blocks. The development of this diagram is where the links to the structural SV-1 are made. This shows that, during this scenario, the 'communications infrastructure' was a key component; in this case, it was damaged. Another example is the 'Video Surveillance' that is linked to 'Attackers begin shooting at substation.' The video surveillance was not pointed in the direction to capture the attackers, but it did capture what seemed like the waving of a flashlight to start the attack. The video system worked partially, but there may be some room for improvement in how much coverage there is of the facility.

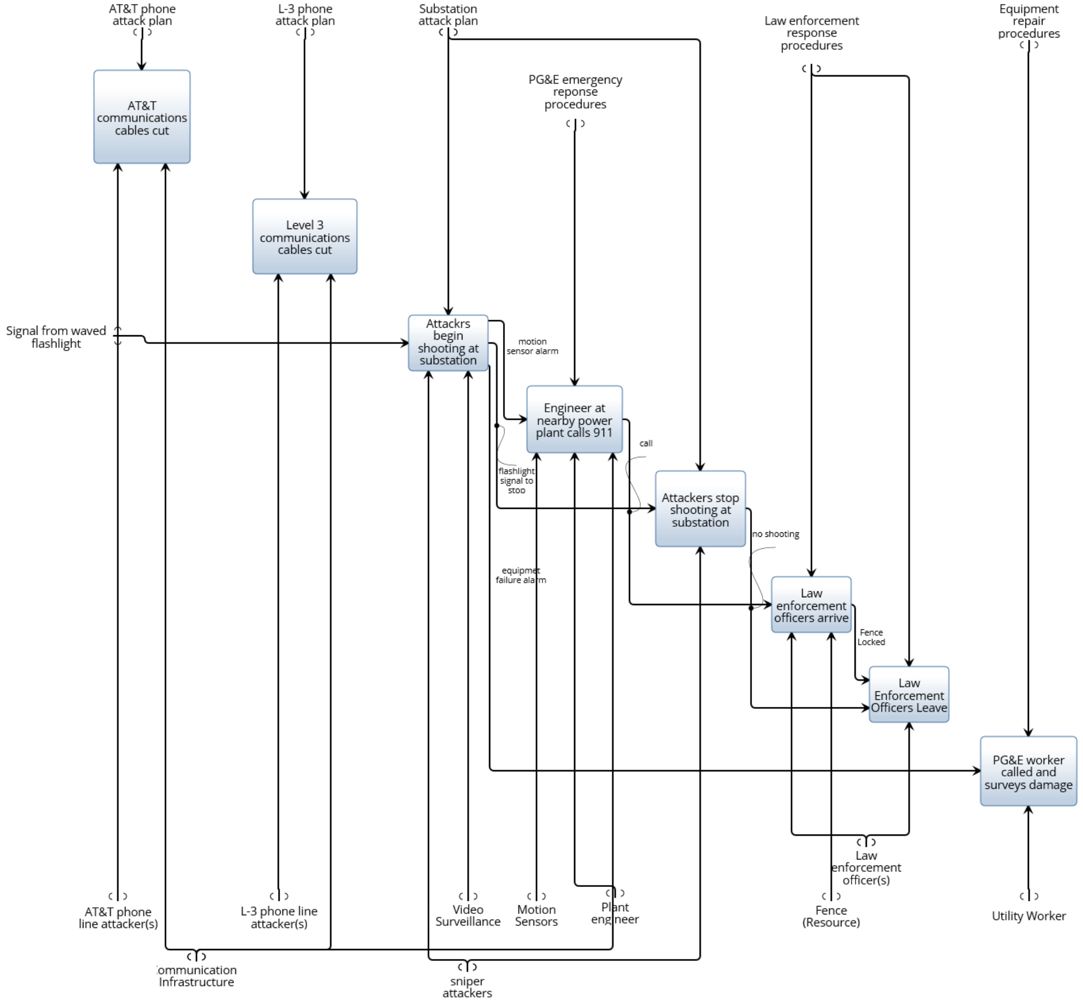

AT&T phone attack plan
L-3 phone attack plan
Substation attack plan
PG&E emergency reponse procedures
Law enforcement response procedures
Equipment repair procedures
AT&T communications cables cut
Level 3 communications cables cut
Signal from waved flashlight
Attackrs begin shooting at substation
motion sensor alarm
Engineer at nearby power plant calls 911
flashlight signal to stoo
call
Attackers stop shooting at substation
no shooting
equipmet failure alarm
Law enforcement officers arrive
Fence Locked
Law Enforcement Officers Leave
PG&E worker called and surveys damage
AT&T phone line attacker(s)
L-3 phone line attacker(s)
Video Surveillance
Motion Sensors
Plant engineer
Law enforcement officer(s)
Fence (Resource)
Utility Worker
ommunication Infrastructure
sniper attackers

Figure 4.11 OV-5b of Metcalf attack

4.3.3.4.2 Potential future substation attack

The next step is for the team to determine the possibility of future attacks based on subject matter expertise and the previous structural and activity artifacts presented in the model. For this case, a possible future attack could involve jamming the wireless communication systems used for security resources in the substation. Specifically, for this example, we will look at jamming the wireless communications for the surveillance cameras that is performed by a malicious employee.

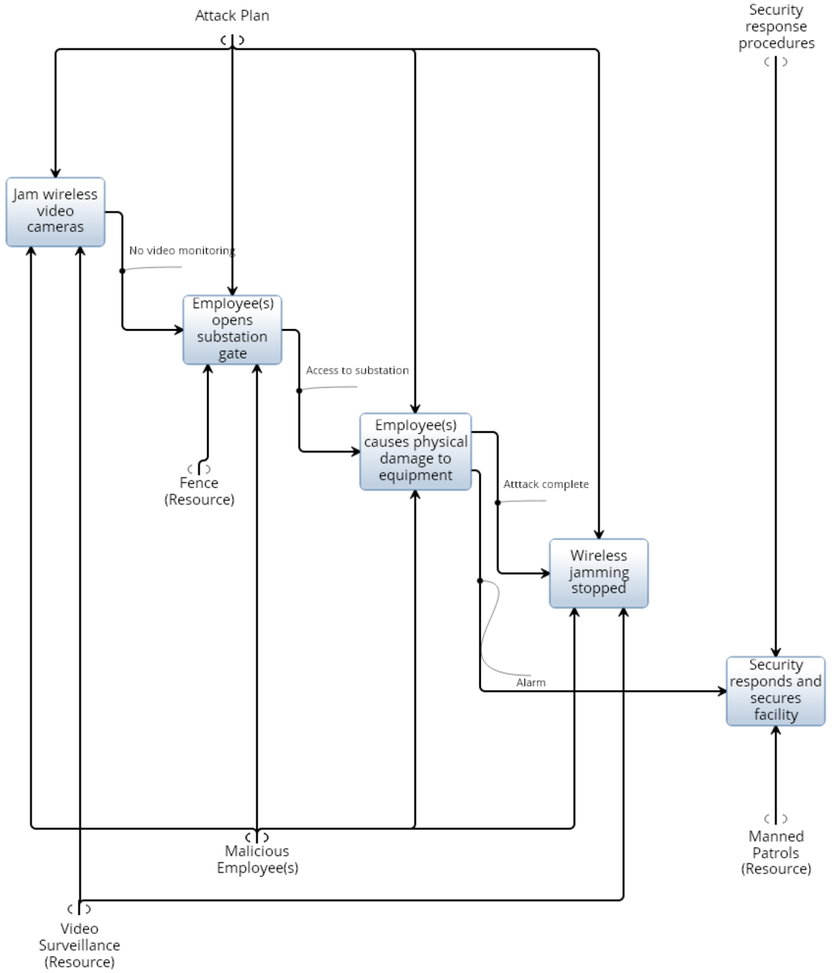


Figure 4.12 OV-5b of malicious insider jamming attack

4.3.3.5 Identify gaps in traceability

In the previous two steps, the standards were linked to the SV-1, and the SV-1 was linked to the OV-5b that captured a historical and future attack scenario. We begin the assessment of the architecture by first identifying any gaps in the architecture, specifically security resources, which can be accomplished in multiple ways. In the Innoslate [2016] tool, a spider diagram can be viewed for each security resource. The Video Surveillance resource is shown in Figure 4.13 as an example.

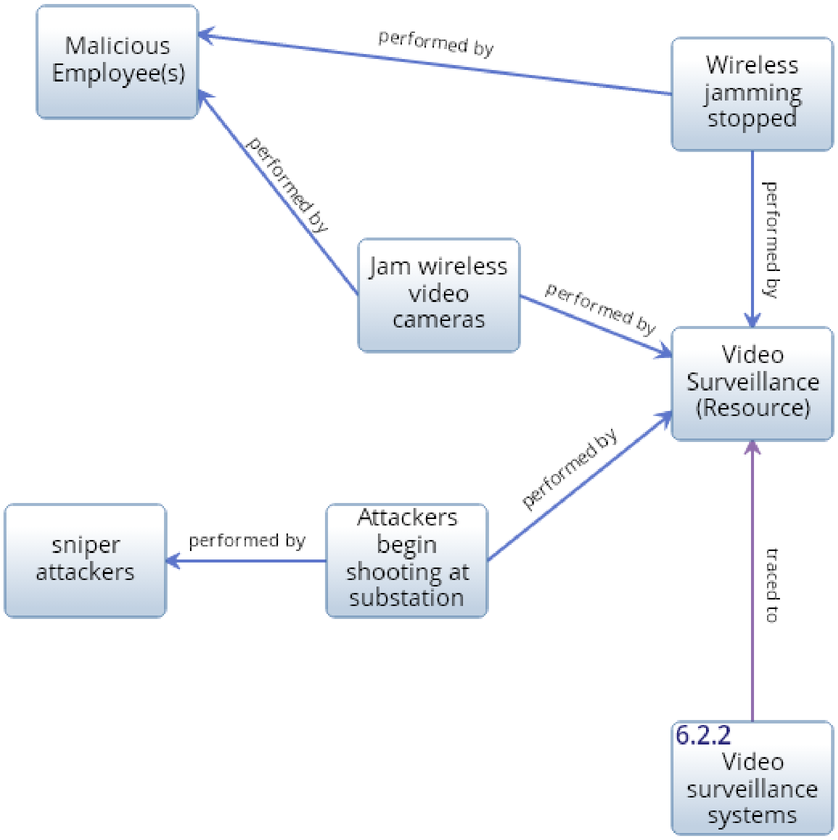


Figure 4.13 Spider diagram of video surveillance

The diagram shows that video surveillance is linked to the IEEE Standard as well as used in some capacity in the Metcalf historical attack and malicious employee future attack. Based on the discussion in the OV-5b section, it is clear that the video surveillance was not capturing everything it should have captured, since the snipers were able to find a place where they could not be seen [Smith, "Assault" 2014]. In the future scenario, it was shown that the video transmission could be stopped with jamming. Based on this analysis, the placement and communication mechanisms for video surveillance are a potential area of investment in the system being developed. Table 4.17 shows an evaluation of the use of each resource based on gaps in traceability. The lessons-learned column is based on actual actions taken by PG&E after the Metcalf attack [Brinkman et al., 2015]. The subject matter expert evaluation explains the assessment of the use of security resources based on the attacks presented.

Table 4.17 Traceability and subject matter expert evaluation

Resource	Traceability to IEEE Standard	Traceability to Historical Attack Scenario	Lessons Learned based on incident [Brinkman et al., 2015]	Traceability to video jamming scenario	Subject Matter Expert Evaluation
Manned Patrols	Yes	No It is not clear that there were any manned patrols at Metcalf.	Deploy security guards to provide 24/7 presence at critical substations and increased patrols from law enforcement	Yes	Manned patrols are a high priority in the future system. In both attack scenarios, manned patrols could have decreased the impact of the attack.
Lighting	Yes	No	Install additional lighting	No	Lighting seemed to play a minor role in both attack scenarios. While a good security measure, it is not the highest priority mitigation approach.
Video Surveillance	Yes	Yes	Enhance camera surveillance	Yes	Video Surveillance was a factor in both scenarios. Where the cameras are pointed and the communication method to get the data back to security shows vulnerabilities. In the future system a detailed analysis of the video surveillance approach should be done.
Fence	Yes	Yes	Install additional fencing	Yes	The fence was shot through in the Metcalf attack, so a wall may be beneficial for the future system.
Wall	Yes	No There were no walls on the perimeter at Metcalf.	Add opaque or solid walls around the perimeter to shield and obstruct views of equipment inside the substation	No	The fence was shot through in the Metcalf attack, so a wall may be beneficial for the future system.
Motion Sensor	Yes	Yes	Enhanced detection and deterrent systems	No	The future system should have motion sensors to detect attackers. However, a study needs to be done to determine where the sensors should be placed and how sensitive they are to a false alarm.

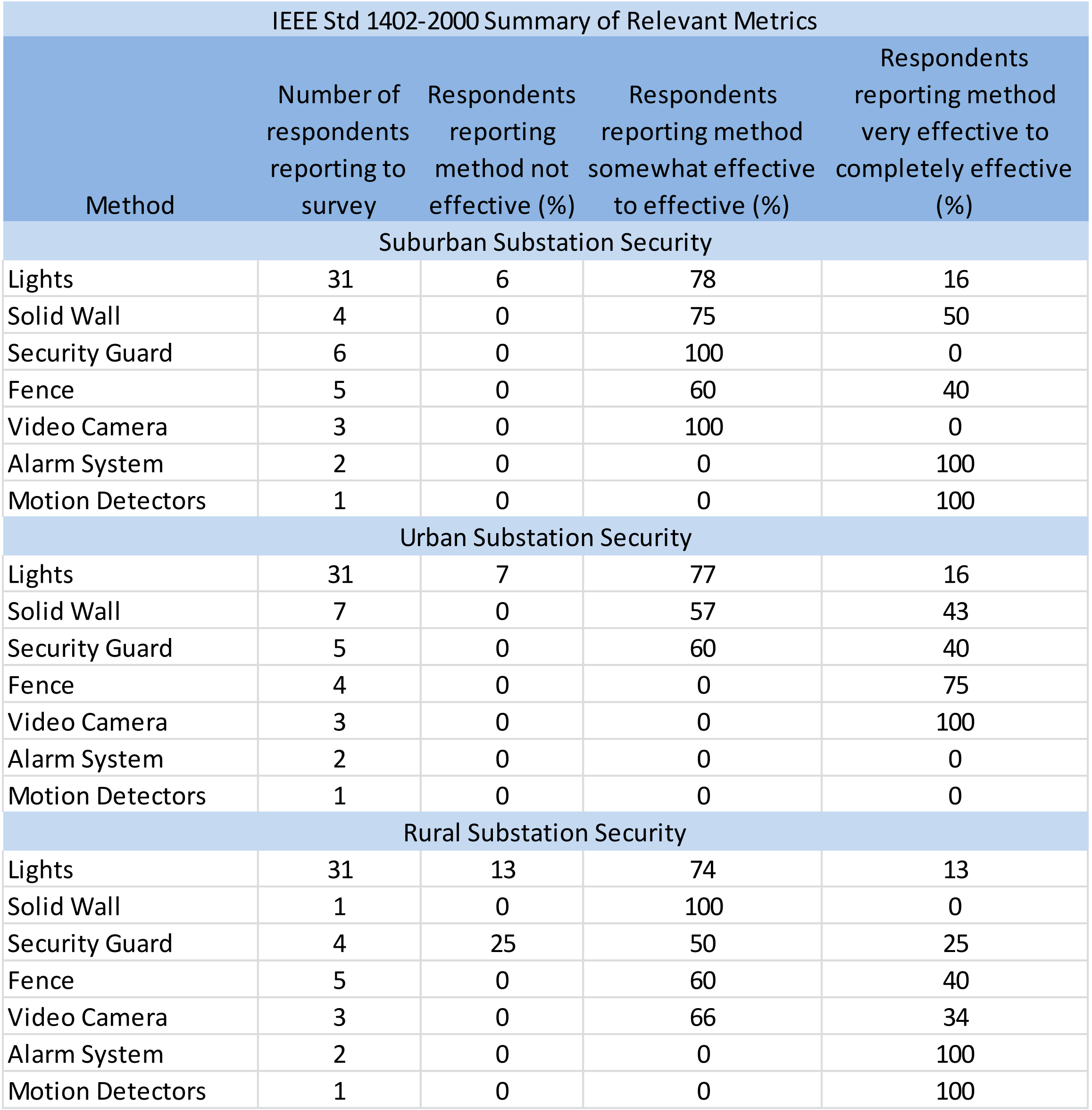
Table 4.17 (continued)

Resource	Traceability to IEEE Standard	Traceability to Historical Attack Scenario	Lessons Learned based on incident [Brinkman et al., 2015]	Traceability to video jamming scenario	Subject Matter Expert Evaluation
Communications Infrastructure	Yes	Yes	Not formally linked to sniper attack, so there were no follow-on recommendations. An assessment and test was conducted of the security systems.	No	The communications infrastructure for the future system should be evaluated to determine points where attackers can access communications infrastructure outside the substation’s immediate perimeter.

4.3.3.6 Collect subject matter expert opinions

The previous step resulted in expert analysis based on the historical attack scenarios' relationship to the new substation structural architecture. The next step is for the experts to use this analysis and knowledge of the field to determine the effectiveness of security methods for the new system. For this case study, existing data from the survey conducted in IEEE Std 1402$^{\text{TM}}$-2000 [2008] is used. In this survey, respondents were asked to provide the effectiveness of security methods used in four types of substations: urban, suburban, rural, and industrial/commercial. In this case study, the first three categories and only the security methods that apply to the case study scenario are used. Table 4.18 shows the survey data used for the analysis.

Table 4.18 Substation security effectiveness survey results [IEEE, 2008]



IEEE Std 1402-2000 Summary of Relevant Metrics				
Method	Number of respondents reporting to survey	Respondents reporting method not effective (%)	Respondents reporting method somewhat effective to effective (%)	Respondents reporting method very effective to completely effective (%)
Suburban Substation Security				
Lights	31	6	78	16
Solid Wall	4	0	75	50
Security Guard	6	0	100	0
Fence	5	0	60	40
Video Camera	3	0	100	0
Alarm System	2	0	0	100
Motion Detectors	1	0	0	100
Urban Substation Security				
Lights	31	7	77	16
Solid Wall	7	0	57	43
Security Guard	5	0	60	40
Fence	4	0	0	75
Video Camera	3	0	0	100
Alarm System	2	0	0	0
Motion Detectors	1	0	0	0
Rural Substation Security				
Lights	31	13	74	13
Solid Wall	1	0	100	0
Security Guard	4	25	50	25
Fence	5	0	60	40
Video Camera	3	0	66	34
Alarm System	2	0	0	100
Motion Detectors	1	0	0	100

To use the data in the table, an ISES is calculated. First, scores in the not effective column are assigned a “0” multiplier, those in the somewhat effective to effective column a “1,” and those in the very effective to completely effective column a “2.” Next, the survey percentage is multiplied by 0, 1 or 2, depending on the column in which it falls. Using lights in an urban substation as an example:

$$0\ .7\ \ +1\ .77\ \ +2\ .16\ \ =1.09 \qquad (4.6)$$

Table 4.19 shows a summary of the security effectiveness scores. It is interesting to note that, while lights are one of the most common security methods employed, alarm systems and motion detectors are identified as most effective [IEEE, 2008]. Possible reasons identified are increased cost, complexity and/or inconvenience [IEEE, 2008]. In the next section, the interaction between the ISES, security resources (see SV-1), and minimizing cost will be explored to determine the best options for decision makers.

Table 4.19 Security effectiveness scores

	Effectiveness Scores		
Method	**Urban**	**Suburban**	**Rural**
Lights	1.09	1.1	1
Solid Wall	1.08	1.75	1
Security Guard	1.4	1	1
Fence	1.25	1.4	1.4
Video Camera	1	1	1.34
Alarm System	2	2	2
Motion Detectors	2	2	2

4.3.3.7 Create OR model to enable analysis of alternatives

In the previous sections, the system was modeled to determine needed security resources, and subject matter experts were surveyed to determine priorities for system security. Based on this information, a decision maker may want to know what security resources should a decision maker invest in based on their budget constraints? In this section, an OR approach is used, specifically an integer linear program to assist a decision maker in determining how to use limited financial resources to obtain the highest security effectiveness from available security resources such as lighting, fences, manned patrols and walls. This type of analysis has been done in other contexts for the purpose of protecting CI during construction [Said and El-Reyes, 2010] and simulating the most effective use of security resources [Marechal et al., 2009]. However, there has not been work done to perform this decision analysis using security effectiveness scores coupled with an integer linear program in the architecture trade-space.

4.3.3.7.1 Assumptions

1. Maintenance costs or increasing wages for security officers are not considered.
2. At a minimum, a fence, wall or combination of both is required.

4.3.3.7.2 Decision variables

The decision variables defined in Table 4.20 are based on the security resources defined in the structural diagram of the architecture. These variables can be modified as needed to ensure that all relevant security resources are captured.

Table 4.20 Decision variables

Variable	Description
X_F	Binary variable (1 or 0) 1 = fence, 0 = no fence
X_W	Binary variable (1 or 0) 1 = wall, 0 = no wall
X_S	Number of sensors (Integer)
X_V	Number of video cameras (Integer)
X_A	Number of alarm systems (Integer)
X_L	Number of lights (Integer)
X_P	Number of security patrol hours (Integer)

4.3.3.7.3 Integer linear program

The objective of (4.7) is to minimize the annual cost of security by implementing a security resource, X_i, with a cost of C_i. Constraint (4.8) ensures that either a fence or a wall is selected for the outer perimeter of the substation. In (4.18) X_w and X_F are defined as binary variables with X_w or $X_F = 1$ if there is a fence or wall and 0 otherwise. Constraints (4.9-11) limit the number of resources (sensors, video cameras, lights) available based on inventory. Constraints (4.12-14) ensure that the number of security resources does not exceed what is needed based on the range of coverage (S_R, V_R, L_R) of the technology and the area (F_F) of the substation or the perimeter length (T_F). Constraint (4.15) constrains the alarm system to be one per building within the substation. Constraint (4.16) ensures that the number of security patrol hours does not exceed that maximum work hours for one year. Finally, in (4.17), the security effectiveness score threshold is set and the benefit scores are multiplied by their respective weighted values of the percent of the maximum usage of a particular resource. The integer linear program is as follows.

$$\min \sum_i C_i X_i \tag{4.7}$$

$$X_W + X_F = 1 \quad \text{must have a fence or wall)} \tag{4.8}$$

$$X_S \leq S_N \quad \text{limiting number of sensor} \tag{4.9}$$

$$X_V \leq V_N \quad \text{limiting number of video cameras} \tag{4.10}$$

$$X_L \leq L_N \quad \text{limiting number of lights} \tag{4.11}$$

$$S_R X_S \leq T_F \quad \text{limit \# sensors to available area} \tag{4.12}$$

$$V_R X_V \leq F_F \quad \text{limit \# of cameras to available area} \tag{4.13}$$

$$L_R X_L \leq F_F \quad \text{limit \# of lights to available area} \tag{4.14}$$

$$X_A \le B \quad \text{limit alarm systems to \# of buildings} \tag{4.15}$$

$$X_P \le P_S \quad \text{limit \# of security patrol hours} \tag{4.16}$$

$$B_F X_F + B_W X_W + B_S \ X_S/S_{max} \ + B_V \ X_V/V_{max} \ + B_A \ X_A/B \ + B_L \ X_L/L_{max} \ +$$

$$B_P \ X_P/P_S \ \ge E_S \quad \text{Must meet security effectiveness score threshold} \tag{4.17}$$

$$X_W, X_F \ binary \tag{4.18}$$

$$X_S, X_V, X_A, X_L \ integer. \tag{4.19}$$

4.3.3.7.4 Constants

The constants shown in Table 4.21 for this proof of concept example are engineering estimates based on books, vendor specifications, and publicly available documents. These constants will need to be further refined for the specific system architecture that is developed using this method. Key parameters such as the total linear feet of substation wall or fence, light and video coverage, and motion sensor range will be based on available technology. The costs of these resources will also vary based on specific company pricing agreements.

Table 4.21 Constants

Constant	Description	Value
T_F	Total linear feet around substation	1120 (280x280) feet
F_F	Total square feet of substation	78400 square feet
S_R	Motion Sensor Range	350 feet
V_R	Video coverage	130 square feet
L_R	Light coverage	5000 square feet
P_S	Maximum Physical Security Hours	8760 hours per year
L_{max}	Maximum number of lights	F_F / L_R (Integer)
V_{max}	Maximum number of video cameras	F_F / V_R (Integer)
S_{max}	Maximum number of sensors	T_F / S_R (Integer)

Table 4.21 (continued)

Constant	Description	Value
B	Number of Buildings in substation	1
S_N	Number of sensors available. This is currently set so it is not a limiting factor. This can be used if there is a limitation of resources.	100000
V_N	Number of video cameras available. This is currently set so it is not a limiting factor. This can be used if there is a limitation of resources.	100000
L_N	Number of lights available. This is currently set so it is not a limiting factor. This can be used if there is a limitation of resources.	100000
C_F	Cost of Fence	$50/linear foot
C_W	Cost of Wall	$200/linear foot
C_S	Cost of sensors	$600/sensor
C_V	Cost of Video Camera	$3000/camera
C_A	Cost of alarm	$10,000/building
C_L	Cost of lighting	$1500/light
C_P	Cost of manned security for 4 security personnel	$600/hour
B_F,B_W,B_S,B_V,B_A,B_P	Effectiveness Score of Fence, Wall, Motion Sensor, Video, Building Alarm, and Manned Patrols	See Table 7
E_S	Minimum Desired Security Effectiveness	This is a measure of how effective the security is based on subject matter expert opinion and historical attack vectors. The maximum security effectiveness means that you have the maximum security that money can buy based on the type of substation – urban, suburban or rural and subject matter expert opinion.

4.3.3.8 Perform Analysis to support key decisions

The execution of the integer linear program for urban, rural and suburban substations yield the results described in Table 4.22. The ISES constitute the data shown in Table 4.19 and are shown in the last column to provide a reference point. The total effectiveness scores (TES) for each scenario (e.g., 95% solution for Suburban Substation security), which are located above the cost on the left column, will add to the ISES for each selected security resource. For the 95% solution for suburban substation security, that would include all the ISES except the fence, which would be 0.95*(1.75+2+1+2+1.1+1) = 8.41.

In the Maximum Security case, the TES is the same for the urban and rural (8.74) but not the suburban (8.85) environment. The Minimum Security case involves either a fence or a wall and is denoted with a TES of 0; this is the same for all the environments. For this analysis, the highest effectiveness (maximum security) and the lowest effectiveness (minimum security) identified for each scenario are considered equivalent.

Table 4.22 Results summary

	Suburban Substation Security									
	Minimum Security	25% solution	50% solution	60% solution	70% solution	80% solution	90% solution	95% solution	Maximum Security	Individual Effectiveness Score
Fence (ft.)	1	1	1	1	1	1	0	0	0	1.4
Wall (ft.)	0	0	0	0	0	0	1	1	1	1.75
Sensors	0	2	2	3	3	3	3	3	3	2
Video Cameras	0	0	0	0	0	7	8	8	8	1
Alarms	0	0	1	1	1	1	1	1	1	2
Lights	0	0	0	0	11	11	15	15	15	1.1
Manned Patrols (hrs)	0	0	0	0	0	0	1008	4884	8760	1
Total Effectiveness Score	0	2.21	4.43	5.31	6.20	7.08	7.97	8.41	8.85	
Cost ($)	$ 143,000	$ 144,200	$ 154,200	$ 154,800	$ 171,300	$ 192,300	$ 1,235,100	$ 3,560,700	$ 5,886,300	
	Urban Substation Security									
Fence (ft.)	1	1	1	1	1	1	1	1	1	1.25
Wall (ft.)	0	0	0	0	0	0	0	0	0	1.08
Sensors	0	2	2	3	3	3	3	3	3	2
Video Cameras	0	0	0	0	0	7	8	8	8	1
Alarms	0	0	1	1	1	1	1	1	1	2
Lights	0	0	0	0	12	12	15	15	15	1.09
Manned Patrols (hrs)	0	0	0	0	0	0	3292	6026	8760	1.4
Total Effectiveness Score	0	2.19	4.37	5.24	6.12	6.99	7.87	8.30	8.74	
Cost ($)	$ 143,000	$ 144,200	$ 154,200	$ 154,800	$ 172,800	$ 193,800	$ 2,176,500	$ 3,816,900	$ 5,457,300	
	Rural Substation Security									
Fence (ft.)	1	1	1	1	1	1	1	1	1	1.4
Wall (ft.)	0	0	0	0	0	0	0	0	0	1
Sensors	0	2	2	3	3	3	3	3	3	2
Video Cameras	0	0	0	0	4	8	8	8	8	1.34
Alarms	0	0	1	1	1	1	1	1	1	2
Lights	0	0	0	0	1	4	15	15	15	1
Manned Patrols (hrs)	0	0	0	0	0	0	1104	4932	8760	1
Total Effectiveness Score	0	2.19	4.37	5.24	6.12	6.99	7.87	8.30	8.74	
Cost ($)	$ 143,000	$ 144,200	$ 154,200	$ 154,800	$ 168,300	$ 184,800	$ 863,700	$ 3,160,500	$ 5,457,300	

Table 4.22 shows the recommended investments from the minimum to maximum security solution. We compare the TES by designating the highest score for each scenario the 100% solution, the middle the 50% solution, and the lowest the minimum solution, with other percentages detailed in between. This allows a decision maker to determine their level of comfort with security based on their budget. The ISES drives the combination of security resources that are used as the TES increases.

For the suburban substation, the wall has a higher ISES and higher cost than the fence, so it follows that, for the lowest TES and minimum cost, the fence would be the selection. As the TES increases, sensors and alarms are introduced as security resources. In the 90% solution, the manned patrols are incorporated; they are introduced at this level due to the relatively low ISES of 1. In addition, the wall is introduced as the primary outer perimeter to meet the maximum effectiveness at the minimum cost. The suburban case can be compared to the urban and rural cases where, because of the effectiveness scores and subject matter expert data, the wall did not have enough benefit (ISES) to be in the maximum security configuration.

Comparing the urban and rural substations at the 70% solution point, the video cameras are introduced into the rural substation but not the urban substation. In the rural substation, the video cameras have an ISES of 1.34 as compared to an ISES of 1 for the urban substation. Comparing these values to the ISES for lights (urban = 1.09, rural = 1) in each case demonstrates that the ISES impacts the selection of security resources. For the urban case, the majority of the lights are introduced prior to the video cameras because the ISES is higher for the lights. The opposite happens in the rural case where the majority of the lights are introduced at the 80-90% solution level. This example shows how the ISES can cause the combination of resources to change even though the maximum security configuration of these two substations is the same. The goal is to incorporate the highest security effectiveness resources at as low a cost as possible. This leads to the next topic of comparing the costs based on the TES.

Figure 4.14 below compares the costs of security effectiveness for each type of substation. The data starts to diverge from the 80-90% data. The reason for this is that the ISES for each resource dictates the mix of resources, and that drives the cost. For example, the data shows that the cost to get to the 90% security effectiveness level for the urban substation (>$2 million) is much less than the cost to get to the 90% configuration for the rural substation (<$1 million). The urban substation costs are higher because of the high ISES for manned patrols, which means that, to obtain a 90% solution based on TES, there need to be more manned patrols. In another example, the suburban substation also has a similar result when compared to the urban substation. Manned patrols are tied for the lowest ISES, in contrast to the urban substation's results in which manned patrols have the highest ISES. When balancing cost and benefit, this results in a reduced cost for the 80% solution for the suburban substation as opposed to the urban workstation. These effects influence the cost difference until the maximum TES is reached, in which the urban and rural substations have the same cost and the suburban substation cost differs due to having a wall rather than a fence.

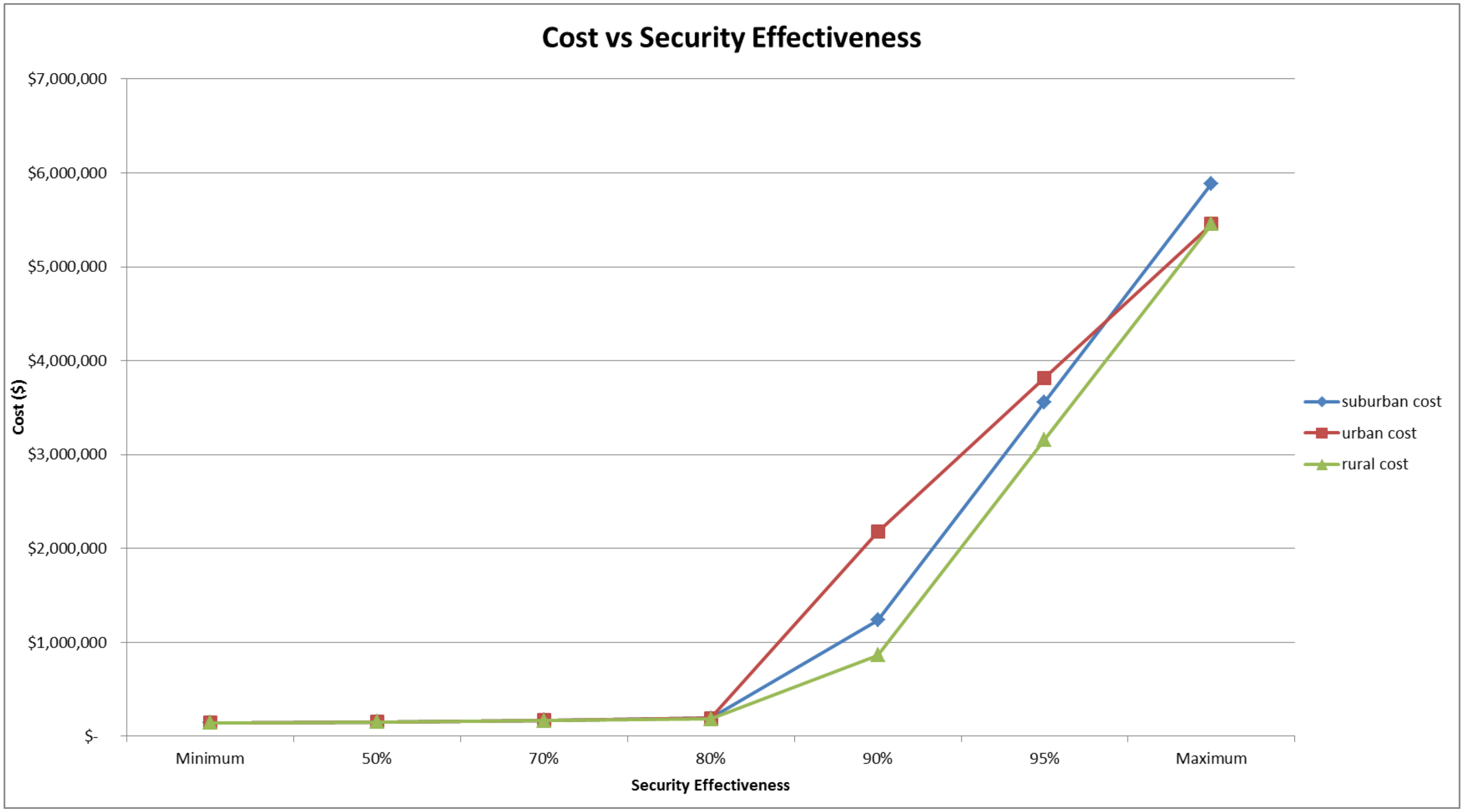


Figure 4.14 Cost versus security effectiveness comparison

The question to answer in this analysis was the following: what security resources should a decision maker invest in based on their budget constraints? Although it is a proof of concept, this case study has demonstrated that a decision maker could use this method to determine the resources they can invest in with the funding available. This methodology allows key decision makers to include all of their organization's expertise in determining the most appropriate investments in the architecture phase of the program. In this case study, if an asset owner had $2.2M to invest in urban substation security, then the analysis shows he or she could afford an 80% solution for security effectiveness. This analysis is valuable because the sooner that a decision maker can plan investments and understand system vulnerabilities, the greater chance there is that mitigations can be put in place. After this system level analysis, the next step is to evaluate the wireless video subsystem.

4.4 Illustrative case study: Subsystem architecture assessment (path 3)

Now that the physical security of the substation has been evaluated, the next step is to look at the design parameters associated with specific components. For this example we focus on one specific component: the wireless video monitoring system. In the previous section of this case study, an analysis of potential future potential attacks identified the case where the wireless security cameras were jammed by malicious insiders. In this section, the method developed will be used to provide decision makers and designers with information to develop a network to support video surveillance that is robust against jamming attacks. In this scenario, battery powered network nodes are used, which simulates the case in which a network needs to be set up quickly as a temporary backup to support secure communications of video data, in the event that the wired video lines are disabled either by a malicious actor or on accident. This type of scenario becomes more important as researchers explore the use of wireless communications for smart grid applications [Aravinthan et al., 2011]. Figure 4.8 shows a representative substation where cameras can be located anywhere along the fence line or internal to the substation.

4.4.1 Subsystem VA approach

4.4.1.1 Develop OV-5b operational activity diagram

Figure 4.12 represents a wireless jamming attack scenario. In this scenario, a malicious employee jams the wireless signal that the video cameras at the substation use to communicate with the operations center. There could be no video monitoring due to either complete loss of connectivity or a data rate so reduced that the video data could not be transmitted. The employee next opens the gate to the substation and causes physical damage to the equipment in the substation, such as transformers and breakers. The equipment damage causes an alarm in the operations center, and, as a result, security personnel respond and secure the facility. The employee stops the jammer after she has completed the planned activity.

4.4.1.2 Questions that the decision maker wants answered

In this scenario, the questions posed a decision maker are as follows. These questions were selected because we suppose that a decision maker wants to understand how securing the network will drive cost, schedule and design tradeoffs that make the network more or less robust against jamming attacks. For example, increasing the density of network nodes may be more expensive since more nodes have to be purchased, but it may make the network more resistant to jamming attacks.

1. Does increasing the density of the network nodes that are used to communicate with the video cameras help prevent a successful jamming attack?

2. Does increasing the number of channels available for each network node help prevent a successful jamming attack?

3. Does changing the transmit current of the network communication nodes help prevent a successful jamming attack?

4. How does changing the battery capacity impact the overall network throughput?

5. What number of jammers would have to have been placed to completely stop communication for the video system?

4.4.1.3 Refine scenario

In order to develop a decision model to answer the questions posed, the scenario needs to be refined. The first step is to identify the information that is not currently present in the OV-5b that will be required to develop the model to answer the questions. If this information does not become available or cannot be reasonably estimated, then we will know that the model will be unable to answer the questions. In the scenario presented, all the data was available that was required for the model to provide answers to the questions.

Table 4.23 Question and data mapping

Question	Data Required	Data
Does increasing the density of the network nodes that are used to communicate with the video cameras help prevent a successful jamming attack?	Current Density of Network Nodes Possibility for future density of network nodes	7x7 grid 9x9 grid
Does increasing the number of channels available for each network node help prevent a successful jamming attack?	Current number of channels Number of channels available	1 3
Does changing the transmit and receive current of the network communication nodes help prevent a successful jamming attack?	Current transmit and receive current Future transmit and receive current	45 each low: 15 / high: 90
How does changing the battery capacity of each node impact the overall network throughput?	Current battery capacity Future options for battery capacity	170 range (0,1000)
What number of jammers would have to have been placed to completely stop communication for the video system?	Current number of jammers available Number of jammers available	2 3

Once the data has been shown to be available, it would help to develop an overall model that shows more details of the scenario. Figure 4.15 shows the operations center, the 7x7 grid of ad hoc network nodes, jammer nodes and then the wireless camera at the substation. The scenario shown is where the operations center is sending commands to the camera, but it could also show the reverse path where the camera is sending data back to the operations center. Each of the nodes in the 7x7 grid has a battery with a specified capacity, transmit and receive current, as well as a radiation pattern based on the nodes' power output and antenna type. The jammers are placed such that they may or may not reduce or eliminate network throughput, depending on the range of the jammer to interfere with the communications. The example shown here is not to scale, but is presented merely to give an idea of how the scenario is configured. The next step is to develop the optimization model.

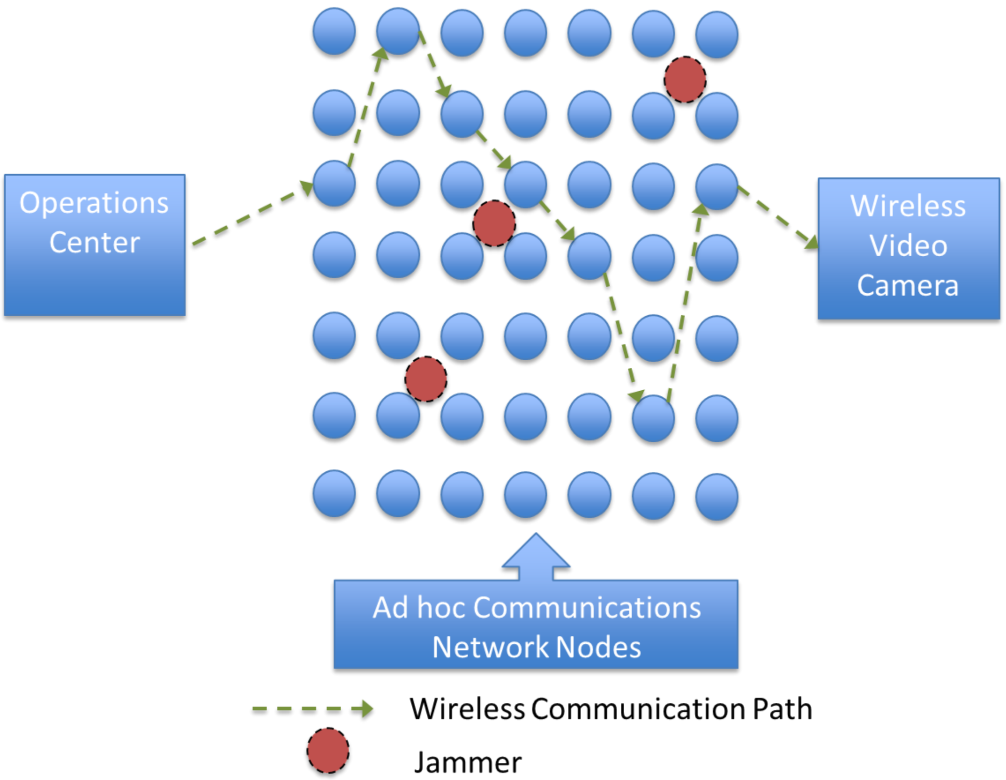

Operations Center
Wireless Video Camera
Ad hoc Communications Network Nodes
Wireless Communication Path
Jammer

Figure 4.15 Scenario example

4.4.1.4 Develop decision model

Based on the questions asked in the previous section, there are multiple models that can be developed to answer these questions. In this case, we will use a bi-level mixed-integer linear program based on Medal's [2016] work that will represent a two level Stackelberg game. This type of analysis allows the computation of the worst possible loss due to jamming attack; therefore, the analysis is pessimistic. In addition, it provides a lower bound on the total flow of the jamming attack, which supports a conclusion that a real jammer cannot cause more damage that the model indicates (provided that the assumptions about the network and jammers are correct). As discussed, this work will be extended to support directional antennas and consider the battery capacity at each node. In this game, the malicious employee (attacker) will place omnidirectional jammers at some location within the set of locations $\mathcal{L}$ in space. r_ℓ will be the cost of locating a jammer at location $\ell \epsilon \mathcal{L}$ with a budget of R. The goal of the malicious employee is to place the jammers such that the total data that is transmitted through the network is minimized.

On the defensive side, the goal of the network security personnel at the company is to maximize the amount of data transmitted through the network while the network is under attack. This model makes the assumption that the operator knows which nodes in the network are jammed, and routes and schedules flow accordingly; the operator can schedule all node to node communications [Medal, 2016].

With these assumptions, equation (1) is solved. Let x be a vector of jammer locations and let X be feasible vectors of jammer locations. Let y represent the total data transmitted through the network, Y(x) be the set of total data amounts given a jamming vector x, and TH(y) be the total data sent through the network. The bi-level formulation is given in equation 4.20. After determining the overall formulation, the next step is to determine a way to represent the network so that it can be analyzed. The network is represented using a three-layer representation.

$$\min_{x \in X} \ \min_{\boldsymbol{y} \in Y \ \boldsymbol{x}} TH \ \ y \tag{4.20}$$

4.4.1.4.1 Three-layer network

Traditionally, studies of the WNJP have only considered networks with omnidirectional antennas – antennas that transmit with the same power in all directions. However, this research is unique because it considers networks composed of directional antennas – antennas that transmit with greater power in a specific direction. In the radiation pattern, the direction where the primary transmission occurs is called the main lobe; 180 degrees from that is the rear lobe. An example of an omnidirectional antenna's radiation pattern is shown in green below in Figure 4.16, while an example of a directional antenna's radiation pattern is shown in blue.

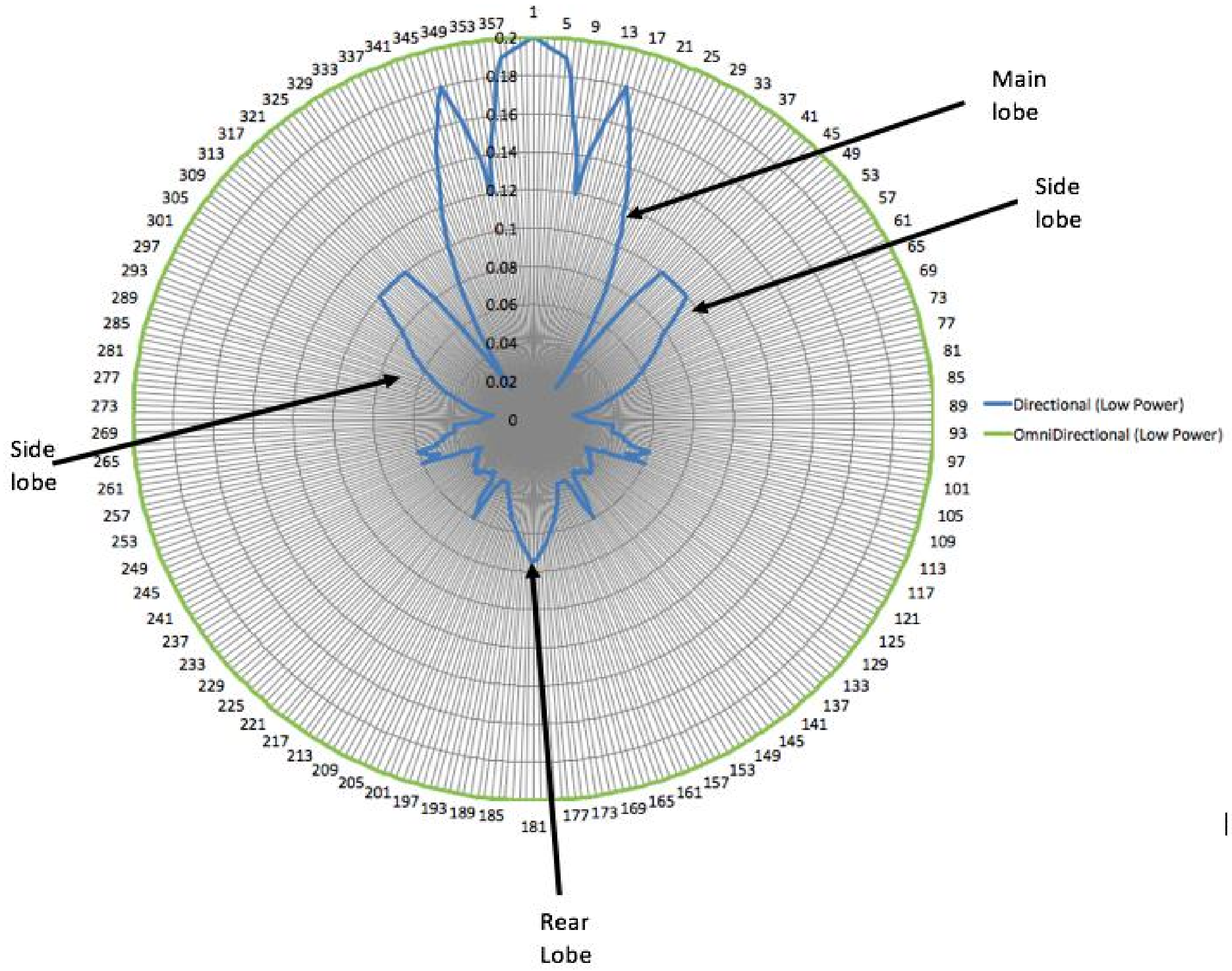


Figure 4.16 Omnidirectional versus directional antenna radiation pattern

4.4.1.4.1.1 Physical layer

A major step related to finding an optimal solution for the WNJP requires consideration of three layers of the network in question. The network's physical layer consists of multiple antennas that broadcast data to one another; each antenna can be illustrated as a node (e.g., node *i*). The nodes in the physical layer all have various attributes characteristic of most any antenna, which include a communication range (the physical distance within which each antenna can broadcast to other nodes) and an interference range (the physical distance within which its own data broadcasts can jam the broadcasts of others).

4.4.1.4.1.2 Connectivity layer

An additional network layer is the connectivity layer, which is depicted by a connectivity graph represented by $G = \ \mathcal{N}, \mathcal{A}$, where $\mathcal{A}$ is a set of arcs that use k as an index. Here, "connectivity" refers to the physical transmission by nodes of data to one another with wireless network signals. An arc, also referred to as an edge, connects any two nodes *i* and *j* if the former is able to transmit a signal successfully to the latter. The third network layer is the interference layer; in this layer, simultaneous network transmissions by different nodes through the same space will interfere with each other. As a result, at any given time, each node can be either sending or receiving a single communication to or from another node; anything else would imply that interference is taking place, rendering the attempted communication null.

When considering the connectivity layer, note that the network considered by the WNJP (as discussed in this chapter) utilizes the 802.11 network protocol. The 802.11

network protocol requires that, for any two nodes, neither can transmit or receive any data while the other node is transmitting or receiving data, assuming that either node is within the interference range of the other. Consequently, each node receiving a signal must transmit and deliver an acknowledgement of its receipt of data to the sending node for the nodes' communication to be validated. Without the receipt of a delivery verification message at the origin node for each transmission to another node, the network would fail to meet the requirements of the 802.11 protocol and the communication would fail. Therefore, special consideration must be given to ensuring that the 802.11 protocol's requirements are met.

When using an omnidirectional antenna for each network node, the 802.11 communication protocol is readily achieved as shown in Figure 4.17a. The successful data transmission by one node (solid circle) implies that the data transmitted by the other node (dashed circle) is also successfully transmitted due to the overlap in the radiation pattern. The analysis to determine if directional antennas meet the 802.11 protocol is more complex because one node's radiation pattern might be able to reach a second node to transmit data, but the second node's pattern might be focused mainly in the opposite direction and not be able to reach the original node. Thus, such a scenario fails to guarantee that the delivery of sent data can be confirmed with a response. An example of such a situation is portrayed in Figure 4.17b, in which the solid radiation pattern overlaps node 2, but node 1's dashed pattern does not overlap node 2, so no communication is established between those two nodes. Figure 4.17c shows a scenario in which both nodes are communicating.

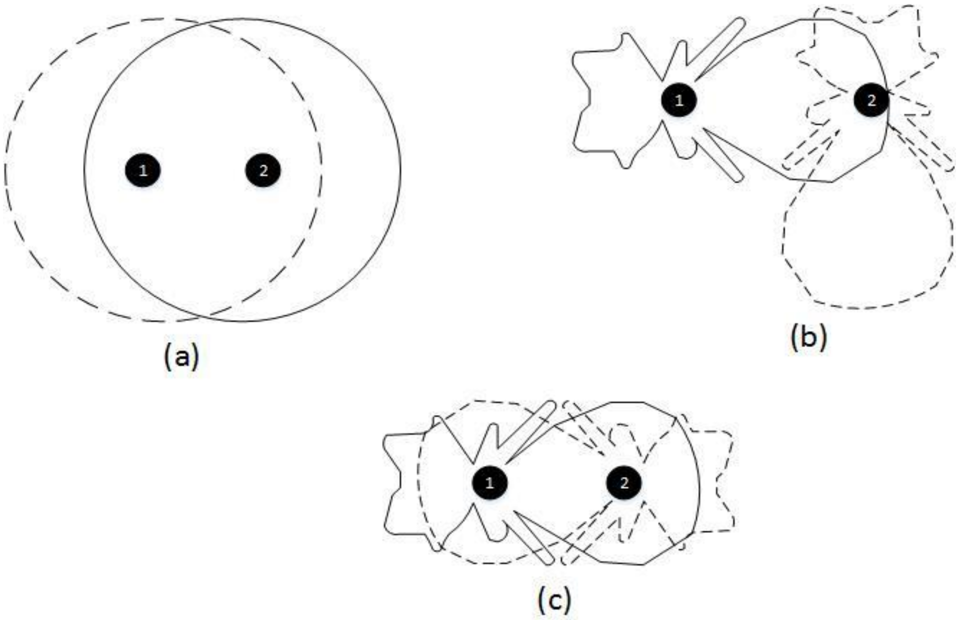


Figure 4.17 Connectivity examples

(a) Omnidirectional connectivity
(b) Directional with no connectivity
(c) Directional with connectivity

Another important attribute to consider for both omnidirectional and directional antennas is the power level of each radiation pattern. For instance, suppose that there are three possible power levels for a given array of antennas: low, medium, and high. If the power level is high, the radiation patterns for the transmissions from each antenna are going to be of a greater magnitude than those at a lower power level. The graph in Figure 4.18 below demonstrates this fact, with radiation patterns of low, medium, and high power levels being shown with solid, dashed, and dotted lines, respectively. Therefore, when considering communications of varying power levels among antennas, it is imperative to be aware of the potential variance in antennas' signal strength at different power levels.

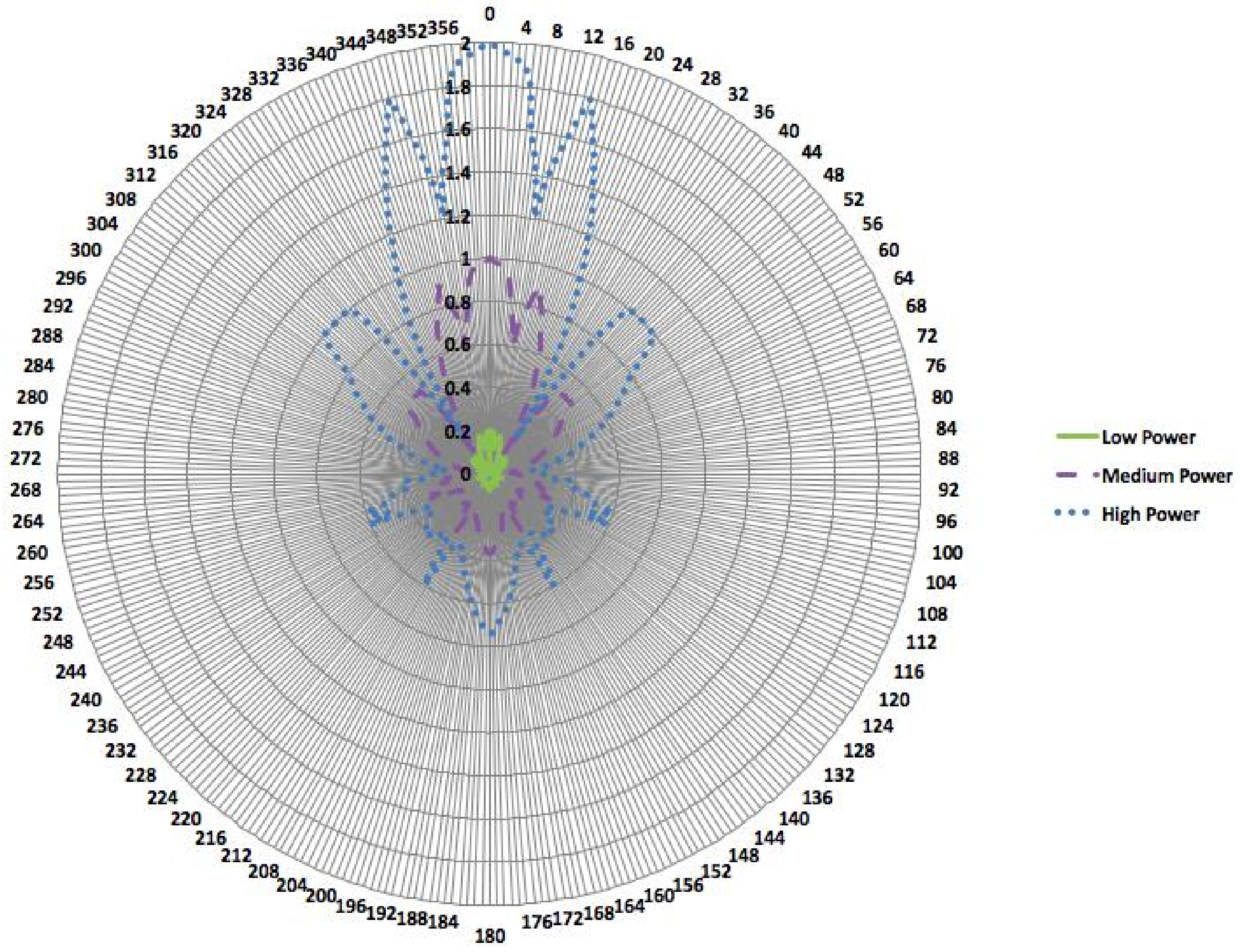


Figure 4.18 Radiation patterns at low, medium and high power levels

4.4.1.4.1.3 Interference layer

The use of directional antennas, in addition, also affects the interference layer of the network model. Previously, when using omnidirectional antennas, one had only to look at the uniform transmission distance at degrees 1 to 360 to determine if the transmission in a given radiation pattern would reach "into" the transmission of another node's radiation pattern and potentially cause a signal conflict that would jam the transmissions. When using directional antennas, however, one must determine whether the radiation pattern transmission distance at a given degree toward another node is aligned to interfere with another radiation pattern's transmission distance at another degree out of 360. Nonetheless, one requirement remains: that is, the interference layer's requirement that simultaneous network transmissions by different nodes through the same space will interfere with each other. Figure 4.19a offers one example of this; while nodes 1 and 2 are connected via their rear lobes, if node 1 or 2 is active, neither node 3 nor 4 can be active. In the example shown in 4.19b, node 2's radiation pattern covers both nodes 1 and 3, which means that nodes 1 and 3 cannot be active while node 2 is active.

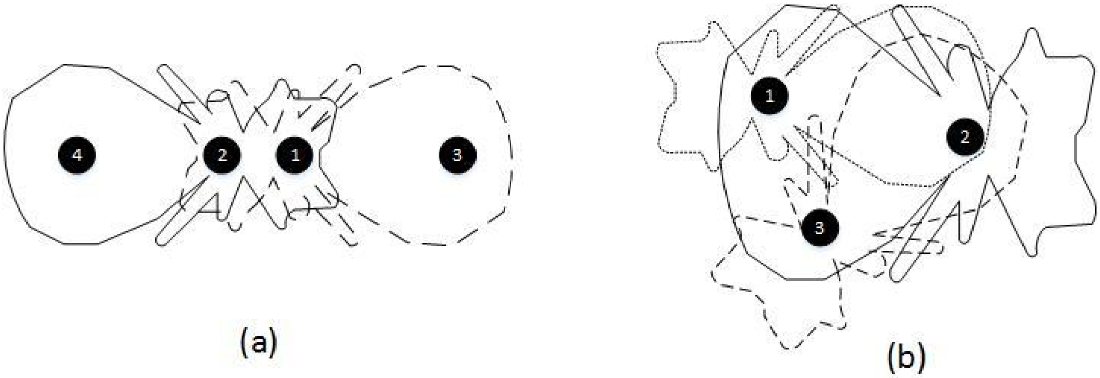


Figure 4.19 Interference examples

(a) Nodes 1 and 2 interfere with each other
(b) Nodes 1 and 3 cannot be active while node 2 is active

4.4.1.4.2 Calculating total data transmitted

The details from each layer will be used to explain how the total data transmitted in the network under interference is calculated. A conflict graph, which was first developed by Jain et al. [2005], will be used to model the interference layer. G'will represent the conflict graph, which has a node that contains each arc in the connectivity graph; i,j represents a node in G'. Nodes i,j and r,s have an arc between them in G' if arcs i,j and r,s interfere in G.

As a result of arcs interfering with each other, simultaneous data transmissions of all nodes are not possible. Because of this fact, nodes must alternate between "on" and "off" states to avoid interference. This is mitigated by Jain et al. [2005], whose work shows that arcs that are active will not interfere with each other if they form an independent set in G'. It follows that the maximum total data transmitted can only be achieved with maximal independent sets in G', which is achieved when adding another node to the set causes it to no longer be independent. The set of all maximally independent sets will be $\mathcal{I} = \{I_1, I_2, I_3, \ldots, I_K\}$ with an index of $\{1,2,3, \ldots, K\}$; therefore, $\mathcal{I}_k$ represents all maximally independent sets with arc k.

Next, how the data is routed and scheduled in the network is defined. Let $\boldsymbol{w} =$ $w_\sigma\ \ _{\sigma\in\, I}$ be a vector that defines the total time the arcs in the I_σ independent set are "on." Let $\boldsymbol{y} =$ $y_k\ \ _{k\in\mathcal{A}}$ represent the total data flow on arc k, which, when multiplied by the capacity of kU_k and $\left(\sum_{\sigma\,\in\, I_k}\ w_\sigma\right)$, provides the total data that has flowed on k.

Finally, the battery capacity and total current (both transmit and receive current) are defined. Let T_σ represent the total current that is required to transmit and receive during a communications interaction; let B_i define the battery capacity for a node. The $\sum_{\sigma\in\, I}\ w_\sigma T_{\sigma i}$ term represents the total usage of the battery to transmit and receive during a communication between two nodes.

4.4.1.4.3 Bi-level mixed integer program

We begin to formulate the appropriate mixed-integer program by defining the vector of binary variables $\mathbf{x} =$ $x_\ell\ \ _{\ell\in\mathcal{L}}$, for which x_ℓ is 1 if a jammer is located at location ℓ but 0 if a jammer is not located at location ℓ. To account for the cost of placing a jammer, it is appropriate to assign a cost of r_ℓ to placing a jammer at any location ℓ, subject to an overall budget limitation valued at R.

In this problem, y_a represents the total data transmitted over the network into sink t. We will also refer to a forward star and a reverse star, which are indicated as $FS\ \ i\ \ =$ $\{k\colon k =\ \ i, j\ \ \in \mathcal{A}\}$ and $RS\ \ i\ \ = \{k\colon k =\ \ j, i\ \ \in \mathcal{A}\}$, respectively.

$$\min_{\boldsymbol{x}\in\{0,1\}^{|\mathcal{L}|}} g\ \boldsymbol{x} \tag{4.21}$$

$$s.t.\ \sum_{\ell\,\in\,\mathcal{L}} r_\ell x_\ell \ \le\ R, \tag{4.22}$$

where

$$g\ \boldsymbol{x}\ = \max y_a \tag{4.23}$$

$$s.t.\ \sum_{k\in\, FS(i)} y_k - \sum_{k\in\, RS(i)} y_k = \begin{cases} y_a & i = s \\ 0 & i\ \in N \backslash \{s,t\}\ \ \forall i\ \in N\quad [\alpha i], \\ -y_a & i = t \end{cases} \tag{4.24}$$

$$0 \le y_k \le \left(\sum_{\sigma\,\in\,\mathcal{J}_k} w_\sigma \right) U_k,\ \ \forall k \in\ A\ [\beta_k], \tag{4.25}$$

$$\sum_{\sigma\in\,\mathcal{J}} w_\sigma T_{\sigma i} \le\ B_i \ \forall\ i \quad [\gamma i], \tag{4.26}$$

$$w_\sigma\ \ge\ 0\ \ \forall \sigma\ \in\ I \tag{4.27}$$

$$0\ \le\ y_k \le\ U_k\ \ 1 - x_\ell\ \ , \forall k\ \in A, \ell \in \mathcal{L}k. \tag{4.28}$$

We determine the total data transmission for a solution involving a particular placement of jammers via the inner problem $g\ \boldsymbol{x}$. In the case of the outer problem's objective function (4.21), it is desired that the network throughput be minimized with the optimal placement of jammers, subject to the budget constraint (4.22). Further, the inner problem's objective function seeks to maximize the network throughput. Constraints

(4.24) balance the data flow at any intermediate nodes between the source and sink nodes. Constraints (4.25) require that the network data flow to and from each node never be less than zero, with the total data flow in each arc (between any two nodes) to be no greater than the arc's data flow capacity multiplied by the fraction of time that the arc is being used. Next, constraint (4.26) confirms that a maximum limit is set for the transmit current of the node relative to the total battery capacity, with the variable w_σ constituting the usage of each node; constraint (4.27) takes care that the total time that an arc is active is not less than zero. Last, understanding that $\mathcal{L}_k$ is the set of available locations within the jamming range of arc k, it should be evident that equation (4.28) requires that the capacity of an arc that is within the proximity of a jammer is zero (i.e., no data flow is possible under jamming conditions).

4.4.1.4.4 Cormican, Morton, and Wood

To make the process of solving the bi-level mixed-integer programming model easier, it might seem appropriate simply to consider taking the dual of the inner maximization problem (g(**x**)). However, to avoid having to account for bi-linear terms in the resulting minimization problem because of equation (4.28), Cormican, Morton, and Wood propose rewriting the inner problem without equation (4.28) simply by assessing a penalty against data flow through jammed arcs. The updated version of the inner problem, therefore, is as follows in equation (4.29).

$$g(\boldsymbol{x}) = \quad max_{y\geq 0} \quad ya - \sum_{k \in A} \sum_{\ell \in \mathcal{L}} x_\ell yk \tag{4.29}$$

s.t. (4.24) – (4.27).

We then can take the dual of equation (4.29) to derive the minimization problem in equation (4.30). In the case of equation (4.30), it is desired that the overall battery usage be kept as low as possible while still maximizing the total data flow overall in the main model.

$$\min_{\boldsymbol{x}\in X,\alpha,\beta,\gamma} \sum_{i} B_i \gamma_i \tag{4.30}$$

$$s.t.\ \alpha_i - \alpha_j + \beta_k + \sum_{\ell\in\mathcal{L}} x_\ell \geq 0 \,\forall\, (i,j) \;=\; k \;\in\; \mathcal{A} \tag{4.31}$$

$$\alpha_i - \alpha_j \geq\; 1 \tag{4.32}$$

$$\sum_{i\,\in N_\sigma} T_{\sigma i}\gamma_i \geq \sum_{k\,\in I_\sigma} U_k\beta_k \qquad \forall\sigma\;\in \mathcal{I}, \tag{4.33}$$

$$\beta_k\;\; \geq 0\,\forall\, k \in\; \mathcal{A} \tag{4.34}$$

$$\gamma\;\geq 0 \tag{4.35}$$

where the set $X=\{x_\ell : \ell\in\mathcal{L}, x_\ell\in\{0,1\}, \sum_{\ell\in\mathcal{L}} r_\ell\, x_\ell \leq R\}$ denotes the feasible jamming location solutions.

4.4.1.4.5 Multiple communication pairs

Up to this point, we have considered only a single source-single sink combination in the context of network data flow; however, a model with multiple sources and multiple sinks is typically more appropriate and is not difficult to formulate. If $\mathcal{M}$ is a set including source-sink node pairs (of the form s_M, t_M), and each pair $m \in \mathcal{M}$ has a particular desired data flow rate D_m between each source and sink pair, the following model may be formulated to find a value for the throughput. It is significant that constraint (4.40) limits the demand for each source-sink pair but does not prevent communication pairs from interfering with one another. The model that follows is the multiple communication pairs extension of equation (4.29).

$$g(\boldsymbol{x}) = \max_{y\geq 0} \sum_{m\,\in\,\mathcal{M}} y_{am} - \sum_{m\,\in\,\mathcal{M}} \sum_{k\,\in\,\mathcal{A}} \sum_{\ell\,\in\,\mathcal{L}} x_{\ell} y_{km} \tag{4.36}$$

$$s.t. \quad \sum_{k\in\,FS(i)} y_{km} - \sum_{k\in\,RS(i)} y_{km} = \begin{cases} y_{am} & i = s_m \\ 0 & i\,\in\,\mathcal{N}\setminus\{s_m, t_m\} \;\; \forall\, m\,\in\,\mathcal{M},\; i\in\mathcal{N} \\ -y_{am} & i = t_m \end{cases} \quad [\alpha_{mi}], \tag{4.37}$$

$$0 \leq \sum_{m\,\in\,\mathcal{M}} y_{km} \leq \Big(\sum_{\sigma\,\in\,\mathcal{J}} w_{\sigma}\Big) U_k, \forall k \in \mathcal{A}\; [\beta_k], \tag{4.38}$$

$$\sum_{\sigma\in\,\mathbb{I}_i} w_{\sigma} T_{\sigma i} \;\leq\; B_i \,\forall\, i \quad [\gamma_i], \tag{4.39}$$

$$y_{am} \;\geq D_m \,\forall\;\, m \in \mathcal{M} \quad [\zeta_m], \tag{4.40}$$

$$w_{\sigma} \geq 0 \,\forall \sigma\; \in\; \mathcal{J} \tag{4.41}$$

After considering the multiple-communication-pair model for the inner problem $g \;\; \boldsymbol{x}$, the multiple-communication-pair model for the overall problem is as follows:

$$\min_{\boldsymbol{x}\in\, X,\alpha,\beta,\gamma} \sum_{l} B_i \gamma_i + \sum_{m\in M} D_m \zeta_m \tag{4.42}$$

$$s.t.\ \alpha_{mi} - \alpha_{mj} + \beta_k + \sum_{\ell \in \mathcal{L}_k} x_\ell \geq 0\ \forall\ m \in \mathcal{M}, (\mathrm{i},\mathrm{j}) = k\ \in\ \mathcal{A} \tag{4.43}$$

$$\alpha_{m,t_{tm}} - \alpha_{m,s_m}\ \geq 1\ \forall m\ \in \mathcal{M} \tag{4.44}$$

$$\sum_{i \in N_\sigma} T_{\sigma i}\gamma_i\ \geq \sum_{k \in I_\sigma} U_k\beta_k\ \forall\sigma\ \in\ \mathcal{I}, \tag{4.45}$$

$$\beta_k\ \geq 0\ \forall\ k \in\ \mathcal{A} \tag{4.46}$$

$$\zeta_m\ \geq 0\ \forall m\ \in \mathcal{M} \tag{4.47}$$

$$\gamma\ \geq 0 \tag{4.48}$$

4.4.1.4.6 Branch-and-cut solution methodology

Because finding an optimal solution for the model requires a large number of constraints, it is useful to use an approach with which the constraints may be generated dynamically. If $\bar{\mathcal{I}}$ is considered to be a particular subset of the independent set $\mathcal{I}$, then equation (4.49) may be considered the "relaxed" version of equation (4.30), based on using $\bar{\mathcal{I}}$ in lieu of $\mathcal{I}$.

$$\min_{\boldsymbol{x} \in X,\alpha,\beta,\gamma} \sum_{i \in N_\sigma} Bi\gamma i \tag{4.49}$$

$$s.t.\qquad 4.31\ ,\ 4.32\ ,\ 4.34 \tag{4.50}$$

$$\sum_{i \in N_\sigma} T_{\sigma i}\gamma_i \geq \sum_{k \in I_\sigma} U_k\beta_k\ \forall\sigma\ \in\ \bar{\mathcal{I}}, \tag{4.51}$$

Solving model (4.49) should eventually provide a solution to equation (4.30), but, by limiting the number of original constraints, the procedure to solve is more easily performed. To account for the constraints not included in equation (4.49), a cutting-plane approach is utilized by adding new independent sets to subset $\bar{\mathcal{I}}$ on an as-needed basis. An iterative process is performed with a set $\bar{\mathcal{I}}$ smaller than $\mathcal{I}$, with the optimal objective function value z* being the same whether considering either the smaller set (z*($\bar{\mathcal{I}}$)) or the larger set of which the smaller set is a part (z*($\mathcal{I}$)). To generate additional constraints of type (4.51), a separation problem is used that looks for an independent set that, when added to $\bar{\mathcal{I}}$, results in a new constraint (4.51) that is maximally violated based on the current values for γ_i and β_k. If $\mathcal{N}\ \ G'$ is defined as the set of nodes in the conflict graph and $\mathcal{A}\ \ G'$ is the set of arcs in the conflict graph, the separation problem previously referenced takes on the form of equation (4.52).

$$z(\boldsymbol{\beta}) = max \sum_{k\epsilon\mathcal{N}(G')} \widehat{\beta}_k U_k v_k - \sum_{i\epsilon N_\sigma} T_{\sigma i}\gamma_i Z_i \tag{4.52}$$

$$s.t. \quad v_k + v_{k'} \leq 1 \,\forall(k, k') \in \mathcal{A}\,(G') \tag{4.53}$$

$$v_k \leq z_i \,\forall k \in \mathcal{N}\,(G')\,\forall i \textit{ such that } i \textit{ is one of the endpoints of } k \tag{4.54}$$

$$v_k \in \{0,1\}\,\forall k \in \mathcal{N}\,(G') \tag{4.55}$$

$$z_i \in \{0,1\}\,\forall i \in \mathcal{N}\,(G') \tag{4.56}$$

In problem (4.52-56) the objective function, (4.52), maximizes the right-hand side of equation (4.51). The v_k variables have to be an independent set for the (4.53) and

(4.55) constraints to be met. To ensure that the value of β_k does not become equal to zero (meaning that equations (4.52-56) would not provide a maximally optimal value), a modified weights factor $\overline{\boldsymbol{\beta}} = \ max\{\beta_k, \varepsilon\}_{\ k\epsilon\mathcal{N}\ G'}$ is utilized with an extremely small number (e.g., 0.001) as the ε value. To perform the operation of equation (4.52-56) effectively, $\overline{\boldsymbol{\beta}}$ is substituted for β_k to find an optimal solution $\boldsymbol{v}*$.

Finding optimal solutions for equations (4.49-51) and (4.52-56) depends on embedding the cutting plane process inside of a branch-and-bound algorithm. Whenever the branch-and-bound algorithm finds a new solution, a separation procedure is utilized in which adding a new cutting plane is considered. If $\hat{\gamma}$ and $\hat{\beta}$ are the current values of γ and $\beta$when a new value is determined for $\boldsymbol{x}$, then the separation procedure is

1. Solve (4.33-37), returning $\boldsymbol{v}*$.
2. If $\hat{\gamma} \ < \sum_{k\epsilon\mathcal{N}\ G'} \beta_k U_k v_k - \sum_{i\in N_\sigma} T_{\sigma i}\gamma_i Z_i$, then add the independent set $\{k: k\ \in\ \mathcal{N}\ \ G'\ , v_k^* = 1\}$ to $\bar{\mathcal{I}}$.

4.4.2 Results

Now that the model is developed, the next step of the decision-making process is to execute the model. Table 4.24 shows the baseline parameters that will be used to execute the model. The experiments were performed with n x n grid networks overlaid on a fixed-size square. Thus, the greater the dimension of the array, the denser the grid of network nodes; e.g., a 7 x 7 grid has 49 nodes and a 9 x 9 grid has 81 nodes. The default grid network is a 7 x 7 grid, but the 9 x 9 grid is also used. The nodes are placed in a unit square with the horizontal and vertical distance of $\frac{1}{\mathrm{n}-1}$. For the baseline case, each network node only communicates on a single channel.

The networks are comprised of 16 communication pairs with a communication rate from 0 to 2 generated randomly. For the two networks discussed, there are four origin or destination nodes at the corner of the grid and four at the center of the sides. The communication range, c_i, is dictated by the radiation pattern selected. For the medium power radiation pattern, the communication range ranges from 0 to 1 depending on the corresponding degree in the radiation pattern (see Figure 4.16). The interference multiplier was set to 1.75 based on the recommendation of Iyer and Karnik [2009], which makes the interference range $1.75c_i$. This means that the interference range for one node interfering with another from a communications standpoint will be 1.75 times the communications range.

Table 4.24 Parameters and baseline values

Parameter	Baseline Value
Network dataset	Grid_7x7
Channels	1
Communication pairs	16
Communication range c_i	Dictated by selected radiation pattern (will use the medium directional antenna pattern for these experiments unless otherwise noted)
Number of possible jammer locations $\lvert\mathcal{L}\rvert$	25
Interference multiplier	1.75
Number of jammers	2
Jammer range	1/12
Transmit current for each node	45mA
Receive current for each node	50 mA
Battery capacity for each node	170 mAh

The number of possible jamming locations, $\mathcal{L}$, is a $n\ x\ n$ grid integrated with the communications layer. The jammer range is set to $\frac{1}{12}$, which is for an omnidirectional radiation pattern with a radius of 1/12. This range was selected because it is the range needed to jam two communications nodes. The number of jammers is set to two, which means that, out of the 25 possible jammer locations, two will have jammers.

Finally, each node will have a transmit and receive current to represent the total current T when a node is transmitting and receiving communications, with a key assumption being that the quiescent current is not accounted for but can be in future iterations of the model for specific devices. Each node will have a battery with a capacity represented in milliamp hours (mAh) – the baseline value will be 170 mAh. The relationship between the transmit and receive current and battery capacity is as follows in (4.57).

$$Total\ current\ (T) * time\ (w) \leq battery\ capacity\ (B) \tag{4.57}$$

The next step is to answer the questions based on the execution of the model.

4.4.2.1 Does increasing the density of the network nodes that are used to communicate with the video cameras help prevent a successful jamming attack?

One of the items important to a decision maker is return on investment, i.e., how much is spent versus how much benefit is received. This question seeks to answer that question by presenting the performance impact of increasing the number of nodes in the network. To answer this question, experiments were run with nodes with 1, 2, and 3 channels on two different grids; a 7 x 7 grid containing 49 nodes and a 9 x 9 grid containing 81 nodes.

As shown in Table 4.25, increasing the density of the network nodes (i.e., increasing from the 7 x 7 network to the 9 x 9 network) increases the total data transmitted through the network. The data represented here is a relative measure of amount of data transferred and will represent some number of bytes depending on the network characteristics such as the network bandwidth and actual data rates transmitted (bits per second) which would impact the total data transmitted for a given period of time. For example, if the total data transmitted as shown by the model is 1.2, that could represent 50 bytes of data transmitted depending on the network parameters. In that case, the model value of 2.4 would indicate 100 bytes of data transmitted. The density of the network allows multiple paths in which the data can be transmitted in the face of jammers. In addition, there is less of a probability that the jammers will interfere with the specific path since there are only two jammers. In general, regardless of the number of channels, the 9 x 9 dataset transmits more data when under interference. Knowing this will allow the network designers and decision makers to design a network that has as many nodes as possible to allow the most paths around the potential jamming attack.

Armed with this information, decision makers can perform a cost benefit analysis to make the tradeoff of the magnitude of improvement in robustness against the cost. For example, in this case, if each node is $1000 and 2 units of data are needed for the target application, then a decision maker could choose to spend $49,000 on 49 nodes or $81,000 on 81 nodes. However if, 4 units of data needed to be transmitted, then a decision maker would have to spend the $81,000. A decision maker could also determine that if they needed 4.5 units of data, then a larger grid would be needed, assuming each node was only limited to three channels. This could also drive requirements for other network components to help make tradeoffs; for example, that only a certain level of resolution of video is actually required to avoid costs in security to create a larger network that is robust against attack.

Table 4.25 Number of channels and total data

Dataset	Number of channels	Total data	% change
Grid-7x7	1	1.2	
	2	3.1	154
	3	3.7	20
Grid-9x9	1	2.4	
	2	4.1	72
	3	4.4	7

4.4.2.2 Does increasing the number of channels available for each network node help prevent a successful jamming attack?

This question would be helpful for a network designer so he or she could understand the benefits of increasing the number of channels when doing design tradeoffs for specific ad hoc network node devices. To answer this question, one should refer again to the results in Table 4.25. The model was first run with one channel, which indicated that the total data that flowed through the system after a jamming attack was 1.2. If the video camera were to require 3 units of data to be effective during the jamming attack, then, with a 7 x 7 grid, a network designer would need at least two communication channels. If the same logic applies to the 9 x 9 grid, then a network designer would need 2 channels as well.

As shown in Table 4.25, as the number of communication channels increases, the total data transmitted through the network also increases. This occurs because, if one channel is jammed, the network device can cycle through the channels until a channel that is not jammed is found. Thus, network designers should design networks with the most available channels to overcome the impact of a jamming attack. The data also shows that, for both the 7 x 7 and 9 x 9 grids, the greatest benefit with two jammers occurs when two channels for each node are created. Using three channels gives about a 20% increase in total data transmission on the 7 x 7 grid but has only a minimal impact on the 9 x 9 grid. In any case, the 9 x 9 grid still transmits more total data.

A decision maker can now use this information to determine the threshold number of nodes and channels for which the system is robust to likely jamming scenarios and therefore where it makes sense or not to make additional investments in network nodes. For example, if 3 units of data need to be transmitted, a decision maker could choose the 7x7 grid with two channels or the 9x9 grid with two channels. Assuming that each of the nodes is the same cost, it makes more sense to select the 7x7 grid. However, if at some point in the future the decision maker anticipates needing to transmit 4 units of data, it may make sense to invest in the 9x9 infrastructure now. Another case to consider is the case where two units of data is desired to be transmitted. To meet the requirement in this case, one must use either the 7x7 grid with two channels or the 9x9 grid with one channel. In the case where a node with two channels is more expensive (e.g., $1500) than the nodes with one channel (e.g., $1000), then the cost tradeoff would be $73,500 (7x7) versus $81,000 (9x9) which makes the 7x7 grid cheaper. While this is the same result, a decision maker could choose to invest in the 9x9 for future capability since the price for the nodes is fairly close. These are the types of tactical and strategic decision the data produced by the model allows a decision maker to make.

4.4.2.3 Does changing the transmit current of the network communication nodes help prevent a successful jamming attack?

Each node has limited battery capacity. In this example, the battery capacity is influenced by the transmit and receive current and how long the device is transmitting and receiving. The data shows that there is a point between 1 and about 50 mA of receive current at which the total data that the system transmits is saturated (i.e., no more data can be sent). As the current increases, the total data transmitted decreases; this is expected because with a higher transmit and receive current for each device comes more battery usage. Knowledge of this fact is useful to network designers because it can help them understand the level of battery capacity required when designing a network by comparing this data with the data in the specifications for specific devices.

Decision makers can use this information to determine the type of network nodes that are needed to transmit the data for a specific application. For example, if transmission of 1.2 units of data is needed then nodes with as little as 1 mA of transmit and receive current may be used. By determining the smallest amount of current needed to transmit a specific amount of data, other design considerations such as battery size can be optimized to fit the specific application needs. In addition to the robustness against jamming, another alternative to consider is how an adversary could cause a network to not transmit data at all or reduce the data transmitted. If an adversary, which could be an insider, were to place 20,000 mA jamming devices then they could stop data transmission. On the other hand, if they placed 90 mA devices then they could reduce the data transmission to a point where it is not useful for a specific application. This could cost the network operators time in troubleshooting and reduce the confidence in the reliability of the network, which would allow the adversary additional time to take other actions. These types of decisions of both the asset owner and adversary are tradeoffs that this analysis allows a decision maker to make..

Table 4.26 Transmit and receive current impact on total data transmitted

Transmit current (mA)	Receive Current (mA)	Total data transmitted
1	1	1.2
45	50	1.2
90	90	0.77
150	150	0.54
300	300	0.27
1,000	1,000	0.08
2,000	2,000	0.04
3,000	3,000	0.03
4,000	4,000	0.02
5,000	5,000	0.02
10,000	10,000	0.01
15,000	15,000	0.01
20,000	20,000	0.00

4.4.2.4 How does changing the battery capacity impact the overall network flow?

Figure 4.20 shows the total data transmitted depending on the battery capacity and the type of radiation pattern, each of which has a different current level. The data shows that, at high power, the data transmitted is four to five times more than the data transmitted at medium power. The reason for this is that high power allows more nodes to connect to each other at any point in time, but there is also a tradeoff because of the potential to interfere with other communication nodes in the network. The other notable characteristic of the results is that eventually further increasing the battery capacity available does not increase the total data transmitted. In the case of high power, this point is at 240-250mAh and at 160-170mAh in the case of medium power. The low power radiation pattern is very close to the medium radiation pattern in terms of the amount of data transmitted. By having this information, network designers can have a preliminary idea of where the point is at which the battery capacity for each node is optimized based on the total data they need to transmit through the network.

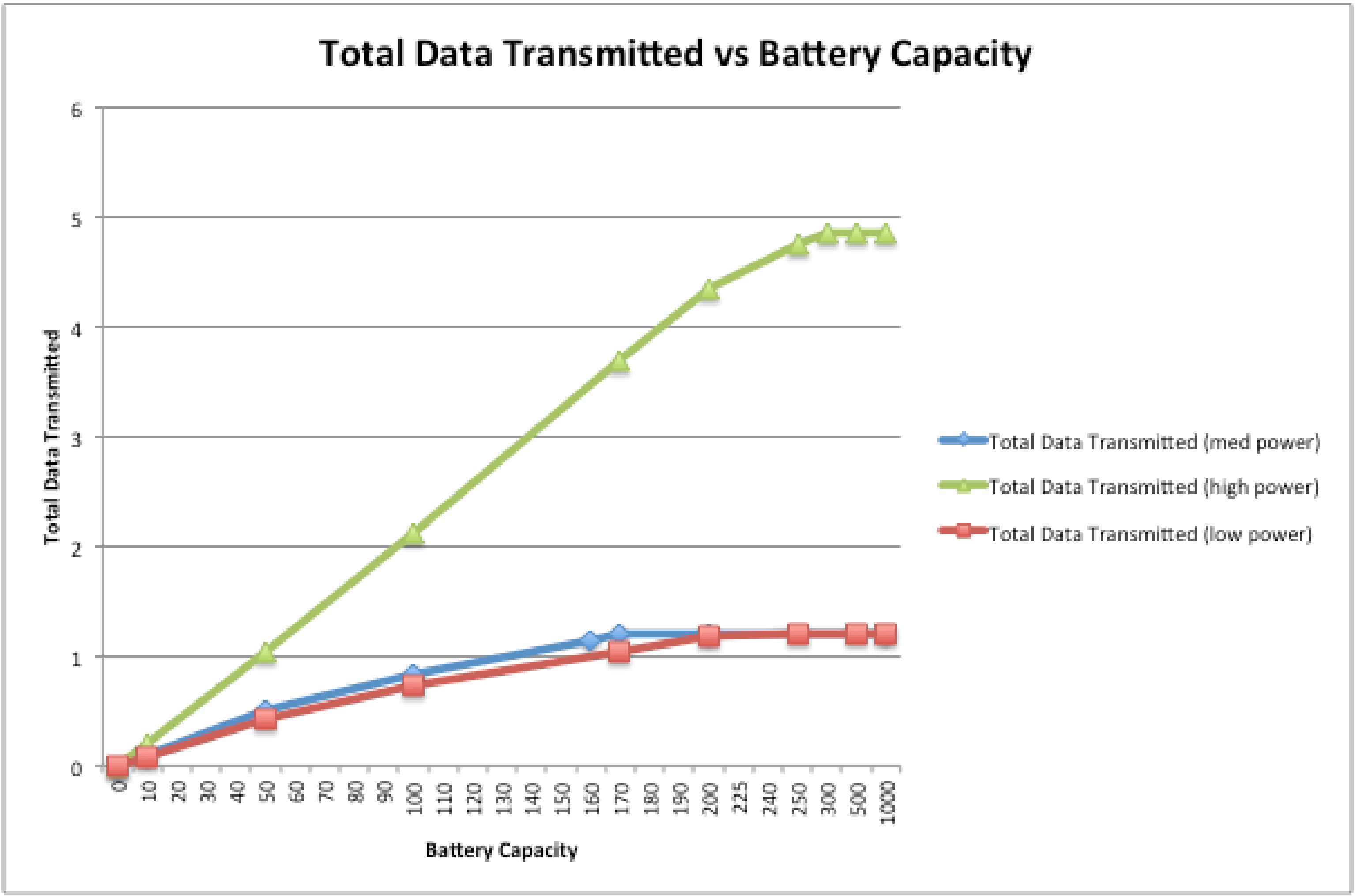


Figure 4.20 Total data transmitted versus battery capacity

The ability to determine the battery capacity required to support the desired amount of data transmitted also allows more detailed design tradeoffs from a size, weight and power perspective. A decreased battery capacity could decrease the cost of each network node and therefore allow more network nodes to be added to the ad hoc network for the same cost. For example, if 49 nodes were needed that required a 1000 mAh battery (e.g., $4) capacity versus an 81 node network that only required a 200 mAh battery (e.g., $1) capacity then the cost of the batteries could drive the cost of implementing more nodes to be closer to the implementation with less nodes. Assuming the nodes were the same cost, the cost tradeoff would be $196 (49 nodes) versus $81 (81 nodes). Therefore, having more nodes could be less cost based on the battery capacity required to meet requirements. Based on the results shown above, increasing the number of network nodes makes the system more robust against jamming attacks and therefore this analysis involving battery capacity needed (Figure 4.20) could result in identifying a more robust network for a similar or less cost while transmitting the same amount data.

4.4.2.5 How many jammers would have to be placed to completely stop communication for the video system?

This question highlights the tradeoff between connectivity, interference, total data transmitted and cost. In the BLMIP, the tradeoff between connectivity and interference is a factor in determining the total data transmitted. Connectivity is determined based on the communication range (c_i and interference range $1.75c_i$) of each node which determines which nodes can communicate with each other. Note that the values of the communication and interference range can be changed in the model which provides a mechanism to perform tradeoffs to understand how these parameters influence the output of the BLMIP, which is the total data transmitted. Once the total data transmitted is determined from the model, the next step is to determine the cost impacts of implementing a particular solution.

This process can be illustrated by using Table 4.27 to answer the question posed about the number of jammers to completely stop communication. The radiation pattern selected is shown in the antenna column of Table 4.27. This was the input to the BLMIP along with the interference range, which is the same for all the data in the table. Note that both the radiation pattern and interference range can be modified based on a specific application. Once the BLMIP is executed, the results show the tradeoff between connectivity and interference as it impacts the total data transmitted, which is shown in the last column of Table 4.27.

Table 4.27 Number of jammers and total data transmitted

Number of jammers	Antenna (power)	Total data transmitted
1	Directional (low)	2.3
1	Directional (medium)	2.6
1	Directional (high)	4.9
2	Directional (low)	1.0
2	Directional (medium)	1.2
2	Directional (high)	3.7
3	Directional (low)	0
3	Directional (medium)	0
3	Directional (high)	2.6

The data in Table 4.27 shows that, as the number of jammers increases for each radiation pattern at the three power levels, the total data transmitted decreases. One should note that, for the low and medium power levels, the data transmission decreases by half, while the effect on the transmission with high power is much less severe. The robustness of higher power is shown in Table 4.27 with a scenario involving three numbers of jammers and the three power levels; the high power level is the only power level that allows any data transmission no matter how many jammers are placed. The low and medium power levels do not allow data transmission with 3 jammers; therefore, network designers would not want to use low or medium power levels in high risk environments (i.e., three or more jammers).

Once the total data transmitted is determined based on the connectivity range, interference range, and number of jammers, the next step is to determine the tradeoff between the total data transmitted and the cost of a solution. As an example, the Directional (medium) antenna with two jammers, one channel, and total data transmitted of 1.2 units will be used. This can be compared to the data in Table 4.25 which is based on a Directional (medium) antenna with two jammers, two channels, and total data transmitted of 3.1. The only difference in these two data points is the number of channels. Assuming that a node with more channels is more expensive and a decision maker needs to transmit 3 units of data, they would likely choose the two channel option. This analysis is not only useful for answering the question about how many jammers prevent data from being transmitted, but as shown it can also be used to enable decision makers to make tradeoffs between multiple factors that influence the overall cost of a system.

4.5 Decision analysis based on the case study results

Based on the results of all the data from the case study, the decision maker was able to determine how to use their funds for security investments. Table 4.28 below describes the decision that the decision maker made as a result of the data from each part of the analysis. For the operations analysis on path 1, the decision maker determined that they would provide additional background checks for the three key influencers and the most highly trained technician. The assumption is that there is only one technician at the level 5 or 6 level. These were the positions that were identified in the analysis as having the potential to cause the most damage as malicious insiders.

Table 4.28 Case study scenario results

Category	Description	Unit Cost	Total Cost
Operations (path 1)	Invest in additional background checks for the following 4 employee job functions: -Director – Electric Grid Operations -Grid Control Manager -EMS Operations Manager -Step 5 & 6 Apprentice Maintenance technician	$10,000 each	$40,000
Electric substation (path 2)	90% solution for rural substation	$863,700	$863,700
Wireless video monitoring (path 3)	81 nodes with two channels to support the data requirements are needed if accounting for 2 jammers present	$1,000 each	$81,000
			$984,700

For the electric substation analysis on path 2 (see Figure 1.2), the decision maker determined that the highest risk substation was a rural substation that currently had no security implemented. The decision maker chose the 90% solution to ensure all the security measures could be done within budget. Finally, the decision maker determined that total data of 4 needed to be transmitted and therefore 81 nodes with 2 channels were needed. This scenario has demonstrated how the data from each path is aggregated to allow a decision maker to determine the best use of security resources based on budget constraints.

CHAPTER V

CONCLUSIONS

5.1 Summary

The primary contribution of this research is to provide a method to perform vulnerability assessment (VA) on critical infrastructure (CI) human and system architectures where the results from the VA are used to help a decision maker determine where to invest security resources to mitigate vulnerabilities. The method developed is a general approach that targets system with operational and cyber-physical system of systems components as shown in Figure 5.1. CI security is an important topic because human beings rely on CI such as energy systems for basic functions in their everyday lives. In order to maintain the security of these assets, it is important to have a method for VA of these systems based on past attacks and future threats. In this research, an approach is developed for identifying vulnerabilities in these systems and helping decision makers determine where to make investments in security resources in order to secure the systems. The new method developed in this research facilitates the creation of a comprehensive model that incorporates industry recommendations and standards, system and human architectures, attack scenarios and models to help decision makers determine the best security investments. In each of the three paths defined in Figure 5.1 and when the final method was executed as a case study for the electrical power system there were contributions to the literature.

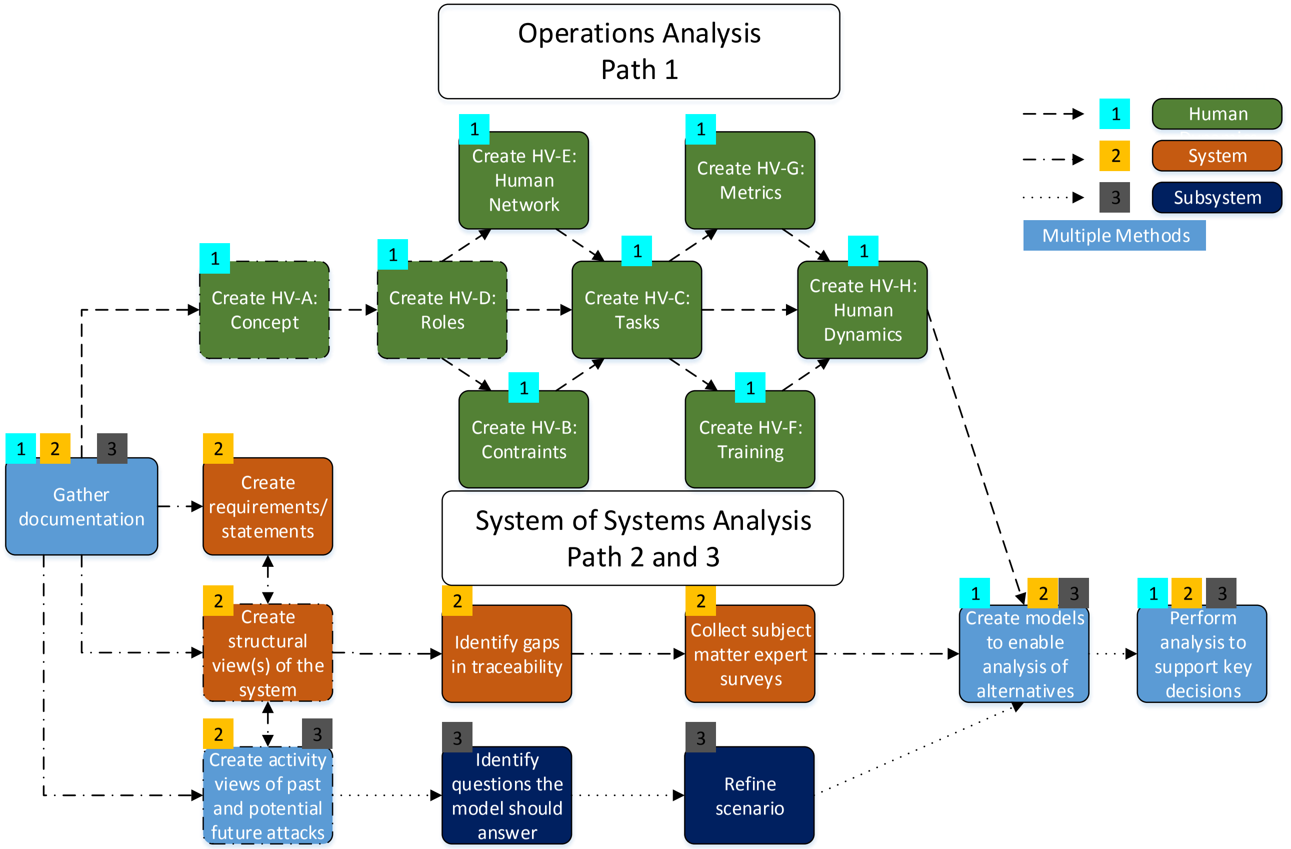

Operations Analysis
Path 1
Create HV-A: Concept
Create HV-D: Roles
Create HV-E: Human Network
Create HV-B: Contraints
Create HV-C: Tasks
Create HV-G: Metrics
Create HV-F: Training
Create HV-H: Human Dynamics
System of Systems Analysis
Path 2 and 3
Gather documentation
Create requirements/ statements
Create structural view(s) of the system
Create activity views of past and potential future attacks
Identify gaps in traceability
Collect subject matter expert surveys
Identify questions the model should answer
Refine scenario
Create models to enable analysis of alternatives
Perform analysis to support key decisions
1
2
3
Human
System
Subsystem
Multiple Methods

Figure 5.1 Approach for CI VA

5.2 Human architecture assessment contributions (path 1)

In analysis path 1 identified in Figure 5.1, the operations component of the system is assessed using a human architecture. As the complexity of attacks on CI increases, architects, analysts and decision makers will continue to need multiple perspectives when evaluating these cyber-physical systems for vulnerabilities. While previous research has focused on the physical components of systems, not much work has been done for evaluating the human aspects of systems for security evaluation. In this case, the NATO Human View perspective is not just being applied to a general area of study; rather, it is being applied to a particularly specialized area, which is CI security. The approach developed in this research is the first to evaluate how each NATO Human View product can be used for the evaluation of internal or external human security threats. As technology continues to spread, and as humans interact more with systems on a regular basis, this approach can provide useful quantitative data for the evaluation of security risks.

The new approach was applied to electric utility operations. While the data for this case study was obtained from various open sources and coupled with assumptions, the analysis methods and approaches to analyzing the products showed that using the NATO Human View for security analysis is a viable alternative to system architectures that only include physical components.

The various NATO Human View products provide unique but interlinked viewpoints on the roles of human beings within a system. From HV-A, which provides a conceptual look at the entirety of the system, to HV-G, which provides specific parameters for measuring humans' functional performance in the system, the NATO

Human View products all present specific ways to identify the roles potentially exploitable by those with malicious intentions. These qualitative methods allow one to see which positions might provide the most risk. However, they also provide the individual pieces of data that are necessary to create more complex analyses, as presented in the HV-H analysis previously. The execution of HV-H, in particular, allows the user to acquire data with analysis of the view and, most importantly, to acquire quantitative results that allow for the evaluation of security threats.

The final conclusions demonstrated that quantitative results could be derived from the use of the architecture products, as shown via HV-H. The SNA of system and task interactions showed how key influencers could cause significant damage to an organization if they were malicious insiders. Specifically, the SNA portion identified key positions such as the Director, EMS Operations Manager, and Grid Control Manager positions as being particularly influential within the organization. In addition, the TTC analysis showed how the skill level of attackers could be used to determine an approximate time to exploit a system; such an approach could allow analysts to focus their efforts on the most important jobs and levels for background checks and security clearances. This quantitative data, if used in the workplace, could provide crucial data for the benefit of managers trying to minimize security threats.

Although this approach was only demonstrated on electric utility operations, it could apply to other CI such as the financial services, chemical, and communications sectors. The analysis methods developed and the electric utility reference architecture provided present a rigorous approach to VA of human system interfaces that can be used by decision makers to help determine where to make investments in securing CI and ensuring that resources are allocated efficiently. The system architecture path is the next path discussed.

5.3 System architecture assessment contributions (path 2)

In analysis path 2 in Figure 5.1, the system architecture assessment was demonstrated using the case study that determined how to secure an electrical substation. The analysis showed that, depending on where the substation was located (in an urban, rural, or suburban environment), the priority of adding security resources such as sensors was heavily based on the ISES derived from subject matter expert opinion. The final conclusions showed that, although this is a proof of concept case study, the method developed provides a mechanism for decision makers to determine the best use of security resources based on their available budget.

Although the approach was only demonstrated on the physical security of an electrical substation, the approach presented can be applied to both physical and cybersecurity (cyber-physical security) of different types of CI. The method developed makes significant contributions to using model-based systems engineering to support decision makers in securing CI by presenting a rigorous approach to the analysis of these systems at the architecture level and using the information produced to aid decision makers in securing their systems within their funding profile. The next path for discussion is path 3 where the wireless video subsystem was assessed.

5.4 Subsystem architecture assessment contributions (path 3)

For the subsystem architecture assessment along analysis path 3 in Figure 5.1, a high fidelity model was created from an OV-5b activity diagram of an attack that involved making an ad hoc network that is used for video transmission at a substation to be robust against a jamming attack. As CI systems begin to use modern forms of communication such as wireless networks, because of the cost of permanent infrastructure such as the cost of digging trenches for cables, it is important to have a method to understand how to assess the vulnerabilities in these networks and provide an analysis of alternatives for decision makers. Because of the potential complexity of attacks, this analysis needs to have a method that can enable the production of high fidelity models; that is where this research fills an evident gap.

The approach developed began with developing the OV-5b and concluded with a decision analysis model. The contributions were not only elaborating on the method to get to a detailed model but also expanding on the work of Medal [2016] to extend the model developed to include directional antennas and power considerations for each node. For instance, using directional antennas rather than omnidirectional antennas provided a more realistic demonstration of the connectivity between antennas based on their radiation patterns, and the power considerations allowed the model further fidelity to aid network designers in making equipment design tradeoffs.

The results of the illustrative case study showed that the total data transmission generally increases with higher power – a result that might be expected, since higher power could correspond to a larger radiation pattern area over which a given antenna's signal may transmit data. The data shows that, in our scenario of designing a communications network to minimize the impact of jamming on a wireless video system in a substation, we should use an ad hoc communications network with high transmit power and a high density of communications nodes from the operations center to the substation.

A meaningful conclusion that can be made is that, in regard to the battery capacity available for each node in the network, at some point additional battery capacity does not increase the total data transmitted in the network. Developers of network nodes for ad hoc and other networks can use knowledge of this occurrence to find an optimal battery capacity such is appropriate for the total data required to be transmitted in the network.

In general, the method developed in this research to derive a complex decision model from an OV-5b activity diagram representing an attack scenario was demonstrated to be a method that decision makers can use.

5.5 Contributions of overall approach

The contributions from the combined approach presented in this research were demonstrated in the results of the case study. The case study showed that this approach can be used for analysis of systems with operations and cyber-physical system of systems components. The approach can be generalized as shown in Figure 5.2. The first step in the process is for the decision maker to determine the questions that they want answered about the system. These questions can be about the human side of the system which includes but is not limited to internal social interactions as well as human system integration points. The questions can also be about the system and subsystem that range from the optimal number of security guards that should protect a group of buildings to the optimal placement of security sensors in an airport.

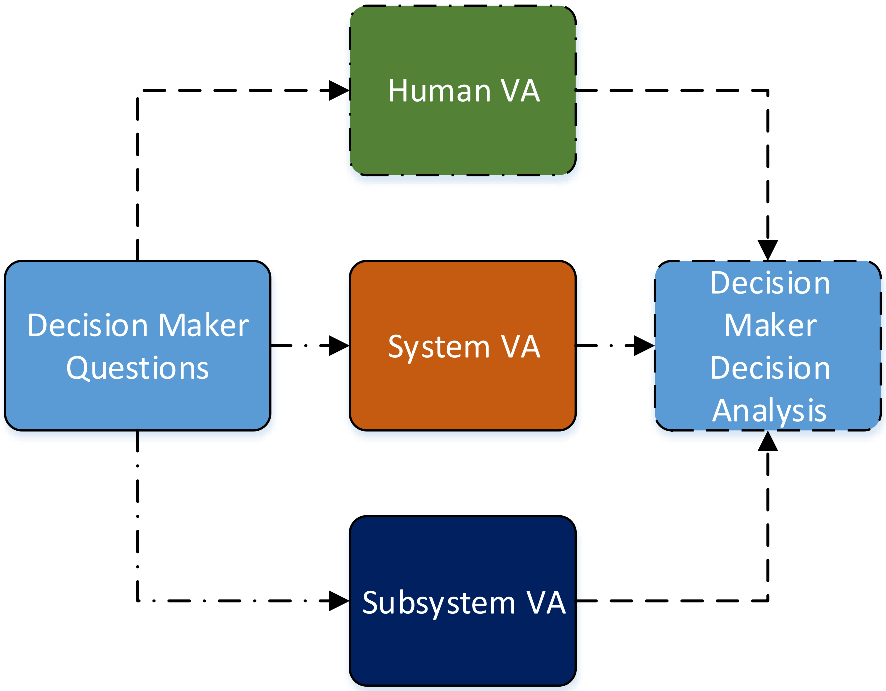


Figure 5.2 High level approach

Once the decision maker determines the questions that need to be answered, the next step is for the architecture team or those designated by the decision maker to perform the VA. The VA is executed as three separate parts and the results of each VA provides data for the decision maker to determine how to use the security resources available. The human, system and subsystem VAs, paths 1,2, and 3 in Figure 5.1 respectively, can be executed using any human or system architecture framework that has the views that are relevant to the questions that the decision maker wants answered. The decision analysis methods used for each VA effort should be an agile approach based on the amount of time that the architecture team has to develop the analysis and the level of detail needed. While SNA, TTC analysis, and OR methods are used, there are many other simulation and modeling tools and techniques that can be used based on the type of questions that need to be answered. Once the analysis phase in the VA is complete, then the decision maker can use all the results to answer the overall questions about the system. In general, as shown in the case study, this method allows a general approach that can be used on systems with operations and cyber-physical system of systems components.

In addition to the analysis of the systems, this approach now allows systems engineers to do CI VA at the system level without low level detail about the system. The capability to do this level of analysis is critical when ensuring high level requirements are met and at the beginning of developments when detailed information about the system may not be available. The approach also brings systems engineers into the CI analysis field by providing a method for the analysis using common frameworks and tools. The requirements mapping and architecture frameworks used for the analysis are commonly used by system engineers. Finally, this work highlighted an opportunity for systems engineers to add OR professionals to architecture development teams for enhanced quantitative analysis capabilities.

5.6 Research limitations and future work

5.6.1 Human analysis (path 1)

The method to analyze the NATO Human View presented in this dissertation was limited to a case study of an electric power system. While the results demonstrate that the analysis presented can apply to multiple sectors, the case study should be expanded in the future to include other CI operations. In addition, when performing an analysis of the other operations, researchers should use a complete architecture development team, which could provide insights into the skill sets that should be represented on a VA architecture team to make the process most effective.

The next area that should be explored is using the method developed with more detailed data from utilities. One limitation of this research is that the data was gathered from open sources, so it would be useful to extend the work by getting utilities to use this method to evaluate a subset of their current personnel or to overlay the method onto historical malicious insider cases within the organizations. Finally, expanding the simulation to use discrete event simulation or other methods for analysis of the HV-H would be useful. It would allow the asset owner to answer more questions, such as what vulnerabilities are introduced by the process through which procedures are approved within the organization. For example, one could determine if such procedures are evaluated by the appropriate personnel to ensure malicious insiders do not add steps that could damage the CI.

As shown, there are many opportunities to expand on the work presented in this dissertation. As the attacks on CI increase in number, it is important to continue to develop methods to assess the vulnerabilities in CI and mitigate those risks where possible.

5.6.2 System and subsystem analysis (path 2 and 3)

While the approach for VA presented in Chapter 4 was effective for the electrical substation case study, one limitation is that the process was not executed with real teams, and subject matter expert opinion surveys were not developed. One area to be explored in future research is the execution of the process developed in this research with teams from electrical utilities. This would allow real-time feedback on potential improvements of the process. In addition, developing surveys to collect the subject matter expert opinion should be done so that this process can be further defined as part of the method developed in this research.

In both the ILP and BLMIP that were developed for analysis, further detail can be added to the models. The ILP that was developed for physical security could be expanded to include an attacker-defender element in the model to better understand how attackers and defenders would interact from a physical security perspective. The BLMIP that was developed could be expanded to include directional antennas and account for jammers' available power. These improvements would continue to make the model more realistic.

Finally, the process developed should be used for other CI sectors using other case studies. A limitation of this research is that the case study focused on the energy sector; future work should focus on other CI sectors to prove the applicability of this approach more broadly.

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