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Analyzing the Critical Supply Chain
For Unmanned Aircraft Systems

THESIS

Megan L. Muniz, 1st Lieutenant, USAF

AFIT-ENS-MS-17-M-149

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Analyzing the Critical Supply Chain For Unmanned Aircraft Systems

THESIS

Presented to the Faculty

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In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Operations Research

Megan L. Muniz, MS

1st Lieutenant, USAF

March 2017

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Analyzing the Critical Supply Chain For Unmanned Aircraft Systems

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AFIT-ENS-MS-17-M-149

Abstract

Unmanned aerial systems (UAS) play a vital role in present day operations due to their asset capability and ability to reduce risk to pilots' lives. A complex supply chain network capable of producing and integrating all raw materials, components, sub-systems, and systems supports the successful acquisition of a UAS. Such a complex network is supported by vital supply chain decisions. Two important decisions regarding supply chain design include supplier selection and optimal flow of material and products. Whether a decision maker wishes to design or interdict a supply chain, the methodology developed in this thesis provides a suite of tailorable models to facilitate these vital decisions. Linear programming and generalized network flow models that incorporate goal programming are developed to integrate the decision maker's priorities. In addition, a targeting matrix employing a House of Quality approach is developed to provide an interdiction planning team with a decision support tool that facilitates interdiction strategy planning. Overall, the different models developed in the study provide modeling flexibility. The incorporation of goal programming into supply chain network design and interdiction allows decision makers to effectively frame their supply chain decisions.

Acknowledgments

I would like to express my sincere appreciation for those that directed and supported me throughout this research. Most importantly, I would like to thank my advisor, Dr. Richard Deckro, for his time, patience, and direction throughout the course of this research. I also wish to thank my reader, Dr. Brian Lunday, for his support and insights throughout the process.

Megan L. Muniz

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Analyzing the Critical Supply Chain
For Unmanned Aicraft Systems

1. Introduction

"Time is passing. Yet, for the United States of America, there will be no forgetting September the 11th."
-President George W. Bush
("A Nation Challenged; 'No Isolation From Evil,' Bush Declares," 2001)

1.1 Background

September 11, 2001 forever changed our great nation. Although it is a decade and a half later, the United States (U.S.) is still facing the implications of the terrorist attacks that occurred that day. This thesis integrates two of those implications: the rise of unmanned aerial systems (UAS) technologies' role in military operations and the profound effects that a supply chain disruption can have on the manufacturing and availability of a product.

The military usage of UAS has risen as a direct result of the 9/11. In fact, armed UAS were first sent into Afghanistan on September 12, 2001 (Gettinger *et al*., 2014), just one day after the attacks. In Afghanistan and the surrounding areas, UAS enable the U.S. fight by providing intelligence, surveillance, and reconnaissance (ISR) as well as a strike capability, in order to understand and defeat its enemies. UAS offer a significant benefit by removing the operator from harm's way while still providing the same, and in some cases superior, capabilities that a manned aircraft offers. For example, some UAS can stay aloft for longer durations than would be expected of crewed aircraft.

The U.S., however, is not the only country seeking this advantage; international military proliferation of UAS continues to grow. It is estimated that, due to the rising number of indigenous producers and growing international market, it will become

common for more countries to possess armed UAS in the next five to ten years (Sayler, 2015). This proliferation of UAS poses a dangerous problem, because "the falling cost threshold of drone technology increases the possibility of drones falling into terrorist possession" (Gettinger *et al*., 2014), a prophetic observation which may already be true. With this possibility evolving into an ever-increasing threat, the U.S. government has a vested interest in sustaining their air superiority. This can be accomplished not only by ensuring their own UAS superiority, but also by impeding this advantageous capability from falling into the wrong hands.

9/11 is also an example of the effects of an extreme disturbance in a supply chain. The attacks created such a disruption that almost no supply chain nationwide went unharmed; this was mainly due to the U.S. immediately closing down its airspace and tightening border control, as well as the infrastructure and firms that were impacted at the site (Rice *et al*., 2003). Manufacturing firms were particularly impeded severely. Ford, a major U.S. automobile manufacturer, shut down five of its U.S. production plants due to a shortage of supplies (Rice *et al*., 2003). While the 9/11 attack is a drastic example, it exemplifies that idea "that supply chain disruptions are unavoidable" and therefore "that all supply chains are inherently risky"(Craighead, Blackhurst, Rungtusanatham, and Handfield, 2007).

To tie these two implications together, consider the importance of a UAS supply chain. The Department of Defense (DoD) defines a supply chain as "the linked activities associated with providing materiel from a raw materiel stage to an end user as a finished product" ("Department of Defense Dictionary of Military and Associated Terms," 2016). Therefore, the supply chain includes activities such as procurement of materials,

manufacturing of parts, integration of components, final system assembly, and delivery to the warfighter. In the case of the U.S.' own UAS supply chains, it is vital that all entities involved in its supply chain are resilient to disruptions to ensure this capability is readily available. In the case of adversarial UAS supply chains, it is valuable for the U.S. to know how to cause such a disruption that could potentially devastate the supply chain and disrupt the system production, thereby preventing its use against the U.S. or its allies. At a minimum, if prevention is not possible, creating an impactful delay or a reduction of capabilities is desired. In either case, a critical analysis of a UAS supply chain is a powerful tool to leverage to gain insight into the vulnerabilities in the supply chain of interest.

1.2 Problem Statement

The purpose of this research is to provide a suite of scalable models to both develop a friendly supply chain and to propose attack vectors for an opposition's supply chain. The framework allows the analyst the ability to investigate an array of options and suggest an opposition's most likely course of actions.

1.3 Research Questions

This research answers the following questions:

1. How can an analyst model optimal UAS supply chain design?
2. How can an analyst model the best UAS supply chain interdiction?
3. How can a decision maker strategize UAS upply chain interdiction?

1.4 Research Focus

The focus of this research includes both the optimal design and optimal interdiction of supply chains of UAS. However, the methodology and models apply to the design and interdiction of any type of supply chain. While an ideal model would include all aspects of the supply chain, the complexity and data requirements are beyond the scope of this thesis. The methodology and models proposed, however, can be applied to a full supply chain if that data is made available. This research effectively demonstrates the utility of the approach.

1.5 Methodology

This research presents a holistic supply chain interdiction model (SCIM), complete with optimal design with regard to supplier selection and flow of materials, and optimal interdiction for the criteria stated. Goal programming models are developed to first model the supply chain tasks that must be accomplished and the manufacturer's optimal decisions in doing so, then to subsequently model the attacker's decision to disrupt the supply chain. This applies to both supplier selection and flow of materials. The models provide enough flexibility to allow adaptation to different levels of fidelity of the supply chain, based on the user's mission objectives and available data. A House of Quality decision support tool is developed to assist a decision maker in planning a supply chain interdiction campaign. The full supply chain interdiction methodology is demonstrated on an illustrative example.

1.6 Assumptions/Limitations

The main assumption underlying this research is that an attacker has knowledge and data about the structure of the supply chain of interest that it wishes to interdict. If this assumption is not met, then it is assumed that the supply chain is designed optimally, according to a set of priorities. Therefore, some information must be known about either the structure of the supply chain itself, or the objectives of the owner's of the supply chain. It is also assumed that goals and priorities can be defined in order to utilize the goal programming models. However, if a decision maker has a single objective, the models in this research can be tailored accordingly. A limitation arises if these assumptions are not met, and the models developed may not lead to optimal interdiction if the data or priorities are unknown or incorrect.

1.7 Implications

The models presented in this research can be utilized from two different perspectives of the supply chain decision-making spectrum. From a friendly supply chain perspective, a supplier selection goal program enables a supply chain manager to choose an optimal set of suppliers and optimal flow of materials to design an effective and efficient supply chain. This model also aids an opposing decision maker who wishes to disrupt a supply chain by targeting suppliers. If a supply chain supplier set is unknown, a decision maker in opposition to a supply chain can utilize the model to estimate the supplier set from which they can choose to target.

Joint Publication 3-60 (2013) states that "targeting is the process of selecting and prioritizing targets and matching the appropriate response to them, considering

operational requirements and capabilities" This research supports the second phase of the joint targeting cycle (shown below in Figure 1) target development and prioritization. Target selection requires a delicate balance between competing objectives. Maximizing benefits implies having the greatest desired impact on the enemy; in a supply chain, this translates to the most effective supply chain disruption while limiting collateral damage. However, target selection comes at a cost, whether it be a financial burden, operational risk, or political sensitivity.

Figure 1. Joint Targeting Cycle

An optimal supply chain interdiction methodology facilitates the target development phase by building a method to critically assess the state of any supply chain. It allows a commander to identify vulnerabilities in a supply chain of interest's production process and supplier base. It does not answer the question of "how" to disrupt (or reinforce, depending on decision maker's position) a supply chain, but rather leads to "where" in the supply chain to focus. The "how" is ultimately left up to the planner and the commander during the third and fourth stages of the joint targeting cycle. The

methodology presented utilizing a House of Quality approach does, however, provide a method in which the commander and staff can begin to consider the question of “how” to exploit (or fortify) vulnerabilities identified by the model.

1.8 Overview

In Chapter 2, a literature review introduces key concepts and reviews the previous research, all of which set the foundation for the remaining chapters and is vital to understanding the topic. In Chapter 3, we develop the full supply chain design and interdiction methodology that includes a model to determine an optimal supplier set, a model to optimally interdict a supply chain, a solution methodology, and a decision support model to support targeting and planning operations. Chapter 4 demonstrates the models, reports the results, and discusses the implications and extensions. Finally, Chapter 5 summarizes the research and suggests options for future research.

2. Literature Review

2.1 Chapter Overview

This chapter provides the reader with an overview of the fundamental concepts underlying this research. This is accomplished by surveying the relevant literature. Section 2.2 develops a basic understanding of supply chains. Section 2.3 gives an overview of the design and supply chain of unmanned aerial systems. Sections 2.4 and 2.5 introduce the modeling techniques used in this research. Section 2.6 then surveys previous research that apply these techniques. Section 2.7 introduces the interdiction aspect of supply chains. Finally in Section 2.8, the House of Quality is introduced. These sections provide the framework of the methodology developed in Chapter 3.

2.2 Supply Chain Overview

Although the DoD defines a product's supply chain only as activities from its beginning stage to finished product, the overall supply chain includes more than just the production activities and does not conclude with a finished product. Christopher and Peck provide a more thorough description defining it as "the network of organizations that are involved … in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer" ("Supply Chain Operations Reference (SCOR) model," n.d.). Therefore, the supply chain not only includes all processes that encompass the phases of the systems' life, from product design, to production, operational life, sustainment, and even onto its retirement, but each the organization performing those processes, or tasks, involved along the way.

The Supply Chain Operations Reference (SCOR) model is the standard management model utilized in industry to evaluate and improve supply chain operations. SCOR describes five top-level processes: Plan, Source, Make, Deliver, and Return. Figure 2 illustrates the infrastructure of a supply chain based on this SCOR model, including all entities involved in a supply chain, such as suppliers, manufacturers, and customers.

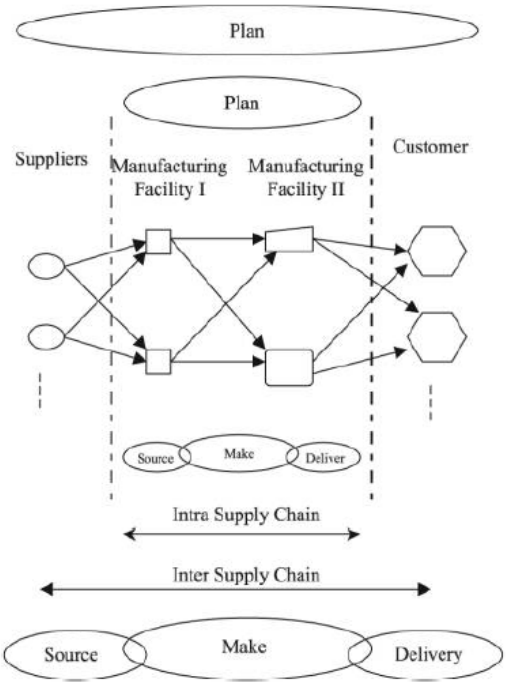

Figure 2. SCOR Model (Huan, Sheoran, and Wang, 2004)

Each entity has a supply chain of its own, hence the intra supply chain model, while the collective group of entities forms the inter supply chain.

As defined in the SCOR model, the main processes that all entities perform are Plan, Source, Make, and Deliver. Source processes include the ordering, scheduling, and receipt of products. Decisions in the Sourcing processes include which suppliers to choose and the volume of materials or products to buy from suppliers based on the

demand determined during the initial process, called the Planning process. The Make processes define all the tasks related to the conversion of materials into a product. This includes the production or manufacturing of a product. During the Make process, materials from downstream suppliers are converted into products for use upstream in the supply chain. As a product moves up the supply chain, value is being created along each phase. Decisions during the Make processes include how to perform and schedule tasks. One particularly imperative decision during the Make process includes whether to “Make or Buy”, also known as “Insource versus Outsource”. Quality, flexibility, control issues, cost, and other factors all present considerations in deciding the insource versus outsource issue. Manufacturing companies, when determining their strategic fit into a supply chain, must decide whether a product, or a component of a product, is in their best interest to make on their own or buy from an outside source who may be able to produce a better product and/or do so at a lower cost than the could do internally. Finally, once the full value of a product is realized in the Make processes of the supply chain, the product is delivered to the next upstream entity and eventually to the customer. During the Deliver processeses, a customer’s order is fulfilled. An interdiction at the Delivery phase (i.e., after a finished good is completed), if feasible, would disrupt the supply chain with the added benefit of having had a foe expend critical time, resources, and effort. The Deliver process includes the physical transportation of the product from one stage of the supply chain to the next.

According to the SCOR model, a supply chain’s effectiveness should be evaluated with respect to five core performance attributes. These attributes, Reliability, Responsiveness, Agility, Costs, and Assets, all respectively have associated metrics that

allow for comparison to facilitate decision making during the supply chain processes. Reliability addresses the ability of supply chain entities to complete tasks up to standard; measures for this attribute track considerations such as quantity, quality, and order fulfillment rates. Reliability can be measured on an entity or the product itself. Responsiveness addresses the speed at which entities provide products upstream, therefore measures for responsiveness are related to time. Agility is the ability of the supply chain entity to respond to outside impacts. This attribute, while vital, is difficult to measure but includes both flexibility and adaptability. Agility relates to supply chain resilience, which will be defined later in detail as it is an important characteristic. The Cost attribute includes all expenses associated with performing the supply chain processes such as labor, material, management, and transportation costs. Finally, the Asset attribute is the supply chain entities' ability to efficiently utilize resources. Supply chain assets include inventory, utilization, and insourcing versus outsourcing, all of which have associated metrics.

While each of the process areas, Plan, Source, Make, and Deliver, provide opportunities for analysis and improvement in the supply chain according to their respective attributes and metrics, they also provide areas of focus for an attacker wishing to disrupt a supply chain. For example, in the Sourcing process, a company must evaluate their potential suppliers and decide which ones are the best for their purposes. Often such a decision requires a balance between measures—for example quality and cost. The manufacturer must prioritize these attributes and make decisions that support those priorities. Most often, specifically in the aerospace industry, suppliers must be certified according to their respective standards, and it is the achievement of certification that

qualifies them to be considered an option. These key supply decisions give room for an attacker to make interdictions decisions as well; they may wish to disrupt a manufacturer's supply chain by affecting the company's supplier base. Likewise, an attacker targeting a manufacturer contemplating a "Make or Buy" decision may wish to force them to a less than desirable decision. Alternatively, an attacker may wish to target the Delivery process by diverting, interdicting, or disrupting the transportation or flow of materials.

A critical analysis of a supply chain aims to identify key characteristics of the supply chain such as risks, vulnerabilities, and susceptibilities—all of which lie within any of the processes in the SCOR model. Depending on the role of the decision maker, the analysis can be utilized to create a more resilient supply chain (if the supply chain of interest is their own) or to identify potential supply chain disturbances (if the supply chain of interest is a foe's). These characteristics of a supply chain are defined as follows for clarity.

Supply chain risk: The effect of uncertainty at any point in the end-to-end supply chain, including sustainment and maintenance, on its objectives. The magnitude of supply chain risk may be measured along three dimensions: likelihood of occurrence, expected consequences, and duration. (Adapted from (Moore and Loredo, 2013))

Supply chain vulnerability: The characteristics of a supply chain that cause it to suffer a definite degradation (incapability to perform the designated mission) as a result of having been subjected to a certain level of effects in an internal, external, or unnatural (man-made) hostile environment. (Adapted from ("Department of Defense Dictionary of Military and Associated Terms," 2016))

Supply chain susceptibility: The degree to which a supply chain is open to effective attack due to one or more inherent weaknesses (Adapted from ("Mandatory Procedures For Major Defense Acquisition Programs (MDAPS) and Major Automated Information (MAIS) Acquisition Programs," 2001))

Supply chain resilience: The supply chain's ability to effectively and efficiently return to its original or move to a new, more desirable state after being disturbed (Adapted from (Christopher and Peck, 2004))

Supply chain disturbance: An event that degrades the normal flow of goods and materials within a supply chain in terms of a defined metric (i.e. cost, lead time, etc) (Adapted from (Craighead *et al*., 2007))

Based on these definitions, it follows that a supply chain interdiction aims to cause a disturbance that targets supply chain risks and vulnerabilities. In other words, it seeks to exploit supply chain susceptibilities. A resilient supply chain will either have fewer risks or susceptibilities for an interdiction to target, or it will be well suited to recover quickly if a disturbance does occur. The methodology and models in this research are all ways in which to assess these characteristics of a supply chain –vulnerability, susceptibility, and resilience—and perform an internal capabilities' assessment to determine the best course of action to interdict or disturb the target by leveraging the supply chain's risks.

2.3 Unmanned Aerial Systems: Design and Supply Chain

Fundamental to developing a UAS supply chain model, a general understanding of a UAS design is required. UAS are made of a number of sub-systems. The main sub-systems of a general UAS are shown in Figure 3.

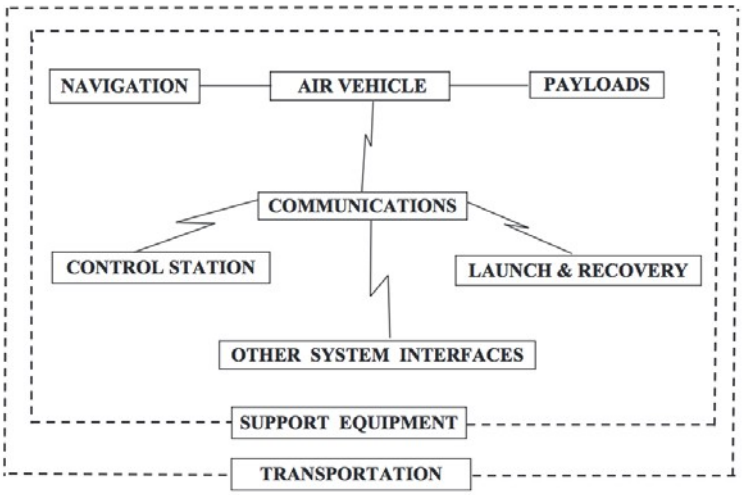

Figure 3. Unmanned Aerial System Design (Austin, 2010)

The control station functions as the control center of the UAS operation. It is where the human-system interface occurs; the operator communicates to and controls the UAS from the control station, and the UAS communicates by responding and sending information to the operator. The control station is an element of the UAS that is different from the control station in traditional aircraft, because the human-system interface with the control system in a traditional aircraft occurs in the aircraft itself with the pilot.

The payload of a UAS is specifically carried to achieve its mission. It can be considered in two basic types: non-dispensable payloads, such as the sensors, cameras, and so forth, which remain with the aircraft, and dispensable payloads, such as armament (Austin, 2010). The payload chosen for each UAS, therefore, depends on its operational mission and task, as well as the platform's capabilities. There is a vast array of payloads available.

The air vehicle is the actual aircraft, whose purpose is to carry the payload and all other sub-systems. The air vehicle includes the design of the fuselage, the engine and

propulsion system, the wings, and all aspects regarding airframe aerodynamics. Again, the design and performance of the air vehicle is dependent upon the operational mission of the UAS (Austin, 2010). The air vehicle, in production, is typically referred to as the airframe.

The navigation systems allow the operators and aircraft to know where it is at all times. This is made possible by technology such as inertial navigation systems (INS), global positioning systems (GPS), or other tracking mechanisms such as radar tracking, radio tracking, and direct reckoning systems (Austin, 2010). The type of navigation depends on the level of autonomy of the UAS as well as the acceptable risk level (in case GPS is in danger of being blocked).

The communications system provides the data links between the control station and the UAS. Most often, the transmission occurs through radio frequency, but other alternatives exist as well. The complexity, weight, and cost of the communications system (in terms of electrical power and antennae design) is determined by the range of operation of the air vehicle from the transmitting station, the sophistication demanded by transmission-down of the payload and housekeeping data, and the need for security (Austin, 2010). Small UAS often do not require complex and expensive communications system, but as the size, range, and operating altitude of the UAS increases, so too does the complexity of the communications system.

The sub-systems just described are all physical considerations of the UAS itself, excluding the control station. The launch, recovery, and retrieval equipment are not physically part of the UAS and are only required if the UAS is not capable of vertical flight or is not man-portable. The most important aspects of the UAS are its interfaces,

both internal to the UAS that ties all sub-systems together and external to the UAS, which allows it to communicate with outside entities. Interfaces allow interoperability and ultimately support the success of the UAS mission. Internally, sub-systems acting as a standalone objects would preclude the UAS from operating; externally, UAS acting standalone may or may not be successful, mission dependent.

Support equipment and transportation are the last two considerations of the UAS design. Support equipment includes all equipment required to operate and maintan the UAS, from manuals to tools to spares (Austin, 2010). Transportation, whether accomplished on its own or by carrier vehicles, allows the UAS mobility and may require a crew. Though not physically part of the UAS design, these considerations are an important aspect to UAS success and of its supply chain.

Due to the design and complexity of the UAS, a supply chain structure that supports the production of a final product composed of many components, subcomponents, and assemblies is necessary. For this reason, the aerospace industry typically utilizes a “tiered” supply chain. Suppliers are classified on a tiered system, whereas the tasks they perform are classified by levels. This creates a hierarchy of suppliers and tasks that is common to the structure of a UAS supply chain. Commonly, there are at least three main tiers of suppliers that perform the four main levels of tasks. Tier One suppliers typically interact directly with the airframe and aircraft manufacturers, called Original Equipment Manufacturers (OEMs), and provide them with the final parts needed to assemble an aircraft. OEMs perform the Level 1 task of assembling the aircraft with these final parts. These parts include the major sub-systems such as the aero structure, the avionics systems, engines, landing gears, actuators, and other complex

components and assemblies made of many subcomponents and subassemblies (ATC Aerospace, 2014); the production of these sub-systems are known as Level 2 tasks. Tier Two suppliers produce the same types of parts as Tier One suppliers, but instead they supply their products to Tier One suppliers. Tier Two suppliers receive their supplies from Tier Three suppliers, who typically manufacture the components and parts necessary to complete the subsystems, which comprises Level 3 and below tasks. Tier Three suppliers rely on smaller suppliers and raw materials suppliers to provide the necessary material and parts to assemble the components.

With this structure, a UAS supply chain can be conceptualized as a series of tasks, according to their level, performed by manufacturers, with a selection of suppliers from which to choose that provide the materials necessary to complete those tasks. In Figure 4, the tasks are represented by blue nodes, arcs represent task precedence (i.e. Level 4 tasks must be accomplished before Level 3 tasks, and so forth). The levels of tasks and tiers of suppliers depends upon the size and complexity of the UAS.

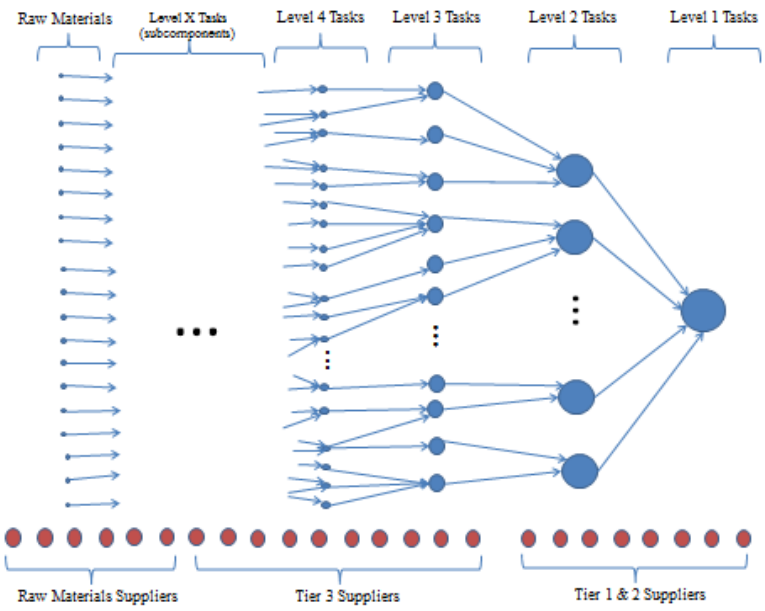

Figure 4. Typical UAS Supply Chain Structure

The suppliers, shown as the red nodes, are responsible for accomplishing the necessary tasks for their individual products. Moving from left to right Figure 4, materials flow from downstream to upstream in the supply chain. The final integration, Level 1 tasks, occurs through the OEM. A detailed tasks list for a generic U.S. military UAS, down to Level 4 tasks, is defined in the Work Breakdown Structures for Defense Material Items document, MIL-STD 881C, Appendix H. The full task list is available in Appendix A of this document. These tasks would represent the blue nodes shown in Figure 4.

2.4 Mathematical and Goal Programming Overview

Mathematical programming is an approach to mathematically represent a problem which seeks to discover the best allocation of limited resources to find an optimal solution subject to some constraints. Analyzing this definition, the phrase “seeks to discover” implies a set of decisions to be made, the phrase “best allocation” alludes to an

optimal solution, and the phrase “limited resources” implies a constrained environment. The main parts of a mathematical programming model (math model) are a set of decision variables, an objective function or functions to be optimized, and a set of constraints.

The decision variables are the factors that the decision maker can control. Typically, they answer the question of “how many” resources to allocate to a certain course of action, but they can also be a binary “yes” or “no” (represented as 1 or 0, respectively) answer to whether or not to allocate resources to a course of action. The objective function incorporates the decision variables to define the best allocation of interest to the decision maker. The objective function is either maximized or minimized. Common examples include maximizing profit or minimizing cost. Finally, the constraints are equations that model the resource limitations of the decision variables. (If an organization had unlimited resources, there would be no need for a model at all!) For a model with strictly linear constraints, the model is called a linear program (LP). A general LP is developed below:

Minimize: $$Z = \sum_{j=1}^{n} c_j x_j \qquad \text{(i)}$$

Subject to: $$\sum_{j=1}^{n} a_{ij} x_j \geq b_i, \text{ for } i=1, ..., m, \qquad \text{(ii)}$$

$$x_j \geq 0, \text{ for } j=1, ..., n, \qquad \text{(iii)}$$

where $x_1, x_2, ..., x_n$ are the decision variables, and $c_1, c_2, ..., c_n$ are the contribution coefficients of each decision variable to the objective function value, Z. In constraints (ii), a_{ij} are known as the technological coefficients and represent the resource usage of each decision variable of the right-hand-side coefficient of b_i (Schniederjans, 1995). This

research will utilize different classes of linear programs to represent characteristics of supply chains.

Linear goal programming is a special application of linear programming. The two approaches differ slightly in the setup of both the objective function and the constraints. Whereas traditional linear programs seek to precisely optimize a single objective, goal programming seeks to fulfill multiple objectives that are often in conflict; where traditional approaches use absolute constraints, goal programming recognizes that, with multiple objectives all constraints are likely not to be simultaneously attainable, the objective instead minimizes deviations from a prespecified level (Schniederjans, 1995). Therefore, a general linear goal program (GP) from (Schniederjans, 1995) is shown as follows:

Minimize: $$Z = \sum_{i \in m} w_i (d_i^+ + d_i^-) \qquad \text{(iv)}$$

Subject to: $$\sum_{j=1}^{n} a_{ij} x_j - d_i^+ + d_i^- = b_i, \text{ for } i=1, ..., m, \qquad \text{(v)}$$

$$d_i^+, d_i^-, x_j \geq 0, \text{ for } i=1, ..., m; \text{ for } j=1, ...,n, \qquad \text{(vi)}$$

where d_i^+ and d_i^- are the positive and negative deviation variables measuring the over-attainment of a goal or its under-attainment, respectively. Notice that the objective function includes a choice of deviation variables that are associated with the decision maker's goals and priorities. These goals and priorities can be preemptively weighted so that each goal is absolutely more important than the next, or they can be nonpreemptively (numerically) weighted so that all priorities share a weighted importance (Schniederjans,

1995). This general model is built upon in Chapter 3 to model supply chain goal programming applications.

2.5 Network Flows Introduction

A common way to represent and analyze supply chain networks is a problem domain known as network flow models. These types of models traditionally yield insight into how to optimally traverse a network with respect to such objectives as distance (shortest path problem), volume (maximum flow problem), or cost (minimum cost network flow problem). The problem of interest in this research is the minimum cost network flow (MCNF) model. A general representation from Bazaara (Bazaraa, Jarvis, and Sherali, 2010) is shown below:

Minimize: $$Z = \sum_{i,j \in A} c_{ij} x_{ij} \qquad \text{(vii)}$$

Subject to: $$\sum_{i,j \in A} x_{ij} - \sum_{j,i \in A} x_{ji} = b_i, \text{ for } i \in N, \qquad \text{(viii)}$$

$$l_{ij} \le x_{ij} \le u_{ij} \forall (i,j) \in A, \qquad \text{(ix)}$$

where x_{ij} are the decision variables which represent the amount of flow to pass through each arc *(i,j)* with lower and upper bounds of l_{ij} and u_{ij} respectively, c_{ij} are the cost per unit of flow across arc *(i,j)*, and b_i is the demand at each node. The objective function (vii) minimizes the cost of the flow passed through the system, and the constraints in (viii) are known as the flow conservation constraints and they ensure that total flow out of a node *i*, $\sum_{i,j \in A} x_{ij}$, minus the total flow into a node *i*, $\sum_{j,i \in A} x_{ji}$, equals the net supply at the node (Bazaraa *et al*., 2010), hence the conservation of flow. If b_i=0, node *i* is an intermediate node, meaning all of the flow that enters the node also leaves the node. If b_i > 0, node *i* sends positive net flow out into the network, a supply node; often times this is

the first node, known as the source. When b_i <0, that node has a net demand that must be satisfied.

This notion of flow relates to a supply chain because materials flow through the supply chain network through a series of suppliers and manufacturers. Each manufacturer converts the products they receive from the previous supplier into another product, often smaller in quantity. For example, Manufacturer X may convert 4 units of a sub-widget from their previous supplier into a single widget to pass forward to the next supplier. This feature lends itself to a generalized network flow problem, also known as a network flow with gains (or losses) (Bazaraa *et al*., 2010). Network flows with gains are useful for many different formulations. Hamill (2007) utilized a generalized network flow problem with gains or losses to model social networks as follows:

Minimize: $$Z = \sum_{i,j \in A} c_{ij} x_{ij} \qquad \text{(x)}$$

Subject to: $$\sum_{j:(i,j)\in A} x_{ij} - \sum_{j:(j,i)\in A} g_{ji} x_{ji} = b_i, \text{ for } i \in N, \qquad \text{(xi)}$$

$$l_{ij} \le x_{ij} \le u_{ij} \forall (i,j) \in A, \qquad \text{(xii)}$$

where the only addition of g_{ji} reprents gain (>1) or loss (<1) of material flowing through a node. Within the context of material flows through a supply chain, the generalized network allows the represesentation of conversion of materials into various parts, components, sub-systems, and systems as they pass through the supply chain.

2.6 Previous Research and Models

As shown in Figure 4 and according to the SCOR model, suppliers are deeply integrated in and extremely important to the supply chain process. Supplier selection is a

critical factor in determing whether a supply chain will be successful or not. When a manufacturer is choosing its suppliers, there are many important considerations that inform their decisions. Liao and Kao suggest that some of the most important factors include quality, price, and delivery lead time (Liao and Kao, 2010). Other notable considerations include performance history, warranties policies, technical capability, financial stability, expertise, reputation, and experience. Overall, quality is generally considered the most decisive factor (Weber, Current, and Benton, 1991).

There has been a great deal of research regarding the issue of optimal supplier selection. Liao and Kao develop a supplier selection method that integrates Taguchi loss functions, analytical hierarchy process (AHP), and multi-choice goal programming (MCGP) (Liao and Kao, 2010). In their model, the Taguchi loss functions quantify supplier deviation from specifications, AHP is utilized to prioritize manufacturer goals according to metrics, and ultimately these values are used as input to a MCGP to determine a set of optimal suppliers. Lee, Kang, and Chang present a similar approach that utilizes “fuzzy” AHP that analyzes the importance of multiple criterion (such as cost, yield, and number of suppliers) and use MCGP to facilitate supplier selection (Lee, Kang, and Chang, 2009).

Ghodsypour and O’Brien develop a decision support system that integrates AHP, to address the qualitative factors, with linear programming, to address the quantitative factors of supplier selection (Ghodsypour and O’Brien, 1998). They use AHP to rate suppliers based on a set of weighted criteria such as cost, quality, and service. Their AHP values then inform a linear program (LP) that includes any resource (supply and demand) or quality constraints and determines a set of optimal suppliers.

Similar to AHP, Gencer and Gurpinar (2007) develop an analytical network process (ANP) model that accounts for the dependencies between decision criteria in supplier selection. Their selection criteria include the business structure, manufacturing capability, and product quality of potential suppliers.

Overall, most of the research regarding supplier selection seems to agree that the decision process is multi-objective, often with objectives that compete with each other. Many utilize AHP to determine the relative importance of criterion when selecting suppliers. While AHP is widely used, it has theoretical problems to be aware of, such as rank reversal, aggregation, a large number of necessary pairwise comparisons, and the limitations of an artificial scale (Kasperczyk and Knickel, 2004). Most research also utilize the attributes and measures suggested by the SCOR model to inform their models.

Once an optimal set of suppliers is selected, it is up to the attacker to determine how to optimally interdict these tasks. Due to the network-like structure of supply chains, we survey network interdiction literature to explore the concepts. Network interdiction has applications in many various fields including communications networks, supply networks, drug networks, and project networks.

Wood (1993) uses deterministic network interdiction to model an interdictor, with limited resources, that wishes to minimize an enemy's maximum flow through a capacitated network. The model and its variants are setup as bi-level min-max integer programming (IP) problems, in which the enemy and interdictor have equal but opposite objective functions. The same problem is modeled stochastically by Cormican *et al* (1998). In contrast to deterministic interdiction, where the interdiction variables are assumed to be binary indicating either a completely successful or a completely

unsuccessful interdiction, the stochastic model incorporates the idea of uncertain interdiction. This allows for partially successful interdictions and analysis on the effects of such. The model and its variants, like those of Wood's, are setup as a bi-level min-max problems.

Another application of bi-level network interdiction was developed by Brown *et al.* (2007). The objective of their research was to model interdiction of a nuclear-weapons project by maximally delaying completion time of the project. The bi-level model is a max-min problem, in which a nuclear weapon proliferator wishes to minimize completion time by following the Critical Path Model principles used in the project management field in scheduling tasks according to time and precedence constraints. The interdictor then wishes to determine which tasks to interdict in order to maximally delay the project.

As previously mentioned, an alternative way to model a supply chain is to view it as a flow of materials and goods through a network in which, at each progressive stage, the materials get more and more refined until it results in a final product. Just as supplier selection decisions often has multiple objectives, this network flow of goods can likewise have multiple, often competing, objectives. Calvete and Mateo (1995) considered the network flow problem with multiple objectives by applying it to a hydrological system to determine an optimal way to distribute water in a water system. They used preemptive priorities to rank the goals, which included demands and other features of the system. The solution approach they proposed included network-based algorithms such as out-of-kilter and primal-dual algorithms (Calvete and Mateo, 1995). In further research, Calvete and Mateo consider a lexicographic generalized network flow problem, and develop another network based primal-dual algorithm: Lexicographic Generalized Primal-Dual (Calvete

and Mateo, 1998). McGinnis and Rao (1977) present a particularly interesting application of goal programming in networks in their research. They formulate goal programming versions of classical network flow models and develop an efficient solution methodology that exploits the network structure of the problem by using Lagrangian relaxation . The models and solution approaches proposed in all of these applications can be directly applied to a supply chain, especially the solution techniques when dealing with large-scale problems.

In his research, Kallemyn (2015) develops a suite of network interdiction models that can applied to these types of network flow problems. In fact, Kallemyn develops interdiction models for maximum flow models and shortest path models, both of which are easily adaptable into MCNF problems.

The models in Chapter 3 incorporate all of these concepts to model optimal supply chain design and interdiction. By taking the priorities and goal programming methods developed in supplier selection literature and combining with network flow and network interdiction approaches, a suite of supply chain interdiction models are developed that can be tailored to the mission objectives of an interdiction scenario.

2.7 Supply Chain Interdiction Considerations

While models for supply chain interdiction developed in this research will provide targets for an attacker, they do not focus on the “how” behind disrupting a supply chain. Additional decision support tools are necessary to determine an actual interdiction strategy that meets mission objectives. A knowledge of common inherent supply chain risks gives a decision maker the ability to consider different courses of action. Extensive

research has been accomplished on the types of risks that supply chains encounter, due to factors such as globalization and terrorist attacks that have exposed the effects of supply chain vulnerabilities. The main categories of risk identified in the literature include supply risks, operations (operational) risks, environmental risks, and financial risks.

Supply risk is defined as "the probability of an incident associated with inbound supply from individual supplier failures or the supply market occurring" (Zsidisin, 2003). They encompass any risk found "in the course of movement of materials from supplier's suppliers to focal firm" (Manuj and Mentzer, 2008). Supply risks also includes the supplier themselves; their credibility, business operations, and dependability. Other supply considerations include single versus multi-sourcing, quality issues, and product complexity (Manuj and Mentzer, 2008). Therefore, interdictions targeted at supply risks, for example, could be directed at suppliers to create logistics delays, introducing counterfeits into their supply system, targeting the transportation network (especially if it is global), or target suppliers' inventory management.

Operational risk as defined by the Basel Committee (2004) is "the risk of loss resulting from inadequate or failed internal processes, people, and systems or from external events. This definition includes legal risk, but excludes strategic and reputational risk". Although the definition of operational risk derives from the financial realm, it is well suited for supply networks because it "reflects the complexity, uncertainty and diversity of risk sources that are valid for supply networks" (Heckmann, Comes, and Nickel, 2015). Interdictions intended for operations risks can target specific tasks, such as the production of a single critical component, part, or raw material. They can also target the people performing the labor of the supply chain operations. An example would be

launching an informations operations campaign to encourage workers to go on strike or scare them into refusing to work.

Environmental risks break down further into sub-categories and are somewhat all-encompassing. They can be considered from a business environment, market environment, or physical environment standpoint. The business environment includes government actions and regulations, while the market environment includes items such as raw materials availability, little or no competition, or cost trends (Moore and Loredo, 2013). The physical environment includes natural disasters that may adversely disrupt transportation or production such as hurricanes, fires, and earthquakes. The environment can be internal to the supply chain, such as operations within and controlled by the business, or external to the supply chain, such as government regulations, natural disasters, or terrorist attacks. Interdictions aimed at environmental risks can target any one of the environments mentioned in a variety of ways. An attacker might target disaster mitigation options, for example.

Financial risks "refers to deviations of expected monetary objectives" (Heckmann *et al*., 2015). This includes both the suppliers' and customers' financial status, and the costs associated with the production, procurement, transportation, and logistics of the product. Finally, interdictions aimed at financial risks can target areas in the supply chain which are very costly to overcome. They might also target a group's financial resrouces or available credit.

While most supply chains face similar risks, the aerospace and defense (AandD) industry, under which military UAS fall, face additional common issues. Verify, a prominent U.S. supplier performance management firm, outlined the four main

challenges that a global AandD supply chain face as export control and compliance, quality infusion in product life cycle, assuring quality product is delivered on-time, and skilled resource availability (Mcintosh, 2012). Additional research (Ghadge, Samir Dani, and Kalawsky, n.d.) argues that the main risks in an aerospace supply chain are due to global sourcing, a diverse supplier base, market volatility, and product complexity. These are also important considerations specific to UAS supply chain interdiction. A summary of these and other risks from the literature are shown in Figure 5 and can assist a decision maker in framing interdiction strategies. All of these risks are inherent in supply chains and are potential targeting options.

Category	***Risk***	***Category***	***Risk***
Supply	Risks and delays with suppliers	Operational	Risks with plans, warehouses, stores
	Logistics delays and disruptions		Equipment, personnel, or facilities
	IP theft, counterfeiting, gray market		Legal Risks
	Global sourcing/Diverse supplier base		Component Production
	Raw material availability		Product complexity
	Poor quality/rework	Environmental	Natural disaster
	Lack of training/knowledge in principles and techniques		Policies and regulations
	Constrained volume capacity		Economic stability
	Long and/or variable purchasing cycle times		Certification/qualification (of supplier
	Transportation condition		Government actions/regulations
	Outsourcing risk		Little or no competition
	Inventory management		Capital requirements
Financial	Pricing risks		Proprietary (i.e. patents); Design
	Unstable prices		Obsolescence
	Cost trends		Knowledge and skills
	Suppliers' financial status		Lack of tech drawings/verification (product model/configuration) modifications
	Customers' financial status		Validity of data
	Production costs		Acquisition strategy
	Transportation costs		Schedule

Figure 5. Common Supply Chain Risks

2.8 House of Quality Introduction

When a decision maker knows “where” a supply chain is susceptible or has vulnerabilities, they can then develop a strategy to address “how” they wish to cause a

disturbance by considering ways to target these risks. A method that is seemingly unrelated but that can be used in supply chain interdiction by an attacker decision maker is an adaptation to what is called the "house of quality" (HOQ). HOQ is used primarily in the design process of products called Quality Function Deployment (QFD) by a team of engineers, marketers, and designers of a company, and its goal is to match product design with customers' needs (Temponi, Yen, and Tiao, 1999). A typical HOQ model is shown in Figure 6. It defines the "what" (customer attributes or needs) and relates them to the "how" (technical requirements), with the rest of the house detailing the relationship between these categories.

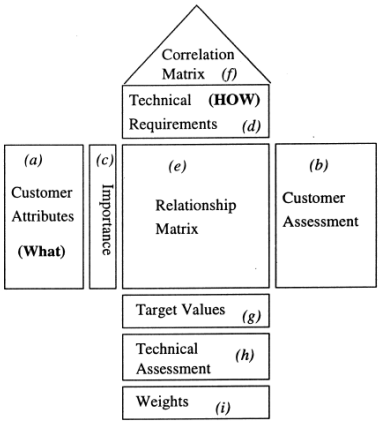

Figure 6. House of Quality (Temponi *et al*., 1999)

Hauser and Clausing (1988) present a description of how to build a house of quality. For each box (a)-(i) shown in Figure 6, they provide a description that the team must contemplate and answer in order to build the house. The descriptions from (Hauser and Clausing, 1988) are shown in Table 1.

Table 1. House of Quality Description

Section of House of Quality	Description
(a) Customer Attributes	What do customers want?
(b) Customer Assessment	Will delivering perceived needs yield a competitive advantage?
(c) Importance	Are all preferences equally important?
(d) Technical Requirements	How can we change the product?
(e) Relationship Matrix	How much do engineers influence customer-perceived qualities?
(f) Correlation Matrix	How does one engineering change affect other characteristics?
(g) Target Values	Establish ideal new measures for each technical requirement
(h) Technical Assessment	Objective measures related to each technical requirement
(i) Weights	Relative weights of technical requirements

The House of Quality approach, while primarily a business-centric tool, can be applied to many other types of decision making processes. For example, Kimbrough (2008) contructed a House of Quality that compared U.S. military irregular warfare doctrine publications to provide insights to doctrine writers by determining critical concepts to consider. Using the same principles, the House of Quality approach can be applied to supply chain network interdiction decisions to develop a targeting screening matrix. The decision maker, i.e. the commander and his or her planning staff, must determine a “what” (a set of optimal targets) and a “how” (the courses of action and capabilities) to develop a strategy that supports achieving a desired disruption. Based on these concepts and approaches, a full targeting adaptation of HOQ is developed in Chapter 3.

2.9 Summary

The sections in this chapter have set the foundation for the development of the models in this study. A discussion of supply chains and UAS set the foundation for the

focus of this research. A discussion of goal programming and network flow models were introduced to familiarize the reader with the models developed in Chapter 3. Previous research on supplier selection goal programming and network interdiction models was surveyed for a background of the work done in these areas. Finally, the House of Quality was discussed to introduce the concepts that are utilized in the final model in Chapter 3.

3. Methodology

3.1 Chapter Overview

This chapter develops the formulations to the supply chain interdiction methodology, SCIM, and present solution approaches. Section 3.2 begins by introducing the methodology, and continues to formulate each of the sub-models and steps that comprise SCIM.

3.2 Supply Chain Interdiction Methodology

The supply chain interdiction methodology (SCIM) consists of three phases. A visual overview is presented in Figure 7. In Phase 1, SCIM-Design, allows an interdictor to model an optimal supply chain, in the case that the supply chain design is unknown or unavailable. The supply chain is modeled two ways, one as a linear program to identify optimal supplier selection and one as an optimal network flow model to emulate the flow of materials through a supply chain. In Phase 2, SCIM-Interdiction, models optimal interdiction of both types of the models in Phase 1. The advantage that the network flow model provides is that any of the network flow interdiction models available can be utilized. Here, we utilize goal programming to develop a model for interdiction. For each model in SCIM-Design, there is an associated interdiction model. Lastly, in Phase 3, a targeting screening matrix is developed utilizing a House of Quality approach.

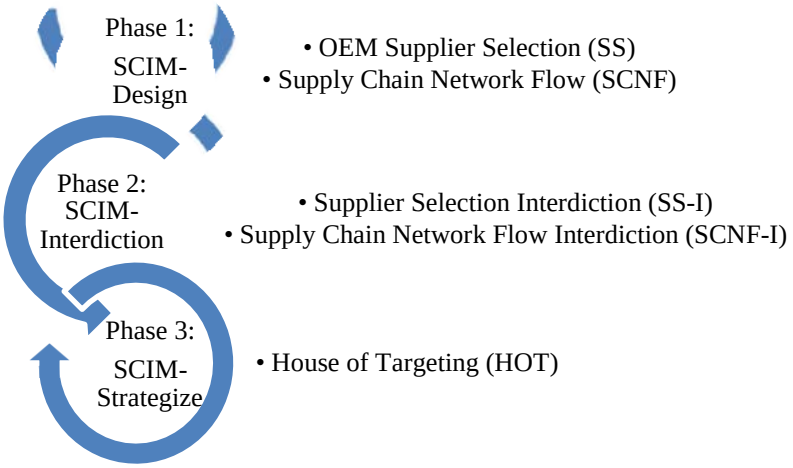

Figure 7. SCIM Phases and Models

Phase 1: SCIM-Design: OEM Supplier Selection Model (SS)

As suggested in the literature review, a decision maker wishing to disrupt a supply chain can consider several areas to affect. The first model proposed, OEM Supplier Selection (SS), focuses on the Sourcing Process from the SCOR model and utilizes goal programming. The OEM Supplier Selection Goal Program models the optimal supplier choices that an OEM would select, in order to create a supplier set from which an attacker can interdict in Phase 2. This first model, however, is unnecessary if an existing supplier selection set is known. If a supplier selection set is unknown, this model demonstrates an optimal supplier selection decision and supply chain design. Therefore, consider a UAS OEM that must choose a set of suppliers from which to purchase their Level II tasks, or sub-systems. For this development, it is assumed that the OEM's priorities are likely to minimize total cost and product lead time and also maximize product reliability, which are all reasonably derived from both the supplier selection literature as well as common metrics from the SCOR model. It is assumed the producer

has a budget they wish to stay under, an overall product reliability they wish to achieve, and a production schedule they wish to meet. Of course, if intelligence is available to suggest other priorities, these can also be modeled—or a single objective can likewise be modeled.The equations for the model will each be developed as follows and then compiled at the end.

We define y_{is} to be a binary decision variable that equals 1 if task *i* is supplied by supplier *s*, and 0 otherwise. These two sets of tasks and suppliers are defined as follows:

$i \in I$ where I = All tasks to be performed $i = 1, 2, ..., n$

$S =$ set of all possible suppliers;
where $s \in S(i)$ when $s = \{1,2,...,m\}$ is able to perform task i

The first constraint ensures that at least one supplier is chosen for each task, as shown in Equation (1).

$$\sum_{s \in S(i)} y_{is} \geq 1, \quad \forall i \in I \tag{1}$$

This equation states that for each task *i*, at least one y_{is} must be equal to 1.

Before formulating the goal constraints, a value for each goal must be determined. The goal is defined by a target, which is “an acceptable level of achievement for any of the attributes considered by the decision maker” (Romero, 1991). Therefore, the goal is interpreted as a certain level of attainment, or aspiration level, that the decision maker reasonably wishes to achieve for each priority. Care must be taken to define the goals appropriately in order to correctly specify the model, which suggests that some information or data must be known about the goal. A more accurate specification of the

goals' aspiration levels leads to a better understanding and interpretation of the models' results.

Once goals and aspiration levels have been defined, the constraints can be constructed. For the purpose of discussion, it will be assumed that the OEM has the following goals in order of preference: cost, reliability, and due date (lead time). Of course, if some other priorities are known, they can be used. The next constraint focuses on the OEM's first priority of attaining an optimal cost. Each task *i* and supplier *s* has an associated cost, defined as c_{is}. With a budget aspiration level of *B*, the cost constraint is defined by Equation (2).

$$\sum_{i \in I} \sum_{s \in S(i)} c_{is} y_{is} + C^{-} - C^{+} = B \tag{2}$$

C^{+} and C^{-} measure the goal attainment. If C^{+} is zero, the constraint is within budget, and if C^{+} has a positive value, then the constraint is over budget. If C^{-} has positive value, the constraint will be below budget.

Similarly, each task *i* and supplier *s* has an associated reliability, defined as r_{is}. Assuming independence, the total reliability, R_{total}, of all suppliers across all tasks is:

$$\prod_{i \in I} \prod_{s \in S(i)} r_{is}^{y_{is}} = R_{total}$$

This, however, violates the linearity necessary for linear programming constraints. To conserve the linearity, the following logarithmic transformation is made:

$$-\ln\left(\prod_{i \in I} \prod_{s \in S(i)} r_{is}^{y_{is}}\right) = -\ln(R_{total})$$

$$\sum_{i \in I} \sum_{s \in S(i)} -\ln(r_{is}^{y_{is}}) = -\ln(R_{total})$$

$$\sum_{i \in I} \sum_{s \in S(i)} y_{is}(-\ln(r_{is})) = -\ln(R_{total})$$

Therefore, with a reliability aspiration level of P, the reliability constraint is defined by Equation (3).

$$\sum_{i \in I} \sum_{s \in S(i)} y_{is}(-\ln(r_{is})) + R^{-} - R^{+} = -n \ln(P) \tag{3}$$

The incorporation of n accounts for the number of estimated decisions, i.e. number of tasks as defined in the set. For example, if eight tasks are to be completed and the reliability aspiration, P, is 90% or 0.90, the right hand side of Equation (3) would be $-8 \ln(0.90)$; this allows for the development of a suitable goal level.

Note here that using the negative natural log reverses the logic for reliability. While normally an OEM would choose a supplier with a higher reliability, this corresponds to a lower value after being transformed. Therefore, if R^{+} is zero, the constraint meets the reliability aspiration level, but if it has positive value, then the reliability falls short of its goal. If R^{-} has value, the reliability exceeds its the goal. It is also important to keep in mind with this transformation is that, wheras the reliability values for all r_{is} and P are on a negative log scale, the deviation variables of R^{-} and R^{+} are not. This makes interpreting the results more difficult, but gauging the magnitudes of R^{-} and R^{+} will provide an idea of whether the OEM is above or below its reliability goal.

Following the same approach as the cost constraint, for each task i and supplier s with associated production lead time t_{is} with aspired schedule time of D, and with the deviations for the desired due date given as T^{-} and T^{+}, the lead time constraint is defined by Equation (4).

$$\sum_{i \in I} \sum_{s \in S(i)} t_{is} y_{is} + T^{-} - T^{+} = D \tag{4}$$

Equation (5) defines the non-negativity of the objective function decision variables and defines the supplier selection decision variables to be binary.

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-} \geq 0 \; ; \; y_{is} \in \{0,1\} \tag{5}$$

It should be noted that, while the model has been proposed with primarily goal constraints (also known as soft constraints due to the deviation variables), it could include hard constraints (i.e., classic inequality constraints).

The optimal solution to the OEM Supplier Selection Goal Program, according to these constraints, identifies a set of suppliers that allows an OEM to best meet its manufacturing and production goals.These goals reflects their priorities: cost, reliability, and production time. These priorities are not limited to just cost, reliability, and time, but they rather can be defined as any number of measures. They are utilized in this model as an example. Following the nature of goal programming, each priority defined as cost, *C*, reliability, *R*, and time, *T*, has an aspiration level of *P*, *B*, and *D*, respectively. Therefore, the goals *C*, *R*, and *T* have associated deviation variables, C^{+}, C^{-}, R^{+}, R^{-},T^{+}, and T^{-}, that represent the over- and under- deviations of decision-based metrics from their respective aspiration levels. We assume that cost is the first priority and assign it an appropriately developed weight of W_1, followed by reliability with weight W_2, with time as the third priority with a weight of W_3.

A brief discussion on weighting is appropriate before the goals are defined—these weights can be developed in many ways, as long as they appropriately reflect the decision maker's priorities. Ignizio (1976) points out that there is no single correct approach to

assigning weights, priorities and ranks. They need not be preemptive, only appropriately and soundly weighted numerically. According to Romero, a naïve weighting of the goals can lead to a meaningless interpretation of the goal program; therefore the proper setting of the weights is imperative. The author suggests several approaches to overcome naïve weighting, such as scaling the weights according to their goals or normalizing weights according the a Euclidean norm (Romero, 1991). Other suggested approaches include swing weighting (Parnell and Trainor, 2009), polynomial weighting (Deckro and Hebert, 1988), or other normalizing techniques. Whether numeric or preemptive weighting is used, it is important that the weights are developed in a justifiable manner that overtly represents the decision maker preference for deviations from the aspiration level. Sensitivity analysis in the weights is often recommended. A sound weighting technique will keep the model consistent and produce meaningful interpretations.

With that discussion, the first goal for SS can be identified as:

$$\text{Minimize } W_1 C^+ - \varepsilon_1 C^-$$

Here, minimizing C^+ ensures that costs do not exceed the budget. Since, according to Equation (5), all variables are non-negative, the optimal value for C^+ is zero. The goal is satisfied when the solution is within budget. Any solution that meets the budget is optimal for the goal attainment. A small value of $-\varepsilon_1$ is added to the function, alongside C^-, to allow the option of selecting a solution, if it exists, that not only meets the goal but exceeds it (in this case, being under budget). The value for ε_1 should be selected to reflect the decision without interfering with the goal satisfaction (see (Sherali and Soyster, 1983) for a discussion on preemptive versus nonpreemptive weighting).

Likewise, the second goal—maximizing supplier reliability—can be defined as:

$$\text{Minimize } W_2 R^+ - \varepsilon_2 R^-$$

Here, remember that the logic is reversed due to the logarithmic transformation discussed in Equation (3), so minimizing R^+ is actually equivalent to maximizing reliability. Because smaller values of R_{total} are more desirable than larger ones, an optimal value of R^+ is zero, while a larger value of R^- leads to a reliability in excess of the goal.

Lastly, the third goal—minimizing production lead time—can be defined as:

$$\text{Minimize} W_3 T^+ - \varepsilon_3 T^-$$

The whole objective function is then defined in the following expression:

$$\text{Minimize} \quad W_1 C^+ + W_2 R^+ + W_3 T^+ - \varepsilon_1 C^- - \varepsilon_2 R^- - \varepsilon_3 T^-$$

While the objective function features multiple objectives, it can also be modeled as a single objective linear programming model. The complete SS model is compiled as follows:

OEM Supplier Selection Goal Program, SS

$$\text{Minimize} \quad W_1 C^+ + W_2 R^+ + W_3 T^+ - \varepsilon_1 C^- - \varepsilon_2 R^- - \varepsilon_3 T^-$$

Subject to

$$\sum_{s \in S(i)} y_{is} \geq 1, \ \forall i \in I, \tag{1}$$

$$\sum_{i \in I} \sum_{s \in S(i)} c_{is} y_{is} + C^- - C^+ = B, \tag{2}$$

$$\sum_{i \in I} \sum_{s \in S(i)} y_{is}(-\ln(r_{is})) + R^- - R^+ = -n * \ln(P), \tag{3}$$

$$\sum_{i \in I} \sum_{s \in S(i)} t_{is} y_{is} + T^- - T^+ = D, \tag{4}$$

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-} \geq 0 \,, \tag{5}$$

$$y_{is} \in \{0,1\} \;\; \forall i \in I \,,\, s \in S\,(i).$$

The variables and sets are defined as:

Decision Variables

$$y^{is} = \begin{cases} 1 \text{ if task } i \text{ is supplied by supplier } s \\ 0 \text{ otherwise} \end{cases}$$

Sets

$i \in I$ $\quad I =$ All tasks to be performed $i = 1, 2, \ldots, n$

$S =$ set of all possible suppliers;
where $s \in S\,(i)$ when $s = \{1, 2, \ldots, m\}$ is able to perform task i

Data

r_{is} = measure of reliability of task i
when performed by supplier s

c_{is} = cost of task i when performed by supplier s

t_{is} = measure of time for task i when performed by supplier s

B = total cost goal (budget) for the manufacturer

P = manufacturer's total product reliability goal

D = production time goal (schedule)
for the manufacturer

W_k = Priority weight of goal k for $k = 1 \ldots g$
where g is the number of goals

ε_k = some small positive scalar

Variables

R^{+} = overage of reliability aspiration level, P

R^{-} = underage of reliability aspiration level, P

C^{+} = overage of price/cost aspiration level, B

C^- = underage of price/cost aspiration level, B

T^+ = overage of production time aspiration level, D

T^- = underage of production time aspiration level, D

Phase 1: SCIM-Design: Supply Chain Network Flow

Instead of selecting specific suppliers, consider a supply chain network consisting of a flow of materials and goods from raw material to delivered finished goods. This network can be modeled as a graph of nodes and arcs, G(N,A), wherein a node represents a transformation of materials from its downstream nodes into a product and sent upstream to the next level of nodes. These nodes can be conceptualized as manufacturers performing work for each level of task, just as in the supplier selection problems; however, instead of simply choosing which supplier from which to purchase material, the manufacturer must determine how much materials they need to perform their task in order to meet demand and from where to purchase it. This is a classic network flow model, and is especially useful for manufacturers considering the "Make or Buy" decision previously discussed during the the Make phase of the SCOR model. To model the "Make or Buy" decision, multiple nodes can be defined for each task: one representing the "Make" node, and the others representing the "Buy" node from the number of available suppliers.

In the Supply Chain Network Flow (SCNF), the decision variables, f_{ij}, denote the amount of flow on the arcs between nodes i and j. To capture the reduction in amount of material from one level of task to the next (the assembly of parts into a component), a "loss" coefficient, l_{ij}, is defined for the generalized network flow extension. If l_{ij} <1, the

flow decreases, if l_{ij} >1, flow increases, and if $l_{ij} = 1$, flow passes through the node unchanged. Each flow has an upper bound, u_{ij}, representing the arc's supply capacity from node *i* to node *j*. The network flow utilizes a flow balance equation for a generalized network flow with losses, defined by Equation (6) as:

$$\sum_{j:(i,j)\in A} f_{ij} - \sum_{j:(j,i)\in A} l_{ji} f_{ji} \leq b_i \ \forall i \in N \tag{6}$$

where *i* is a supply node with supply b_i (if b_i>0), a demand node with demand $|b_i|$ (if b_i <0), or an intermediate node (if $b_i = 0$).

An addition to the SCNF model is the introduction of demand. A manufacturer has a demand that they wish to achieve, which led to the desire to determine the optimal flow of material. The demand constraint can be viewed as a hard constraint in the manufacturer's model—it is unlikely they will buy more than they need, but they must meet at least the demand. This constraint is covered by Equation (6) for the last node of the network, with demand $|b_i|$ that will at the very least be met. If, in the solving of this model, the instance infeasible, it is likely that demand cannot be met and one might consider adjusting their demand accordingly.

Next, Equation (7) constrains the flow to be a positive number between zero and its upper limit, u_{ij}, or capacity:

$$0 \leq f_{ij} \leq u_{ij} \quad \forall (i,j) \in A \tag{7}$$

The lower bound here is assumed to be zero, but it can be defined as a positive number, if known and applicable.

For the illustration of the SCNF model, it is again assumed that the decision maker has priorities of minimizing cost, maximizing reliability, and minimizing time. Any single goal or set of goals and priorities may be used. Given these priorities, the SCNF can also be setup as a goal program, similar to the Supplier Selection model. For the goal constraint corresponding to the first goal, minimizing cost, c_{ij} is defined to be the cost to flow one unit of flow, f_{ij}, from node *i* to node *j*. With a budget goal of B, and over- and under- deviations from cost of C^{+} and C^{-}, respectively, Equation (8) reflects the first goal's constraint:

$$\sum_{i,j \in A} c_{ij} f_{ij} + C^{-} - C^{+} = B \tag{8}$$

Similarly, the second objective has reliability goal of P, and over- and under- deviations of and R^{-}. The reliability of sending one unit of flow, f_{ij}, from node *i* to node *j*, is r_{ij}. Utilizing the same logarithmic transformation from Equation (3), the reliability goal constraint can be formulated as shown in Equation (9):

$$\sum_{i,j \in A} f_{ij}(-\ln(r_{ij})) + R^{-} - R^{+} = -n \ln(P) \tag{9}$$

The *n* in Equation (9) is defined by the estimated number of components that will flow through the system. In terms of the manufacturer, it is an estimation of the materials necessary to build their product.

Finally, the third goal is minimizing production lead time to meet a schedule, *D*. The schedule has over- and under- deviations of T^{+} and T^{-}, respectively. The time it takes one unit, f_{ij}, to flow from node *i* to node *j*,is given by t_{ij}. The time goal's constraint is shown in Equation (10).

$$\sum_{i,j \in A} t_{ij} f_{ij} + T^- - T^+ = D \tag{10}$$

It is important to note the units in this model. The data (c_{ij}, r_{ij}, and t_{ij}) correspond to a single unit of flow, f_{ij}. For example, if it is known that a shipment of 500 units from node *i* to node *j* will be $10,000, then c_{ij} would be $\frac{\$10,000}{500} = \$20 / unit$.

Because goal programming is employed in SCNF, all deviation decision variables must be non-negative, as defined by Equation (11).

$$C^+, C^-, R^+, R^-, T^+, T^- \geq 0 \tag{11}$$

Since the goal weighting for the SCNF model example are assumed to be the same as the SS model, the objective function remains the same.Therefore, the full SCNF model formulation for the design of flow of materials is shown below.

Supply Chain Network Flow Goal Program

Minimize $W_1 C^+ + W_2 R^+ + W_3 T^+ - \varepsilon_1 C^- - \varepsilon_2 R^- - \varepsilon_3 T^-$

Subject to

$$\sum_{j:(i,j) \in A} f_{ij} - \sum_{j:(j,i) \in A} l_{ji} f_{ji} \leq b_i, \ \forall i \in N, \tag{6}$$

$$0 \leq f_{ij} \leq u_{ij} \quad \forall (i,j) \in A, \tag{7}$$

$$\sum_{i,j \in A} c_{ij} f_{ij} + C^- - C^+ = B, \tag{8}$$

$$\sum_{i,j \in A} f_{ij}(-\ln(r_{ij})) + R^- - R^+ = -n \ln(P), \tag{9}$$

$$\sum_{i,j \in A} t_{ij} f_{ij} + T^- - T^+ = D, \tag{10}$$

$$C^+, C^-, R^+, R^-, T^+, T^- \geq 0. \tag{11}$$

Phase 2: SCIM-Interdiction: Attacker's Supplier Selection Interdiction (SS-I)

Phase 2, SCIM-Interdiction transitions to the attacker's point of view. Phase 1 is only necessary if a supply chain is unknown due to lack of intelligence. For the attacker's supplier selection interdiction (SS-I) model, the focus is on determining which supplier(s) makes the most effective target and will cause the most detrimental effects. Whether a set of suppliers is determined using the OEM's model (SS) from Phase 1, or it is already known, that set is the set of potential targets for an attacker wishing to cause a disturbance. Perhaps, an attacker wishes to drive up cost and production lead time, and reduce product reliability; these are in contrast to the OEM's goals in the SS model. Or, perhaps, the attacker has their own set of objectives, such as keeping the interdiction costs under a budget. Just as in the SS model, any set of goals and priorities can be determined for this model. It should also be noted that a single objective would work as well. The objective depends upon the mission objectives of the attacker. Along with solving for optimal supplier interdiction, a model that simultaneously indicates where the OEM's next best option lies would offer more insight for the attacker when deciding attack strategies.

Supplier Selection Interdiction (SS-I), incorporates two sets of decision variables for the two entities involved in the interdiction process: the attacker performing the interdiction and the OEM adjusting their supplier selection according to the disruption. The new decision variable for the attacker, x_{is} is defined to be 1 if task *i* supplier *s* is

disrupted, 0 otherwise. The OEM's decision variable is now y'_{is}, where $y'_{is} = 1$ if supplier *s* is chosen to complet task *i*, and zero otherwise (i.e., $y_{is} = 1$ in SS) . The set of suppliers is divided into two subsets, defined as follows:

> S_u is subset of suppliers chosen ($y_{is} = 1$) in OEM's original problem (or the set of suppliers already known) and therefore eligible for disruption;
> S_{u^c} is subset of suppliers not chosen ($y_{is} = 0$) in OEM's original problem;
> $S_u \cap S_{u^c} \subseteq S(i)$.

First, the constraints for SS-I are formulated. Equation (12) is the same as Equation (1) in the SS model; it ensures each task is accomplished by selecting a supplier for each one.

$$\sum_{s \in S(i)} y'_{is} \geq 1, \quad \forall i \in I \tag{12}$$

Equation (13) specifies that for each task, the attacker can only choose to disrupt from the set of suppliers the OEM had previously selected, and if that supplier task combination is interdicted, the OEM can only choose from the new set of suppliers.

$$\sum_{s \in S_{u^c}(i)} y'_{is} \leq \sum_{s \in S_u(i)} x_{is}, \quad \forall i \in I \tag{13}$$

The y'_{is}-variables on the left-hand side of Equation (13) are only from the set $s \in S_{u^c}(i)$, which was defined as the set of suppliers *not* chosen in the original SS model (or the set of suppliers currently not being utilized by the supply chain but available as options, if already known without solving the SS model). Equation (13) stipulates that a new supplier, y'_{is}, from this set of suppliers not yet utilized can only be chosen for task *i*, if x_{is}

is chosen for disruption (i.e., set to a value of 1). Otherwise, the set of potential suppliers must remain at a value of zero to hold the inequality.

Equation (14) ensures that a supplier can only be interdicted if it was previously chosen by the OEM in the SS model. For each task/supplier combination, x_{is} can only be "turned on" or set to 1, if y'_{is} is 1. Otherwise, x_{is} must be zero to hold the inequality.

$$x_{is} \leq y'_{is}, \forall i \in I, s \in S \tag{14}$$

Equation (15) incorporates the interaction between the interdiction and supplier selection variables and forces the supplier to choose a new supplier if its original supplier is interdicted to ensure that each task *i* still gets accomplished.

$$\sum_{s \in S(i)} (y'_{is} - x_{is}) \geq 1 \ \forall i \in I \tag{15}$$

If x_{is} =1, task *i* supplier *s* is interdicted, and supplier *s* is no longer eligible to be chosen to complete task *i*.

Equations (16)-(18), defined below, are nearly the same as Equations (2)-(4), except that, for the set of suppliers that were chosen ($s \in S_u(i)$) in the SS problem, y_{is} is replaced by $y'_{is} - x_{is}$ to ensure a supplier task combination is "turned off" (set to zero), if interdicted. Therefore, for the set $s \in S_u(i)$, y'_{is}= 1 originally, but will be offset in Equation (15) if the arc is interdicted, i.e., the corresponding x_{is}-variable is set to 1. These equations are included into the attacker's model for two reasons. First, they allow the attacker to evaluate the effect that their decisions will have on the OEM's original goals by comparing with the results from the SS model. Second, it also allows the

attacker to model the behavior of the OEM and gain insight into the OEM's future supplier selection decisions if the attacker interdicts their best option.

$$\sum_{i \in I} \sum_{s \in S_u(i)} c_{is}(y_{is} - x_{is}) + \sum_{i \in I} \sum_{s \in S_{u^c}(i)} c_{is}(y_{is}) + C^- - C^+ = B \tag{16}$$

$$\sum_{i \in I} \sum_{s \in S_u(i)} (y_{is} - x_{is})(-\ln(r_{is})) + \sum_{i \in I} \sum_{s \in S_{u^c}(i)} (y_{is})(-\ln(r_{is})) + R^- - R^+ = -n \ln(P) \tag{17}$$

$$\sum_{i \in I} \sum_{s \in S_u(i)} t_{is}(y_{is} - x_{is}) + \sum_{i \in I} \sum_{s \in S_{u^c}(i)} t_{is}(y_{is}) + T^- - T^+ = D \tag{18}$$

The constraints up to this point in SS-I have dealt with the OEM and attacker interacting with each other. SS-I assumes that the attacker is aware of an OEM's priorities and supplier options, and that the OEM becomes aware of an interdiction when it occurs and can switch its supplier selection accordingly.

The following constraints reflect only the point of view of the attacker. Assume, for each supplier and task, that an attacker can estimate the cost of an attack (denoted c_attack_{is}), as well as the potential "damage" they can cause (denoted as d_{is}). Damage can be defined in any way the interdictor can measure it. It is important to note that some form of consistent metric is developed for the damage coefficients. There are many ways to assess the value of a target, and notably the most important aspect to any approach is that the values are valid and reproducible. While the development of such values is beyond the scope of this thesis, approaches such as value hierarchy or analytical hierarchy processes are solid frameworks with which to start (the reader is referred to (Saaty, 1982) or (Keeney, 1992) as an example). For demonstration purposes, damage

will be defined on a 1-10 scale with 10 being catastrophic damage, and 1 being minimal damage.

The attacker's objective is to cause the most damage at the least cost. The attacker defines an interdiction budget goal, C_{attack}, and a "damage" goal, D_{attack}, with associated over- and under- deviation variables. Equation (19) incorporates the interdiction budget goal for the attacker.

$$\sum_{i \in I} \sum_{s \in S(i)} c_attack_{is} x_{is} + C_{attack}^{-} - C_{attack}^{+} = C_{goal} \tag{19}$$

Equation (20) reflects the attacker's "destruction" goal, where d_{is} indicates the amount of damange an interdiction causes on task *i* supplier *s*.

$$\sum_{i \in I} \sum_{s \in S(i)} d_{is} x_{is} + D_{attack}^{-} - D_{attack}^{+} = D_{goal} \tag{20}$$

Because the attacker's constraints are goals with large weights on their priorities, the optimal solution will naturally suggest that they interdict all of the targets. To restrict the attacker to a realistic scenario, we introduce a hard constraint that limits the number of attacks or interdictions they can perform, *r*. This limit is shown in Equation (21).

$$\sum_{i \in I} \sum_{s \in S(i)} x_{is} \leq r \tag{21}$$

The value of *r* will depend on the mission objective and resource capabilities. Equations (22) defines binary constraints for decision variables, and non-negativity for the deviation variables.

$$y'_{is} \in \{0,1\},\ x_{is} \in \{0,1\}\ \forall i \in I,\ s \in S(i), \tag{22}$$

$$C^+, C^-, R^+, R^-, T^+, T^-, D^+_{attack}, D^-_{attack}, C^+_{attack}, C^-_{attack} \geq 0$$

Finally, the SS-I objective function, defined in the following expression, reflects the attacker's objective: to minimize the overage cost of interdiction, $C_{attack}{}^+$, and underage of damage, $D_{attack}{}^-$. The rest of the objective function reflects the OEM's objective function from the original SS problem and is necessary to ensure that the model suggests where the OEM's next optimal move would be, given the interdiction by the attacker.

Minimize $\quad W_1 C^+_{attack} + W_2 D^-_{attack} - \varepsilon_1 C^-_{attack} - \varepsilon_2 D^+_{goal} + W_3 C^+ + W_4 R^+ + W_5 T^+$

Therefore, the full model, Supplier Selection Interdiction (SS-I) is formulated as follows:

Attacker's Supplier Selection Interdiction Goal Program, SS-I

Minimize $\quad W_1 C^+_{attack} + W_2 D^-_{attack} - \varepsilon_1 C^-_{attack} - \varepsilon_2 D^+_{goal} + W_3 C^+ + W_4 R^+ + W_5 T^+$

Subject to $\quad \sum_{s \in S(i)} y'_{is} \geq 1,\ \forall i \in I,$ (12)

$$\sum_{s \in S_{u^c}(i)} y'_{is} \leq \sum_{s \in S_u(i)} x_{is},\ \forall i \in I, \tag{13}$$

$$x_{is} \leq y'_{is},\ \forall i \in I,\ s \in S, \tag{14}$$

$$\sum_{s \in S(i)} (y'_{is} - x_{is}) \geq 1,\ \forall i \in I, \tag{15}$$

$$\sum_{i \in I} \sum_{s \in S_u(i)} c_{is}(y'_{is} - x_{is}) + \sum_{i \in I} \sum_{s \in S_{u^c}(i)} c_{is}(y'_{is}) + C^- - C^+ = B, \tag{16}$$

$$\sum_{i\in I}\sum_{s\in S_u(i)}(y'_{is}-x_{is})(-\ln(r_{is}))+\sum_{i\in I}\sum_{s\in S_{u^c}(i)}(y'_{is})(-\ln(r_{is}))+R^- - R^+ = -n\ln(P), \tag{17}$$

$$\sum_{i\in I}\sum_{s\in S_u(i)} t_{is}(y'_{is}-x_{is})+\sum_{i\in I}\sum_{s\in S_{u^c}(i)} t_{is}(y'_{is})+T^- - T^+ = D, \tag{18}$$

$$\sum_{i\in I}\sum_{s\in S(i)} c_attack_{is}\, x_{is} + C_{attack}^{\ -} - C_{attack}^{\ +} = C_{goal}, \tag{19}$$

$$\sum_{i\in I}\sum_{s\in S(i)} d_{is}\, x_{is} + D_{attack}^{\ -} - D_{attack}^{\ +} = D_{goal}, \tag{20}$$

$$\sum_{i\in I}\sum_{s\in S(i)} x_{is} \le r, \tag{21}$$

$$y'_{is}\in\{0,1\},\ x_{is}\in\{0,1\}\ \ \forall i\in I,\ s\in S(i), \tag{22}$$

$$C^+, C^-, R^+, R^-, T^+, T^-, D^+_{attack}, D^-_{attack}, C^+_{attack}, C^-_{attack} \ge 0.$$

The variables and sets are primarily the same as the OEM supplier selection model, but the new variables and sets introduced are defined below.

Decision Variables $x^{is} = \begin{cases} 1 \text{ if task } i \text{ supplier } s \text{ is targeted for interdiction} \\ 0 \text{ otherwise} \end{cases}$

Sets S_u is subset of suppliers chosen ($y_{is} = 1$) in OEM's original problem;
S_{u^c} is subset of suppliers not chosen ($y_{is} = 0$) in OEM's original problem;
$S_u \subseteq S(i)$ and $S_{u^c} \subseteq S(i)$

Data c_attack_{is} = cost to attacker to disrupt task i for supplier s

d_{is} = damage caused by interdiction on task i supplier s

C_{goal} = interdiction cost (budget) aspiration level

D_{goal} = interdiction destruction goal

r = upper limit on number of interdiction attacks

Variables C_{attack}^{+} = overage of interdiction budget aspiration level, C_{goal}

C_{attack}^{-} = underage of interdiction budget aspiration level, C_{goal}

D_{attack}^{+} = overage of interdiction destruction goal, D_{goal}

D_{attack}^{-} = underage of interdiction destruction goal, D_{goal}

Phase 2: SCIM- Interdiction: Supply Chain Network Flow-Interdiction

Just as SCNF was similar to SS, likewise Supply Chain Network Flow-Interdiction (SCNF-I) is also similar to SS-I. Because SCNF has a classic network flow structure, existing interdiction models based on networks can be utilized for planning an attack. SCNF-I is an interdiction approach utilizing goal programming. SCNF-I begins by utilizing the structure of SCNF, and incorporates interdiction by using the same approach as SS-I and dividing the solution set from SCNF into arcs chosen (A_u), and arcs not chosen (A_{u^c}). The new decision variables in SCNF-I are f'_{ij} , the new flow over arcs (*i,j)*, and x_{ij}, the interdiction over arcs (*i,j)*. The new flow balance interdiction constraint is shown in Equation (23):

$$\sum_{j:(i,j)\in A_u} (f'_{ij} - x_{ij}) - \sum_{j:(j,i)\in A_u} l_{ji}(f'_{ji} - x_{ji}) + \sum_{j:(i,j)\in A_{u^c}} (f'_{ij}) - \sum_{j:(j,i)\in A_{u^c}} l_{ji}(f'_{ji}) \le b_i, \forall i \in N \qquad (23)$$

This constraint follows the same logic as Equation (6), and essentially allows flow to pass through a node only if it is not fully disrupted. A node is considered fully disrupted if $x_{ij} = f'_{ij}$. Otherwise, if $0 < x_{ij} \le f'_{ij}$, the flow from node *i* to node *j* is only partially

disrupted, and in essence its capacity is decreased. With regard to an arc's capacity, Equation (24) ensures an arc can only be interdicted if flow is passing through it, and it establishes an upper bound, u_{ij}, on both the flow and the interdiction.

$$0 \le x_{ij} \le f'_{ij} \le u_{ij}, \quad \forall (i,j) \in A \tag{24}$$

The goal constraints in this example of SCNF-I are split into subsets of arcs utilized (A_u) and arcs unchosen (A_{u^c}) from the orginal SCNF-I model. They are formulated below:

$$\sum_{j \in A_u(i)} c_{ij}(f'_{ij} - x_{ij}) + \sum_{j \in A_{u^c}(i)} c_{ij}(f'_{ij}) + C^- - C^+ = B \tag{25}$$

$$\sum_{j \in A_u(i)} (f'_{ij} - x_{ij})(-\ln(r_{ij})) + \sum_{j \in A_{u^c}(i)} (f'_{ij})(-\ln(r_{ij})) + R^- - R^+ = -n\ln(P) \tag{26}$$

$$\sum_{j \in A_u(i)} t_{ij}(f'_{ij} - x_{ij}) + \sum_{j \in A_{u^c}(i)} t_{ij}(f'_{ij}) + T^- - T^+ = D \tag{27}$$

These are nearly identical to the goal constraints in Equations (16)-(18) in SS-I, with the appropriate notation and subscripts applicable to SCNF. The variables are all defined as they were in SCNF.

The final constraints in SCNF are nearly identical to those in SS-I, with the appropriate set notation, and they represents the attacker's goals.

$$\sum_{(i,j) \in A} c_attack_{ij} x_{ij} + C_{attack}^- - C_{attack}^+ = C_{goal} \tag{28}$$

$$\sum_{(i,j) \in A} d_{ij} x_{ij} + D_{attack}^- - D_{attack}^+ = D_{goal} \tag{29}$$

Just as in SS-I, we also introduce a limit on the number of attacks based on mission objectives and resource constraints, shown in Equation (30)

$$\sum_{i,j \in A} x_{i,j} \le r \tag{30}$$

Finally for the constraints, the deviation variables are defined to be non-negative in Equation (31).

$$C^+, C^-, R^+, R^-, T^+, T^-, C_{attack}^{\ +}, C_{attack}^{\ -}, D_{attack}^{\ +}, D_{attack}^{\ -} \ge 0 \tag{31}$$

The objective function in SCNF-I is identical to the SS-I model. However, as noted before, the objective can be specified however the decision maker deems appropriate, and can be multi- or single- objective. The objective function is restated to complete the formulation.

Minimize $\quad W_1 C^+_{attack} + W_2 D^-_{attack} - \varepsilon_1 C^-_{attack} - \varepsilon_2 D^+_{goal} + W_3 C^+ + W_4 R^+ + W_5 T^+$

Therefore, the final SCNF-I formulation is shown below.

Supply Chain Network Flow-Interdiction Goal Program

Minimize $\quad W_1 C^+_{attack} + W_2 D^-_{attack} - \varepsilon_1 C^-_{attack} - \varepsilon_2 D^+_{goal} + W_3 C^+ + W_4 R^+ + W_5 T^+$

Subject to

$$\sum_{j:(i,j)\in A_u} (f'_{ij} - x_{ij}) - \sum_{j:(j,i)\in A_u} l_{ji}(f'_{ji} - x_{ji}) + \sum_{j:(i,j)\in A_{u^c}} (f'_{ij}) - \sum_{j:(j,i)\in A_{u^c}} l_{ji}(f'_{ji}) \le b_i, \ \forall i \in N, \tag{23}$$

$$0 \le x_{ij} \le f'_{ij} \le u_{ij}, \quad \forall (i,j) \in A, \tag{24}$$

$$\sum_{j\in A_u(i)} (f'_{ij} - x_{ij})(-\ln(r_{ij})) + \sum_{j\in A_{u^c}(i)} (f'_{ij})(-\ln(r_{ij})) + R^- - R^+ = -n\ln(P), \tag{25}$$

$$\sum_{j\in A_u(i)} c_{ij}(f'_{ij} - x_{ij}) + \sum_{j\in A_{u^c}(i)} c_{ij}(f'_{ij}) + C^- - C^+ = B, \tag{26}$$

$$\sum_{j\in A_u(i)} t_{ij}(f'_{ij} - x_{ij}) + \sum_{j\in A_{u^c}(i)} t_{ij}(f'_{ij}) + T^- - T^+ = D, \tag{27}$$

$$\sum_{i,j \in A} c_attack_{ij} x_{ij} + C_{attack}^{-} - C_{attack}^{+} = C_{goal}, \tag{28}$$

$$\sum_{i,j \in A} d_{ij} x_{ij} + D_{attack}^{-} - D_{attack}^{+} = D_{goal}, \tag{29}$$

$$\sum_{i,j \in A} x_{i,j} \leq r, \tag{30}$$

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-}, C^{+}_{attack}, C^{-}_{attack}, D^{+}_{attack}, D^{-}_{attack} \geq 0. \tag{31}$$

Phase 3: SCIM-Strategy: House of Targeting

It is possible to consider other goals, given the mission objectives, moreover, in deliberate planning, varying the goal priorities can give different target priorities.The House of Targeting (HOT) for Phase 3 adapts the House of Quality (HOQ) approach discussed in Chapter 2 to develop a target screening model. Similar to that in Table 1, each section of the HOT addresses different aspects of the decision making process that must be considered when planning a supply chain network interdiction. The HOT is simply another way to depict targeting doctrine and incorporate screening. Where the HOQ helps identify products suitable for a firm to produce, HOT helps identify targets that meet mission objectives given both kinetic and non-kinetic weaponeering options. The descriptions specific to the different sections of HOT are shown in Table 2.

Table 2. House of Targeting Description

Section of House of Targeting	Description
(a) Potential Targets	Who/what are the targets? These targets are determined by the SS-I and SCNF-I models in Phase 2.
(b) Goal Assessment	Will a disruption to this target achieve our mission priorities? What does it do to our opponents' priorities? This section annotates the deviation variables from SS-I and SCNF-I.
(c) Importance	Are all targets equally important? A numerical value must be applied to each target to quantitatively assess its importance.
(d) Capabilities Assessment	What are our potential available courses of action (COAs)? Different strategies are developed based on the mission and target set, while considering the resources available to conduct the COAs.
(e) Relationship Matrix	Are the courses of action feasible for this target? A subjective assessment is conducted to quantify the feasibility and effectiveness for the relationship between each COA and target. An appropriate weighting system must be used.
(f) Correlation Matrix	How does one course of action affect the others? A correlation assessment between COAs is conducted to ensure they will not negatively interfere with each other, and may reveal that some COAs indeed complement each other.
(g) Target Values	Establish ideal disruption measures. Based on the mission objective, establish measures for each COA. These measures can be derived from SS-I and SCNF-I, or developed according to the mission.
(h) Weights	Relative weights of courses of action. Incorporates the importance of each target and the relationship matrix scores to assign a final weight to each COA.
(i) Mission Objective Assessment	A final assessment, based on the HOT holistically, taking into account the final weights, the goal assessment, and the mission objectives.

Based on these descriptions, a template HOT is displayed in Figure 8.

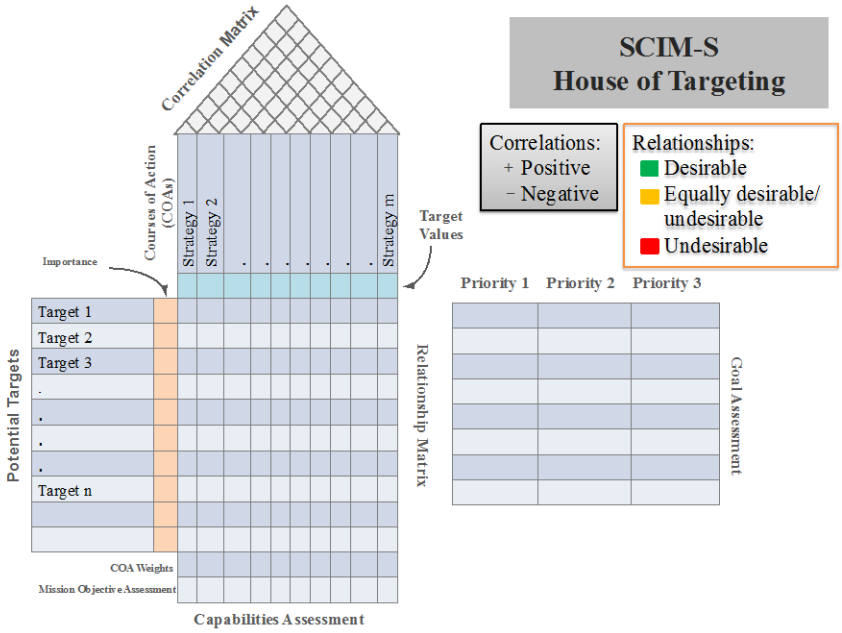

Figure 8. Template House of Targeting

The HOT, therefore, can be built by filling in the questions or description from Table 2 in a template HOT in Figure 9. Following are the steps to build a HOT.

Step 0: Develop an interdiction mission and objectives. Before going through the steps in HOT, a planning team must define the mission and mission objectives. The purpose of the HOT is to develop a strategy to support the mission and its objectives, so without a mission, HOT is a moot point. Mission objectives should be quantifiable as they are utilized in the Target Values row, filled in during Step 7. Throughout the building of the HOT, it is important to keep the purpose of the SCIM in mind. In the bigger picture, the SCIM ultimately supports the phases of the Joint Targeting Process. Therefore, the building of the HOT should be viewed from a doctrinal lens, such as that found in Joint Publication 3-60 or Air Force Doctrine Annex 3-0. The target and COA

development should utilize an effects-based approach to operations to ensure that all interdiction effects can be traced back to the mission objectives.

Step 1: Identify the targets. The Potential Targets are the outputs of the model(s) from Phase 2. They can be a list of suppliers identified by SS-I or a critical flow of material identified by SCNF-I, or a combination of the two. For example, the left column of HOT could be filled in as shown in Figure 9, with the top two targets from each of the interdiction models.

Potential Targets
Target 1 from SS-I
Target 2 from SS-I
Target 3 from SCNF-I
Target 4 from SCNF-I
⋮

Figure 9. Potential Target List

Step 2: Rank the targets. The importance column allows the decision maker to rank the targets. The ranks can be a direct result of the models from Phase I. To facilitate a weighted sum in evaluation, an inverse ranking is suggested. For example, the target identified by the model chosen in Phase I with the worst objective function value can be ranked #1, followed by the second best target as #2, and so forth. However, the decision maker, analyst, and planners can adjust ranks as they see fit. Any numerically sound ranking method may be used; (for further discussion, the reader is referred to (Burke, Kloeber, and Deckro, 2003)). The scoring method, however, must be repeatable and theoretically sound.

As an example, the column next to the Potential Targets would be filled in as shown in Figure 10, with 4 being the most important target, followed by 3, 2, 1.

Potential Targets	
Target 1 from SS-I	1
Target 2 from SS-I	2
Target 3 from SCNF-I	3
Target 4 from SCNF-I	4
⋮	

Figure 10. Target Ranks

Step 3: Relate the goals to the targets. The Goal Assessment is also informed by Phase 2 of SCIM and takes into account the the priorities, goals, and associated deviation variables. Since the priorities in the models in Phase 2 are weighted in the goal programming models, the goal assessment gives the decision maker a visual reminder of which goal the target is most vulnerable to. For each target, a "+" or a "-" sign will be input into the Goal Assessment matrix to identify how each target relates to each priority. The signs in this step reflect the deviation variables from the optimal solution in the SS-I and SCNF-I models. For example, if the positive cost deviation variable, C^+, appears in the solution to Target 1 from SS-I, then the corresponding box in the Goal Assessment would get a "+". Alternatively, if C^- appears in the solution to Target 1 from SS-I, then the Goal Assessment box would receive a "-". As an example, consider if, for Target 1 from SS-I, the variables $C^+, R^-, T^+, C^+_{attack}$, and D^+_{attack} are all variables in the optimal solution. If a goal is precisely met, with no overage or underage, their block will be filled in with a "o". Their corresponding row in the Goal Assessment matrix, then, is shown in Figure 11. This allows the decision maker to incorporate the results of the models and goal programming priorities into their decision.

MfgCost	MfgRel	MfgTime	IntCost	Dest
+	-	+	+	+

Goal Assessment

Figure 11. Goal Assessment

Step 4: Develop courses of action (COAs) for interdiction. The Capabilities Assessment provides the interdiction planners to develop COAs. The courses of action must take into consideration the types of targets they have, the mission objective, the resources and capabilities available to be expended. They should also consider the inherent vulnerabilities within supply chains, as discussed in Chapter 2. The risks shown in Figure 5 are a good place to start. COAs can target any of the risks considered in Figure 5 by focusing on a supply chain's human networks (such as the workforce), specific business organizations (such as the suppliers and manufacturers), and infrastructure networks (such as the physical structures where supply chain tasks occur). Of course, specific mission requirements and constraints would dictate the COA options. The vertical columns atop the HOT would then be filled in as shown in Figure 12. Note that each strategy in Figure 12 actually represents a tactic to be utilized in developing an overall interdiction strategy. Here, they are used interchangeably but we recognize the difference between the two. Only tactics must be determined in developing COAs.

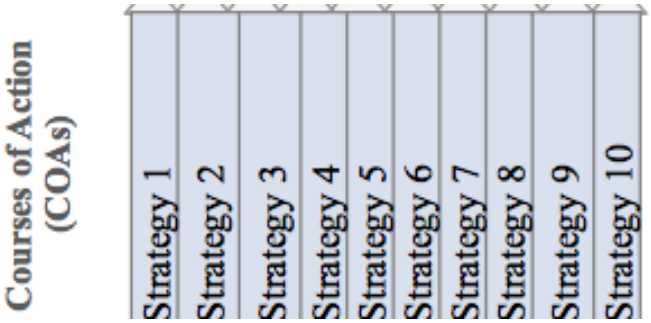

Figure 12. Courses of Action

Step 5: Fill in the Correlation Matrix. The Correlation Matrix, the roof of HOT, represents the relationship between COAs. For a decision making team, it is important to consider how the choice of one COA affects another, especially if multiple targets are going to be attacked. A "+" denotes a positive relationship, while a "-" denotes a negative relationship. For example, consider the following three strategies: (1) bomb the target, (2) intercept raw materials to the target, and (3) introduce counterfeits into the target's supply chain. Strategies (2) and (3) will have positive relationships because they can be performed simultaneously, whereas Strategy (1) would have a negative relationship with both (2) and (3). This is shown in Figure 13.

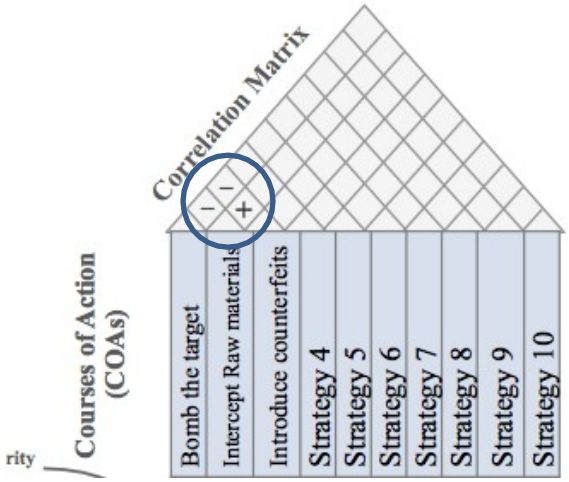

Figure 13. Correlation Matrix

Step 6: Fill in the Relationship Matrix.

The scoring of the relationship matrix is perhaps the most important step in building the HOT. While the methodology will vary according to the decision maker preferences, it is vital that a sound numerical approach is used (refer to (Burke *et al*., 2003) for a discussion on scoring techniques). Similar to the discussion regarding consistent scoring of the damage coefficients in the interdiction models, the scoring methodology must be reproducible and consistent in order to be most effective.

The scoring methodology can be both color coded and quantified. One example of a targeting screening matrix used by the International Warfare Planning Capability (Allen, 2003) is shown in Figure 14, where the matrix is color coded as well as numerically coded. The idea is that the relationship between a target and COA pair be evaluated objectively in order to properly inform an interdiction decision.

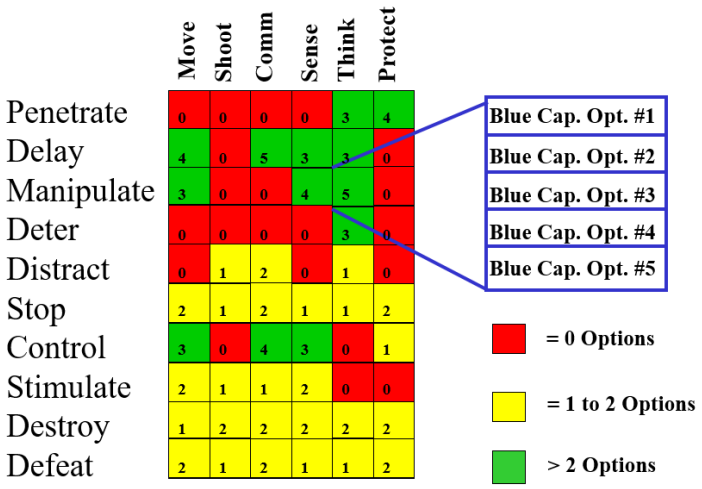

Figure 14. Example Screening Matrix

Factors to consider during the scoring of the relationship matrix include risk tolerances of the decision maker and the feasibility of each COA for each target. A comprehensive method of determination to establish consistency and elicitation of bounds is necessary when scoring this matrix. The principles from Joint Publication 3-60, Targeting Doctrine and the updated Air Force Doctrine Annex 3-0 (2016), Operations and Planning are foundational to not only the scoring of this matrix but the development of the HOT as a whole.

Step 7: Determine Target Values for each COA. The Target Values determine an ideal outcome for each COA. They are based on the mission objectives and should follow the effects based approach to measuring objectives. An example for the three COAs from Figure 13 is shown in Figure 15.

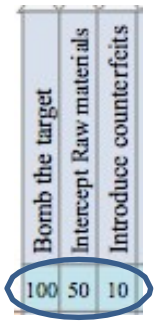

Figure 15. Target Values

In the illustration, it is determined that in order for the "bomb the target" COA to succeed, 100% damage would have to be incurred. However, for the "intercept raw materials" COA, intercepting 50% of the materials would suffice. Lastly, if the "introduce counterfeits" is chosen, only an introduction of 10% counterfeits would effectively disrupt the target's supply chain.

Step 8: Determine weights for each COA. Attach weights to each COA by combining the Importance of each target and the Relationship Matrix. In the original House of Quality, often the weight of a COA is the sum product of an item's importance with its corresponding COA column values. This approach can be utilized in the weighting of the HOT as well. Again, the weighting must be a numerically sound approach and must not be taken as a literal figure, but rather an aid to the decision maker's final evaluation.

Step 9: Evaluate HOT using Mission Objective Assessment. The Mission Objective Assessment allows the decision maker and planners to holistically consider HOT once all of the information is filled in. A final decision can be made after all considerations and comparisons between COAs have been accomplished.

The purpose of the incoroporation of the HOT into the SCIM methodology ties back to the implications of this research stated in Chapter 1. The SCIM methodology is designed to support the Joint Targeting Process. HOT is not designed to replace the process but rather to complement it, so it supports and should include all methodologies and frameworks established in the targeting doctrine found in Joint Publication 3-60 and Annex 3-0.

Overall, HOT allows an interdiction planning team to systematically consider important aspects of a supply chain interdiction and synthesize a coherent strategy based on the targets, potential COAs, and the impact of and interaction between the target-COA pairs to attain mission objectives. The HOT is completely mission dependent, but it provides a valuable framework that can be used to structure a targeting and decision making process. A detailed example is demonstrated in Chapter 4.

3.3 Summary

In this chapter, a full supply chain interdiction methodology (SCIM) was developed. SCIM consists of 3 phases. Phase 1 includes goal programming linear and network models to build an optimal supply chain. Phase 2 builds upon the models in Phase 1 to include an interdiction and facilitate target identification. Phase 3 utilizes a House of Quality approach to develop a decision support tool that facilitates interdiction strategy development. Chapter 4 demonstrates each of the models in SCIM.

4. Analysis and Results

4.1 Chapter Overview

In this chapter, we work through all phases of SCIM and each model on an illustrative example, in Section 4.2. While the illustrative example is small, it can be tailored to any size supply chain that data avilability and modeling platform allow. Solution techniques used in this chapter are straightforward mixed-integer linear programs solvers, but with larger problems, other techniques mentioned in Chapter 2 may be utilized to solve large-scalee systems more efficiently. Section 4.3 summarizes key considerations in the application of the SCIM models, and Section 4.4 concludes the chapter.

4.2 Illustrative Examples

SCIM: SS and SS-I

Consider an attacker wishing to disrupt the acquisition of a manufacturer's UAS production. While the manufacturer's suppliers are undetermined, the attacker has access to the following data considering the manufacturer: the UAS manufacturer is currently choosing suppliers for four major tasks. The tasks in this case are Level 3 tasks from Appendix I, or the major systems of a UAS. They must acquire an airframe among three suppliers, a propulsion system among two suppliers, vehicle subsystems among four suppliers, and an avionics package among seven suppliers. Some suppliers are able to perform multiple tasks, so overall there are ten suppliers available to the UAS manufacturer. The attacker is able to estimate their interdiction cost, as well as a damage coefficient, for each of the task/supplier combinations. This damage coefficient can be

determined using a value hierarchy, but for demonstration purposes in this illustrative example, the damage coefficient is assigned using a uniform 1 to 10 distribution, where 1 is the least damage and 10 is the most damage. The data is shown in Table 3.

Table 3. SS/SS-I Illustrative Example Data

Task Name	Task #	Supplie r #	Re liability	-ln(Re l)	Cost ($Millions)	Time (Weeks)	Interdiction Cost ($10K)	Damage
Airframe	1	6	0.662	0.413	0.953	3	5	4
Airframe	1	10	0.913	0.091	1.782	4	1	6
Airframe	1	2	0.857	0.154	1.816	3	3	8
Propulsion	2	6	0.663	0.410	1.775	7	1	9
Propulsion	2	8	0.734	0.309	1.511	5	1	3
Vehicle Subsystems	3	8	0.894	0.441	2.033	5	2	3
Vehicle Subsystems	3	5	0.644	0.111	1.659	6	5	3
Vehicle Subsystems	3	1	0.554	0.591	1.273	5	4	3
Vehicle Subsystems	3	3	0.577	0.550	1.869	4	4	7
Avionics	4	8	0.881	0.127	2.001	8	2	9
Avionics	4	4	0.795	0.229	2.037	9	2	2
Avionics	4	9	0.899	0.106	2.117	7	5	6
Avionics	4	1	0.818	0.201	1.974	8	5	10
Avionics	4	6	0.876	0.133	2.150	9	4	6
Avionics	4	2	0.593	0.523	1.035	7	3	3
Avionics	4	7	0.787	0.239	1.720	6	5	8

Because the suppliers are unknown, the attacker must estimate the manufacturer's selection by utilizing the Supplier Selection (SS) model before developing the interdiction set. The attacker reasonably assumes that a manufacturer's first priority (W_1) is cost, followed by reliability (W_2), followed by time (W_3). The weights for the priorities in the objective function must be chosen carefully taking into account the difference in magnitude of the units. For this example, weights are assigned based on order of magnitude as follows: W_1=1,000, W_2=100, W_3=10, ε_1, ε_2 and ε_3 = 0.001. The attacker assumes the following goals for both the manufacturer in the SS model and itself in the SS-I model.

Table 4. SS and SS-I Goals

SS OEM Goals			SS-I Attacker Goals		
OEM Cost, B	**OEM Reliability,** P	**OEM Time (weeks),** D	**Interdiction Resource Limit,** r	**Damage,** D_{goal}	**Interdiction Cost,** C_{goal}
$ 5 (M)	(0.80) 0.893	18	2	20	$ 100

OEM cost and time goals are based off of a best case scenario estimation. OEM reliability goal was determined by using Equation (32) with n=4 tasks being the multiplier:

$$P = -4\ln(0.80) = 0.89257 \tag{32}$$

This goal implies that the manufacturer overall (across all four tasks/systems) wishes to have a product with 80% reliability.

The attacker's resource limitations, interdiction cost goal, and damage goal are mission dependent. The attacker's priorities are to first cause the most damage, then at the least cost. They have the hard constraint of no more than two interdictions.

Based on the data in Tables 3 and 4 and the goals and priorities of the manufacturer and the attacker, the following models are setup for SS and SS-I:

OEM Supplier Selection Goal Program, SS

Minimize $1000C^{+} + 100R^{+} + 10T^{+} - 0.001C^{-} - 0.001R^{-} - 0.001T^{-}$

Subject to $\sum_{s \in S(i)} y_{is} \geq 1,\ \forall i \in I,$

$$\sum_{i \in I} \sum_{s \in S(i)} c_{is} y_{is} + C^{-} - C^{+} = 5,$$

$$\sum_{i \in I} \sum_{s \in S(i)} y_{is}(-\ln(r_{is})) + R^- - R^+ = 0.89257,$$

$$\sum_{i \in I} \sum_{s \in S(i)} t_{is} y_{is} + T^- - T^+ = 18,$$

$$C^+, C^-, R^+, R^-, T^+, T^- \geq 0 ; y_{is} \in \{0,1\}.$$

This model was coded into GAMS and solved as a mixed-integer linear program (MILP) invoking CPLEX. The code template for SS is shown in Appendix B, where the user can fill in with the appropriate data. This model contains 22 variables (16 supplier selection variables and 6 deviation variables), and 8 equations. The execution time utilizing the NEOS Server was 0.002 seconds.

The GAMS solution to this model is depicted in Table 5 and shows that the optimal solution occurs when $y^*_{16} = y^*_{28} = y^*_{31} = y^*_{42} = 1$ and the rest of the y's are zero. This indicates that, according to the manufacturer's priorities, they will choose Supplier 6 for Task 1 (Airframe), Supplier 8 for Task 2 (Propulsion), Supplier 1 for Task 3 (Vehicle Subsystems), and Supplier 2 for Task 4 (Avionics).

Table 5. Manufacturer's Supplier Selection

	LOWER	LEVEL
1.2	.	.
1.6	.	1.000
1.10	.	.
2.6	.	.
2.8	.	1.000
3.1	.	1.000
3.3	.	.
3.5	.	.
3.8	.	.
4.1	.	.
4.2	.	1.000
4.4	.	.
4.6	.	.
4.7	.	.
4.8	.	.
4.9	.	.

As shown in Table 6 for the deviation variables, this results in a budget underage of $0.228M, or $228,000, a reliability overage of 0.943, and a time overage of two weeks. Note the reliability overage is actually considered a shortage due to the transformation discussed in setting up Equation (3) in SS development. These results suggest that the manufacturer was only able to meet, and in fact exceed, its first priority of cost. For their given budget/cost priority, the best they can do in terms of reliability is 0.943 (where optimal would be zero). Reliabilities are normally measured on a zero to one scale, but due to the linear transformation utilized in Equation (3) this value can exceed 1 because it is an additive value. To interpret these values, rather than evaluate the value itself, the magnitude of the deviation variable can be used as a proxy. If the actual reliability was desired, the analyst would have to go back to the data and calculate its value. However, for the purposes of goal attainment, suffice it to say that the manufacturer has not met its goal. Finally, given this supplier selection set, the manufacturer will be two weeks behind their desired due date.

Table 6. SS Deviation Variable Values

Deviation Variable	Value
C^-	0.228
R^+	0.943
T^+	2

Given this set of optimal suppliers to the manufacturer, the attacker's problem is then modeled by SS-I according to the data in Tables 3, 4 and 5 as well as their desired priorities. Again, the weights are assigned based on order of magnitude; here the interdictor gives equal preference to desired cost and damage levels.

Their SS-I model is formulated as follows:

Attacker's Supplier Selection Interdiction Goal Program, SS-I

Minimize $10000D_{attack}^{-}+10000C_{attack}^{+}-D_{attack}^{-}-C_{attack}^{-}+1000C^{+}+100R^{+}+10T^{+}$

Subject to $\sum_{s\in S(i)} y'_{is} \geq 1,\ \forall i \in I,$

$$\sum_{s\in S_{u^c}(i)} y'_{is} \leq \sum_{s\in S_u(i)} x_{is},\ \forall i \in I,$$

$$x_{is} \leq y'_{is},\ \forall i \in I,\ s \in S,$$

$$\sum_{s\in S(i)} (y'_{is} - x_{is}) \geq 1,\ \forall i \in I,$$

$$\sum_{i\in I}\sum_{s\in S_u(i)} c_{is}(y'_{is} - x_{is}) + \sum_{i\in I}\sum_{s\in S_{u^c}(i)} c_{is}(y_{is}) + C^{-} - C^{+} = 5,$$

$$\sum_{i\in I}\sum_{s\in S_u(i)} (y'_{is} - x_{is})(-\ln(r_{is})) + \sum_{i\in I}\sum_{s\in S_{u^c}(i)} (y'_{is})(-\ln(r_{is})) + R^{-} - R^{+} = -4\ln(0.80),$$

$$\sum_{i\in I}\sum_{s\in S_u(i)} t_{is}(y'_{is} - x_{is}) + \sum_{i\in I}\sum_{s\in S_{u^c}(i)} t_{is}(y'_{is}) + T^{-} - T^{+} = 18,$$

$$\sum_{i\in I}\sum_{s\in S(i)} c_attack_{is}\, x_{is} + C_{attack}^{-} - C_{attack}^{+} = 10,$$

$$\sum_{i\in I}\sum_{s\in S(i)} d_{is}\, x_{is} + D_{attack}^{-} - D_{attack}^{+} = 20,$$

$$y_{is} \in \{0,1\},\ x_{is} \in \{0,1\}\ \forall i \in I,\ s \in S(i),$$

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-}, D^{+}_{attack}, D^{-}_{attack}, C^{+}_{attack}, C^{-}_{attack} \geq 0.$$

where for the set $s \in S_u(i)$, $y^*_{16} = y^*_{28} = y^*_{35} = y^*_{42} = 1$ and are therefore the interdictable suppliers. Once again, the SS-I model was coded into GAMS and solved as a MILP (also shown in Appendix B). In SS-I, there are two sets of decision variables: the attacker's interdiction set, and the manufacturer's new decision based on the interdiction. Tables 7 and 8 show the GAMS output for these decision variables, respectively. In total, there are 42 variables (10 deviation variables, 16 supplier selection variables, and 16 interdiction variables) and 34 constraints. Execution time for SS-I in the NEOS Server is 0.001 seconds.

Table 7. Attacker's Interdiction Set

	LOWER	LEVEL	UPPER	MARGINAL
1.2	.	.	1.000	-8.000E+5
1.6	.	1.000	1.000	-4.010E+5
1.10	.	.	1.000	-6.000E+5
2.6	.	.	1.000	-9.000E+5
2.8	.	1.000	1.000	-3.016E+5
3.1	.	.	1.000	-3.014E+5
3.3	.	.	1.000	-7.000E+5
3.5	.	.	1.000	-3.000E+5
3.8	.	.	1.000	-3.000E+5
4.1	.	.	1.000	-1.000E+6
4.2	.	.	1.000	-3.012E+5
4.4	.	.	1.000	-2.000E+5
4.6	.	.	1.000	-6.000E+5
4.7	.	.	1.000	-8.000E+5
4.8	.	.	1.000	-9.000E+5
4.9	.	.	1.000	-6.000E+5

Table 8. Manufacturer's New Supplier Selection

	LOWER	LEVEL	UPPER	MARGINAL
1.2	.	.	1.000	1861.400
1.6	.	1.000	1.000	1024.300
1.10	.	1.000	1.000	1831.100
2.6	.	1.000	1.000	1886.000
2.8	.	1.000	1.000	1591.900
3.1	.	1.000	1.000	1382.100
3.3	.	.	1.000	1964.000
3.5	.	.	1.000	1730.100
3.8	.	.	1.000	2127.100
4.1	.	.	1.000	2074.100
4.2	.	1.000	1.000	1157.300
4.4	.	.	1.000	2139.900
4.6	.	.	1.000	2253.300
4.7	.	.	1.000	1803.900
4.8	.	.	1.000	2093.700
4.9	.	.	1.000	2197.600

From Table 7, the attacker's optimal interdiction target set is $x^*_{16} = x^*_{28} = 1$ which suggests the manufacturer will choose new suppliers for Tasks 1 and 2 (Airframe and Propulsion, respectively). Their optimal replacement choices for these tasks, from Table 8, are $y^*_{1,10} = y^*_{26} = 1$ while their original suppliers for Tasks 2 and 4 remain the same ($y^*_{31} = y^*_{42} = 1$). Therefore, the model suggests that if Supplier 6 is interdicted for Task 1 and Supplier 8 is interdicted for Task 2, given the knowledge of the manufacturers preferences, they are most apt to switch to Suppliers 10 and 6 for Tasks 1 and 2, respectively.

The new deviations variables are shown in Table 8, and denote the new under/over-achievements of the manufacturer and the effectiveness of the attacker's goals.

Table 9. SS-I Deviation Variable Values

Deviation Variable	Value
C^+	0.865
R^+	0.722
T^+	5
C^-_{attack}	4
D^-_{attack}	13

The interdiction of Suppliers 6 and 5 for Tasks 1 and 3 and replacement by Suppliers 10 and 1 increases the manufacturer's cost by \$0.637M (\$637,000) (i.e. ΔC^+ =0.865-0.228), and reliability decreases by 0.221 (ΔR^+ =0.943-0.722) (remember this is actually a *increase* in reliability due to the transformation, so it is less than ideal for the attacker), but the time is delayed by another three weeks (ΔT^+ =5-2). The attacker is able to stay under budget by \$4 and is under its damage goal of 20 by 13 points, but based on the possible supplier set given, the damage is maximized.

SCIM: SCNF and SCNF-I

One way to utilize SCNF and SCNF-I in conjunction with SS-I is to model the flow of the materials (or systems, components, suppliers, and so forth) for the supplier identified as vulnerable in SS-I. In SS-I, two systems' suppliers were identified as vulnerable, one for the Airframe and the other for the Propulsion. Suppose the supply chain network flow of materials in order to produce an Airframe appears as shown in Figure 16.

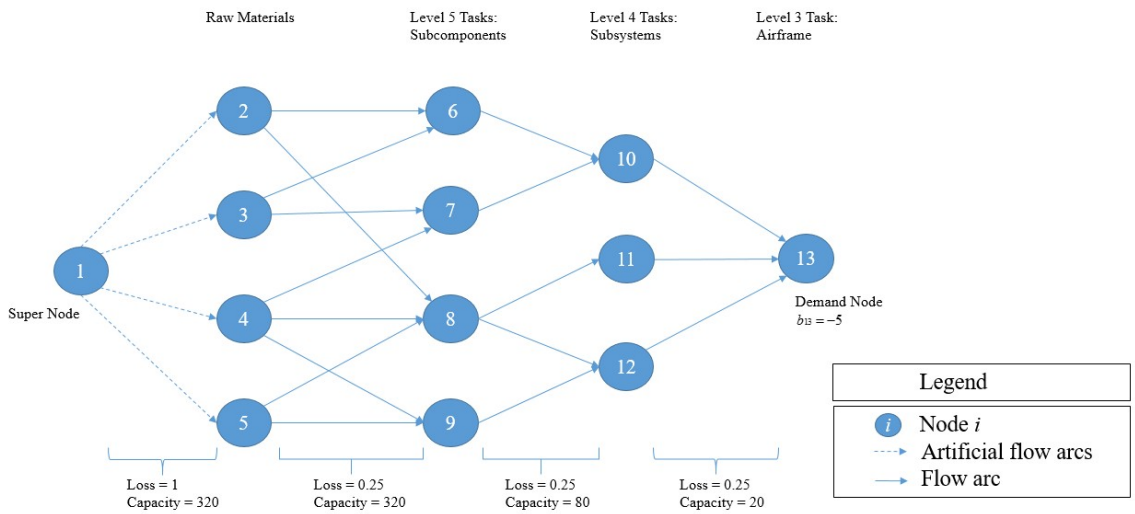

Figure 16. Illustrative Supply Chain Network Flow

The supply chain consists of Nodes 2 to 13. Node 1 is introduced as a super node with artificially large supply that facilitates the network flow formulation. For this reason, the arcs flowing out of the super node are dashed to denote that material is not actually flowing through these arcs, but rather it embodies the decision to choose one of the nodes to which it enters (i.e., 2, 3, 4, or 5). The loss across these arcs is therefore 1 because no loss is incrued. However, the loss of 0.25 on the remaining arcs represents the assembling of materials into parts from each node to the next. A loss of 0.25 means that four parts from a previous node is required to make one part at the current node. The Airframe manufacturer, represented by Node 13, must meet a demand of five airframes. The data for a manufacturer and attacker is shown in Table 10 with associated goals in Table 11.

Table 10. SCNF/SCNF-I Data

Nodei	Nodej	Costij	Re lij	Time ij	Lossij	Uij	AttackCostij	Destructij	Bi
1	2	0	0.010	0	1	320	10000	0	1E+12
1	3	0	0.010	0	1	320	10000	0	0
1	4	0	0.010	0	1	320	10000	0	0
1	5	0	0.010	0	1	320	10000	0	0
2	6	19.11	0.846	4	0.25	320	89.93	7	0
2	8	26.05	0.071	3	0.25	320	102.9	10	0
3	6	26.85	1.100	3	0.25	320	172.2	9	0
3	7	31.41	0.111	5	0.25	320	145.3	6	0
4	7	23.98	0.155	2	0.25	320	124.5	8	0
4	8	28.95	0.801	3	0.25	320	112.8	9	0
4	9	20.5	1.059	3	0.25	320	91.51	3	0
5	8	20.75	0.918	3	0.25	320	111.7	5	0
5	9	23.85	0.869	3	0.25	320	102.9	2	-5
6	10	51.73	1.079	2	0.25	80	118.5	9	
7	10	51.2	0.328	2	0.25	80	120.2	6	
8	11	59.8	1.296	5	0.25	80	188.9	9	
8	12	40.8	0.293	3	0.25	80	60.37	9	
9	12	54.33	1.282	1	0.25	80	114	3	
10	13	101.79	1.160	2	0.25	20	102.7	5	
11	13	123.17	3.126	1	0.25	20	143.5	8	
12	13	112.25	0.251	1	0.25	20	124	6	

Table 11. SCNF and SCNF-I Goals

SCNF Manufacturer Goals			**SCNF-I Attacker Goals**		
OEM Cost, B	**Reliability,** P	**OEM Time (days),** D	**Interdiction Resource Limit,** r	**Damage,** D_{goal}	**Interdiction Cost,** C_{goal}
$13,000	(0.80) 112	1095	50	500	$5,000

The manufacturer's cost is based off of historical data—they estimate that each Airframe costs $2.6M. The time is also based off of recent contracts and they estimate a total time frame of 3 years to develop these airframes. Finally, their reliability goal is

determined using equation (32), with an estimation of 500 components necessary to build the airframe each with a reliability goal of 80%

$$P = -500 \ln(0.80) = 112 \tag{32}$$

Given this data, the Airframe manufacturer wishes to determine the optimal flow of materials in order to reach their demand. If their priorities are again cost, reliability, and time in that order, with an illustrative order of magnitude weighting system of W_1 =1,000, W_2 =10, W_3 =1, ε_1 -10, ε_2 =-1, and ε_3 = 0.001, the manufacturer's SCNF is shown:

Supply Chain Network Flow Goal Program

Minimize $1000C^{+} + 10R^{+} + T^{+} - 10C^{-} - R^{-} - 0.1T^{-}$

Subject to

$$\sum_{\{j:(i,j)\in A\}} f_{ij} - \sum_{\{j:(j,i)\in A\}} l_{ji} f_{ji} \le b_i, \ \forall i \in N,$$

$$0 \le f_{ij} \le u_{ij}, \quad \forall (i,j) \in A,$$

$$\sum_{i,j\in A} c_{ij} f_{ij} + C^{-} - C^{+} = 13000,$$

$$\sum_{i,j\in A} f_{ij}(-\ln(r_{ij})) + R^{-} - R^{+} = 112,$$

$$\sum_{i,j\in A} t_{ij} f_{ij} + T^{-} - T^{+} = 1095,$$

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-} \ge 0.$$

The SCNF model was coded into GAMS (see Appendix C) and solved invoking CPLEX using integer linear programming. The model consists of 28 variables (1 objective function variable, 21 flow variables, and 6 deviation variables) and 37 constraints. The total run execution time was 0.002 seconds. A visual of the optimal flow of materials is

shown in Figure 17. In order to meet demand of 5 airframe, the manufacturer must utilize four suppliers in total (2, 5, 8, and 12).

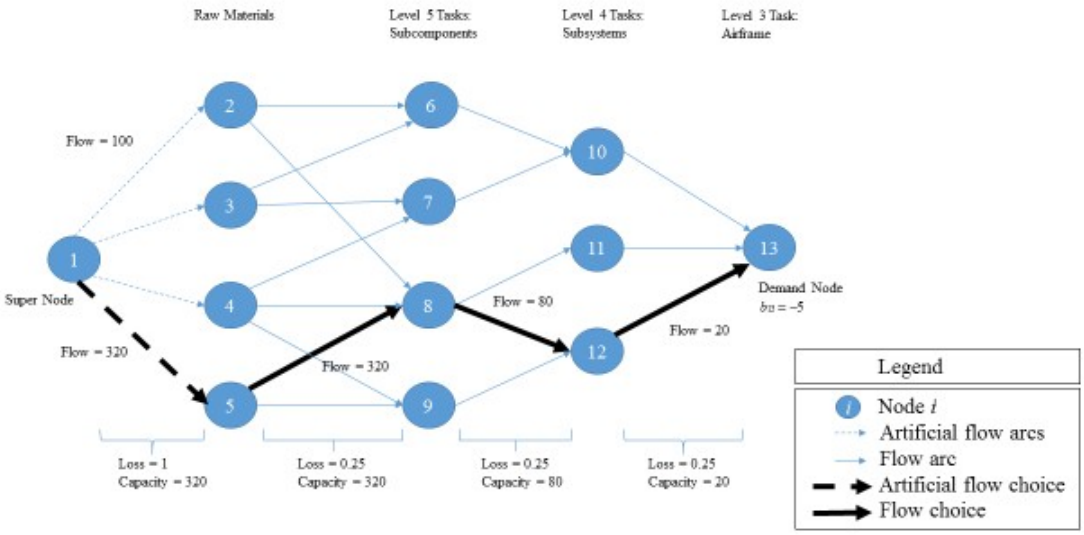

Figure 17. Optimal SCNF

As shown in Table 12, the manufacturer can be under budget by $531 (or $513,000 in correct units). With this budget, however, they will be over their reliability goal by 213.505 (but this is actually under its goal due to the transformation). Given that time is their last priority, the manufacturer will be behind its due date by 125 days. They can achieve this by purchasing 320 units of raw material from Supplier 5. These 320 units are sent to Supplier 8 and assembled into 80 parts (320*0.25). Supplier 8 sends these 80 parts to Supplier 12, who assembles them into 20 parts (80*0.25), and finally sends them to the manufacturer to assemble the products into 5 airframes (20*0.25).

Table 12. SCNF Deviation Variable Values

Deviation Variable	Value
C^-	531
R^+	213.505
T^+	125

Now that the attacker has determined what a manufacturer's network flow looks like, the can utilize the SCNF-I to determine an optimal interdiction. Their goals and constraints are shown in Table 11. Assuming the attacker also uses a order of magnitutude weighting, their SCNF-I model appears as follows:

Supply Chain Network Flow-Interdiction Goal Program

Minimize $10000C^+_{attack} + 10000D^-_{attack} - 10C^-_{attack} - 10D^+_{goal} + 1000C^+ + 10R^+ + T^+$

Subject to

$$\sum_{j:(i,j)\in A_u} (f'_{ij} - x_{ij}) - \sum_{j:(j,i)\in A_u} l_{ji}(f'_{ji} - x_{ji}) + \sum_{j:(i,j)\in A_{u^c}} (f'_{ij}) - \sum_{j:(j,i)\in A_{u^c}} l_{ji}(f'_{ji}) \le b_i, \forall i \in N,$$

$$0 \le x_{ij} \le f'_{ij} \le u_{ij}, \quad \forall (i,j) \in A,$$

$$\sum_{j\in A_u(i)} (f'_{ij} - x_{ij})(-\ln(r_{ij})) + \sum_{j\in A_{u^c}(i)} (f'_{ij})(-\ln(r_{ij})) + R^- - R^+ = 112,$$

$$\sum_{j\in A_u(i)} c_{ij}(f'_{ij} - x_{ij}) + \sum_{j\in A_{u^c}(i)} c_{ij}(f'_{ij}) + C^- - C^+ = 13000,$$

$$\sum_{j\in A_u(i)} t_{ij}(f'_{ij} - x_{ij}) + \sum_{j\in A_{u^c}(i)} t_{ij}(f'_{ij}) + T^- - T^+ = 1095,$$

$$\sum_{(i,j)\in A} f'_{ij} x_{ij} + C_{attack}^{-} - C_{attack}^{+} = 5000,$$

$$\sum_{(i,j)\in A} d_{ij} x_{ij} + D_{attack}^{-} - D_{attack}^{+} = 500,$$

$$\sum_{(i,j)\in A} x_{ij} \leq 50,$$

$$C^{+}, C^{-}, R^{+}, R^{-}, T^{+}, T^{-}, C^{+}_{attack}, C^{-}_{attack}, D^{+}_{attack}, D^{-}_{attack} \geq 0.$$

This SCNF-I was likewise coded to generate the model and solved by GAMS invoking CPLEX (also in Appendix III). SCNF-I has a total of 53 variables (1 objective function variable, 21 flow variables, 21 interdiction variables, and 10 deviation variables) and 61 constraints. The total execution time was 0.001 seconds.

With the resources to interdict 50 units of flow, the optimal interdiction is shown in Figure 18 with the residual network from SCNF. The attacker's optimal interdiction occurs by interdicting 50 units of subcomponents over arc (8,12), shown in red in Figure

18. This interdiction causes the creation of two whole new paths in order for demand to be met, shown by the green arcs in Figure 18.

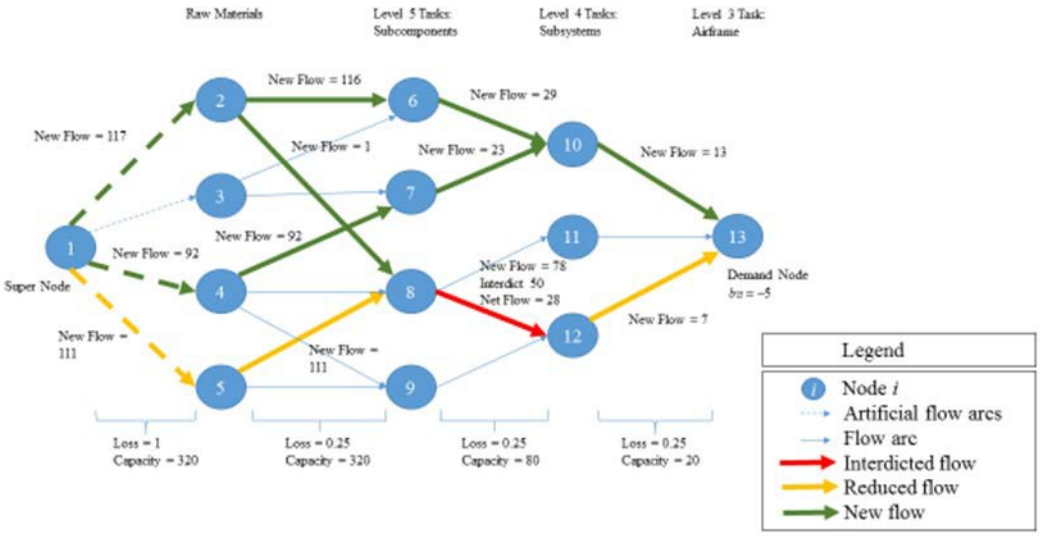

Figure 18. Optimal SCNF-I

Therefore, by interdicting 50 units from arc (8,12), the attacker has now forced the manufacturer to seek other suppliers. Rather than only utilizing three suppliers (5, 8, and 12), the manufacturer must also utilize suppliers 2, 4, 6, 7, and 10 to meet demand, because their original flow across suppliers 5, 8, and 12 has been decreased due to interdiction. This interdiction results in Table 13 show the deviation variables in the SCNF-I model.

Table 13. SCNF-I Deviation Variable Values

Deviation Variable	Value
C^+	1.41
R^+	169.496
T^+	110
C^-_{attack}	1981.5
D^-_{attack}	50

The interdictor has significantly affected the manufacturer's cost. Whereas originally they were under budget, because they had to include more suppliers than originally intended, they are now forced to execute over their budget. Their reliability has improved, but they are still nowhere near their goal. While their time has improved by 15 days, they are still behind schedule, and an improvement in time is not given high priority assuming it is still their last priority, so the attacker is willing to accept this. The attacker can achieve this interdiction under their budget, and just short of their damage goal as well. In fact, given their target options and resource restrictions, they have achieved optimal interdiction (referring to Table 10, arc (8,12) scores a "9" in damage—which is the highest value given the original SCNF selection by the manufacturer).

While the values given by the deviation variables in the interdiction models provide insight into a theoretical interdiction on the supply chain of interest, the real value of the interdiction models lies in the target identification they provide. These targets can then be utilized by an attacker in order to strategize how to carry out an interdiction.

SCIM: HOT

Based upon the targets identified in the two interdiction models, a notional HOT is developed.

Step 0. The attacker commander defines the mission as follows: the attacker wishes to immediately prevent or delay superior UAS technology from reaching an enemy who is known to be seeking a specific UAS system. Because the enemy resides in a highly politicized area, rules of engagement (ROEs) state that civilian casualties be minimized as well as collateral damage. The HOT is shown in Figure 19 and discussed thereafter.

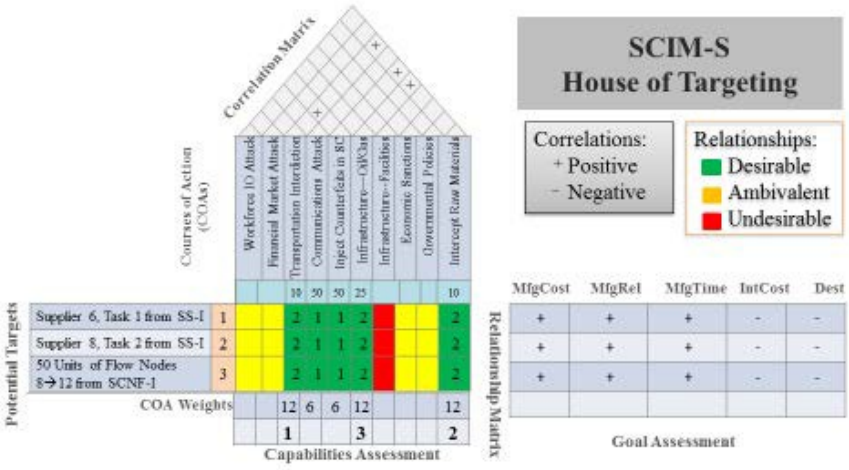

Figure 19. HOT Illustrative Example

Step 1. The targets in the left column denote the targets that were directly identified by the interdiction models, SS-I and SCNF-I in the previous phase.

Step 2. The target from SCNF-I is deemed most important and given an inverse ranking of 3, followed by the two targets identified by SS-I ranked 2 and 1. The SCNF-I target is given a higher ranking due to its over-achievement of the damage (destruction) goal.

Step 3. The Goal Assessment matrix is filled in with the associated deviation variables. The signs are taken directly from Tables 9 and 13. For all targets, C^+, R^+, and $T^+ \geq 0$ causing an overage in budget, schedule, and reliability (keep in mind that, due to the transformation of reliability, an overage is actually interpreted as a detriment rather than a good quality). For all of the targets, in both in SS-I and SCNF-I, the attacker is under both their interdiction budget and their damage goal.

Step 4. The COAs developed are shown in the top columns of the HOT. The COAs were developed according to the notional mission objective, in conjunction with considerations to the common supply chain risks developed in Figure 5 as well as deliberation considering effects based operations and the Joint Targeting Doctrine.

Step 5. The correlation matrix has four "+" signs, symbolizing the positive relationship between the following COA pairs: transportation interdiction with raw materials interdiction, transportation interdiction with inject counterfeits into SC, inject counterfeits into SC with raw materials interdiction, and infrastructure—oil/gas with raw materials interdiction. The positive relationship among these pairs implies that, if possible, performing these COAs in conjunction could be mutually beneficial and achieve the effects stated by the mission more effectively than if performed separately.

Step 6. The relationship matrix is filled with their colors based on their perceived feasibility and effectiveness. The Infrastructure—Facilities COA is filled in as red

because the ROEs specifically prohibit collateral damage and the targets are all in highly congested areas of civilians and other restricted targets. The COAs filled in completely as yellow are Workforce information operations (IO) attack, financial market attack, economic sanctions, and governmental policies. This is due to the fact that such attacks would take a long time to plan and put into effect and does not support the mission of immediate prevention. The COAs deemed desirable in supporting the mission and feasible are Transportation Interdiction, Communications Attack, Inject Counterfeits in the SC, Infrastructure—Oil/Gas, and Raw Materials Interdiction. They are given a green assignment, but also a score. A score of "1" denotes an interdiction with a longer time-frame to implement and subsequently reap the benefits of the effects, while a score of "2" denotes an interdiction that can be carried out and cause effects immediately. As shown, a communications attack and injecting counterfeits into SC score a "1" while transportation interdiction, infrastructure—oil/gas, and raw materials interdiction score a "2" based on the timing of their implementation and effects.

Step 7. Targets are developed only for those COAs deemed desirable in step 6. The target analysis determined that a transportation interdiction, or likewise a interception of raw materials, of only 10% of materials would result in the desired objectives, while a communications attack on 50% of the communications network, 50% injection of counterfeits, or interception of 50%, or a destruction of 25% of the infrastructure for oil/gas would achieve the same success.

Step 8. A weighted sum of the targets' ranks and its relationship score is used to determine the COA weights (again, using weights developed in an appropriate fasion).

For example, the COA weight for Transportation Interdiction is 1*2+2*2+3*2=12. The rest of the weights are determined accordingly.

Step 9. The HOT is now completely built. The COAs with the largest weights are Transportation Interdiction, Infrastructure—Oil/Gas, and Intercept Raw Materials. Because the SCNF-I target is ranked as most important and has the best goal assessment, the first recommended COA is to conduct a Transportation Interdiction on the target identified in SCNF-I. This is denoted by a "1" in the Capabilities Assessment row in the bottom of HOT. Because the COA Intercepting Raw Materials is also a complementary COA to Transportation Interdiction, that is recommended as a second option, or possibly an augmentation. Of course, the final decision will be made after an equity review at the discretion of the commander.

4.3 Key Considerations

This illustrative example effectively demonstrates the process of the SCIM phases and how the models work, and how they are all tied together. Because it is a notional example and based on synthetic data, and based on the nature of the models themselves, there are some key considerations to point out.

While the models are setup as goal programs, this feature is not required. All of the goal constraints might have been expressed as hard constraints (with strict inequalities); the models are flexible enough to handle such considerations. If goal programming is to be used, the determination of the goals and their aspiration levels is an important factor in the effectiveness of the models. Goals can be based on historical data,

best or worst case scenarios, or other methods of estimation that lend themselves to the problem.

Goal programs are suited for multiple objectives, but this is also not a requirement and the models are still valid with single objective functions. However, if goal programming is utilized, the determination of the weights is another important factor. Whether they are preemptive or numerical, it is important that they accurately reflect the decision maker's priorities and are developed using a consistent numerical method.

While in the examples and formulations we used cost, reliability, and time for the manufacturer's priorities and cost and damage for the attacker's, the definition of the priorities are completely decision maker dependent and also rely upon the availability of data. The models are not limited to these attributes, but rather can be tailored to the supply chain at hand.

Lastly, although this research focused on UAS supply chains, the models developed are applicable to any supply chain and provide flexibility to model any level of fidelity that the data can support.

4.4 Summary

The phases of SCIM offer decision making support in the targeting development phase of the Joint Targeting Process. The first phase of SCIM allows an attacker to frame or estimate their enemies' supply chain design. If the design is already known, the attacker can begin the SCIM process with the second phase. The flexibility of the goal programming interdiction models provide the decision maker the ability to explore different views of the supply chain, whether it be from a supplier selection or network

flow perspective, and determine optimal interdiction targets. The last phase of SCIM ties together the targets identified by the models with targeting doctrine. This allows decision makers to incorporate what they already know—doctrine—with the insights provided by the models.

5. Conclusions and Recommendations

5.1 Chapter Overview

This chapter provides the research conclusions derived from developing the supply chain interdiction methodology. Section 5.2 provides a summary of the research questions. Section 5.3 discusses the significance of the models developed and their applicability to operational supply chain design and interdiction. Finally, Section 5.4 suggests possible areas of future research to expand upon the models developed in this study.

5.2 Conclusions of Research

This study developed a supply chain interdiction methodology (SCIM) consisting of three phases. Each phase of SCIM was designed to answer the research questions posed in Chapter 1.

Research Questions Answered

1. How can an analyst model optimal UAS supply chain design?

   Important decisions during the design of a supply chain include which suppliers to choose and how to integrate the flow of materials between all suppliers in order to make a product. These decisions are be modeled utilizing goal programming to reflect a decision maker's priorities. Specifically, the supplier selection decision is be modeled as a simple assignment problem, matching suppliers to tasks, with the incorporation of goals that must set by the manufacturing decision maker. Likewise, the flow of materials is be modeled as a classic network flow model with the incorporation of the goals set by the manufacturing decision maker.

2. How can an analyst model the best UAS supply chain interdiction?

   Models intended to interdict a supply chain expand upon supply chain design models. This occurs by taking the optimal design models and introducing new decision variables and goals to represent the attacker's perspective. The attacker's objective is given more priority, but the manufacturer's objective is still included so that the model not only defines optimal interdiction but suggests how the manufacturer may act to overcome the interdiction.

3. How can a decision maker strategize UAS supply chain interdiction?

   Building on the House of Quality, a targeting screening matrix that incorporates all of the insights provided by the interdiction models with targeting doctrine is developed to provide a decision making framework with which to utilize the models and develop an interdiction plan and assessment.

5.3 Significance of Research

As discussed in Chapter 2, there is a large amount of research in the area of goal programming applied to supplier selection and generalized network flow models. There is also a vast amount of network interdiction models. As far as we can tell, this study is the first attempt to incorporate all of these concepts and integrate goal programming techniques with supply chain interdiction.

The flexibility of the models provide the decision maker with a vast amount of options in their employment of the methodology. The suite of models provides the supply chain designer or interdictor the ability to consider vital supply chain decisions from two points of view: supplier selection and flow of materials. The models are expandable and

can represent any level of hierarchy and fidelity of the supply chain to include any tier of suppliers or level of tasks. For example, the models can be applied on a macroscopic level to consider only prominent suppliers or large systems, or they can be applied on a microscopic level and hone in on a particular system's supply chain of components and materials. This idea was demonstrated in the illustrative example wherein SS-I was utilized to view the supply chain from a macroscopic level to identify vulnerable Level 3 tasks suppliers, and SCNF-I was used on a microscopic level to model the supply chain interdiction of the specific suppliers network flow identified by SS-I.

For an interdictor employing the models, the supply chain network flow interdiction model supports a commander's deliberate planning for interdiction and allows the opportunity to build and investigate different target cut sets and cut set trees.

Flexibility is also inherent in the goal programming nature of the models. Decision makers are free to define and prioritize any set of goals. Sensitivity analysis on these priorities will provide even greater insight to the attainment of their goals.

5.4 Recommendations for Future Research

Because this research is a new application of goal programming and supply chain network interdiction, there are many areas to consider for future research. One area particular area of interest for the interdiction component is to expand upon supply chain network flow model and transform the conservation of flow constraint for the demand node into a goal constraint. This would allow an interdictor to identify how much material they must interdict in order to cause a certain desired effect on the manufacturer's demand.

Another suggested approach is to explore all of the models' applicability to supply chains with real, rather than notional, data. This can be accomplished via case studies, particularly for the supply chain design models (SS and SCNF). The application of SS and SCNF can be compared with other supply chain models, like those discussed in Section 2.6, to validate the approach.

Finally, a robust sensitivity analysis on the manufacturer's and attacker's priorities, weights, and aspiration levels in all models is an area of research that would provide great insight to those wishing to utilize the interdiction models. As discussed in Section 4.3, the setting of these values is key in determining an optimal solution. If misspecified or misunderstood, the solution can lead to an outcome that was not originally intended. A study that delved into the interactions between priorities, weights, and aspiration levels would facilitate a greater understanding of the models and lead to better use of them.

Appendix A: Excerpt from MIL-STD-881C

Table 14. Work Breakdown Structure for UAV Systems

WBS #	Level 1	Level 2	Level 3	Level 4
1.0	UAV System			
1.1		Air Vehicle		
1.1.1			Airframe	
1.1.1.1				Airframe Integration, Assembly, Test and Checkout
1.1.1.2				Fuselage
1.1.1.3				Wing
1.1.1.4				Empennage
1.1.1.5				Nacelle
1.1.1.6				Other Airframe Components 1…n (Specify)
1.1.2			Propulsion	
1.1.3			Vehicle Subsystems	
1.1.3.1				Vehicle Subsystems Integration, Assembly, Test and Checkout
1.1.3.2				Flight Control Subsystem
1.1.3.3				Auxiliary Power Subsystem
1.1.3.4				Hydraulic Subsystem
1.1.3.5				Electrical Subsystem
1.1.3.6				Environmental Control Subsystem
1.1.3.7				Fuel Subsystem
1.1.3.8				Landing Gear
1.1.3.9				Rotor Group
1.1.3.10				Drive System
1.1.3.11				Vehicle Subsystems Software Release 1…n
1.1.3.12				Other Vehicle Subsystems 1…n (Specify)
1.1.4			Avionics	
1.1.4.1				Avionics Integration, Assembly, Test and Checkout
1.1.4.2				Communication/Identification
1.1.4.3				Navigation/Guidance
1.1.4.4				Automatic Flight Control
1.1.4.5				Health Monitoring System
1.1.4.6				Stores Management
1.1.4.7				Mission Computer/Processing
1.1.4.8				Fire Control
1.1.4.9				Avionics Software Release 1…n
1.1.4.10				Other Avionics Subsystems 1…n (Specify)
1.1.5			Auxiliary Equipment	
1.1.6			Air Vehicle Software Release 1…n	
1.1.7			Air Vehicle Integration, Assembly, Test and Checkout	
1.2		Payload		
1.2.1			Payload Integration, Assembly, Test and Checkout	
1.2.2			Survivability Payload 1...n (Specify)	
1.2.3			Reconnaissance Payload 1...n(Specify)	
1.2.4			Electronic Warfare Payload 1...n (Specify)	
1.2.5			Armament/Weapons Delivery Payload 1..N (Specify)	
1.2.6			Payload Software Release 1…n	
1.2.7			Other Payload 1…n (Specify)	
1.3		Ground/Host Segment		
1.3.1			Ground Segment Integration, Assembly, Test and Checkout	
1.3.2			Ground Control Systems	
1.3.3			Command and Control Subsystem	
1.3.4			Launch and Recovery Equipment	

1.3.5			Transport Vehicles
1.3.6			Ground Segment Software Release 1…n
1.3.7			Other Ground/Host Segment 1…n (Specify)
1.4	UAV Software Release 1…n		
1.5	UAV System Integration, Assembly, Test and Checkout		
1.6	System Engineering		
1.7	Program Management		
1.8	System Test and Evaluation		
1.8.1			Development Test and Evaluation
1.8.2			Operational Test and Evaluation
1.8.3			Mock-ups/System Integration Labs (SILs)
1.8.4			Test and Evaluation Support
1.8.5			Test Facilities
1.9	Training		
1.9.1			Equipment
1.9.2			Services
1.9.3			Facilities
1.10	Data		
1.10.1			Technical Publications
1.10.2			Engineering Data
1.10.3			Management Data
1.10.4			Support Data
1.10.5			Data Depository
1.11	Peculiar Support Equipment		
1.11.1			Test and Measurement Equipment
1.11.2			Support and Handling Equipment
1.12	Common Support Equipment		
1.12.1			Test and Measurement Equipment
1.12.2			Support and Handling Equipment
1.13	Operational/Site Activation		
1.13.1			System Assembly, Installation and Checkout on Site
1.13.2			Contractor Technical Support
1.13.3			Site Construction
1.13.4			Site/Ship/Vehicle Conversion
1.13.5			Sustainment/Interim Contractor Support
1.14	Industrial Facilities		
1.14.1			Construction/Conversion/Expansion
1.14.2			Equipment Acquisition or Modernization
1.14.3			Maintenance (Industrial Facilities)
1.15	Initial Spares and Repair Parts		

Appendix B: GAMS Code for Supplier Selection and Supplier Selection-Interdiction Models

```
$inlinecom /* */
*offdigit
*$offsymxref offsymlist

*   option
*      solprint = off,
*      sysout = off;

*SUPPLIER SELECTION

Set
i   tasks/ INSERT DATA / ;
*alias(i,j)

Set
j possible_suppliers/ INSERT DATA /;

Set
suppliers(i,j) task_suppliers / INSERT DATA /;

Parameters
cost(i,j) cost to supply task(i) from supplier(j) / INSERT DATA /,

time(i,j) lead time to supply task(i) from supplier(j) / INSERT DATA /,

reliability(i,j) reliability to supply task(i) from supplier(j) / INSERT DATA /,

interdiction_cost(i,j) cost to interdict task(i) from supplier(j) / INSERT DATA /,

damage(i,j) damage to disrupt supply task(i) from supplier(j) / INSERT DATA /;

Scalars
CostGoal                Manufacturers budget goal
ReliabilityGoal                 Manufacturers quality goal
TimeGoal                Manufacturers time goal
Variables
z       objective function;
Binary Variables
y(i,j)    supplier choice;
Positive Variables
```

```
Cplus   "Over Deviation of Cost Goal"
Cminus          "Under Deviation of Cost Goal"
Rplus   "Over Deviation of Reliability Goal"
Rminus          "Under Deviation of Reliability Goal"
Tplus   "Over Deviation of Time Goal"
Tminus          "Under Deviation of Time Goal";

CostGoal = INSERT DATA
ReliabilityGoal = INSERT DATA
TimeGoal = INSERT DATA

Equations
      Obj           first priority objective function
      ChooseOne(i)     Choose one supplier
      Budget        Budget or Cost goal
      ReliabilityG        Rel goal
      TaskLT                 Time Goal;

            Obj..             z=e= INSERT DATA ;
            ChooseOne(i)..     sum(j,y(i,j)$suppliers(i,j))=e=1;
            Budget..           sum(suppliers(i,j),cost(i,j)*y(i,j))+CMinus-Cplus=e=CostGoal;
            ReliabilityG..     sum(suppliers(i,j),reliability(i,j)*y(i,j))+RMinus-
Rplus=e=ReliabilityGoal;
            TaskLT..          sum(suppliers(i,j),time(i,j)*y(i,j))+Tminus-Tplus=e=TimeGoal;

            Model SS / Obj, ChooseOne, budget, ReliabilityG, TaskLT /;

            Solve SS using mip minimizing z ;

*************************************************************************
*******
*************************************************************************
*******
*************************************************************************
*******

*SUPPLIER SELECTION-INTERDICTION

            Variables
              zz        objective function;
              Positive Variables
          Cattackplus    "Over Deviation of Interdiction Cost Goal"
          Cattackminus "Under Deviation of Interdiction Cost Goal"
          Dattackplus    "Over Deviation of Damage Goal"
          Dattackminus "Under Deviation of Damage Goal";
```

```
        Binary Variables
          x(i,j)    interdiction choice
          ynew(i,j) mfg new choice;
        Parameters
          Iu(i,j)        indicator for u current supplieri for taskj (ij)
       Cgoal      interdiction goal
       Dgoal      destruction interdiction goal;

      Scalar
          r   Number disruptions allowed;

*Parameter definition
          r = INSERT DATA
          Iu(i,j) = y.l(i,j);
     Cgoal = INSERT DATA
     Dgoal = INSERT DATA

          Equations
          Obj2          objective function
          ChooseOne2(i)      Choose one supplier
          ChooserInt(i)      Proxy suppliers
          IfThen(i)          If interdicted mfg chooses another
          XltY(i,j)          X must be less than Y
          Disrupt                  choose r suppliers to target
          Budget2                  Budget or Cost goal
          Reliability2Rel goal
          TaskLT2                  Time Goal
        InterdictionCost    Cost to Interdict
        DamageGoal    Interdiciton damage goal;

        Obj2..                     zz=e= INSERT DATA;
        ChooseOne2(i)..      sum(j,ynew(i,j)$suppliers(i,j))=g=1;
        ChooserInt(i)..      sum(j,ynew(i,j)$suppliers(i,j)-x(i,j)$suppliers(i,j))=g=1;
        IfThen(i)..          sum(j,(1-
Iu(i,j))*ynew(i,j)$suppliers(i,j))=l=sum(j,(Iu(i,j)*x(i,j)$suppliers(i,j)));
        XltY(i,j)..          x(i,j)$suppliers(i,j)=l=ynew(i,j)$suppliers(i,j);
        Disrupt..       sum(suppliers(i,j),Iu(i,j)*x(i,j))=l=r;
        Budget2..           sum(suppliers(i,j),cost(i,j)*((Iu(i,j)*(ynew(i,j)-x(i,j)))+(1-
Iu(i,j))*ynew(i,j)))+CMinus-Cplus=e=CostGoal;
        Reliability2..       sum(suppliers(i,j),reliability(i,j)*((Iu(i,j)*(ynew(i,j)-
x(i,j)))+(1-Iu(i,j))*ynew(i,j)))+RMinus-Rplus=e=ReliabilityGoal;
        TaskLT2..           sum(suppliers(i,j),time(i,j)*((Iu(i,j)*(ynew(i,j)-x(i,j)))+(1-
Iu(i,j))*ynew(i,j)))+TMinus-Tplus=e=TimeGoal;
```

```
        InterdictionCost..
sum(suppliers(i,j),interdiction_cost(i,j)*x(i,j)$suppliers(i,j))+Cattackminus-
Cattackplus=e=Cgoal;
        DamageGoal..
sum(suppliers(i,j),damage(i,j)*x(i,j)$suppliers(i,j))+Dattackminus-Dattackplus=e=Dgoal;


Model SSI / Obj2,ChooseOne2, ChooserInt, IfThen, XltY, Disrupt, Budget2,
Reliability2, TaskLT2, InterdictionCost, DamageGoal /;

Solve SSI using mip minimizing zz ;
```

Appendix C: GAMS Code for Supply Chain and Supply Chain Network Flow-Interdiction Models

```
$inlinecom /* */
*offdigit
*$offsymxref offsymlist

*   option
*      solprint = off,
*      sysout = off;


Set
i nodes/ INSERT DATA HERE / ;
alias(i,j);
Set
arcs(i,j)   network_arcs  / INSERT DATA HERE /;

Parameters
cost(i,j)  cost to supplier / INSERT DATA HERE /,
reliability(i,j) reliability of transportation for (i) from (j) / INSERT DATA HERE /,
time(i,j) lead time to supply (i) to (j) / INSERT DATA HERE /,
interdiction_cost(i,j) cost to interdict (i) to (j) / INSERT DATA HERE  /,
damage(i,j) damage to disrupt  (i) to (j) / INSERT DATA HERE /,
loss(i,j) loss from  (i) to (j) / INSERT DATA HERE  /,
u(i,j) upper limit from (i) to (j) / INSERT DATA HERE /,
b(i) demand at node i / INSERT DATA HERE  /;

Scalars
CostGoal                Manufacturers budget goal
ReliabilityGoal                 Manufacturers quality goal
TimeGoal                Manufacturers time goal;

CostGoal =  INSERT DATA HERE ;
ReliabilityGoal = INSERT DATA HERE ;
TimeGoal =  INSERT DATA HERE ;

Variables
    z        objective function;
```

```
Positive Variables
flow(i,j)    flow per arc
Cplus   "Over Deviation of Cost Goal"
Cminus          "Under Deviation of Cost Goal"
Rplus   "Over Deviation of Reliability Goal"
Rminus          "Under Deviation of Reliability Goal"
Tplus   "Over Deviation of Time Goal"
Tminus          "Under Deviation of Time Goal";;

Equations

    Obj             objective function
    ConsOfFlow(i)    conservation of flow
          Budget        Budget or Cost goal
      ReliabilityG        Rel goal
      TaskLT                  Time Goal
          FlowLimit(i,j) Upper bound on flow;

          Obj..             z=e= INSERT DATA HERE  ;
          ConsOfFlow(i)..        sum(j,flow(i,j)$arcs(i,j))-
sum(j,loss(j,i)$arcs(j,i)*flow(j,i)$arcs(j,i))=l=b(i);
          Budget..          sum(arcs(i,j),cost(i,j)*flow(i,j))+CMinus-Cplus=e=CostGoal;
          ReliabilityG..     sum(arcs(i,j),reliability(i,j)*flow(i,j))+RMinus-
Rplus=e=ReliabilityGoal;
          TaskLT..          sum(arcs(i,j),time(i,j)*flow(i,j))+Tminus-Tplus=e=TimeGoal;
          FlowLimit(i,j)..          flow(i,j)$arcs(i,j)=l=u(i,j)$arcs(i,j);

   Model SCNF / Obj, ConsOfFlow, Budget, ReliabilityG, TaskLT, FlowLimit /;

   Solve SCNF using mip minimizing z ;

*************************************************************************
*******
*************************************************************************
*******
*************************************************************************
*******THIS MODEL IS AN INDICATOR MODEL TO IDENTIFY CURRENT
FLOW PATH
   Variables
     zz        objective function;



Binary Variables
```

```
    Iu(i,j)   binary proxy for current flow;


Positive Variables
Holder(i,j);

Scalar
    BigM  big M;

*Scalar Definition

BigM = 1000000;

Parameters
current(i,j);

*Parameter Definition
current(i,j)=flow.l(i,j);

Equations
ObjI
IfThen2;

   ObjI.. zz=e=sum(arcs(i,j),Iu(i,j));

   IfThen2(i,j).. BigM*(Iu(i,j)$arcs(i,j))=g=current(i,j)$arcs(i,j);

Model BinaryModel/ ObjI, IfThen2 /;

   Solve BinaryModel using mip minimizing zz ;

*************************************************************************
*******
*************************************************************************
*******

*************************************************************************
*******

   Variables
    zzz        objective function;

Positive Variables
    newflow(i,j)  suppliers next move
```

```
    y(i,j)    interdiction arc choice
    Cattackplus"Over Deviation of Interdiction Cost Goal"
   Cattackminus        "Under Deviation of Interdiction Cost Goal"
   Dattackplus         "Over Deviation of Damage Goal"
   Dattackminus        "Under Deviation of Damage Goal";

   Parameters
    Cgoal       interdiction goal
    Dgoal      destruction interdiction goal
    Iup(i,j);

   Scalar
    r   resouce limit;

*Parameter definition

    r= INSERT DATA HERE  ;
    Cgoal = INSERT DATA HERE ;
    Dgoal =  INSERT DATA HERE  ;
    Iup(i,j)=Iu.l(i,j);

  Equations

    Obj2         objective function
    Interdict    interdiction of flow
    NewPick(i)      Suppliers new choice
    FlowLimit2(i,j)      Upper bound on flow
    Budget2         Budget or Cost goal
    ReliabilityG2         Rel goal
    TaskLT2                  Time Goal
    InterdictLimit(i,j)
    InterdictionCost    Cost to Interdict
  DamageGoal    Interdiciton damage goal;

  Obj2..    zzz=e= INSERT DATA HERE  ;

  Interdict..    sum(arcs(i,j),Iup(i,j)*y(i,j))=e=r;

  NewPick(i)..        sum(j,Iup(i,j)*(newflow(i,j)$arcs(i,j)-y(i,j)$arcs(i,j))+(1-
Iup(i,j))*newflow(i,j)$arcs(i,j))-sum(j,loss(j,i)*((Iup(j,i)*(newflow(j,i)$arcs(j,i)-
y(j,i)$arcs(j,i))+(1-Iup(j,i))*newflow(j,i)$arcs(j,i))))=l=b(i);

  ReliabilityG2..     sum(arcs(i,j),reliability(i,j)*(newflow(i,j)-y(i,j)$arcs(i,j)))+RMinus-
Rplus=e=ReliabilityGoal;
```

```
Budget2..            sum(arcs(i,j),cost(i,j)*newflow(i,j))+CMinus-Cplus=e=CostGoal;
TaskLT2..            sum(arcs(i,j),time(i,j)*newflow(i,j))+Tminus-Tplus=e=TimeGoal;
FlowLimit2(i,j)..      newflow(i,j)$arcs(i,j)=l=u(i,j)$arcs(i,j);
InterdictLimit(i,j).. y(i,j)$arcs(i,j)=l=current(i,j)$arcs(i,j);
InterdictionCost.. sum(arcs(i,j),interdiction_cost(i,j)*y(i,j)$arcs(i,j))+Cattackminus-
Cattackplus=e=Cgoal;
DamageGoal..         sum(arcs(i,j),damage(i,j)*y(i,j)$arcs(i,j))+Dattackminus-
Dattackplus=e=Dgoal;
Model SCNFI / Obj2, Interdict, NewPick, FlowLimit2, ReliabilityG2, TaskLT2,
Budget2, InterdictLimit, InterdictionCost, DamageGoal /;

Solve SCNFI using mip minimizing zzz ;
```

Analyzing the Critical Supply Chain For Unmanned Aircraft Systems

Future Operations Investigation Laboratory

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Problem Statement

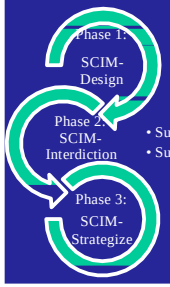
The purpose of this research is to provide a suite of scalable models to both develop a friendly supply chain and to propose attack vectors for an opposition's supply chain. The framework allows the analyst the ability to investigate an array of options and suggest an opposition's most likely course of actions.

Research Questions

- How can an analyst model optimal UAS supply chain design?
- How can an analyst model the best UAS supply chain interdiction?
- How can a decision maker strategize UAS supply chain interdiction?

Methodology Framework

Supply Chain Interdiction Methodology (SCIM)



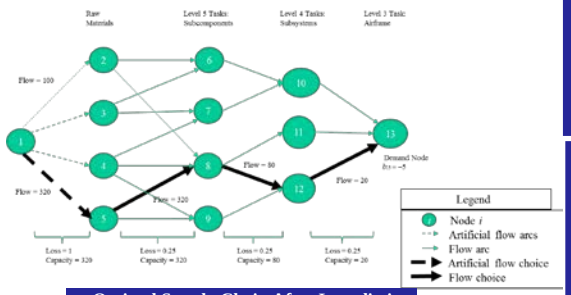
- OEM Supplier Selection (SS)
- Supply Chain Network Flow (SCNF)
- Supplier Selection Interdiction (SS-I)
- Supply Chain Network Flow Interdiction (SCNF-I)
- House of Targeting (HOT)

Software Utilized

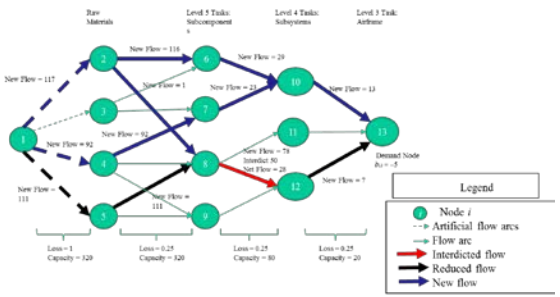
- MATLAB to read data and write GAMS file
- GAMS invoking CPLEX to solve goal programs

Illustrative Example for SCNF and SCNF-I

Optimal Supply Chain Before Interdiction



Optimal Supply Chain After Interdiction



Model Descriptions

- Linear programming and generalized network flow models that incorporate goal programming are developed to integrate the decision maker's priorities.
- SS models the optimal supplier choices that a manufacturer would select
- SCNF models the optimal flow of materials through a manufacturer's supply chain
- SS-I models the optimal interdiction of a selected supplier set
- SCNF-I models the optimal interdiction of a manufacturer's flow of materials
- HOT allows an interdiction planning team to systematically consider important aspects of a supply chain interdiction and synthesize a coherent strategy

Significance of Research

- First attempt to incorporate goal programming with supply chain interdiction, especially applied to supplier selection and generalized network flows
- The flexibility of the models provide the decision maker with a vast amount of options in their employment of the methodology.

Future Work

- Explore transforming demand constraint from SCNF into goal constraint
- Sensitivity analysis on manufacturer and attacker priorities
- Apply models to real supply chain data

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14. ABSTRACT

Unmanned aerial systems (UAS) play a vital role in present day operations due to their asset capability and ability to reduce risk to pilots' lives. A complex supply chain network capable of producing and integrating all raw materials, components, sub-systems, and systems supports the successful acquisition of a UAS. Such a complex network is supported by vital supply chain decisions. Two important decisions regarding supply chain design include supplier selection and optimal flow of material and products. Whether a decision maker wishes to design or interdict a supply chain, the methodology developed in this thesis provides a suite of tailorable models to facilitate these vital decisions. Linear programming and generalized network flow models that incorporate goal programming are developed to integrate the decision maker's priorities. In addition, a targeting matrix employing a House of Quality approach is developed to provide an interdiction planning team with a decision support tool that facilitates interdiction strategy planning. Overall, the different models developed in the study provide modeling flexibility. The incorporation of goal programming into supply chain network design and interdiction allows decision makers to effectively frame their supply chain decisions.

15. SUBJECT TERMS

Supply Chain Design, Supply Chain Interdiction, Goal Programming, Generalized Network Flow

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