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Resilient Aircraft Maintenance Constructs: Enhancing Repair Network Designs to Effectively Manage Risks and Supply Chain Interruptions

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RESILIENT AIRCRAFT MAINTENANCE CONSTRUCTS: Enhancing Repair Network Designs to Effectively Manage Risks and Supply Chain Disruptions

THESIS

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RESILIENT AIRCRAFT MAINTENANCE CONSTRUCTS: ENHANCING REPAIR NETWORK DESIGNS TO EFFECTIVELY MANAGE RISKS AND SUPPLY CHAIN DISRUPTIONS

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Abstract

This research aims to extend the understanding of supply chain resiliency by utilizing a simulation model of a U.S. Air Force aircraft engine repair network to evaluate the degree of resiliency built into the system. The study compares the recovery time of the disrupted current system to that of a fully-integrated repair network; the objective being the quantification of resiliency in the current networks design and gauging the effectiveness of various strategies in reducing recovery time. This contributes to current literature by bridging the explicit gap on how to quantify, measure, and compare resilient supply chain strategies and also provides an objective means for basing managerial decisions.

To the enemies of this great nation.

I shall drink from the burnt, broken and defiled remnants which were once your skulls.

And to my wife.

For if I fail to mention her steadfast support, she shall be drinking from mine.

Acknowledgements

I would like to express my gratitude to my faculty research advisor, Dr. Daniel Steeneck, for all of his guidance, patience and assistance. Thank you for your steadfast support, both inside and outside of the academic arena and your dedication in fostering and developing new ideas and approaches to solving such a complex and relatively unexplored problem. Thank you expanding my educational horizons and expanding my ability to overcome complex challenges.

Thomas S. Bihansky

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RESILIENT AIRCRAFT MAINTENANCE CONSTRUCTS: ENHANCING REPAIR NETWORK DESIGNS TO EFFECTIVELY MANAGE RISKS AND SUPPLY CHAIN DISRUPTIONS

I. Introduction

The line between disorder and order lies in logistics...

–Sun Tzu

The goal of maximizing profits and reducing costs have moved many firms and organizations to increase asset utilization and centralize operations in order to achieve greater economies of scale [2]. However, these efficiencies can come at the cost of the inability of an organization to effectively respond to and recover from disruptions [2]. As these networks become increasingly complex, firms and organizations experience growing degrees of turbulence, creating the potential for unpredictable disruptions [7]. Traditional risk management approaches are limited in their ability to deal with unforeseeable events, however, supply chain resiliency strategies can fill many of these gaps and create competitive advantage [7].

The purpose of this research is to develop a quantitative measure to gauge the degree to which resiliency is built into a network. The specific metrics utilized to compare variations in the design of a network include recovery time and disruption severity (as its impact upon performance). In order to explore the relationship between network design and proposed resilient strategies, the F110-100 aircraft engine repair network in the Pacific Air Force (PACAF) theater was selected as the basis for the model. This repair network was selected based upon the recommendation of decision makers at the Air Force Sustainment Center (AFSC). It is also important to note that the resource levels allocated to each node and the various distributions associated with asset repair do not reflect real-world capabilities in order to preserve the operational security of U.S. military forces in the region.

1.1 Problem Statement

Decision makers at the AFSC need to know: (1) the degree of vulnerability that the F110-100 aircraft engine repair network construct is to disruptions, (2) how long it would take to resume steady-state operations following an unexpected, disruptive event, and (3) what strategies can be employed in order to reduce both the severity of a disruption and the time it takes to recover from it. By identifying how long and to what degree a disruption would affect the repair networks capabilities, this research seeks to assist those decision makers in minimizing the impact and recovery time of repair network disruptions.

1.2 Research Questions

1. How severe of an impact would an unexpected disruption have upon the F110-100 aircraft engine repair network in PACAF?

2. How long would it take for the F110-100 aircraft engine repair network in PACAF to resume steady-state operations following an unexpected, disruptive event?

3. What network design strategies can be employed in order to reduce both the severity of a disruption and the time it takes to recover from it?

1.3 Investigative Questions

To answer the research question, the following investigative questions (IQ) will need to be answered:

IQ1. What is the current layout and design of the F110-100 aircraft engine repair network in PACAF?

IQ2. To what degree is the F110-100 aircraft engine repair network integrated and how well is capacity being efficiently utilized laterally between nodes?

IQ3. What data is needed to simulate the current and integrated states of the F110-100 aircraft engine repair network?

IQ4. What databases contain the data required to simulate the current and integrated states of the F110-100 aircraft engine repair network?

IQ5. What effects does the integration of repair facilities have upon the overall number of spare engines available to the system?

IQ6. How long does it take for the current and integrated states of the F110-100 aircraft engine repair network to recover from a disruption?

IQ7. Does the integration of repair facilities mitigate the severity of a disruption upon the F110-100 aircraft engine repair network?

1.4 Background

The vast geographical separation of Pacific Air Forces (PACAF) bases from Depot maintenance facilities located within the continental United States, makes their aircraft repair networks more susceptible to disruptions than that of stateside bases. This susceptibility is due to the increased time that is required in order to ship parts and equipment between the two regions, as compared to intra-regional transportation times. In response to this higher degree of risk, the Air Force Materiel Command (AFMC) stood up the 525th Electronics Maintenance Squadron (Support Center Pacific) at Kadena Airbase, Japan. The organization serves as a supplementary source of depot repair for nine weapon systems and pro-actively supports the AFMC mission by rapidly repairing 175 national stock number items, in addition to manufacturing new resources. Performing this work in theater significantly reduces turnaround times of critical assets by eliminating the shipping times required to get them back and forth from the United States. Despite the added capabilities provided by the Support Center Pacific (SCP), due to factors such as separate chains of command, decision makers at PACAF are unable to influence the flow of parts and the prioritization of repair for items at the SCP.

Another factor, which precludes the flexible and agile shifting of resources in order to meet varying requirements and capacity constraints at the depot echelon, is the Depot Source of Repair (DSOR) process. According to Air Force Instruction (AFI) 63-101, the DSOR process is the method by which the DoD postures its depot level maintenance workloads as organic, contract, or a combination of both. It applies to workloads for hardware, software, new acquisitions, and fielded systems for both Government and private contractor managed systems or subsystems [8]. Since the SCP is a sub-organization of the Ogden Air Logistics Center (ALC), the parent organization (309th EMXG) is able to shift the capacities and capabilities that are allocated to it through the DSOR process to the SCP. However, if PACAF requires depot-level repair capabilities that are allocated to a different ALC, the 309th EMXG cannot shift resources to the SCP in order to begin performing the required function without a change to the current DSOR. This time consuming and politically charged process thus hinders the ability to fully optimize and integrate the repair network in order to provide maximum support to the PACAF mission.

The amalgamation of all of these aforementioned issues and barriers highlights the overarching problem as to whether or not the current overall repair network construct and its associated processes provide enough resilience. Resiliency is needed to ensure that organizational objectives will be met, within an acceptable amount of recovery time, in the event of an unforeseen disruption. Having recognized the need to maximize responsiveness, agility and operational effectiveness, the Air Force Chief of Staff approved the Repair Network Integration (RNI) initiative in the Fall of 2008 with the intent of transitioning the Air Force from the concept of multiple levels of repair operating within MAJCOMs and the ANG, to an enterprise of all Non-Mission Generating maintenance organized to optimize support to the Warfighter [1]. The initiatives foremost responsibility is to design repair networks that leverage the similar repair capabilities of bases that utilize the same type of weapon systems and components. Such a design allows the network to harness the full capacity of the Total Force system and maximize support to mission-generating units, as demonstrated in Figure 1. In order to facilitate such an undertaking, an organization was founded under AFMC and staffed by members from various MAJCOMs with the sole onus of executing the RNI concept. This RNI team itself has no direct authority over the repair network nodes themselves, but rather acts as a liaison to collaborate among all stakeholders to meet the enterprises needs. In other words, RNI does not replace the chain of command, but rather creates a matrixed team to facilitate more rapid stakeholder communications across organizations to quickly resolve repair constraints [1].

Although the RNI concept sets the foundation to capitalize upon the potential for increased throughput, agile response to changing mission needs, and an overall increase in operational effectiveness given limited resources [1], its benefits are limited to a single situation as it lacks the authority to modify the repair network construct and ensure long-term optimization. Similar convolution and disjointedness in the Air Forces supply chain construct led to the creation of the Supply Chain Operations

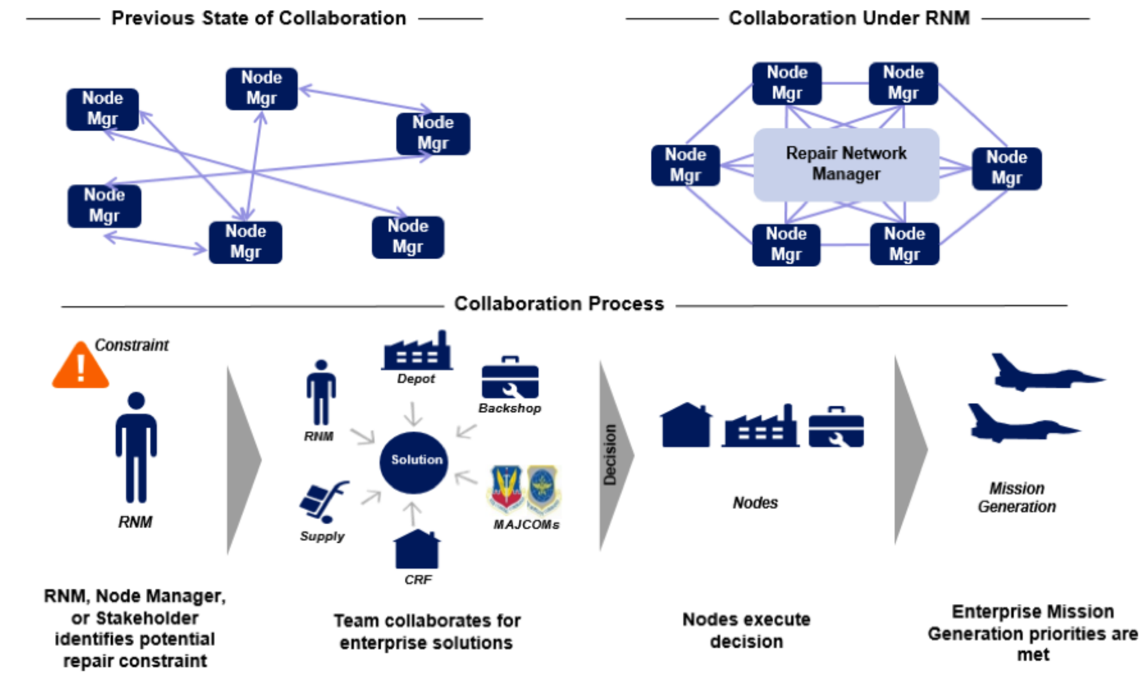


Figure 1. RNI construct [1]

Wing (SCOW), which eliminated the need to contact multiple organizations in order to solve a supply-related issue and instead acted as the single focal point for the customer [9]. In order to leverage similar benefits in the design of the RNI construct, the Repair Network Manager (RNM) positions have also been aligned within the SCOW. However, it is important to note that the SCOW does not possess chain of command authority over the nodes and networks in which it is seeking to optimize, thereby limiting its impact in terms of effectiveness and endurance. This is not to say that the RNI concept is ineffectual (it is in fact the opposite), but rather that there is a larger fundamental need to optimize repair network designs and processes in order to meet the enterprise repair network vision.

As of October 2016, three Product Repair Groups (PRGs) have reached full operation capability under the RNI initiative: Propulsion, Precision Measurement Equipment Labs (PMEL), and most recently, Hydraulic component repair [10]. The hydraulic component repair group, when created, not only established the integration of its particular repair network, but also encompassed the centralization of repair facilities. Specifically, repair actions shifted from 12 backshops to 5 Centralized Repair Facilities (CRFs) and despite the reduction of backshops and recapitalization of 69 maintenance positions, the data shows CRFs and CRF supported bases sustained the same, if not more, repair volume during this period [10]. Although the metrics presented by Chevalier [10] suggest that hydraulic component repair actually improved, identifying the degree to which those improvements were generated from the integration of the repair network, its consolidation, or a combination thereof, is difficult to determine. Furthermore, from the standpoint of resiliency, the researcher is skeptical as to whether the statement that without a doubt, our Air Force is in a better position to rapidly respond to disruptions in hydraulic component production [10] is actually accurate due to the consolidation effort. As a rebuttal, the researcher would postulate that the accuracy of the aforementioned statement is dependent upon the nature of the disruption and the node(s) being affected, since capacity has effectively been removed from the system.

This research seeks to determine the degree to which the design of a repair network affects the ability of that network to respond to and recover from an unexpected disruption. The parameters which define the design of a repair network include density, complexity, and node criticality [3]. Specifically, this research studies if integration on an enterprise level would leverage greater benefits. The parameters which define integration include visibility [3] and the ability of the system to laterally share capacity between nodes. This is achieved by shipping engines to repair nodes and/or to bases requiring inventory based upon factors outlined in section 3.5 and section 3.6.

It is further postulated that the consolidation of repair capabilities retracts from, rather than bolsters, the ability of a repair network to rapidly recover from disruption.

In order to test these postulations, the F110-100 aircraft engine was selected to map and test the resilience of the repair network due to its commonality as an asset utilized by bases throughout the PACAF area of responsibility.

1.5 Thesis Overview

In Chapter 1, the foundational background of the research topic is provided, including the motivation for the research, the current state of the U.S. Air Force supply chain as it pertains to resiliency, along with the problem statement, research question, and investigative questions.

In Chapter 2, relevant research is discussed, primarily from published articles and books, and provides further insight and current frames of thought on the research topic. The literature review begins with identifying the importance of resilient supply chains, definitions of resiliency in this context, how it can be measured, and strategies to improve a networks ability to cope with disruptions. Additionally, in Chapter 2, gaps in the current research are identified, which are addressed within the context of the intended contributions of this thesis.

In Chapter 3, the methodology utilized to conduct a quantitative analysis of the degree to which resiliency has been designed into the F110-100 aircraft engine repair network is outlined. The model of the system is constructed based upon the current layout of the repair network, an identification of key variables needed to conduct the analysis, the location of those data sources, and the design of the simulation.

In Chapter 4, the results of the simulations are analyzed based upon both the current and integrated states of the F110-100 aircraft engine repair network. Furthermore, statistical analyses are performed upon these outputs to determine comparative results and gauge the degree to which resiliency has been designed into the current network.

In Chapter 5, the implications that this research has upon measuring the resiliency of a network is discussed. Furthermore, the researcher provides recommendations based upon the findings in order to improve the methodology used so that decision makers could utilize it to enhance the robustness of the repair networks design. Refinement of this method could lead to an advancement in the U.S. Air Force's ability to provide rapid support to the warfighter despite supply chain or repair network disruptions.

II. Literature Review

As organizations become increasingly globalized and business functions are outsourced, the flow of products, resources, information, and currency becomes longer and more complex [6, 2]. The cumulative effect of these paradigms have increased the vulnerability of supply chains and resulted in the inability of some firms to recover from disruptions and its subsequent loss of customers, whereas others seem to prosper [6, 7, 2]. Those firms that find themselves poised to benefit from disruptions and the inability of their competitors to cope with such events have done so through the deliberate design of resiliency into their strategic business model [2]. The effective design of resiliency into a firms supply chain therefore becomes a competitive edge that is not only necessary for short-term survival, but also to long-term competitiveness [2]. However, before strategies that enhance resiliency can be employed, a thorough understanding of what constitutes resiliency and the factors that effect it must first be attained.

2.1 Supply Chain Resiliency

For the purpose of this research, resiliency, in both the context of supply chains and repair networks, is defined as: The adaptive capability of a supply chain or repair network to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations ideally, a better state than prior to the disruption.

As shown in Figure 2, the most significant amount of time is often consumed within the preparation for recovery and recovery stage, during which the disruption and its impacts are realized, the problem is communicated across various managerial channels, and a decision is made as to how the recovery will be executed. This research seeks to explore and quantitatively analyze the various strategies proposed within current literature on how recovery time can be effectively reduced.

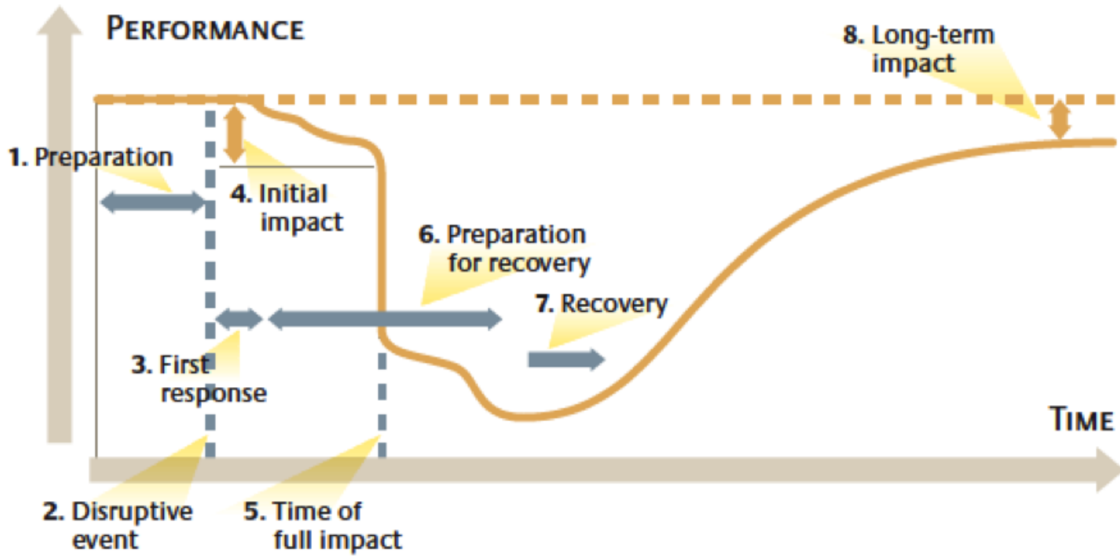


Figure 2. Stages of Disruption [2]

2.2 Strategies for Supply Chain Resiliency

Christopher and Peck [6] assert that there are four key principles in increasing supply chain resilience, which include: (1) resilience can be built into a system in advance of a disruption, (2) a high level of collaboration is required to identify and manage risks, (3) agility is essential to react quickly to unforeseen events, and (4) the culture of risk management is a necessity. From these principles and in concert with a focus group research methodology, 14 unique capability factors were identified which could be utilized to bolster supply chain resilience (see Table 1).

Table 1. Capability Factors [6]

Capability Factor	Definition	Sub-Factors
Flexibility in sourcing	Ability to quickly change inputs or the mode of receiving inputs	Part commonality, Modular product design, Multiple uses, Supplier contract flexibility, Multiple sources
Flexibility in order fulfillment	Ability to quickly change outputs or the mode of delivering outputs	Alternate distribution channels, Risk pooling/sharing, Multi-sourcing, Delayed commitment, Production postponement, Inventory management, Re-routing of requirements
Capacity	Availability of assets to enable sustained production levels	Reserve capacity, Redundancy, Backup energy, sources and communications
Efficiency	Capability to produce outputs with minimum resource requirements	Waste elimination, Labor productivity, Asset utilization, Product variability reduction, Failure prevention
Visibility	Knowledge of the status of operating assets and the environment	Business intelligence gathering, Information technology, Products, Assets, and People visibility, Information exchange
Adaptability	Ability to modify operations in response to challenges or opportunities	Fast re-routing of requirements, Lead time reduction, Strategic gaming and simulation, Seizing advantage from disruptions, Alternative technology development, Learning from experience
Anticipation	Ability to discern potential future events or situations	Monitoring early warning signals, Forecasting, Deviation and Near-miss analysis, Contingency planning, Preparedness, Risk management, Business continuity planning
Recovery	Ability to return to normal operational state rapidly	Crisis management, Resource mobilization, Communications strategy, Consequence mitigation
Dispersion	Broad distribution or decentralization of assets	Distributed decision-making, Distributed capacity and assets, Decentralization of key resources, Location-specific empowerment, Dispersion of markets
Collaboration	Ability to work effectively with other entities for mutual benefit	Collaborative forecasting, Customer management, Communications, Postponement of orders, Product life cycle management, Risk sharing with partners
Organization	Human resource structures, policies, skills and culture	Learning, Accountability and Empowerment, Teamwork, Creative problem solving, Cross-training, Substitute leadership, Culture of caring
Market position	Status of a company or its products in specific markets	Product differentiation, Customer loyalty/retention, Market share, Brand equity, Customer relationships, Customer communications
Security	Defense against deliberate intrusion or attack	Layered defenses, Access restrictions, Employee involvement, Collaboration with governments, Cyber-security, Personnel security
Financial strength	Capacity to absorb fluctuations in cash flow	Insurance, Portfolio diversification, Financial reserves and liquidity, Price margin

Craighead, Blackhurst, Rungtusanatham, and Handfield (2007) identified two categories of capabilities that moderate the severity of a supply chain disruption based upon the design of the system: recovery and warning (see Figure 3). In order to ensure the feasibility of this research, the scope will be limited to only recovery capabilities.

Furthermore, this research will incorporate varying facets of design characteristics into the analysis in order to determine both their baseline effects and the degree to which recovery strategies can reduce the severity of their influence upon recovery time.

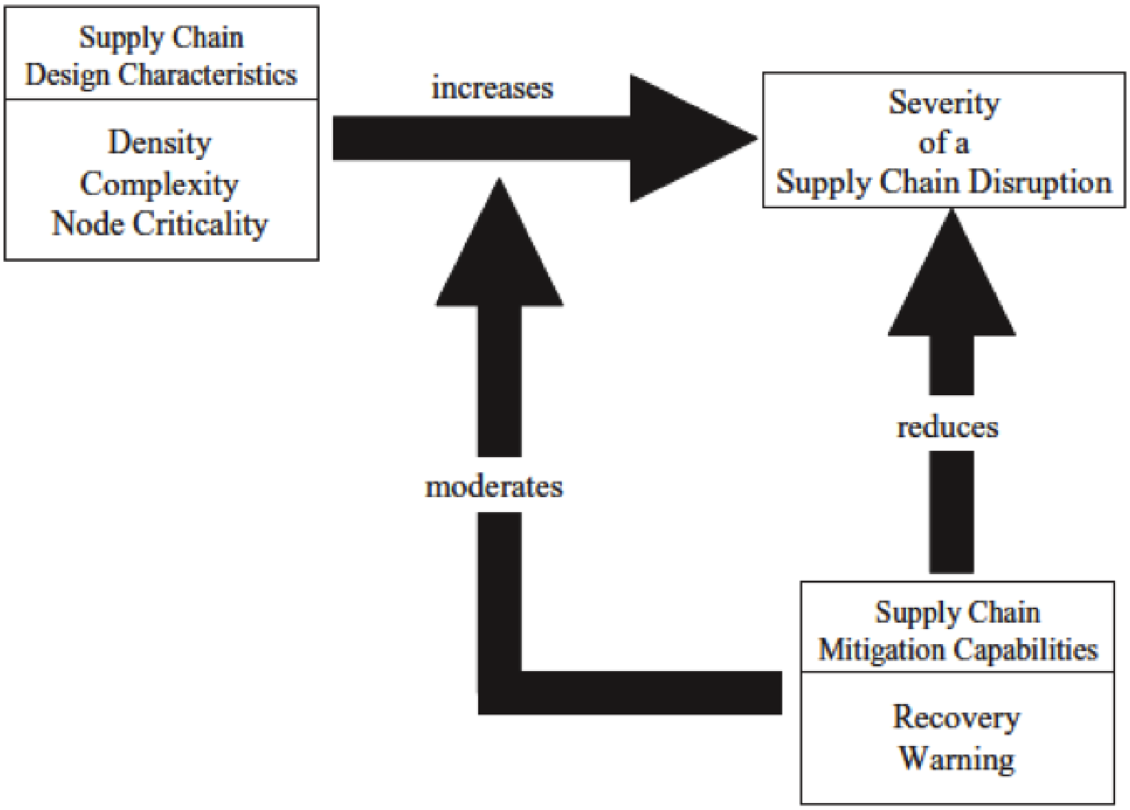


Figure 3. Theoretical Relationship Between Design and Disruption Severity [3]

2.3 Recovery

The review of current literature on the topic has identified two overarching methods for increasing supply chain resiliency in terms of recovery: redundancy and flexibility [7, 2, 11]. Redundancy, which is the duplication of capacity [4], has been viewed in terms of an insurance policy, whereby the benefits of such strategies remain unrealized until the moment that a disruption occurs and is otherwise considered as a sheer cost

[7, 11]. Redundancy involves the strategic and selective use of spare capacity, such as additional tools or machinery, and inventory that can be invoked during a disruption or in response to a variance in demand that surpasses the normal operating capacity of the system [6].

Conversely, flexibility is advocated as the preferred method since its underlying sub-strategies not only mitigate the likelihood and impact of a disruption, but also provides the organization with low cost capabilities that enable the firm to capitalize upon fluctuations [6, 7, 12, 11]. Such methods include utilizing multiple supply sources and transportation methods, holding emergency strategic stocks, employing process standardization, postponing product differentiation, maintaining multiple locations with built-in interoperability, increasing supply visibility, and creating an organizational culture that promotes resiliency [6, 7, 12, 11]. These strategies benefit a system both during a disruption and in daily operations. Specifically, these benefits include reserved capacity to meet increased demand, lead-time reduction, early detection of disruptions, and increased forecast accuracy [6, 7, 12, 11]. Furthermore, it is postulated that training maintenance personnel in more that one specialty field could dampen the severity of a disruption by allowing supervision to restructure their workforce and increase throughput by transferring the spare capacity from one shop to another which is constrained. Flexibility, therefore, enables resources to be more easily redeployed in order to subjugate constraints, which due to the nature of a disruption, might not be able to be known in advance [4]. Flexibility is considered preferable to redundancy due to its inherent ability to sense threats and respond to them quickly, without the high costs associated with purchasing, holding, and maintaining redundant resources [2].

Since many of the works conducted by authors such as Sheffi and Rice (2005), Pettit Fiksel and Croxton (2010), Tang (2006) are conceptual in nature, they have advocated that future empirical and quantitative studies be conducted to explore the effectiveness of such flexible strategies upon resiliency [7, 2, 11]. One particular study, conducted by Petit, et al. (2010), has led to the creation of a framework that breaks vulnerabilities and capabilities into distinct categories, allowing for an evaluation to be made on the balancing the resources. This study too, however, recommends that additional quantitative studies be conducted in order to measure the degree to which various vulnerabilities and capabilities are linked [7]. The lack of quantitative analysis on supply chain resiliency presents a distinct knowledge gap and this research seeks to contribute to academia by providing a quantitative analysis of the effects that these strategies and designs have upon the ability of a system to quickly recover from a disruption. First, however, the literature must be explored further to identify possible methods by which resiliency can be quantified and comparatively analyzed.

2.4 Supply Chain Resiliency Measures

To our knowledge, few methods have been proposed to measure supply chain resiliency. Multiple authors, such as Kleindorfer and Saad (2005), Wu, Backhurst, and O'Grady (2007), Tang (2006), and Thun and Hoening (2011), conclude that no clear consensus has been agreed upon regarding what should be analyzed for the effective management of network disruptions. However, in those methods which are proposed, measuring the performance level over time is a reoccurring theme [5, 2, 4].

One proposed measure of resilience is the area between the performance curve and pre-disruption performance level, as shown in Figure 4. The corresponding area of a successive disruption (Period B) can be compared to the area of the earlier disruption (Period A) [4].

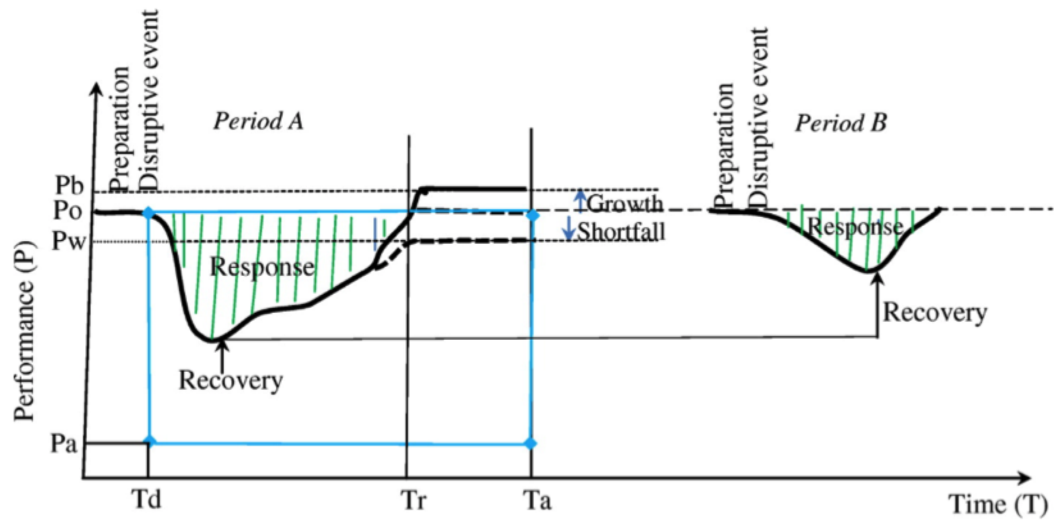


Figure 4. Measuring Supply Chain Resiliency [4]

Similarly, Munoz and Dunbar (2015), identify multiple dimensions by which resiliency can be measured. As shown in Figure 5, these dimensions include: the time that it takes to reach an acceptable recovery performance range, the severity that the impact has upon performance, the total performance loss (area above the curve), the length of the profile curve, and a time-dependent deviation-weighted sum to capture the speed and shape of the transient response. In addition to these measures, Munoz and Dunbar (2015), provide equations that could be utilized to determine each specific dimension of performance.

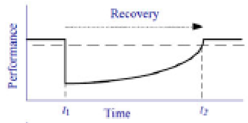
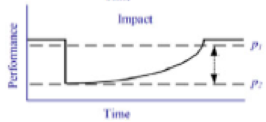
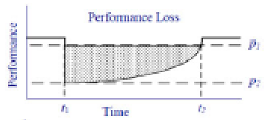
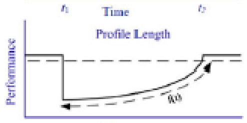
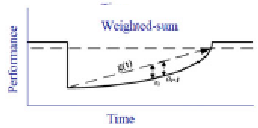
Dimension of resilience	Rationale	Equations
	Captures the time required to return to the acceptable performance range	$t_2 - t_1$
	Captures the severity of the impact on performance	$p_2 - p_1$
	Calculates the total performance loss as the area above the curve $p(t)$, between t_1 and t_2	$(t_2 - t_1) \times p_1 - \int_{t_1}^{t_2} p(t)dt$
	Captures the length, of the profile as it reaches the acceptable performance level	$\int_{t_1}^{t_2} \sqrt{1 + (\frac{dp}{dt})^2} dt$
	A time-dependent deviation-weighted sum to capture the speed and shape of the transient response, where: $t_1 = a_1, a_2, \ldots, a_n = t_2$	$\sum_{i=1}^{n} a_i[g(a_i) - p(a_i)]$

Figure 5. Dimensions of Resilience [5]

In the first row of Figure 5, recovery time following a disruption is calculated as the difference between the time at which the system has recovered (t_2) and the at which the lowest performance value is attained (t_1). In the second row of Figure 5, the severity of a disruption is calculated as the difference between the pre-disruption performance level (p_2) and the minimum performance level reached during a disruption (p_1).

III. Methodology

This research fills gaps in the literature on supply chain resiliency by providing a quantitative method for measuring the degree to which resiliency is designed into a repair network. Furthermore, a comprehensive examination of the system's variables will provide key insights into the relative importance of each variable and its effect on the repair networks resiliency, as measured by the time it takes to return to or exceed the pre-disruption level of performance. It is also fathomable that a system, which has little or an insufficient level of resiliency built into its design, may not recover to its pre-disruption level of performance. If such an event were to occur, once the new steady-state operating level was achieved, the system would be considered to be recovered from the disruption.

The research methodology adopted in this research consists of the following steps:

1. Develop a conceptual design of the F110-100 aircraft engine repair network in PACAF that identifies the various nodes within the system and the current level of interoperability between them.

2. Identify key variables that describe the repair process of the network at each node (demand, capacity of both manpower and equipment, transportation times between nodes, unit repair times, etc.)

3. Identify database systems, which contain the required data previously identified, gain access to those databases, and compile required data.

4. Create a simulation that models the conceptual F110-100 aircraft engine repair network and incorporates the details and distributions identified by the previously collected data.

5. Introduce a disruption into the model in order to gauge the degree to which the repair network is affected.

6. Adjust the model to incorporate various resilient strategies identified during

the literature review and gauge the degree to which the redesigned repair network is affected by the same disruption.

7. Identify which system design strategies minimize the time required for the system to return to or exceed the pre-disruption level of performance.

3.1 Developing a Conceptual Design

The basis of this research is centered around the actual and current design of F110-100 aircraft engine repair network in PACAF. However, in order to protect sensitive information, the numbers utilized in this simulation do not reflect the actual (real-world) distribution of assets, resources, or repair node capabilities. As such, this research can only be utilized as a proof of concept for the methodology and not as a basis for evaluating the actual design of the F110-100 aircraft engine repair network in PACAF.

Utilizing Arena, a discrete event simulation software from Rockwell Automation, a model of this repair network was created. It is assumed that in this current-design model that each of the four PACAF bases are self-contained, in that they only repair their own engines and once complete, return the repaired engine to its own pool of spares. Later, this basic model will be expanded into a fully-integrated network, whereby engines can be shipped laterally for repair and repaired spares are sent to the base which need them the most. It is also important to note that this model only considers Organizational level (O-level) repairs and does not account for Intermediate level (I-level) or Depot level repairs. It is assumed that all engines are repairable at the O-level and none of them are damaged to the point where they require decommissioning (i.e., aircraft crash).

3.2 System Description

In all of the models of the repair network, entities (engines) enter the system at the onset of the simulation and arrive at time zero. Each base receives a predetermined amount of entities, as shown in Table 2, which is a function of the number of aircraft assigned to base and the number of spares authorized for each base:

$$Arrivals_i = NumberofAircraftAssigned_i + NumberofSparesAuthorized_i \quad (1)$$

where, $NumberofAircraftAssigned_i$ is the number of aircraft assigned to base i and $NumberofSparesAuthorized_i$ is the number of spare engines authorized to base i.

Table 2. Entity Arrivals

Base	Number of Arrivals	Arrival Time
Misawa	48	Instant
Osan	30	Instant
Kunsan	48	Instant
Eielson	30	Instant

Once the system is seeded with engines, each aircraft is loaded with a single engine. The time to failure for each aircraft's engine is normally distributed mean 180 days and standard deviation 40 days (see Table 3). Since the number of entities which enter the system at each base exceeds the number of aircraft, not all engines will be initially loaded onto an aircraft. The remaining engines will be used as an inventory of replacement engines. In Table 3, the number of aircraft, the authorized number of spares, and the on-aircraft distribution-based time period for each base is listed.

Failed engines are repaired, however the engine failure mode is not explicitly modeled. Engine repair times follow the triangular distribution and vary for each base (see Table 4). Initiation of engine repairs require (1) a repair station and (2) a repair crew

Table 3. Engine Utilization

Base	Aircraft	Spares Auth.	Distribution	Mean (days)	Std Dev (days)
Misawa	40	8	Normal	180	40
Osan	25	5	Normal	180	40
Kunsan	40	8	Normal	180	40
Eielson	25	5	Normal	180	40

to be available. Each base as its own set of resources available in order to perform repairs. Engines are repaired on a first come, first served basis. The amount of each resource available to each base and its respective distribution for repair is shown in Table 3.

After the engine is repaired, it acquires serviceable status and is transported to the appropriate base's engine inventory. In section 3.6, the method for determining which base to stock is discussed.

3.3 Integration

Within the repair network, a decision must be made on where (1) engines can be repaired and (2) where engines can be restocked. The following cases are considered:

1. Baseline: engines remain at their assigned base.
2. Back-end Integration: engines are repaired at their assigned base, but once repaired can be shipped to another base to replenish inventory.
3. Fully-Integrated: engines can be shipped to another base for both repair and to replenish inventory.

Table 4. Repair Location Capabilities

Base	Crews	Stations	Distrib.	Min (days)	Mode (days)	Max (days)
Misawa	2	2	Triangular	1	5	9
Osan	2	2	Triangular	1	5	9
Kunsan	2	2	Triangular	1	5	9
Eielson	2	2	Triangular	1	5	9

3.4 Selection of Repair Location

For the decision of where to send an engine for repair, Equation 2 is utilized to determine which base has the shortest (minimum) expected time to repair an engine and return it to serviceability. This decision takes into account the current number of engines in a base's repair queue, the number of engines inbound to that base for repair from other bases, the average queue waiting time per engine for that base's repair facility, and the distribution-based time to ship the engine from the originating base to the repair base (note: this time equals zero when the repair base is also the originating base). Specifically, the repair base is given by

$$RepairLocation = \arg\min_i(((R_i + \sum_{j=1}^{\infty} S_{ji}) * H_i) + Td_{ji}), \tag{2}$$

where, R_i represents the number of engines in the repair queue for base i. S_{ji} represents the number of engines being shipped from base j to base i for repair. H_i represents the average waiting time that an engine spends in the repair queue for base i. Td_{ji} represents the distribution-based time that it takes to ship an engine from originating base j to potential repair base i. Once again, Td_{ji} equals zero when $i = j$.

The distribution-based times that it takes to ship an engine from one base to another is shown in Table 4.

Table 5. Engine Shipment Matrix

Base (from)	Base (to)	Distribution	Min (days)	Mode (days)	Max (days)
Misawa	Osan	Triangular	1	3	5
Misawa	Kunsan	Triangular	1	3	5
Osan	Kunsan	Triangular	1	2	3
Osan	Misawa	Triangular	1	3	5
Kunsan	Osan	Triangular	1	2	3
Kunsan	Misawa	Triangular	1	3	5

3.5 Deciding which Base to Stock

Once an engine has been repaired and considered serviceable, it enters a second decision block which determines which base is in the greatest need of it. Specifically, the replenishment location is given by

$$BasetoSendSpare = \arg\min_i((Q_i + \sum_{j=1}^{\infty} Sp_{ji}) - W_i), \tag{3}$$

where, Q_i represents the number of engines currently in the spares pool queue for base i. Sp_{ji} represents the number of engines being shipped from base j to base i for serviceable spare stock. W_i represents the number of engines required by base i for WRE purposes.

Equation 3 is utilized to determine which base is the furthest below or closest to its WRE requirement. This equation enables the simulation to objectively compare differences in a base's authorized number of spares, since not all base's are equally resourced, and provides a means for cross-base comparison of current stock levels.

3.6 Simulation Setup

For this simulation, each model is first ran for a period of two years (730 days) in order to establish a baseline measurement of performance. The length of this simulation enabled adequate time for each model to reach steady state both before and after the introduction of a disruption.

Furthermore, each model is replicated 200 times. In order to determine how many replications to run, the integrated model was replicated 10 times. From those 10 replications, the standard deviation (SD) of the average number of serviceable engines in the system for each replication was calculated. The estimated standard error (SE) is given by

$$SE = \sqrt{SD^2/R} \quad (4)$$

where, SE is the estimated standard error which is being calculated, SD is the standard deviation of the average number of serviceable engines for each replication, and R is the number of replications utilized.

The standard deviation and number of replications were then substituted into equation 4, in order to determine the standard error. The acceptable SE was determined to be 0.25 engines, which corresponded to a 200 replication requirement, in order to achieve this level of precision.

3.7 Simulation Output

Results from the simulation were saved into a text output file containing the replication number, arrival time for each entity, and the current number of spares in inventory for each replication.

3.8 Measuring Resiliency

In order to measure resiliency, three critical points must be identified for each replication's output. These critical points are the time in which performance begins to drop due to a disruption, the minimum performance value hit during the disruption, and the time at which the system recovers from the disruption. However, the performance level over time is highly variable and as such, the output must be smoothed in order readily identify these critical points. As shown in Figure 6, by taking the moving average over 50 time periods, a smooth plot (blue line) can be created which makes the identification of the critical points more apparent.

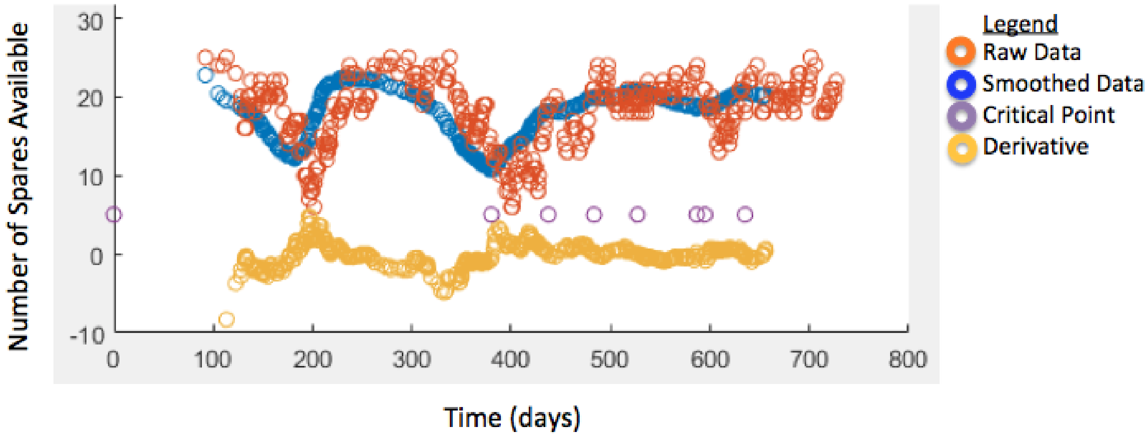


Figure 6. Example of Performance Smoothing

Once smoothed, an algorithm is utilized to determine the critical points. The algorithm, as denoted in Appendix B, looks for the points in which the derivative of the performance line goes from positive to negative (onset of a disruption), back to positive (system begins to recover), and back to negative again (system has surpassed its point of recovery). Using these critical points, the recovery time can be calculated by determining the delta between the time at which the system recovers from the disruption and the time in which performance begins to drop due to a disruption. A smaller delta would signify a shorter recovery period and thus a greater degree of resiliency built into that model as compared to a model with a larger delta.

Additionally, the severity of the disruption for each model is measured by comparing the minimum performance value reached. Furthermore, these measures could also be utilized to determine which strategies have the most influence on increasing resiliency. For instance, once a model of a system has been created, all but one variable can be held constant during several iterations of introducing a disruptive event. A measurement of the impact that the variable had upon the severity and recovery time could then be realized and compared against the effect that other strategies had upon performance. Such an analysis would be useful in determining which variable(s) decision makers should focus upon in order to increase resiliency in the most effective, efficient, and cost conscientious manner.

3.9 Model Performance Measurement Without a Disruption

In order to measure and compare the performance of each model without a disruption, a Matlab algorithm was created to capture the average part level (number of serviceable engines available) for each replication (see Appendix A). A histogram was then created for each model that shows the distribution of these average part levels, which can then be compared against other models (see Figure 7 in the Results and Analysis section).

3.10 Disruptive Events

After running each model without a disruption in order to gauge baseline performance, a planned disruption was introduced into each of the three models at a simulation time of 365 days. This allowed enough time for the systems to reach steady state prior to the disruption occurring. At the time of disruption, one node (Misawa) loses its entire capability to repair engines for a period of 100 days. The length of this disruption allowed for a clear visual degradation in the system's performance. At the end of the disruption (simulation time of 465 days), the affected node's repair capability is restored in full to its pre-disruption level.

IV. Results and Analysis

In determining the answer to investigative question 1 (IQ1), this research found that at the O-level of repair, F110-100 aircraft engines within PACAF are repaired only by the base at which they are assigned. As such, engines are not shipped to other repair nodes based upon capacity and/or workload.

As discussed in the background, integration of the repair network is achieved via coordination on telecoms between each node and the item managers and weapon system teams at PACAF in order to solve specific problems once they have been identified. There is however, no capacity that is being utilized laterally between nodes as denoted in the answer to IQ1. This design was incorporated into the baseline model of the simulation and satisfies IQ2.

As it applies to IQ3, in order to simulate PACAF's F110-100 aircraft engine repair network, data must be gathered on how many engines are assigned to each node, the distribution by which they require repairs, the distribution by which each node performs repairs, the repair resources allocated to each node, and the distributions for transportation times between nodes.

The aforementioned datasets were pulled from the Logistics, Installations and Mission Support-Enterprise View (LIMS-EV) system. The Engine and Repair Network sections allow the user to search for these data sets for various nodes over a specified time period. Transportation times between nodes, however, are not available through LIMS-EV and must be gathered from the SCOW. As such, in response to IQ4, LIMS-EV and the SCOW posses the data required to simulate the current and integrated states of the F110-100 aircraft engine repair network.

As shown in Figure 7, analysis of the simulation results indicate that the integration of repair nodes at the O-level decreased, rather than increased, the overall number of spare engines available to the system. This finding satisfies IQ5, which seeks to determine the effects that integration of repair facilities has upon the overall number of spare engines available to the system. Unfortunately, this result is counter to the expected outcome, as integration should only help and not hinder the performance of a network. As such, it is clear that the decision logic used to determine where and when to ship and engine for both repair and restocking of inventory is either incomplete or sub-optimal. This concern will be discussed further in the limitations and recommendations for future research sections.

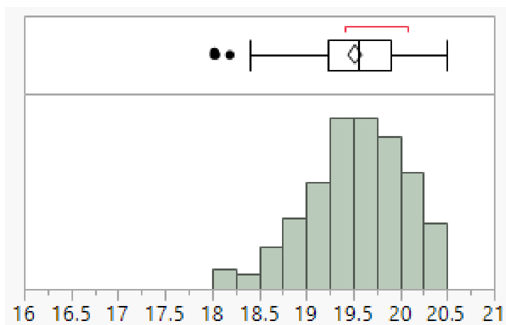
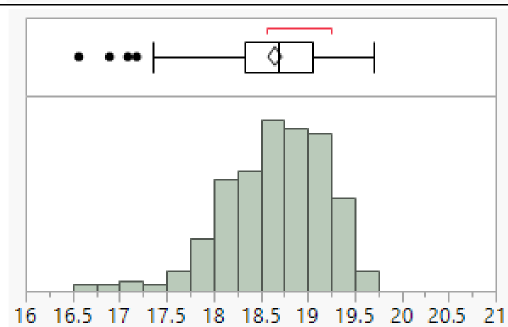
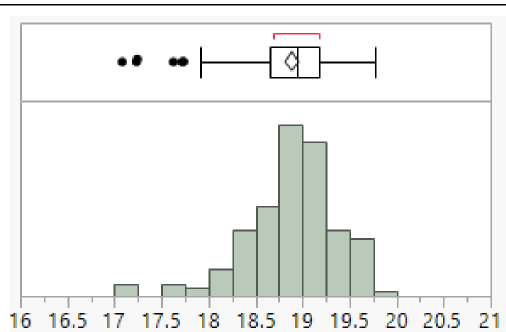
Baseline		Mean: 19.5 Std Dev: 0.51
Backend Integration		Mean: 18.7 Std Dev: 0.53
Fully Integrated		Mean: 18.9 Std Dev: 0.46

Figure 7. Model Part Level Performance without Disruption

Of the three models originally developed, there was no statistically significant improvement noted from integration once a disruption was introduced (see Figure 8). In fact, once again, the back-end integrated model performed significantly worse than both the baseline and fully-integrated designs. This reaffirms the previously discussed finding that the decision logic used to determine where and when to ship and engine for both repair and restocking of inventory requires refinement in order for this method to be useful to decision makers. However, the results do illustrate the significant impact that poor decision making in network design could have upon its ability to recover from a disruption. As shown in the last column in Figure 8, the recovery time for various network designs can be calculated, which satisfies IQ6.

In order to ensure that the distribution of transportation times were not the cause of the poor performance by integrated designs, they were eliminated from the simulation. In essence, engines could instantly be transported from one base to another for both repair and/or inventory replenishment. As shown in Figure 8, removing transportation times only resulted in a slight improvement in part level and recovery time. As such, transportation times could be ruled out as the reason for the poor performance of the integrated designs. This result does however suggest that reducing transportation times between nodes could provide some benefit to the networks level of resiliency.

Next, the capacity available to the fully-integrated and baseline models was doubled in order to gauge the impact that it would have upon resiliency. As shown in Figure 8, both models showed a respective increase in part level and reduction in recovery time. This result suggests that adding redundancy to system does have a clear impact on improving resiliency.

As previously discussed, the impact that integration has upon mitigating the severity of a disruption could not be clearly identified, which only partially answers IQ7. As discussed in section 4.1, the decision logic utilized for engine shipment will need

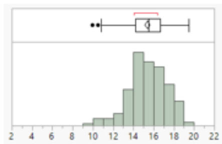
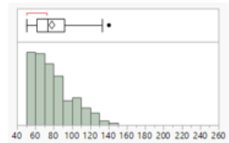
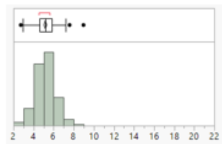
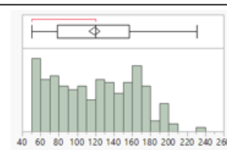
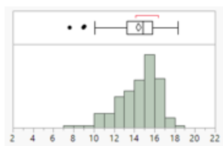
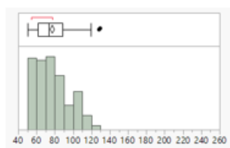
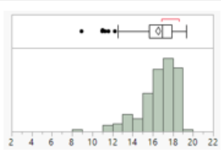
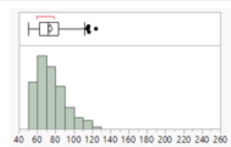
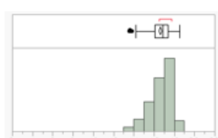
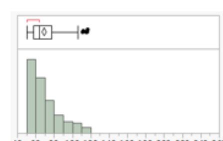
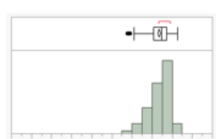
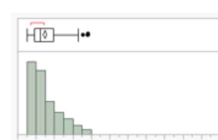
	Minimum Part Level		Recovery Time	
Baseline with Disruption		Mean: 15.4 Std Dev: 1.8		Mean: 78.2 Std Dev: 20.9
Backend Integration with Disruption		Mean: 5.2 Std Dev: 0.9		Mean: 119.1 Std Dev: 44.3
Fully Integrated with Disruption		Mean: 14.5 Std Dev: 1.9		Mean: 77.3 Std Dev: 18.6
Fully Integrated with Disruption (Instant Trans)		Mean: 16.6 Std Dev: 1.8		Mean: 74.3 Std Dev: 15.8
Fully Integrated with Disruption (2x Capacity)		Mean: 16.6 Std Dev: 1.0		Mean: 69.3 Std Dev: 15.7
Baseline with Disruption (2x Capacity)		Mean: 16.7 Std Dev: 0.9		Mean: 69.9 Std Dev: 15.4

Figure 8. Resiliency Performance Measures with Disruption

to be refined in order to show the benefit that integration could present. However, once again, the results do illustrate the significant impact that poor decision making in network design could have upon its ability to recover from a disruption.

4.1 Limitations

Inventory Decision Logic

As shown in the results and analysis section, the integrated models failed to perform better than the baseline model in terms of increasing the number of spares available and minimizing recovery time. Unfortunately, this result is counter to the expected outcome, as integration should only help and not hinder the performance of a network. As such, it is clear that the decision logic used to determine where and when to ship and engine for both repair and restocking of inventory is either incomplete or sub-optimal. Further research will need to be conducted in order to identify an effective and optimal decision logic so that the value of integration can be identified. Instead, this research only shows the significant impact that poor network design could have upon its ability to recover from a disruption.

Identifying Critical Performance Points

As shown in figure 9, Munoz and Dunbar [5] identified four types of of performance profiles: (a) linear, (b) concave, (c) convex, and (d) non-specific, non-linear behaviors. The critical points outlined in section 3.10 can be easily identified by the algorithm shown in Appendix E for all of these types with the exception of non-specific, non-linear behaviors. Since the derivative of the non-specific, non-linear performance profile will change between positive and negative direction more than three times, the algorithm was unable to accurately determine the critical points outlined in section 3.10. As such, replications that had a non-specific, non-linear performance profile were discarded. Further research will need to be conducted in order to create an effective algorithm that can accurately identify these critical points for any performance profile.

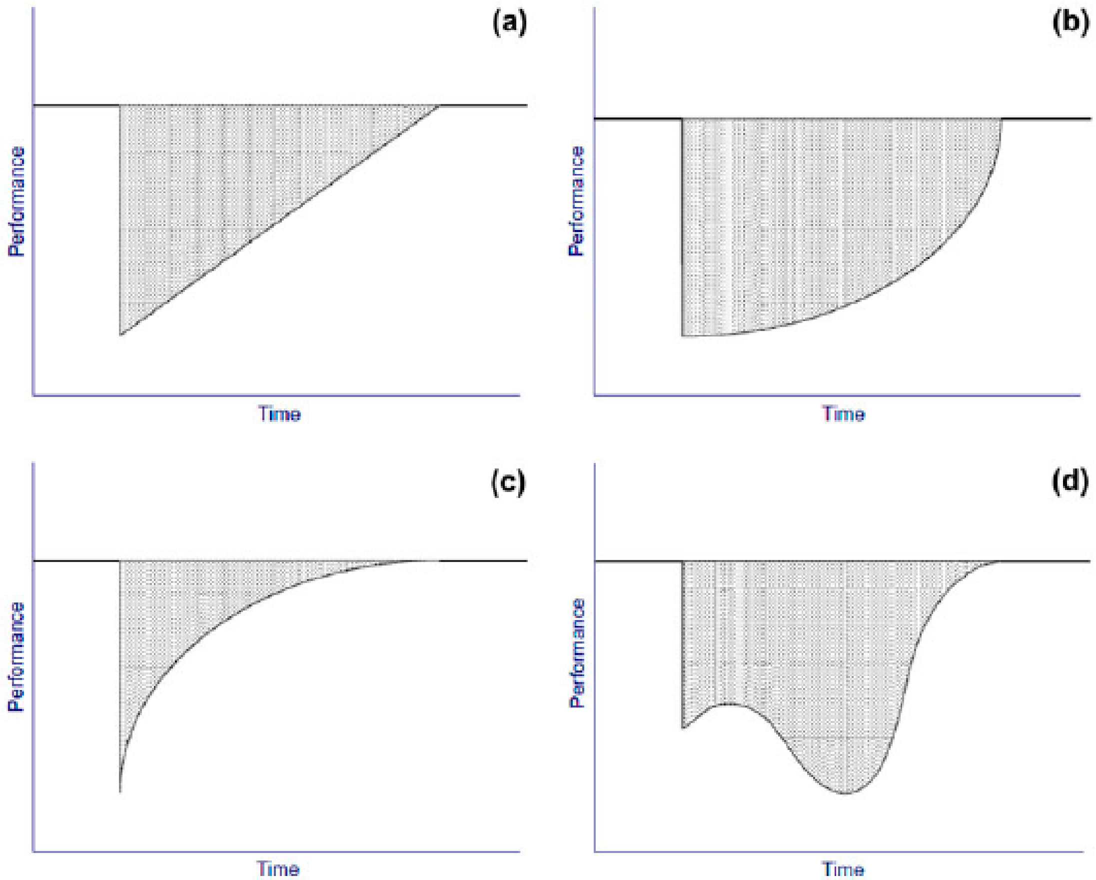


Figure 9. Typology of Performance Profiles [5]

V. Discussion

This research provides a comparative method for evaluating the effects that various network designs have upon performance during a disruption and recovery time. This is accomplished by demonstrating how resiliency can be measured and that the benefit from various resilient strategies can be compared. Furthermore, this research illustrates the significant impact that poor decision making in network design and decision logic could have upon its ability to mitigate the severity of and recover from an unanticipated disruption.

5.1 Problem Statement Resolution

As stated in section 1.1, decision makers at the AFSC need to know: (1) the degree of vulnerability that the F110-100 aircraft engine repair network construct is to disruptions, (2) how long it would take to resume steady-state operations following an unexpected, disruptive event, and (3) what strategies can be employed in order to reduce both the severity of a disruption and the time it takes to recover from it.

In response to research question 1, this research tested the degree of vulnerability that the F110-100 aircraft engine repair network construct is to a specific disruption, namely the temporary loss of throughput at a single node. Although this method does allow for the testing and comparison of other variables, such as the effect of various mitigation capabilities, a much more robust approach would include varying where a disruption occurs, its duration, and its area of effect. Due to this limitation, the severity of this one particular disruption can be gauged as factor of the networks design. The first column in Figure 8 shows the degree of vulnerability (severity) that a particular design is to the selected disruption. From this figure, an inference can be drawn that of the capabilities tested, increasing capacity provides the greatest benefit to reducing severity.

In response to research question 2, the second column in Figure 8 shows the recovery time that a particular design has to the selected disruption. For this particular disruption, an inference can be drawn that of the capabilities tested, increasing capacity provides the greatest benefit to reducing recovery time.

From these findings, research question 3 can easily be addressed, as this method enables the direct comparison of mitigating capabilities. This research tested the effects that network design capabilities such as integration, reduced transportation times, and increasing capacity, has upon the resiliency of a network. Once again, it appears that increasing capacity provides the greatest benefit to both dimensions of resiliency (severity and recovery time).

However, since research question 1 and 2 were not fully satisfied, a more robust approach would include varying where a disruption occurs, its duration, and its area of effect.

5.2 Significance of Findings

Although this research does not analyze the effect that different types of disruptions has upon a network, it does clearly provide a means by which resilience can be measured and the performance of multiple design prospects compared against each other. Furthermore, this research bridges the gap in literature between the theory of how resilience can be measured, which strategies poses the greatest potential to mitigate a disruption, and a quantitative analysis that actually tests those theories.

As such, the importance of this research lies in its findings that this research does serve as a proof of concept in that resiliency can be measured and that the benefit from various resilient strategies can be weighed. Furthermore, this research does illustrate the significant impact that poor decision making in network design and decision logic could have upon its ability to mitigate the severity of and recover from an unanticipated disruption.

5.3 Managerial Implications

As it applies specifically to decision makers at AFSC, this method can be used to compare the performance of proposed design changes to a repair network. In the background, section 1.4, the SCP was identified by AFSC as a possible candidate for redesign. Proposed alternative designs can be evaluated and compared against the current design to determine both the levels of performance and the degree to which resiliency is incorporated into each respective design. Additionally, by keeping severity and recovery time as two separate dimensions in the measure of resilience, as this method does, enables decision makers to quickly and easily discern the results. Both the part level and recovery time metrics are easily understood and each paint a specific and valuable picture, unlike methods which combine the two measures. For example, if this research utilized the area above the curve method for calculating resilience, then the output would be in engine-days. Such a unit of measure is convoluted, as it masks the true shape of the disruption in terms of the performance curve and it provides little useful description of the behavior of the network.

The method utilized in this research allows the decision makers at AFSC to base their selection of which design to implement upon a quantitative comparison, rather than "gut feel" or cost alone. Although cost should be a factor in determining which design to implement, it must be balanced against capability. Future recommendations based upon this notion will be discussed in the next section.

5.4 Recommendations for Future Research

It is recommended that future studies conduct quantitative research on the effect that various capabilities factors have upon resiliency in order to further bridge the identified gaps in literature. Specifically, the following research questions can be explored in greater depth in order to further this research and expand upon the understanding of resiliency:

What are the effects that various inventory decision policies have upon the performance of a network?

As shown by the research, decision policies could have a wide range of effects upon the performance of a network and its ability to recover from a disruptive event. Therefore, it is recommended that further studies be conducted in order to determine which variables should be considered when integrating a network and how decision logic can be improved to ensure enhanced system performance.

To what degree do various strategies affect resiliency and which provide the greatest benefit to cost ratio?

Although this research tests to see the impact that capacity, integration, and transportation times have upon resiliency, there are many more capability factors, as identified in figure 3, that can and should be analyzed. Furthermore, the benefits from implementing each capability factor should be weighed against the cost required to implement it. From such an analysis, the researcher could determine which strategies have the greatest benefit to cost ratio. As such, this investigation could prove useful to decision makers who wish to bolster the resiliency of their networks given a limited budget.

How should resources and capabilities be spread across a repair network during wartime in order to ensure system resiliency?

The notion of adaptive basing has become quite popular in the U.S. Air Force as a means to ensure continued operations in a contested environment. However, little quantitative research has been conducted on how to best disperse limited assets and resources in order to balance combat effectiveness and survivability. The methodology presented in this research can be modified to compare the performance of a network based upon various dispersion plans. Furthermore, given a particular dispersion plan, the effects that an attack (or disruption) on various nodes would have upon the performance of the system could be analyzed.

Appendix A. Matlab Code for Identifying Moving Average Part Level

```
num_rep = max(Rep);

AvgPL=[];

StdPL=[];

for i = 1:num_rep

    PL = PartLevel(Rep==i);

    AvgPL(i) = nanmean(PL);

    StdPL(i) = nanstd(PL, 1);

end
```

Appendix B. Matlab Code for Identifying Critical Points

```
num_rep = max(Rep);
MA_data = [];
Crit_t = [];
KeyMeasures=[];
for i = 1:num_rep
    T = Time(Rep==i);
    PL = PartLevel(Rep==i);
    nT = numel(T);
    dT = T - [0;T(1:nT-1)];
    k = 50;
    MA_PL=zeros(size(T));
    for t = 1:nT-k
        MA_PL(t) = sum(dT(t:t+k-1).*PL(t:t+k-1))/sum(dT(t:t+k-1));
    end
    dMA_PL = MA_PL - [0;MA_PL(1:nT-1)];
    dMA_PLsmoothed = movmean(dMA_PL(1:nT-k),5);
    t_start = find(T >350 & T < 375);
    t_end = find(T > 580 & T < 600);
    crit_t = [];
    c = 0;
    d = 2;
    x=0;
    [min_MA_PL, t_min0] = min(MA_PL(t_start(1):t_end(1)));
    t_min = t_min0+t_start(1);
```

```
  crit_t(1) = 0;
  crit_t(2) = T(t_min);
  for j = t_min:numel(dMA_PLsmoothed)-1
      if (dMA_PLsmoothed(j)>0 && dMA_PLsmoothed(j+1)<0)&&
      (T(j)-T(t_min) > 50)
          d= d+1;
          crit_t(d)=T(j);
      end
  end

  min_MA_PL = min(MA_PL(t_start(1):t_end(1)));
  pre_dis_MA_PL = nanmean(MA_PL(t_start(1)-50:t_start(1)));
  post_dis_MA_PL = nanmean(MA_PL(t_end(1):nT-k));

  MA_rep_data = [T(1:nT-k),MA_PL(1:nT-k), movmean(dMA_PL(1:nT-k),5)];

  MA_data = [MA_data;[repmat(i,nT-k,1), MA_rep_data]];
  Crit_t = [Crit_t;[repmat(i,numel(crit_t),1),crit_t']];
  if(numel(crit_t)>2)
      KeyMeasures = [KeyMeasures; [i, pre_dis_MA_PL, min_MA_PL,
      post_dis_MA_PL, T(t_min), crit_t(3)-T(t_min)]];
  end
end
```

Appendix C. Matlab Code for Graphing Simulation Outputs

```
num_rep = max(Rep);

for i = 1:num_rep

    T = MA_data(MA_data(:,1)==i,2);

    T2 = Time(Rep==i);

    PL = PartLevel(Rep==i);

    MA_PL = MA_data(MA_data(:,1)==i,3);

    dMA_smoothed = MA_data(MA_data(:,1)==i,4);

    crit_t = Crit_t(Crit_t(:,1)==i,2);

    clf

    scatter(T, MA_PL);

    hold;

    scatter(T2, PL)

    scatter(T, dMA_smoothed*10);

    scatter(crit_t, repmat(5, size(crit_t)));

    system('pause')

    clf

end
```

Bibliography

1. J. Chevalier, D. Langefeld, and P. Tracy, "Repair network integration: Connecting the dots," *The Exceptional Release*, vol. Spring 2017, pp. 15–22, 2017.

2. Y. Sheffi and J. Rice Jr, "A supply chain view of the resilient enterprise," *MIT Sloan Management Review*, vol. 47, no. 1, pp. 41–48, 2005.

3. C. Craighead, J. Blackhurst, M. Rungtusanatham, and R. Handfield, "The severity of supply chain disruptions: Design characteristics and mitigation capabilities," *Decision Sciences*, vol. 38, no. 1, pp. 131–156, 2007.

4. B. Tukamuhabwa, M. Stevenson, J. Busby, and M. Zorzini, "Supply chain resilience: definition, review and theoretical foundations for further study," *International Journal Of Production Research*, vol. 53, no. 18, pp. 5592–5623, 2015.

5. A. Munoz and M. Dunbar, "On the quantification of operational supply chain resilience," *International Journal Of Production Research*, vol. 53, no. 22, pp. 6736–6751, 2015.

6. M. Christopher and H. Peck, "Building the resilient supply chain," *The International Journal of Logistics Management*, vol. 15, no. 2, pp. 1–14, 2004.

7. T. Pettit, J. Fiksel, and K. Croxton, "Ensuring supply chain resilience: Development of a conceptual framework," *Journal of Business Logistics*, vol. 31, no. 1, pp. 1–21, 2010.

8. Department of the Air Force *Integrated Life Cycle Management*, AFI 63-101, Washington: HQ USAF, 07 March 2013.

9. D. Sanford, "The supply chain operations wing," *The Exceptional Release*, vol. Spring 2017, pp. 8–11, 2017.

10. J. Chevalier, M. Pasaretti, and P. Greenwood, "Repair network integration: Hydraulic product repair group metrics," *The Exceptional Release*, vol. Summer 2017, pp. 8–13, 2017.

11. C. Tang, "Robust strategies for mitigating supply chain disruptions," *International Journal of Logistics*, vol. 9, no. 1, pp. 33–45, 2006.

12. Y. Sheffi, "Supply chain management under the threat of international terrorism," *The International Journal of Logistics Management*, vol. 12, no. 2, pp. 1–11, 2001.

13. P. Kleindorfer and G. Saad, "Managing disruption risks in supply chains," *Production and Operations Management*, vol. 14, no. 1, pp. 53–68, 2005.

14. T. Wu, J. Blackhurst, and P. O'Grady, "Methodology for supply chain disruption analysis," *International Journal of Production Research*, vol. 45, no. 7, pp. 1665–1682, 2007.

15. J. Thun and D. Hoenig, "An empirical analysis of supply chain risk management in the german automotive industry," *International Journal of Production Economics*, vol. 131, no. 1, pp. 242–249, 2011.

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14. ABSTRACT

This research aims to extend the understanding of supply chain resiliency by utilizing a simulation model of a U.S. Air Force aircraft engine repair network to evaluate the degree of resiliency built into the system. The study compares the recovery time of the disrupted current system to that of a fully-integrated repair network; the objective being the quantification of resiliency in the current networks design and gauging the effectiveness of various strategies in reducing recovery time. This contributes to current literature by bridging the explicit gap on how to quantify, measure, and compare resilient supply chain strategies and also provides an objective means for basing managerial decisions.

15. SUBJECT TERMS

Resiliency, Repair Network Integration, Simulation, Network Disruption, Risk Management

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