

<b>REPORT DOCUMENTATION PAGE</b>					<i>Form Approved OMB No. 0704-0188</i>	
<small>The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.</small>						
<b>PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</b>						
<b>1. REPORT DATE (DD-MM-YYYY)</b>		<b>2. REPORT TYPE</b>			<b>3. DATES COVERED (From - To)</b>	
<b>4. TITLE AND SUBTITLE</b>				<b>5a. CONTRACT NUMBER</b>		
				<b>5b. GRANT NUMBER</b>		
				<b>5c. PROGRAM ELEMENT NUMBER</b>		
<b>6. AUTHOR(S)</b>				<b>5d. PROJECT NUMBER</b>		
				<b>5e. TASK NUMBER</b>		
				<b>5f. WORK UNIT NUMBER</b>		
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b>					<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>					<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
					<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b>						
<b>13. SUPPLEMENTARY NOTES</b>						
<b>14. ABSTRACT</b>						
<b>15. SUBJECT TERMS</b>						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON</b>	
a. REPORT	b. ABSTRACT	c. THIS PAGE			<b>19b. TELEPHONE NUMBER (Include area code)</b>	

**AFOSR Final Performance Report**

**A Human-Centered Approach to Sense and Respond Logistics**

**AFOSR Award No. FA9550-05-1-0182**

**John English, Ph.D. (PI-2006-2007)**

**Russell D. Meller, Ph.D. (Co-PI)**

**Edward A. Pohl, Ph.D. (PI-2008, Co-PI-2006-2007)**

**Department of Industrial Engineering**

**University of Arkansas**

## Executive Summary

The goal of this research effort was to develop *quantitative and scientific methods* that capable of assisting researchers and military logisticians in the analysis of the effectiveness of logistics technology and processes in a Sense & Respond Logistics (S&RL) environment that incorporated both a *human-centered* and a *system-based* perspective. Because of the complexities involved with S&RL concepts, it is imperative that scientific and engineering approaches based on a *holistic* and *systems engineering* perspective be utilized to improve logistics support and responsiveness within this evolving defense logistics archetype. The logistics support function should be treated as a socio-technical system where human elements, technology, and software/algorithms interact to develop solutions that can impact the entire system. To this end, with the assistance of the Logistics Readiness Branch of the Air Force Research Lab (AFRL/HEAL), Air Mobility Command (AMC) and the United States Transportation Command (USTRANSCOM), a *human-centered* research initiative consisting of eight distinct research efforts designed to investigate and support the tenants of a S&RL paradigm for the United States Air Force was developed. The specific research efforts included: 1) Effective Scheduling and Coordination of Disaster Relief Operations, 2) Experimental Evidence on Team Coordination and Collaboration Within a Distributed Logistics Network, 3) A New Paradigm For Studying Trust In Virtual Teams, 4) Developing and Evaluating Operationally Robust Forecasting Techniques in Military Logistics, 5) Integrated Distribution Planning and Forecasting for Medical Logistics, 6) An Auction-Based Framework for Resource Allocation in Disaster Relief Operations, 7) Comparing Maintenance Policies for Single-Unit, Markovian Systems, and 8) Improved Outbreak Detection for Bio Terror Response Logistics. Key contributions from this effort include: 1) New modeling paradigms for supply chain modeling and analysis in support of disasters, 2) New simulation methodologies, mathematical models and techniques for the optimization, performance evaluation, and improvement of future military logistics support networks, and 3) New methods of modeling and incorporating human performance issues and collaborative decision making within an S&RL environment. During the period of performance for this research effort, a total of 15 graduate research assistants, 4 undergraduate research assistants, and 11 faculty members were supported. The research efforts have resulted in 1 related thesis, 7 related dissertations, 14 conference papers, and 11 journal submissions.

## Table of Contents

<b>List of Figures.....</b>	<b>vi</b>
<b>List of Tables .....</b>	<b>vii</b>
<b>1      Research Task #1 .....</b>	<b>1</b>
1.1    Executive Summary .....	2
1.2    Introduction.....	3
1.3    Literature Review.....	5
1.3.1 <i>Previous Mathematical Programming-Based Optimization Research.....</i>	<i>5</i>
1.3.2 <i>Previous Heuristic-Based Optimization Research.....</i>	<i>6</i>
1.4    Mathematical Programming Model .....	8
1.4.1 <i>Sets .....</i>	<i>9</i>
1.4.2 <i>Parameters.....</i>	<i>9</i>
1.4.3 <i>Variables.....</i>	<i>10</i>
1.4.4 <i>Model .....</i>	<i>10</i>
1.5    Experimental Scenario Development .....	12
1.5.1 <i>Landslide Scenario.....</i>	<i>13</i>
1.5.2 <i>Flood Scenario.....</i>	<i>15</i>
1.5.3 <i>Tsunami Scenario.....</i>	<i>17</i>
1.6    Conclusions and Future Research.....	20
1.7    Acknowledgements.....	21
1.8    References.....	21
<b>2      Research Task #2 .....</b>	<b>23</b>
2.1    Executive Summary .....	24
2.2    Introduction.....	25
2.3    Participants.....	26
2.4    Experimental Task and Apparatus.....	27
2.4.1 <i>Computer-Based Aerial Port Simulation (CAPS): .....</i>	<i>27</i>
2.5    Experimental Design.....	30
2.6    Procedures.....	32
2.7    Results and Discussion .....	34
2.7.1 <i>Team Performance.....</i>	<i>34</i>
2.7.2 <i>Team Cognition.....</i>	<i>35</i>
2.8    References.....	38
2.9    Appendixes .....	39
2.9.1 <i>Appendix 1: Critical Task in CAPS .....</i>	<i>39</i>
2.9.2 <i>Appendix 2: Interpersonal Trust (based on Naquin &amp; Paulson, 2000).....</i>	<i>44</i>
<b>3      Research Task # 3 .....</b>	<b>45</b>
3.1    Executive summary.....	46
3.2    Objectives .....	48
3.3    Experimentation.....	48
3.3.1 <i>Instrumentation.....</i>	<i>48</i>

3.3.2	<i>Scenario</i> .....	49
3.3.3	<i>Participants and Team Development</i> .....	50
3.3.4	<i>Procedures</i> .....	51
3.4	Data analysis .....	53
3.4.1	<i>Statistical Data Analysis</i> .....	55
3.4.2	<i>Qualitative Analysis</i> .....	62
3.5	Discussions and conclusions .....	63
3.6	Recommendations for future work .....	67
3.7	References .....	68
3.8	Appendixes .....	69
3.8.1	<i>Appendix A—Gameplay Instructions</i> .....	69
3.8.2	<i>Appendix B—Key Map</i> .....	71
3.8.3	<i>Appendix C—Situation Awareness Calibration</i> .....	72
3.8.4	<i>Appendix D—Commander Information Sheet</i> .....	73
3.8.5	<i>Appendix E—Resource Checklist</i> .....	74
3.8.6	<i>Appendix F—Example Mission Order</i> .....	74
3.8.7	<i>Appendix G—Alpha Soldier Information Sheet</i> .....	74
3.8.8	<i>Appendix H—Us Army Reference Sheet</i> .....	75
3.8.9	<i>Appendix I—Enemy Reference Sheet</i> .....	76
3.8.10	<i>Appendix J—Mission Orders And Delivery</i> .....	77
<b>4</b>	<b>Research Task # 4</b> .....	<b>82</b>
4.1	Executive Summary .....	83
4.2	The MCARTA Technique for Intermittent Demand Forecasting.....	85
4.2.1	<i>Problem/Background</i> .....	85
4.2.2	<i>Methods, Assumptions, and Procedures</i> .....	85
4.3	Results and Discussion .....	86
4.4	The Effects of Forecasting Techniques on the Operational Performance Measures of an Inventory System .....	88
4.4.1	<i>Problem/Background</i> .....	88
4.4.2	<i>Methods, Assumptions, and Procedures</i> .....	88
4.4.3	<i>Results and Discussion</i> .....	89
4.5	A Meta Forecasting Methodology for Large Scale Inventory Systems with Intermittent Demand.....	90
4.5.1	<i>Problem/Background</i> .....	90
4.5.2	<i>Methods, Assumptions, and Procedures</i> .....	90
4.5.3	<i>Results and Discussion</i> .....	91
4.6	Forecast based inventory policy updating.....	91
4.6.1	<i>Problem/Background</i> .....	91
4.6.2	<i>Methods, Assumptions, and Procedures</i> .....	92
4.6.3	<i>Results and Discussion</i> .....	93
4.7	References.....	93
<b>5</b>	<b>Research Task #5</b> .....	<b>95</b>
5.1	Executive Summary .....	96
5.2	Introduction.....	97
5.3	Background Discussions and Motivation .....	99

5.4	Mathematical Model for Class VIII Materiel Distribution .....	100
5.4.1	<i>Sets</i> .....	100
5.4.2	<i>Parameters</i> .....	100
5.4.3	<i>Variables</i> .....	101
5.4.4	<i>Model Formulation</i> .....	101
5.5	Experimental Study .....	102
5.6	Conclusions and Future Research .....	107
<b>6</b>	<b>Research Task #6</b> .....	<b>109</b>
6.1	Executive Summary .....	110
6.2	Introduction .....	111
6.3	Methods, Assumptions, and Procedures .....	112
6.3.1	<i>Announcement construction phase</i> .....	115
6.3.2	<i>Bid construction phase</i> .....	115
6.3.3	<i>Bid evaluation phase</i> .....	117
6.3.4	<i>Experimental Study</i> .....	119
6.3.5	<i>Environmental factors</i> .....	120
6.3.6	<i>Auction design parameters</i> .....	121
6.4	Results and Discussion .....	128
6.5	Conclusions .....	129
6.6	References .....	132
<b>7</b>	<b>Research Task #7</b> .....	<b>133</b>
7.1	Executive Summary .....	134
7.2	Introduction .....	134
7.3	Methods, Assumptions, and Procedures .....	136
7.4	System definition .....	136
7.5	Analysis of time to first failure for constant threshold .....	137
7.6	Analysis Of Time To First Failure For Random Variable Threshold .....	139
7.7	Age-Based Maintenance Policy .....	140
7.8	Condition-Based Maintenance Policy .....	141
7.9	Results and Discussion .....	141
7.10	Constant Failure Threshold .....	141
7.11	Random Failure Threshold .....	143
7.12	Conclusions .....	145
7.13	Recommendations .....	145
7.14	References .....	146
<b>8</b>	<b>Research Task #8</b> .....	<b>147</b>
8.1	Executive Summary .....	148
8.2	Introduction .....	149
8.3	Methods, Assumptions, and Procedures .....	150
8.4	Results and Discussion .....	151
8.5	Conclusions .....	155
8.6	Recommendations .....	155
8.7	References .....	157

## **List of Figures**

Figure 1. Communication Diagram of the Air Terminal Operations Flight (ATOF).....	29
Figure 2. An Example of Passenger Services Interface.....	30
Figure 3. An Example of Training Materials (for passenger services section) .....	33
Figure 4. Real Time Map Available to Commander.....	49
Figure 5. Example Views of Soldiers .....	50
Figure 6. Example Supply Chain Network .....	99
Figure 7. Prime Vendor-Driven Supply Chain Network of Project Focus .....	100
Figure 8. Top Class VIII Lines at USAMMC-SWA Sourced by Prime Vendor.....	103
Figure 9. Time Period 1 Model Solution for Line 1 'Pad Prep Alcohol 100S' .....	106
Figure 10. Procurement Auctions Framework.....	113
Figure 11. Experimental design factors .....	119

## List of Tables

Table 1. Aircraft Type Characteristic Data.....	13
Table 2. Landslide Aircraft Usage.....	14
Table 3. Landslide Load Distribution Airplane A1 .....	14
Table 4. Landslide Weight Distribution Airplane A1 .....	15
Table 5. Aircraft Type Characteristic Data.....	15
Table 6. Flood Helicopter Usage .....	16
Table 7. Flood Load Distribution Helicopter A1 .....	17
Table 8. Flood Weight Distribution Helicopter A1 .....	17
Table 9. Tsunami Aircraft Usage.....	18
Table 10. Landslide Load Distribution Airplane A1 .....	19
Table 11. Landslide Weight Distribution Airplane A1 .....	19
Table 12. An Example of Task Scenario .....	27
Table 13. Mixed Factor Experimental Design Used in the Study .....	31
Table 14. Frequency Table for Assessment of Commander's Trust of Teammates .....	53
Table 15. Synopsis of Team Trust Assessment Questionnaire.....	54
Table 16. Descriptive and Statistical Results for "Measures of Trust" Scale.....	56
Table 17. Descriptive and Statistical Results for "Trustworthiness" Scale .....	57
Table 18. Descriptive and Statistical Results for "Perceived Cohesion" Scale .....	58
Table 19. Descriptive and Statistical Results for "Trust in Systems" Scale .....	59
Table 20. Descriptive and Statistical Results for "Interpersonal Trust" Scale .....	61
Table 21. Commander and Alpha Soldier's Examples of Events or Actions that Influenced Their Trust in Their Teammates.....	62
Table 22. Annual Demand for Top 20 Class VIII Lines--Random Distribution by Month .....	104
Table 23. From/To Travel Time Matrix for Supply Chain Locations (Sites).....	104
Table 24. Initial Inventory for Top 20 Class VIII Lines by Prime Vendor .....	105
Table 25. Assumed Maximum Total Inventory by Site.....	105
Table 26. Projected Periodic Inventory Levels for Line 1 'Pad Prep Alcohol 100S' by Site ...	107
Table 27 Parameters and decision variables in bid construction phase.....	117
Table 28. Environmental Factors and Their Levels.....	120
Table 29. Four scenarios to evaluate different auction design parameters. ....	122
Table 30. First scenario results .....	123
Table 31. Second scenario results.....	124
Table 32. Third Scenario Results.....	127
Table 33. Fourth Scenario Results.....	127
Table 34. Comparison of Four Scenarios .....	128
Table 35. Log likelihood Values Associated with Main Effects GLM given Reasonable Combinations of Distribution and Link .....	152
Table 36. Example Details of the Log-Gamma Model for 2001-2003 Lab Data .....	153
Table 37. Probabilities of Finding an Outbreak in Error for SPC Alone, Linear Regress +, and Gamma Regress + .....	154



## **1 Research Task #1**

### **Effective Scheduling and Coordination of Disaster Relief Operations**

#### **Submitted By:**

Scott J. Mason, Ph.D. (PI)  
Nebil Buyurgan, Ph.D. (Co-PI)  
Mustafa Alp Ertem (Graduate Research Assistant)  
Behlul Saka (Graduate Research Assistant)  
Troy Long (Undergraduate Research Assistant)  
Sarah Brotherton (Undergraduate Research Assistant)

Department of Industrial Engineering  
University of Arkansas  
4207 Bell Engineering Center  
Fayetteville, AR 72701

#### **Presentations and Papers:**

Al-Otaibi, M.M., Kurz, M.E., Mason, S.J., 2009, Multiobjective Disaster Relief Operations Scheduling, Industrial Engineering Research Conference, Miami, Florida.

Long, T.C., Mason, S.J., Buyurgan, N., Brotherton, S., 2009, Effective Scheduling and Coordination of Disaster Relief Operations, *Military Operations Research*, to be submitted.

Montgomery, W., Mason, S.J., 2009, Mission Assignment and Leave Block Scheduling: Maintaining Readiness and Sustainment of Military Troops During War-Time, Industrial Engineering Research Conference, Miami, Florida, *to appear*.

Montgomery, W. \*, Mason, S.J., Pohl, E.A., 2008, Military Troop Leave Scheduling During Wartime, INFORMS Annual Meeting, Washington, D.C.

#### **Dissertation Related:**

Al-Otaibi, M.M., 2008, Scheduling Disaster Relief Operations, Doctoral Dissertation, University of Arkansas.

## 1.1 Executive Summary

The United States (US) Transportation Command (TRANSCOM) is the US Department of Defense's primary distribution agent for transporting military troops during deployment activities and delivering disaster relief supplies during humanitarian aid operations. Transportation and scheduling decisions are vital for supplying personnel, food, medical supplies, and building materials to an area affected by a disaster—they impact how and when these critical items arrive in theater. Moreover, the capabilities and associated capacities of available transportation vehicles (resources) add an additional layer of complexity into the transportation scheduling problem. In an attempt to minimize transportation system inefficiencies, we present an optimization model for scheduling transportation operations that incorporates the important practical considerations of dependency and precedence relationships between items. Our model seeks to minimize inventory holding. Initial experimental results suggest the proposed optimization model is an attractive alternative to current simulation-based theater distribution models.

## 1.2 Introduction

Troop deployment and humanitarian aid operations in air mobility are a series of efforts conducted by interconnected transportation and logistics systems composed of airlift, air fueling, and air mobility support (Hazdra, 2001). Airlift, which is the focus of this research, consists of the transportation of military and civilian personnel (passengers), materials (cargo), and supplies (cargo) through air when and from/to where they are needed. In a disaster relief/humanitarian aid environment, passengers may be doctors, construction personnel, or relief workers, while cargo may consist of medical supplies, construction equipment, or food. These passengers and cargo are transported from their initial staging locations (e.g., military bases, hospitals, etc.) to the impacted geographic area(s).

The United States Transportation Command (USTRANSCOM) is responsible for the transportation and delivery of passengers and cargo for the US Department of Defense. In a typical transportation scenario, USTRANSCOM receives requirements and information on the passengers and cargo to move, as well as origin and destination information. Scheduling data pertaining to 1) when items to be transported are available at the origin and 2) when these same items are due at the destination are also essential pieces of information for USTRANSCOM. Considering all available data, USTRANSCOM plans and executes item transportation and distribution.

Transported items often are of variable size, dimension, or priority/importance, and have dissimilar planned/required arrival dates on location. Some key issues that must be considered for successful delivery is item compatibility between items being transported. For example, some pairs of items are not compatible to occupy the same aircraft at the same time (e.g., medical

equipment should not be on the same aircraft as ammunition due to potential contamination of the medical equipment).

These considerations are essential for rapid, efficient disaster relief operations and should be considered simultaneously for maximum efficacy. Disaster relief operations efficacy is a function of both item-to-transportation vehicle (e.g., aircraft) assignment and vehicle scheduling decisions. Considering that scheduling transportation resources in disaster relief operations is already a logistics challenge, focused research is needed into integrated cargo load building/formation (i.e., multiple items of different attributes are grouped to “form” loaded aircraft) and scheduling (cargo transportation and distribution assets are scheduled in complex logistics networks) problems.

In this study, we investigate the use of a time-indexed mathematical model to analyze this important and integrated problem. While our primary motivation comes from disaster relief operations scheduling, it is important to note that another application of this same integrated load building and scheduling problem is troop deployment. When battalions/companies/divisions of soldiers are deployed to a combat theater or other location, their associated equipment, gear, and weapons systems must be transported effectively and efficiently using USTRANSCOM resources. In this case, various item dependence and precedence relationships can also exist.

Our proposed model provides decision makers with the ability to deliver timely for any desired number of available transportation resources. The remaining sections of this paper are organized as follows. Section 2 begins by defining key terms in air mobility operations, and then reviews the current literature pertaining to military applications. Our proposed mathematical programming model and some extensions are presented in Section 3. Section 4 explains the

heuristic development, and Section 5 discusses our experimental design and results. Finally, research conclusions and directions for future research are provided in Section 6.

### 1.3 Literature Review

There exists a considerable amount of previous research related to item-to-vehicle assignments and mission scheduling for different military operations. A number of researchers try to capture the dynamic aspects of deployment operations using optimization-based techniques. Two primary classes of optimization-based techniques are evident: mathematical optimization and heuristic optimization.

#### 1.3.1 Previous Mathematical Programming-Based Optimization Research

Morton *et al.* (1996) present a multi-period, multi-commodity, network-based optimization formulation containing demand satisfaction, aircraft balance, aircraft capacity, aircraft utilization, and airfield capacity constraints. The model's objective is to minimize total weighted penalties for late deliveries and non-deliveries. If sufficient resources exist to meet all delivery targets, then the model seeks to minimize the number of aircraft used. Rosenthal *et al.* (1997) apply this same model to a fleet-selection problem and make it more tractable via variable-elimination techniques.

An optimal requirements airlift mobility study is discussed in Yang *et al.* (1996). The authors formulate the mobility system as a pickup and delivery vehicle routing and scheduling problem with time-window constraints. After developing a set-partitioning based formulation, the authors apply column-generation and column-elimination heuristics to decrease the computational complexity of their mathematical model.

Baker *et al.* (2002) provide an extensive discussion on the history of mathematical models within airlift mobility. The NRMO model presented in Baker *et al.* (2002) captures time-dynamic movement of large-scale military deployment operations and considers aerial refueling, crew availability, intra-continental aircraft shuttles, and unit resolution for cargo. Finally, deNijs (2004) develops an integer programming formulation of the airlift problem. The model's objective is to minimize the number of ship sailings and aircraft sorties (the number of ships and aircraft allocated to the deployment operation).

### *1.3.2 Previous Heuristic-Based Optimization Research*

In addition to mathematical programming-based methodologies, a number of authors have investigated heuristic solution methodologies for air mobility operations. McKinzie and Barnes (2004) review Strategic Mobility Models (SMMs) from the viewpoint of strategic logistics and force protection. The authors provide an extensive review of force deployment practices within and outside CONUS, and describe cargo and passenger and passenger flow during deployment.

Crino *et al.* (2004) investigated the theater-distribution vehicle routing and scheduling problem using group-theoretic tabu search. In their study, the authors describe both the conceptual context, based on a flexible group-theoretic tabu search framework, and the software implementation of a robust, efficient, and effective, prescriptive generalized-theater-distribution methodology. Their methodology evaluates and prescribes the routing and scheduling of multimodal theater transportation assets with the objective of minimizing unmet customer demand, late deliveries, and vehicle costs (fixed and variable). Weber and Bojduj (2006) also utilize a tabu search algorithm for simultaneously solving strategic and operational levels of

planning. Their algorithm uses partial order planning to separate the optimization process from the constraint verification process.

Godfrey *et al.* (2004) present negotiation protocols for the distributed optimization problem of commercial air carriers supporting military airlifts. Their approach to the airlift planning and scheduling problem uses software agents to collaboratively plan the airlift. The current approach is auctioning the missions subject to a reserved price and allowing carriers to swap missions when mutually beneficial. Their study cuts the controllable operating costs and schedule-disruption costs by more than half compared with the centralized planning approach currently used. Furthermore, their approach protects the military by capping mission profit potential using a Vickrey auction mechanism (deVries and Vohra, 2003), and protects the carriers from being forced to share information or cooperate with its economic competitors. Smith *et al.* (2004) describe an incremental, constraint-based scheduling model that provides support for day-to-day allocation and management for barrel allocation problems. The presented system in that study utilizes search procedures to provide a range of automated and semi-automated scheduling capabilities.

Clark *et al.* (2004) present a large-scale optimization-based planning method that uses column generation to schedule the movement of ammunition and transportation resources through a time-space network representation of the distribution system. In their method, the optimization-based planner is initialized using a feasible solution generated by a heuristic planning method. Both the optimization-based planner and the heuristic planner generate plans with improved vehicle utilization and delivery tardiness values as compared to plans generated using current planning techniques. In addition, the heuristic planner is implemented within a closed-loop planning and control framework and is used to generate plans on a rolling horizon

basis. Johnstone *et al.* (2004) developed a mixed integer program model of munitions flow with the primary objective of minimizing the overall response time to meet demands of the various air bases. They also demonstrate an analysis methodology using their model by implementing it in an algebraic modeling environment, employing a standard general-purpose solution routine, and verifying against a realistic planning scenario.

Although most of the abovementioned research focuses on creating mathematically sound optimization models, the research does not take dependency and precedence constraints into account simultaneously. Besides, some network flow and simulation models are unable to provide timely results, while some mathematical models lack capturing the overall system behavior due to dynamic and non-hierarchical structure-of-problem domain. In this study, we present a mathematical model for item-to-aircraft assignment and scheduling of air missions for military disaster and humanitarian relief operations. For making assignment and scheduling decisions, dependency and precedence constraints are considered. Aircraft are the only transportation mode used in this study, and every aircraft is assumed to have passenger and cargo weight and volume capacity. Performance of the model is evaluated via test cases using real data.

#### 1.4 Mathematical Programming Model

The following mathematical model takes item-dependent constraints into account. As of our knowledge, this is the first use of these constraints in the military context. The constraints included in this model are dependability and precedence of the items shipped. The main idea is that if different types of loads are not considered in deployment operation, inefficiencies will occur. Examples can be given as military equipment would not be useful without the soldiers,



transporting medical equipment with construction equipment might be harmful to some types of medicine.

There are certain characteristics of the model. Only one depot and one contingency location are considered. A load consists of passengers and cargo items. Depending on the situation, different modes of transportation are considered with different capacities related to passengers and cargo items. This model takes the cumulative multi-period demand, aircraft availability, aircraft capacity, weights and volumes of the cargo items as parameters and assigns the loads to available aircrafts while meeting scheduling requirements. Aerial refueling, crew availability, maximum-on-the-ground constraints are excluded from the model.

#### 1.4.1 Sets

$I$	set of first type of containers
$J$	set of second type of containers
$R$	set of all containers where $R = I \cup J$
$P$	set of passengers
$C$	set of cargo items
$N$	set of all load where $N = P \cup C$
$T$	set of periods

#### 1.4.2 Parameters

$W_j$	weight capacity of aircraft $j$ (pounds) for $\forall j \in J$
$w_i$	weight of an cargo item $i$ (pounds) for $\forall i \in C$
$V_j$	volume capacity of aircraft $j$ (cubic feet) for $\forall j \in J$
$v_i$	volume of an cargo item $i$ (cubic feet) for $\forall i \in C$
$Q_j$	passenger capacity of aircraft $j$ (quantity) for $\forall j \in J$
$D_i^t$	demand of item $i$ (quantity) at the contingency by period $t$
$a_j$	round trip travel time (periods) for $\forall j \in J$
$B$	normalizing value for percent demand satisfied
$r_i^t$	cumulative availability of item $i$ (quantity) at the supply base by period $t$
$b$	$n \times n$ binary matrix that shows the compatibility relationship between items

$$\begin{bmatrix}
b_{1,1} & b_{1,2} & \text{L} & b_{1,n-1} & b_{1,n} \\
b_{2,1} & b_{2,2} & \text{L} & b_{2,n-1} & b_{2,n} \\
\text{M} & \text{M} & & \text{M} & \text{M} \\
\text{M} & \text{M} & & \text{M} & \text{M} \\
\text{M} & \text{M} & & \text{M} & \text{M} \\
b_{n-1,1} & b_{n-1,2} & \text{L} & b_{n-1,n-1} & b_{n-1,n} \\
b_{n,1} & b_{n,2} & \text{L} & b_{n,n-1} & b_{n,n}
\end{bmatrix}$$

$b_{i,i'}$   $\begin{cases} 1, i \text{ and } i' \text{ are not compatible} \\ 0, \text{o/w} \end{cases}$ , where  $\forall i \in N, \forall i' \in N, i \neq i'$   
 $L_{i,t}$  importance of item  $i$  during time  $t$ , where  $i \in N, t \in T$

### 1.4.3 Variables

$y_{i,j}^t$   $\begin{cases} 1, \text{if item } i \text{ is assigned to aircraft } j \text{ at time period } t \\ 0, \text{o/w} \end{cases}$ ,  $\forall i \in N, \forall j \in J, \forall t \in T$   
 $x_{i,j}^t$  quantity of flow of item  $i$  in aircraft  $j$  at time period  $t$   
 $z_j^t = \begin{cases} 1, \text{aircraft } j \text{ is available at the depot at the beginning of time period } t \\ 0, \text{o/w} \end{cases}$   
 $h_{i,t}$  quantity of item  $i$  delivered early at time period  $t$   
 $s_{i,t}$  quantity of item  $i$  delivered late at time period  $t$   
 $u_{i,t}$  volume utilization of aircraft  $j$  in period  $t$   
 $q_{i,t}$  weight utilization of aircraft  $j$  in period  $t$

### 1.4.4 Model

$$\min \sum_{i \in N} \sum_{t \in T} ((h_{i,t} + s_{i,t}) \times (B_i) \times (L_{i,t})) / 1000000 \quad (1)$$

$$\sum_{i \in C} w_i x_{i,j}^t \leq W_j \quad \forall j \in J, \forall t \in T \quad (2)$$

$$\sum_{i \in P} x_{i,j}^t \leq Q_j \quad \forall j \in J, \forall t \in T \quad (3)$$

$$\sum_{i \in C} v_i x_{i,j}^t \leq V_j \quad \forall j \in J, \forall t \in T \quad (4)$$

$$\sum_{x=t}^{x+a_j-1} z_j^t = 1 \quad \forall j \in J, \forall t \in T \quad (5)$$

$$y_{i,j}^t \leq z_j^t \quad \forall i \in N, \forall j \in J, \forall t \in T \quad (6)$$

$$w_i x_{i,j}^t \leq W_j y_{i,j}^t \quad \forall i \in N, \forall j \in J, \forall t \in T \quad (7)$$

$$\sum_{j \in J} \sum_{k=0}^{\lceil \frac{a_j}{2} \rceil} x_{i,j}^k + s_{i,t} = h_{i,t} + D_{i,t} \quad \forall i \in N, \forall t \in T \quad (8)$$

$$\sum_{j \in J} \sum_{t' \in T} x_{i,j}^{t'} \leq r_{i,t} \quad \forall i \in N, \forall t \in T \quad (9)$$

$$y_{i,j}^t + y_{i',j}^t \leq 2 - b_{i,i'} \quad \forall i \in N, \forall i' \in N, i \neq i', \forall j \in J, \forall t \in T \quad (10)$$

$$u_{j,t} = \sum_{i \in N} x_{i,j}^t \times \frac{v_i}{V_j} \quad \forall j \in J, \forall t \in T \quad (11)$$

$$w_{j,t} = \sum_{i \in N} x_{i,j}^t \times \frac{w_i}{W_j} \quad \forall j \in J, \forall t \in T \quad (12)$$

$$y_{i,j}^t \in \{0,1\} \quad \forall i \in N, \forall j \in J, \forall t \in T$$

$$x_{i,j}^t \geq 0 \text{ and integer} \quad \forall i \in N, \forall j \in J, \forall t \in T$$

$$z_j^t \in \{0,1\} \quad \forall j \in J, \forall t \in T$$

$$h_{i,t} \geq 0 \text{ and integer} \quad \forall i \in N, \forall t \in T$$

$$s_{i,t} \geq 0 \text{ and integer} \quad \forall i \in N, \forall t \in T$$

The model's objective function (1) is to minimize the normalized total weighted earliness and tardiness. Constraint set (2) ensures that cargo weight capacity of an aircraft is not violated. Constraint set (3) ensures that passenger capacity of an aircraft is not violated. Constraint set (4) ensures that the cargo volume capacity of an aircraft is not violated. Constraint set (5) makes sure that the availability of aircraft at the depot. Constraint set (6) links the availability and assignment decisions. Constraint set (7) links the availability and assignment decisions. Constraint set (8) assigns early and late items. Constraint set (9) verifies that the items are released before loaded on aircraft. Constraint set (10) satisfies the compatibility between items (mutual exclusiveness). Constraint set (11) sets the volume utilization of an aircraft. Constraint set (12) sets the weight utilization of an aircraft. Finally, constraint set (13) sets the time utilization over all periods.

## 1.5 Experimental Scenario Development

Our mathematical model is tested with realistic test scenarios where different demands are required for different scenarios. We took into consideration three different scenarios that our model could be used. The purpose of using different scenarios such as a landslide, flood, and tsunami disaster is to prove that our model could be flexible to handle different types of demand with different time constraints using various modes of transportation. It is vital to us that it could all be changed to what the user considers to be the realistic for different situations.

Generally, the types of cargo items are living, medical, and military equipments, food, and clothing. Types of passengers are soldiers, doctors, and workers. Medical equipment is assumed to be a container full of medical supplies for one doctor, construction equipment is assumed to be a midsize Bobcat excavator. Food is Meal, Ready to Eat (MRE) and military equipment is considered to be a foot locker of needed weapons for one soldier.

The release date matrix shows the demand quantity in certain mission points and weights associated with different types of loads. The amount released was determined using the product of the maximum total demand scaled by a scalar of 1.05 and gamma(2,2) distribution. The scalar was used to elongate the time, in periods, that the maximum demand for each item was met halfway. Further, the importance of items over time depended on the scenario. Our information was received through interviews with retired military experts.

The earliness and tardiness values are normalized by multiplying the value by the ratio of the total demand of the greatest numerically demanded item to the total demand of the item in question. This places the item in question's demand in the units of the greatest numerically demanded item, allowing them to be proportionately added in the objective function. The values are further weighted by the time-dependent importance.

### 1.5.1 Landslide Scenario

First, a landslide scenario is tested. Specific numbers of aircraft are assumed to be available at the beginning of deployment. The aircraft used are shown below in Table 1. The time horizon is 23 periods, where a period is assumed to be 12 hours. The demand is ordered according to the time periods. Along with doctors, medical and living equipment, food, and construction workers, we need heavier machinery and utility workers as well. The compatibility relationships were determined to not allow the heavy machinery to be loaded on the same aircraft as the food/water and medical equipment due to the possible damage and/or contamination that the machinery can inflict. According to retired military experts one of the main tasks in a landslide is to uncover the bodies. Therefore we send construction equipment and workers first, then the doctors and medical and living equipment for the survivors, as landslide response consists of uncovering bodies then dealing with infrastructure and transportation.

Table 1. Aircraft Type Characteristic Data

Characteristic name	Aircraft Type	
	C-17	C-5
cargo capacity (lb)	170,000	400,000
passenger capacity	102	73
speed (miles/hr)	470	330
travel time to contingency (periods)	2	3
volume capacity(ft <sup>3</sup> )	24,000	42,000

Our mixed-integer program is coded in AMPL and analyzed using CPLEX v10.1. The test case scenarios are run on a quad core, quad processor PC-based server with 128 GB of RAM. All runs produced feasible results. Aircraft are used multiple times with round trips during the time horizon. The longest solve time was 35.9 minutes. The average solve time was 7.6

minutes. The airplane usage is shown in Table 2. Further, Tables 3 and 4 show example load information for aircraft A1.

Table 2. Landslide Aircraft Usage

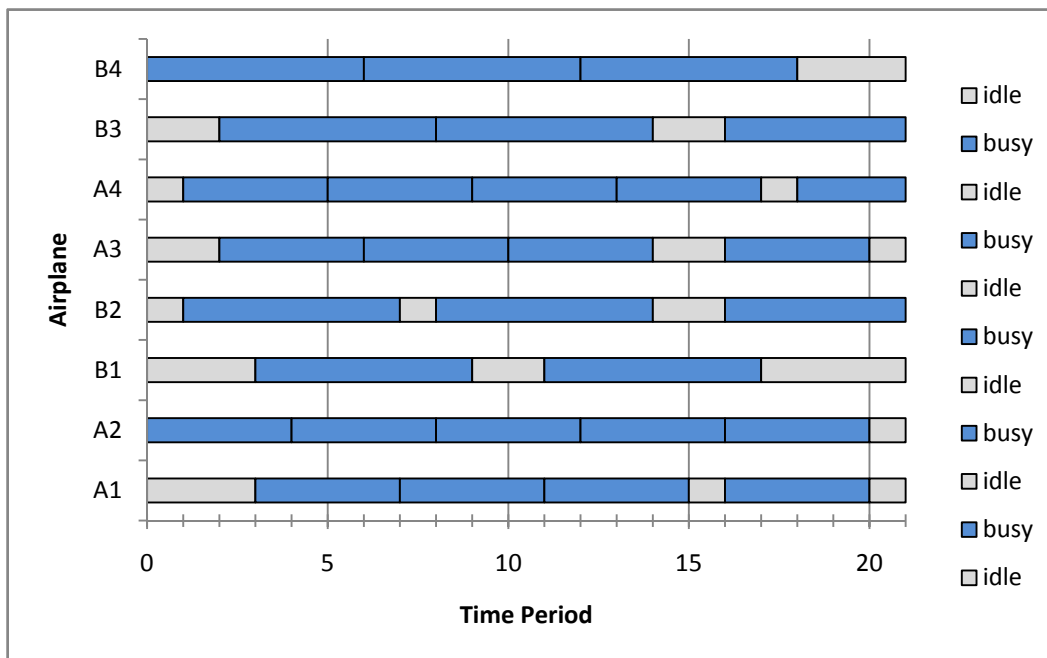


Table 3. Landslide Load Distribution Airplane A1

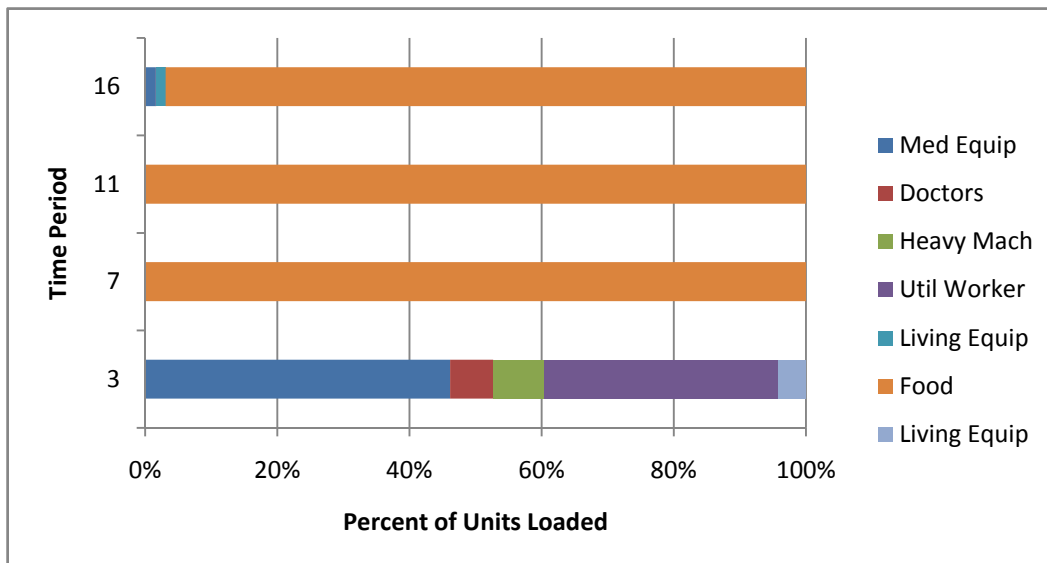
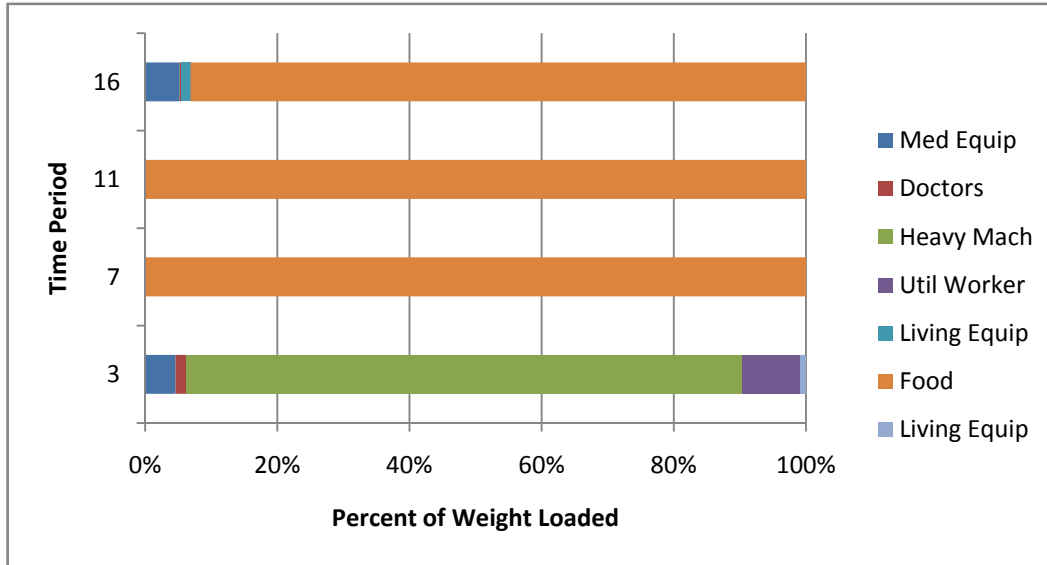


Table 4. Landslide Weight Distribution Airplane A1



### 1.5.2 Flood Scenario

For this scenario we assume that helicopters would also be used due to the area that needs the relief will most likely be unusable for a cargo transporter plane to land safely. The data for the helicopters used are explained in Table 5. The compatibility relationships were issued to be that the food/water and living equipment could not be loaded on the same aircraft. Living equipment is assumed to be generators that carry gas in which it might be considered harmful to the food/water if some were damaged during transport.

Table 5. Aircraft Type Characteristic Data

Characteristic name	Aircraft Type	
	HH -60 G	CH - 47
	Pave Hawk	Chinook
cargo capacity (lb)	6000	28000
passenger capacity	10	40
speed (miles/hr)	184	137
travel time to contingency (periods)	2	3
volume capacity(ft <sup>3</sup> )	416	1400

In terms of our experimental results, helicopters are used multiple times with round trips during the time horizon. The longest solve time was 11.1 minutes. The average solve time was 3.1 minutes. The helicopter usage is shown in Table 6. Further, Tables 7 and 8 show the load information for aircraft A1.

Table 6. Flood Helicopter Usage

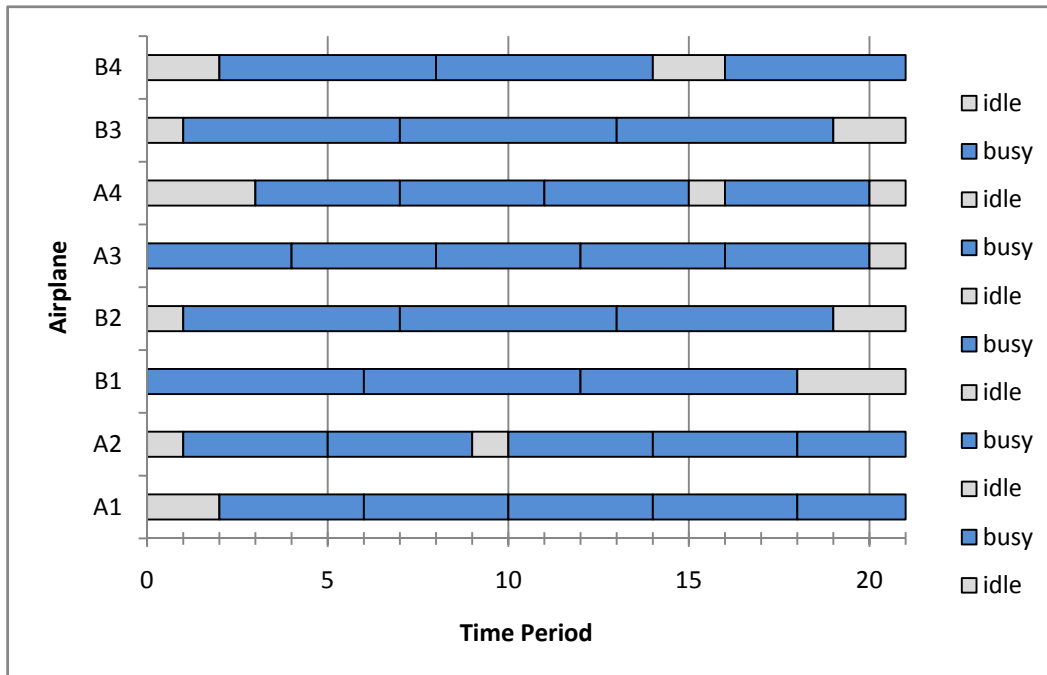




Table 7. Flood Load Distribution Helicopter A1

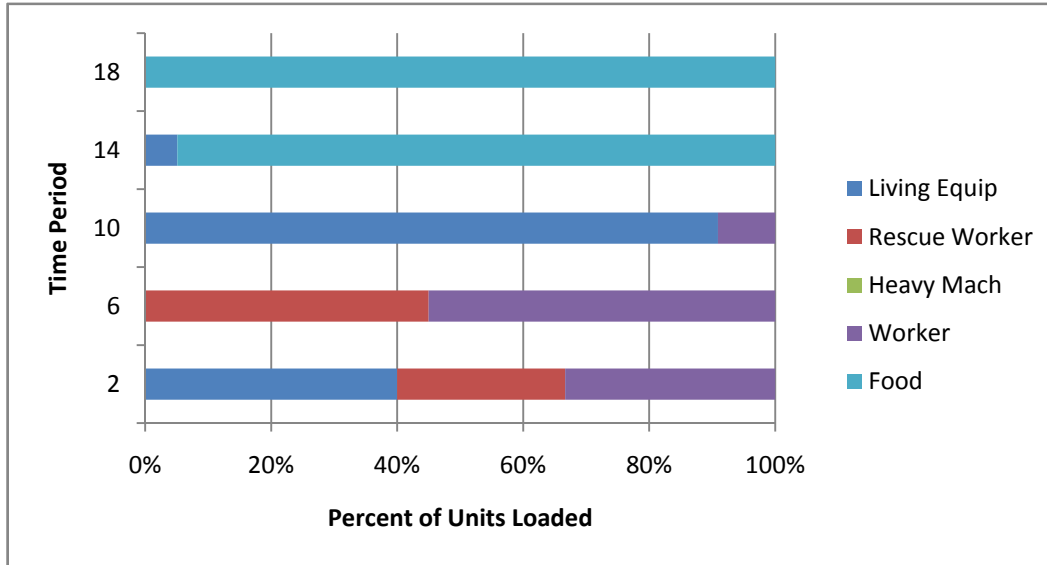
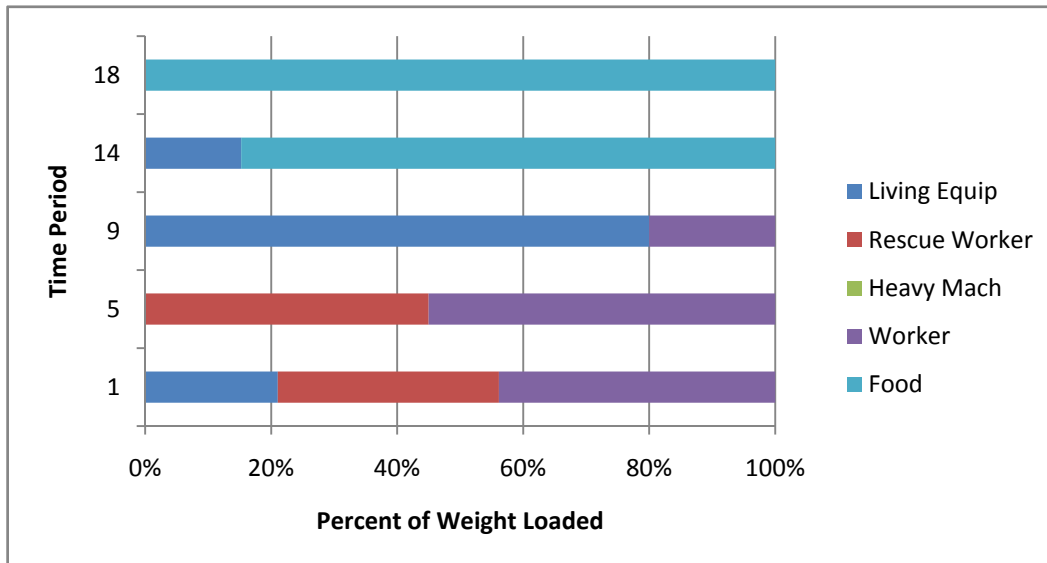


Table 8. Flood Weight Distribution Helicopter A1



### 1.5.3 Tsunami Scenario

We used the same plane assumptions as the landslide scenario shown in Table 1 for our tsunami scenario investigations. The compatibility relationships between the items are that medical equipment cannot be loaded into the same aircraft as construction or military equipment

as well as military equipment cannot be loaded on the same aircraft as food/water because the food/water and medical equipment could be damaged or contaminated during flight. We added soldiers and military equipment to the demand to guard and control the area of the disaster location. Living equipment, in this case, is considered to be tents and their contents.

In this final scenario, aircraft are used multiple times with round trips during the time horizon. The longest solve time was 46.5 minutes. The average solve time was 6.1 minutes. The airplane usage is shown in Table 9. Finally, Tables 10 and 11 show the load information for aircraft A1.

Table 9. Tsunami Aircraft Usage

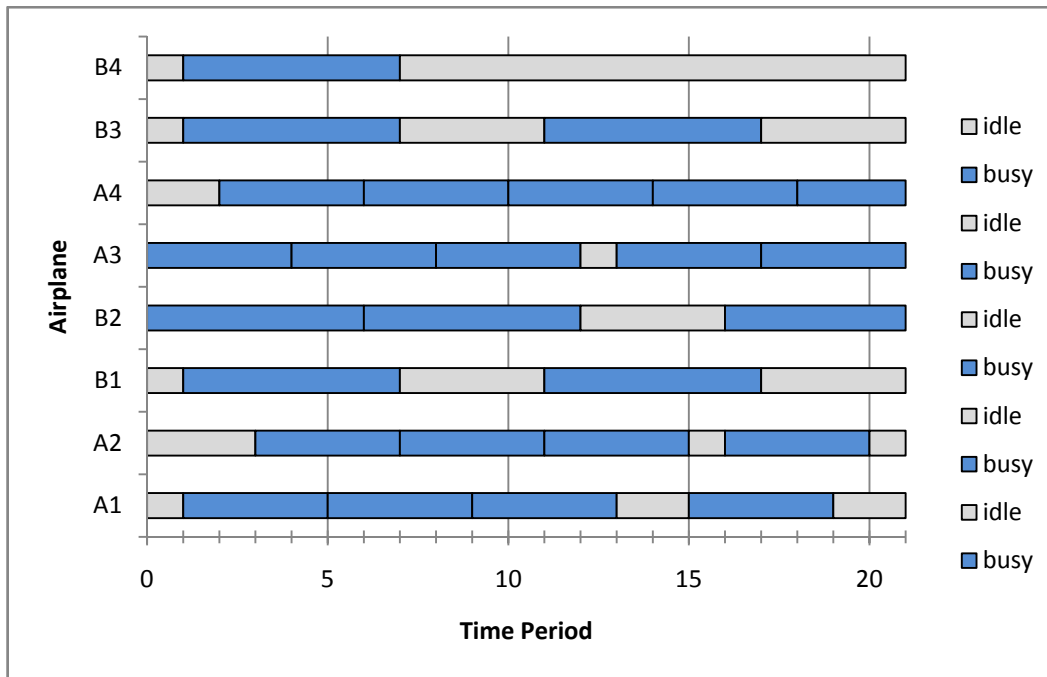


Table 10. Landslide Load Distribution Airplane A1

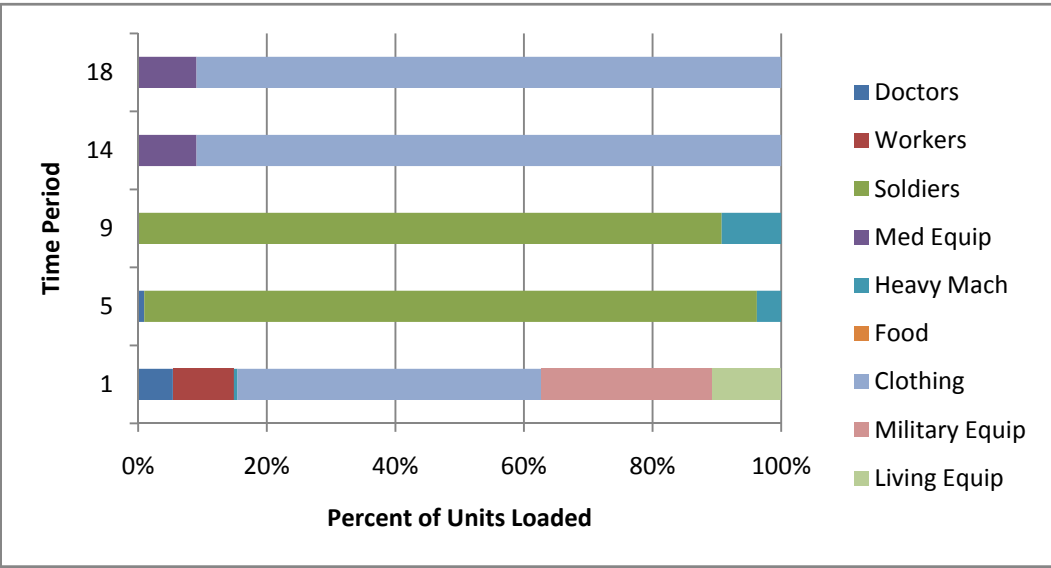
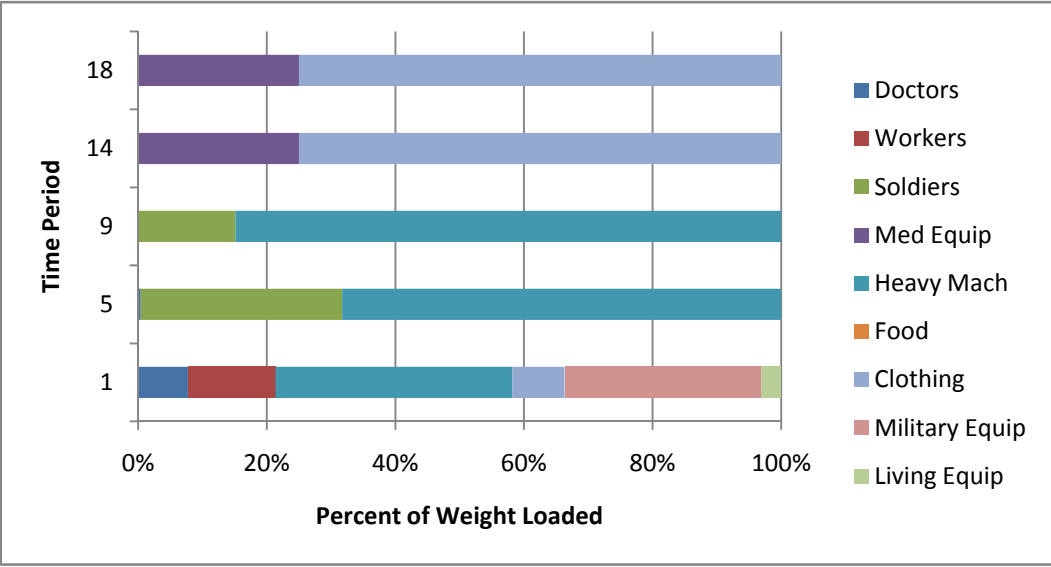


Table 11. Landslide Weight Distribution Airplane A1



## 1.6 Conclusions and Future Research

The problem of item-to-aircraft assignment and scheduling of air missions for military disaster and humanitarian relief operations is analyzed in this paper. Item-specific dependency and precedence constraints are embedded in a Mixed Integer Programming (MIP) formulation with time-varying demands as critical periods. The MIP formulation is tested via realistic scenarios and is shown to be functioning correctly. As of authors' knowledge, this is the first use of item-specific dependency and precedence constraints simultaneously in a military context.

The computational results point toward more thorough analysis of tractability of MIP formulation. Although results are obtained for six and eight aircraft, ten aircraft case couldn't be solved by MIP formulation in a reasonable amount of time. The formulation should be improved to get better cuts during MIP branching. Our optimization model is capable of accommodating different types of transportation assets with varying capacities (e.g., airplane vs. helicopter). Experimental results show different vehicle loading profiles corresponding to item-type due dates, compatibilities, and precedence relationships.

Look-ahead scheduling, improvement in plane packing, and combining unit types might be studied in future work to get more realistic formulations, along with Aerial refueling, crew availability, and maximum-on-the-ground constraints. The MIP formulation developed in this paper can be used in the previous literature (Baker *et al.*, 2002; Rosenthal *et al.*, 1997). This will be a significant improvement for the current models.

## 1.7 Acknowledgements

The authors would like to thank Rear Adm. (ret) Jack Buffington, Associate Director of the Mack-Blackwell Rural Transportation Center, for his invaluable guidance and inputs during scenario development phase of this research effort.

## 1.8 References

- Baker, S.F., Morton, D.P., Rosenthal, R.E., Williams, L.M. (2002) Optimizing military airlift. *Operations Research*, 50(4), 582-602.
- Clark, S.J., Barnhart, C., Kolitz, S.E. (2004) Large-Scale Optimization Planning Methods for the Distribution of US Army Munitions, *Mathematical and Computer Modeling Journal*, 39(6-8), 697-714.
- Crino, J.R., Moore, J.T., Barnes, J.W., Nanry, W.P. (2004) Solving The Theater Distribution Vehicle Routing and Scheduling Problem (TDRSVP) Using Group Theoretic Tabu Search, *Mathematical and Computer Modeling Journal*, 39(6-8), 599-616.
- deNijs, J.J. (2004) The NATO Strategic Commanders' Assessment of Requirements for Sea and Airlift, *Mathematical and Computer Modeling Journal*, 39(6-8), 859-883.
- deVries, S., Vohra, R. V. (2003) Combinatorial auctions: a survey. *INFORMS Journal on Computing*, 15(3), 284-309.
- Godfrey, G.A., Hellings, C., Knutsen, A. (2004) A Multiagent Framework for Collaborative Airlift Planning using Commercial Air Assets, *Mathematical and Computer Modeling Journal*, 39(6-8), 885-896.
- Hazdra, R.J. (2001), Air Mobility: The Key to the U.S. National Security Strategy, Air University Press, USAF.
- Johnstone, D.P., Hill, R.R., Moore, J.T. (2004) Mathematically Modeling Munitions Prepositioning and Movement, *Mathematical and Computer Modeling Journal*, 39(6-8), 759-772.
- McKinzie, K., Barnes, J.W. (2004) A review of Strategic Mobility Models Supporting the Defense Transportation System, *Mathematical and Computer Modeling Journal*, 39(6-8), 839-868.
- Morton, D.P., Rosenthal, R.E., Lim, T-W. (1996) Optimization modeling for airlift mobility. *Military Operations Research*, 1(4), 49-67.
- Rosenthal, R.E., Baker, S.F., Lim, T-W., Fuller, D.F., Goggins, D., Toy, A.O., Turker, Y., Horton, D., Briand, D., Morton, D.P., (1997) Application and Extension of the THROUGHPUT II Optimization Model for Airlift Mobility, *Military Operations Research*, 3, 55-74.
- Smith, S.F., Becker, M.A., Kramer, L.A. (2004) Continuous Management of Airlift and Tanker Resources: A Constraint Based Approach, *Mathematical and Computer Modeling Journal*, 39(6-8), 581-598.

- Weber, B., Bojduj, B. (2006) Tabu Search for Optimization of Military Supply Distribution” Special Focus Symposium on Advances in Intelligent Software Systems, *18th International Conference on Systems Research, Informatics and Cybernetics*, August 2006.
- Yang, F., Rodin, E.Y., Amin, S.M. (1996) Modeling and Optimization of Mobility Analysis: Optimal Requirements Study. *Military Operations Research*, 1(4), 81-106.

## **2 Research Task #2**

### **Experimental Evidence on Team Coordination and Collaboration Within a Distributed Logistics Network**

#### **Submitted by**

Chang S. Nam, Ph.D. (PI)  
Yueqing Li (Graduate Research Assistant)  
Young-Joo Kim (Graduate Research Assistant)

Department of Industrial Engineering  
University of Arkansas  
4207 Bell Engineering Center  
Fayetteville, AR 72701

#### **Presentation published in proceedings (related):**

Nam, C. S., Lyons, J., and Li, Y. (2007). Team coordination and collaboration within a distributed logistics network. Annual Symposium on Applied Experimental Research. Fairfax, VA.

#### **Manuscript to be submitted (related):**

Nam, C. S., and Lyons, J. (2009). The effects of workload and communication availability on performance and team cognition in a distributed logistics context. International Journal of Industrial Ergonomics.

Nam, C. S., and Lyons, J. (2009). Usability of a computer-based aerial port simulation (CAPS) system. International Journal of Human-Computer Interaction.

## 2.1 Executive Summary

Team-based work structures have increasingly adopted to address a variety of complex and difficult logistics tasks due to substantial benefits associated with teamwork. The reality is, however, that there is little guarantee of success as many teams fail for any number of reasons. This is the case especially when a distributed logistics team must make decisions with severe consequences, while coordinating and collaborating with other parties involved. Thus, it is critical to have a full understanding of the factors affecting team effectiveness that perform logistics operations which require additional attention, intensive management, and continuous monitoring. However, there is a lack of empirical evidence on factors that may affect team performance and cognition, including the complex cognitive factors driving the behavioral phenomena associated with the distributed logistics teams. The main focus of the project was to provide experimental evidence on team coordination and collaboration within a distributed logistics network. Relatively few empirical research studies have been conducted on how geographically dispersed logistics teams coordinate their logistics activities and collaborate with other involved parties to perform logistics operations in a joint environment (e.g., aerial port simulation).



## 2.2 Introduction

Much of the work in organizations today is completed through team based work structures, aimed at facilitating team member interactions in an effort to promote successful task completion (Cannon-Bowers et al., 1993), which has proved to increase productivity and expertise as well as minimize workloads for individuals (Marks et al., 2001; O'Connor et al., 2008). The reality is, however, that many teams tend to fail for any number of reasons (Hackman, 1998).

Existing studies on team effectiveness fall far short of providing practical guidance for managing distributed logistics teams for at least three reasons. First, many aspects of team coordination and collaboration in distributed logistics contexts still remain unclear, because team effectiveness has been determined mainly by team performance. However, recent evidence supports the assertion that common cognitions among team members and their effective communication process are closely associated with team effectiveness. Thus, team cognition and team communication should also be considered to fully uncover the various aspects of distributed logistic teams (Levi and Slem, 1995; Littlejohn, 2002; May and Carter, 2001). Second, relatively few studies have been carried out to systematically investigate the influence of the factors that may facilitate or hinder team coordination and collaboration in logistics contexts (Nam and Thomas, 2006; Nam et al., 2009). Finally, only a few simulation platforms are still available for researchers to use as a test-bed in order to perform collaborative logistics research (Nam et al., 2007). The research platform is required, which allows researchers to manipulate and investigate a variety of logistics scenarios (e.g., inclusion of unexpected events such as

diverted mission and transportation system breaking down to diagnose team-based planning, coordination, and collaboration).

The goal of the present study was to provide experimental evidence on team coordination and collaboration within a distributed logistics network by conducting an empirical experiment on factors that may facilitate or hinder team effectiveness in logistics contexts. Specifically, the objectives are:

1. To evaluate the overall effectiveness of a computer-based platform for collaborative logistics research, *Computer-Based Aerial Port Simulation (CAPS)* system;
2. To manipulate and empirically investigate two contributing factors such as task workload and communication availability; and
3. To uncover comprehensive aspects of team effectiveness in distributed logistics contexts by collectively measuring team performance (e.g., departure time) and team cognition (e.g., team mental model and team interaction process).

### 2.3 Participants

Fifty participants from the University of Arkansas student population were recruited for the experiment. Participants were given extra credit for compensation for their participation. There were 38 male and 12 female participants with a mean age of 23.4 years ( $SD = 3.02$  years).

## 2.4 Experimental Task and Apparatus

A computer-based laboratory task that requires collaboration within a distributed logistics network, *Computer-Based Aerial Port Simulation (CAPS)*, was developed in collaboration with Dr. Joseph Lyons of Air Force Research Laboratory/Logistics Readiness Branch (AFRL/HEAL). Participants were asked to perform an aerial port task as a team in CAPS, in which they needed to provide air transportation to all users of the Defense Transportation System (DTS) in the timely manner.

### 2.4.1 *Computer-Based Aerial Port Simulation (CAPS):*

CAPS enables a team of five interdependent participants to simulate logistics operations associated with an aerial port squadron (e.g., movement of air cargo and passengers through the Defense Transportation System). Aerial ports consist of five primary functional sections: the air terminal operations flight (ATOF), passenger services (PS), fleet services (FS), cargo services (CS), and ramp services (RS) (see Appendix 1 for critical tasks to be performed at each functional section in CAPS).

Table 12. An Example of Task Scenario

<p><i>ATOF receives information from command post about an inbound C-17 originating from Dover AFB in transit to Travis AFB. The aircraft will be arrived in approximately 25 minutes. The C-17 will need to download 5 terminating pallets and upload 7 pallets in route to Travis AFB. Twenty-five passengers will need to be downloaded from the aircraft and 12 will need to be boarded in route to Travis AFB. Each passenger requires an in-flight meal. Once the C-17 has landed, the aerial port will have 3 hours to complete port operations and clear the aircraft from the port. Once cleared from the port, the aircraft can take off.</i></p>
---

One team member represents one section within the aerial port during the CAPS scenario. Team members communicate using a chat system, and all chat data were stored in an automated database for subsequent coding and analysis. Unexpected events, such as diverted missions and aircraft malfunctions, can be injected into the scenario to diagnose team-based problem-solving, coordination, and collaboration. Figure 1 shows a sample task scenario used in the experiment.

**(1) Air Terminal Operations Flight (ATOF):** As shown in Figure 2, the ATOF provides the aerial port sections with information to manage available resources to receive, document, and move passengers and cargo. It is the focal point through which all information relating to airlift flow is received, processed, and dispatched to functional areas. All functional sections will need to be notified when the aircraft has landed. ATOF should remind the sections about what the aircraft needs (e.g., cargo & passenger requirements). All sections will need to be monitored to insure that the aircraft is not delayed. ATOF will trouble shoot any problems during the port operations (e.g., vehicle maintenance will need to be notified if a vehicle breaks down, or all sections will need to be notified if an aircraft's status changes). As soon as all functional sections have completed their duties, ATOF can port clear the aircraft and it can depart.

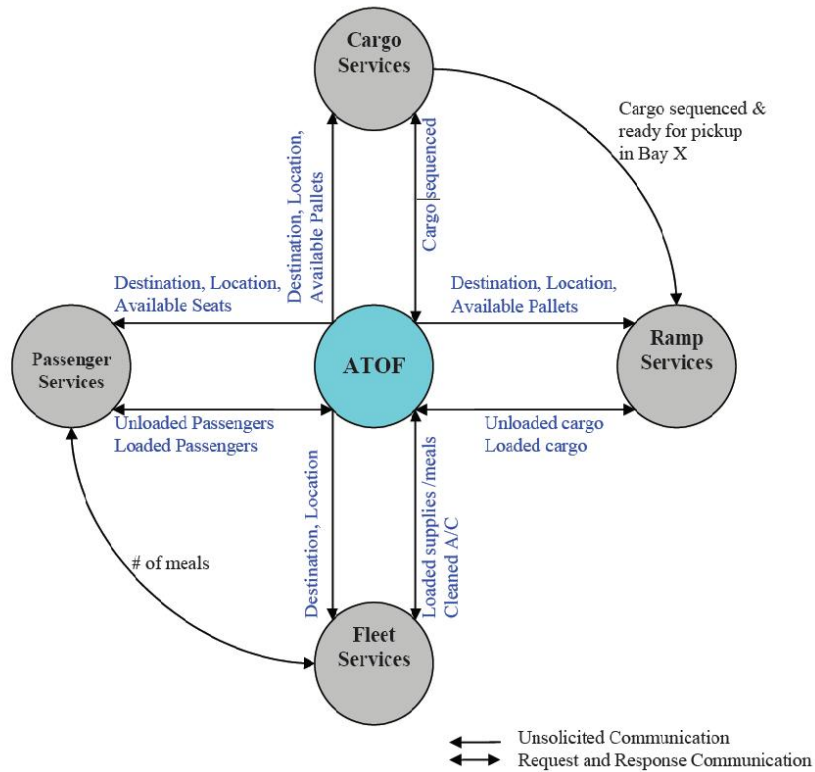


Figure 1. Communication Diagram of the Air Terminal Operations Flight (ATOF)

**(2) Ramp Services (RS):** Ramp services load out-bound cargo and download in-bound palletized cargo for the aerial port. Ramp will need to download the necessary pallets and return them to the cargo section for processing. They will also need to load the necessary pallets onto the C-17 that are required to be transported to Travis AFB.

**(3) Passenger Services (PS):** Passenger services process, embark, and debark all passengers in the aerial port (see Figure 2). This section will need to download the passengers coming in from Dover and return them to the passenger terminal for processing. They will also need to upload any passengers going to Travis. They must coordinate with Fleet services to get the appropriate number of passenger meals ordered and delivered to the aircraft.

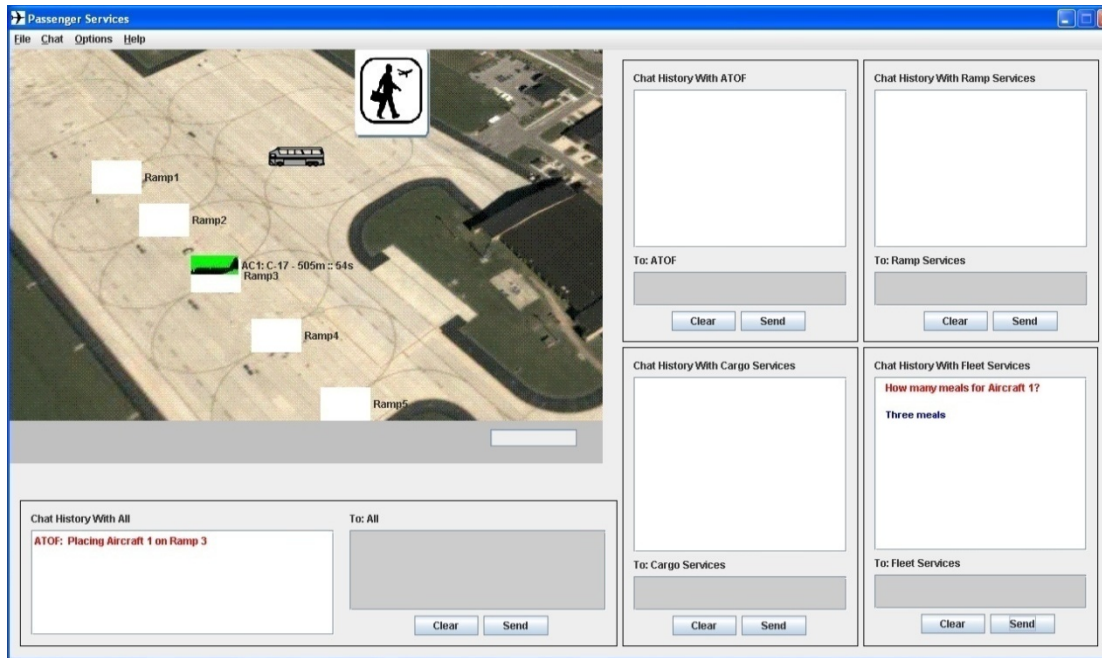


Figure 2. An Example of Passenger Services Interface

**(4) Fleet services (FS):** This section supplies transport aircraft with passenger and crew comfort items (including meals) while ensuring that transport aircraft interiors are clean and presentable.

**(5) Cargo services (CS):** This section must prioritize cargo by destination: where the cargo is going, and priority: some cargo must be transported before others. Once information is received about what an aircraft needs, this section must sequence loads so that ramp can pick them up. This section must also process all incoming cargo.

## 2.5 Experimental Design

There were two independent variables manipulated in the study: (1) workload (low vs. high) and (2) communication availability (partly and indirectly vs. all and directly). The workload factor was a within-subject variable and the communication availability was a

between-subject variable. As shown in Table 1, a 2 (workload) x 2 (communication availability) mixed-factor design was used in the study.

Table 13. Mixed Factor Experimental Design Used in the Study

		<b>Workload</b> (within-subject variable)	
		Low(Session 1)	High(Session 1)
<b>Communication Availability</b> (between-subject variable)	All and directly	Team 1 ... Team 5	Team 1 ... Team 5
	Partly & indirectly	Team 6 ... Team 10	Team 6 ... Team 10

**Workload:** Workload variable was manipulated by altering the number of air craft per session and the time demands under which team members must operate (e.g., arrival and departure times).

**Communication Availability:** Communication availability was manipulated either all communication channels open (i.e., all and direct communication among all the team members) or only individual chat capability available (i.e., communication among team members is limited according to the predefined communication protocol).

## 2.6 Procedures

Participants were randomly assigned to 1 of 10 work groups with five members, in which they remained in the same group for the duration of the study. The participants were asked to come to the Human-Computer Interaction (HCI) lab in the Department of Industrial Engineering at the University of Arkansas for the experiment lasting about two hours to complete. Team members were asked to perform an aerial port task in CAPS (Computer-based Aerial Port Simulation), in which they needed to provide air transportation to all users of the Defense Transportation System (DTS) in the timely manner. Two sessions were conducted in the experiment and the entire session was video- and audiotaped for later examination. After the each session, the participants were also asked to complete a questionnaire designed to investigate team cognition (e.g., team mental model).

Before the experiment, the participants were asked to complete a background survey questionnaire such as personality and education level. The participants also performed the training exercise to get themselves familiarize with the functional section they were assigned. Figure 3 demonstrates an example of the training material designed to train the Passenger Services section.



## Passenger Services (PS) Primary Tasks:

### 1. Unload (Disembark) Passengers

- Right-click on the bus and select "Move to Ramp #" from the menu.
- Once the bus is at the aircraft, select "Download Passengers" from the menu.
- Right-click again on the bus and select "Return to PS Bldg" from the menu.
- Right-click on the bus and select "Disembark Passengers" from the menu.
- **Notify ATOF and Ramp Services via IM Chat immediately after you have unloaded the passengers.**



### 2. In-Process Passengers

Before passengers can fly on military flights, they must be entered into the system.

Use passengers' social security numbers (SSN) from their Travel Request (TR) to retrieve information about the passenger. Assign passengers to a gate based on their desired destination (e.g., Germany).

**It is important that you assign all passengers heading to the same destination to the same gate.**

- Right click on the PS Terminal and select "In-Process Passengers" from the menu.
- A Travel Request will appear. Locate the SSN on the TR and type it into the SSN text box in the in-processing section.
- Press the "Search" button. The Name, Rank/Grade and Service of the passenger will appear in the form.
- Based on the travel request, select the correct number of Seats and the correct Travel Status in the form.
- Make selections for the Destination Country and the Passenger Gate Number in the form.
- Click on the "Submit" button or select another Passenger via the "Next >>>" button to continue working.

### 3. Load Passengers

- Select "Load Passengers" from the bus menu and enter the correct Gate Number (i.e., where the passengers are waiting).
- Select "Move to Ramp #" from the bus menu to move the bus to the appropriate aircraft.
- Select "Upload Passengers" from the bus menu.
- **Notify both ATOF and Fleet Services via IM Chat immediately after you have loaded the passengers.**

Figure 3. An Example of Training Materials (for passenger services section)

## 2.7 Results and Discussion

To empirically investigate the effects of task workload and communication availability on team effectiveness in a distributed logistics context, this study used several dependent measures, which can be categorized into two characteristics of variables: team performance and team cognition. Two-way analyses of variances (ANOVAs) will be performed to determine the effects of workload and communication availability on task performance and team cognition. Since the experiment is still being performed and the data collection has not been completed yet, the PI will briefly describe the plan of the data analysis and the expected results in this section.

### 2.7.1 Team Performance

**(1) Success/Failure of Task:** Team's performance will be assessed on the basis of whether the aircraft left on time.

**(2) Performance Score:** Three types of scores will be utilized, which are provided by CAPS system.

- **General Score:** General score is the score a station can get by performing actions that are not directly related to a specific aircraft. For example, Passenger Services in-processing passengers is a action that does not directly affect an aircraft so that action would be recorded under the 'General Score' section.
- **AC# Score:** AC# score where # is the aircraft number is modified by any action that directly affects an aircraft. For example, Passenger Services loading passengers onto an aircraft will be recorded under the 'AC# Score' section where x is the aircraft number.

- **All Score:** All score value is sums the performance scores across aircraft, general score, and station/team member

### 2.7.2 Team Cognition

- (1) **Stressor Appraisal Scale (SAS)** (Schneider, 2008): Ten items assessed stressor appraisals. Primary appraisal items included: (1) how threatening do you expect the upcoming task to be; (2) how demanding do you think the upcoming task will be; (3) how stressful do you expect the upcoming task to be; (4) to what extent do you think you will need to exert yourself to deal with this task; (5) how much effort (mental or physical) do you think the situation will require you to expend; (6) how important is it for you to do well on this task; and (7) how uncertain are you about what will happen during this task. Secondary appraisal items included: (1) how well do you think you can manage the demands imposed on you by this task; (2) how able are you to cope with this task; and (3) how well do you think you will perform this task. Items were rated on seven-point Likert scales.
- (2) **Interpersonal Trust** (Naquin & Paulson, 2003): To measure trust level among team members, Naquin & Paulson's (2003) interpersonal trust questionnaire will be used (see Appendix 2).
- (3) **Shared Team Mental Model:** Kendall's coefficient of concordance will be used to investigate the mental model shared by team members (Lewis and Johnson, 1971). Kendall (1955) presented a Coefficient of Concordance,  $W$ , to evaluate the extent of agreement among a set of judges each of whom ranks in entirety a set of objects; this statistic is well known and has been widely used in the sociometric literature.

Let  $R$  be an  $n \times m$  matrix in which  $r_{ij}$  is the rank of the  $j$ -th of  $m$  objects as judged by the  $i$ -th of  $n$  judges. Then

$$W = 12S/m^2n (n^2 - 1)$$

where  $S$  is the sum of the squared deviations of the column sums from the mean column sum,

$$S = \sum (r_{.j} - r_{..}/m)^2$$

In the case where the objects to be ranked are the judges themselves,  $n=m$  and

$$W = 12S/n^3 (n^2 - 1)$$

As applied to ranking matrices, Youden arrays are characterized by the fact that each pair of objects to be ranked appears the same number of times. In this case

$$W = 12S/\lambda^2n (n^2 - 1)$$

where  $\lambda$  is the number of times that a given comparison occurs. When each member of a group ranks all of the members except himself, each pair of members is ranked  $n-2$  times. This is obvious from the fact that the  $(i, j)$  pair is omitted by person  $i$  and person  $j$  but by no one else. In this case,  $\lambda=n-2$  and

$$W = 12S/n(n-2)^2 (n^2 - 1)$$

The data matrix,  $R$ , corresponding to (1) is characterized by zero on the major diagonal. The following results for the sampling distribution of  $S$  pertain to that case.

The anticipated outcomes of this research include:

1. Increasing our understanding of the dynamic factors driving team effectiveness

2. Developing theoretically driven and empirically based guidelines for designing and managing effective distributed logistics teams
3. Providing a research platform for collaborative logistics tasks
4. Informing the design and implementation of collaborative technologies and paradigms for use in the distributed logistics domain.

## 2.8 References

- Cannon-Bowers, J. A., Salas, E., & Converse, S. A. (1993). Shared mental models in expert team decision making. In N. J. Castellan, Jr. (Ed.), *Individual and group decision making: Current issues* (pp. 221-246). Hillsdale, NJ: LEA.
- Hackman, J. R. (1998). Why teams don't work. *Leader to Leader*, 7, 24-31.
- Kendall, M. G.. (1955). Rank Correlation Methods. New York, Hafner.
- Levi, D., & Slem, C. (1995). Team work in research and development organizations: The characteristics of successful teams. *International Journal of Industrial Ergonomics*, 16(1), 29-42.
- Lewis, G. H., & Johnson, R. G. (1971). Kendall's coefficient of concordance for sociometric rankings with self excluded. *Sociometry*, 34(4), 406-503.
- Marks, M. A., Mathieu, J. E., & Zaccaro, S. J. (2001). A temporally based framework and taxonomy of team process. *Academy of Management Review*, 26(3), 356-376.
- May, A., & Carter, C. (2001). A case study of virtual team working in the European automotive industry. *International Journal of Industrial Ergonomics*, 27(3), 171-186.
- Littlejohn, S. (1992). *Theories of Human Communication (4<sup>th</sup> Edition)*. California: Wadsworth Publishing Company.
- Nam, C. S., & Thomas, K. (2006). Effects of Cultural Difference and Task Complexity on Team Interaction Process. *Journal of the Ergonomics Society of Korea*, 25(3), 7-16.
- Nam, C. S., Lyons, J., & Li, Y. (2007). Team Coordination and Collaboration within a Distributed Logistics Network. *Annual Symposium on Applied Experimental Research*. Fairfax, VA.
- Nam, C. S., Lyons, J. B., Hwang, H., & Kim, S. (2009). The Process of Team Communication in Multi-Cultural Contexts: An Empirical Study Using Bales' Interaction Process Analysis (IPA). *International Journal of Industrial Ergonomics* (to appear).
- Naquin, C. E., & Paulson, G. D. (2003). Online bargaining and interpersonal trust. *Journal of applied psychology*, 88(1), 113-120.
- O'Connor, P., O'Deab, A., Flinc, R., & Belton, S. (2008). Identifying the team skills required by nuclear power plant operations personnel. *International Journal of Industrial Ergonomics*, 38(11-12), 1028-1037.
- Schneider, T. R. (2008). Evaluations of stressful transactions: what's in an appraisal? *Stress and Health*, 24, 151-158.

## 2.9 Appendixes

### 2.9.1 Appendix 1: Critical Task in CAPS

**Note: I: Independent** task that is **not** necessary to cooperate and communicate with other services; **D: Dependent** task that is necessary to cooperate and communicate with other services

Functional Section	Critical Task	Relation with other services	Task Description
<b>Air Terminal Operations Flight (ATOF):</b> Provides the aerial port sections with information to manage available resources to receive, document, and move passengers and cargo.	1. Communicate Aircraft Requirements	D	<ul style="list-style-type: none"> <li>When an aircraft arrives at the Air Terminal, you must update your team members with information about the aircraft so that they can plan their activities.</li> <li>You must inform your teammates of the following information:               <ul style="list-style-type: none"> <li>✓ Destination – all members</li> <li>✓ Location – all members</li> <li>✓ Seats available – Passenger Services</li> <li>✓ Pallets available – Cargo Services &amp; Ramp Services</li> </ul> </li> </ul>
	2. Log Flight Line Activities	D	<ul style="list-style-type: none"> <li>One of your duties is to keep track of all activities.</li> <li>You'll need to record:               <ul style="list-style-type: none"> <li>✓ When Passenger Services completes the loading and unloading of passengers.</li> <li>✓ When Fleet Services completes the servicing of an aircraft (cleaning the aircraft and delivering meals to the aircraft).</li> <li>✓ When Ramp Services completes the loading and unloading of cargo.</li> </ul> </li> </ul>
	3. Port Clear Aircraft	I	<ul style="list-style-type: none"> <li>One of your most important duties is to ensure that all activities have been performed on an aircraft before it departs – this is called “port clearing” an aircraft.</li> <li>After you clear an aircraft, it will depart the aerial port and travel to its next destination.</li> </ul>
	4. Update Team Members	D	<ul style="list-style-type: none"> <li>You are the information manager for the entire aerial port. You need to keep the various services (Fleet, Passenger, Cargo, and Ramp) up to date with the latest information as you receive it so that they can perform their duties.</li> <li>You will also need to reply to questions from the various services.</li> </ul>

Functional Section	Critical Task	Relation with other services	Task Description
<b>Cargo Services (CS):</b> In-processes in-bound and out-bound cargo and sequences palletized cargo for pick-up by ramp services.	1. Unload Cargo Trucks	D	<ul style="list-style-type: none"> <li>The aerial port receives cargo from trucks.</li> <li>This cargo must be taken off the trucks and moved into the warehouse for processing. The warehouse stores all unprocessed cargo.</li> </ul>
	2. In-process Cargo	I	<ul style="list-style-type: none"> <li>Cargo services must in-process the cargo by assigning pallets to bays.</li> <li>The bays should be organized according to the destination of the cargo. For example, all cargo going to Germany may be stored in bay 1.</li> <li>You assign cargo to specific bays so that ramp services know where to pick up the cargo.</li> <li>You will continually in-process cargo because the highest priority cargo needs to be transported first.</li> </ul>
	3. Sequence Bay Cargo	I	<ul style="list-style-type: none"> <li>Cargo services must sequence all cargo within a bay according to priority.</li> <li>The system will automatically sort the cargo for you when you tell it to.</li> <li>By sequencing the cargo in a bay, you make it easy for ramp services to go to a bay and select the appropriate pallets.</li> <li>Remember high priority pallets (e.g., priority 1) must be shipped before low priority pallets (e.g., priority 2 or 3).</li> <li>Anytime you add cargo to a bay you must re-sequence the cargo in the bay before ramp services can take any pallets.</li> </ul>
	4. Notify ATOF and Ramp Services After Bay Is Sequenced	D	<ul style="list-style-type: none"> <li>You need to IM (instant message) Ramp Services when you have finished sequencing a cargo load so that they can pick it up and deliver it to the aircraft. Specifically, they need to know which bay the load is in and to which aircraft it should be delivered.</li> <li>Notify ATOF when a bay has been sequenced by opening a chat window via the Chat menu.</li> <li>Type your message in the bottom text box and click on Send button or press Enter key.</li> </ul>



Functional Section	Critical Task	Relation with other services	Task Description
<b>Fleet Services (FS):</b> Supplies aircraft with passenger and crew comfort items (blankets, pillows, meals, etc.) while ensuring that transport aircraft interiors are clean and presentable.	1. Clean Aircraft	I	<ul style="list-style-type: none"> <li>One of your duties is to clean the inside of the aircraft after it lands.</li> <li>You can't clean the aircraft until both the passengers and the terminating cargo (i.e., the cargo that is staying at your base) are removed from the plane.</li> <li>You will need to coordinate your activities with passenger services and ramp services to ensure that these activities are done before you clean the aircraft.</li> </ul>
	2. Order Flight Meals and Restock Supplies in FS Truck	D	<ul style="list-style-type: none"> <li>One of the duties of Fleet Services is to provide aircraft with supplies (such as pillows, blankets, etc.)</li> </ul>
	3. Deliver Supplies (Including Flight Meals) to Aircraft	I	<ul style="list-style-type: none"> <li>One of the duties of Fleet Services is to deliver meals to aircraft.</li> <li>You will need to know how many passenger meals to order, and you get this information from Passenger Services.</li> <li>The meals go onto the plane after the passengers are boarded. You will need to coordinate this activity with Passenger Services to ensure that the passengers are on the plane before the meals are loaded.</li> </ul>
	4. Notify ATOF when each activity is completed	D	<ul style="list-style-type: none"> <li>You need to keep ATOF updated of when the aircraft is cleaned, when supplies are delivered, and when meals are delivered.</li> <li>After you complete one of these activities, you should send ATOF a message to let them know that that task is complete.</li> </ul>

Functional Section	Critical Task	Relation with other services	Task Description
<b>Passenger Services (PS):</b> In-processes passengers, loads, and unloads passengers for aircraft in the aerial port.	1. Unload (Disembark) Passengers	I	<ul style="list-style-type: none"> <li>Aircraft will arrive at a ramp and the passengers on board need to be unloaded.</li> <li>The passengers must be unloaded before any cargo can be removed.</li> <li>You will move a bus out to the aircraft to pick up the passengers, then you will move the bus back to the terminal to disembark the passengers.</li> <li>To “disembark” the passengers means to drop them off at the terminal and means they are out of the system.</li> </ul>
	2. In-Process Passengers	I	<ul style="list-style-type: none"> <li>Before passengers can fly on military flights, they must be entered into the system.</li> <li>You will use passengers’ social security numbers (SSN) to retrieve information about the passenger.</li> <li>You assign passengers to a gate based on their desired destination (e.g., Germany).</li> <li>It is important that you assign all passengers heading to the same destination in the same gate.</li> </ul>
	3. Load Passengers	D	<ul style="list-style-type: none"> <li>Before an aircraft departs, it’s necessary to load the passengers</li> </ul>
	4. Notify ATOF of when passengers are loaded or unloaded	D	<ul style="list-style-type: none"> <li>You need to keep ATOF updated of when passengers are loaded or unloaded so that they can properly keep track of all aerial port activities.</li> <li>After you complete a task (e.g., downloading or uploading passengers), you should send ATOF a message to let them know that the task is complete.</li> </ul>

Functional Section	Critical Task	Relation with other services	Task Description
<b>Ramp Services (RS):</b> Loads out-bound cargo and downloads in-bound palletized cargo for the aerial port.	1. Unload Terminating Cargo From Arriving Aircraft	I	<ul style="list-style-type: none"> <li>When aircraft land, they often have cargo that stays at your home base which is Scott Air Force Base. The cargo that stays at Scott Air Force Base is referred to as terminating cargo.</li> <li>Terminating cargo must be removed to make room for other cargo going to other destinations.</li> <li>Using forklifts, you must move terminating cargo from the aircraft into a warehouse.</li> <li>The forklifts are in a parking lot near the Cargo Services building.</li> </ul>
	2. Load Cargo To Departing Aircraft	D	<ul style="list-style-type: none"> <li>Cargo needs to be loaded onto departing aircraft.</li> <li>You will pick up the cargo from bay areas that are organized by cargo services.</li> <li>You will need to check with cargo services to see where the cargo is (i.e., which bay #).</li> <li>Cargo with the highest priority (e.g., priority 1) must be shipped before cargo with a lower priority (e.g., priority 2 or 3).</li> <li>Cargo services should sequence the bays so that the highest priority items are the first to be picked up.</li> </ul>
	3. Notify ATOF When Loading Or Unloading Are Completed	D	<ul style="list-style-type: none"> <li>You need to keep ATOF updated of when an aircraft is loaded or unloaded so that they can keep track of the information.</li> <li>After you either load or unload an aircraft, you should send ATOF an IM (instant message) to let them know that the task is complete.</li> </ul>

### 2.9.2 Appendix 2: Interpersonal Trust (based on Naquin & Paulson, 2000)

Scale: (1=Strongly Disagree, 2=Disagree, 3=Somewhat Disagree, 4=Neither Agree nor Disagree, 5=Somewhat Agree, 6=Agree, 7=Strongly Agree)

Instructions: Using the scale provided, please rate your agreement with the following items.

- I think other team members told the truth during the task
- I think other team members met their obligations during the task
- In my opinion, other team members are reliable
- I think that other team members succeed by stepping on other people (-)
- I feel that other team members try to get the upper hand (-)
- I think other team members took advantage of my problems (-)
- I feel that other team members performed the task with me honestly
- I feel that other team members will keep their word
- I think other team members have misled me (-)
- I feel that other team members try to get out of their commitments (-)
- I feel that other team members take advantage of people who are vulnerable (-)

### 3      **Research Task # 3**

## **Toward A New Paradigm for Studying Trust In Virtual Teams**

### **Submitted by:**

Ray Hill, PhD (PI)

Misty Gripper, PhD (Co-PI)

Sriram Mahadevan (Graduate Research Assistant)

*Wright State University*

*Department of Industrial and Human Factors*

*Dayton, Ohio*

Laura Militello (Co-PI)

Drew Bowers (Graduate Research Assistant)

*University of Dayton Research Institute*

*Dayton, Ohio*

### **Papers and Presentations:**

Mahadevan, S. and R. R. Hill. 2008. "Survey on Multi-task Environments and Challenges in Designing User Interfaces for Time-Critical Dual-Task Supervisory Control Systems." Submitted to IEEE Transactions on Systems, Man, and Cybernetics - Part C: Applications and Reviews.

Mahadevan, S, R. R. Hill, M. Gripper, L. Militello, and D. Bowers. 2008. "Interruptions: Influence on Trust and Coordination in Small Virtual Teams. 2008 Industrial Engineering Research Conference, Vancouver, Canada.

### **Dissertation (related):**

Mahadevan, S. "Visualization Methods and User Interface Design Guideline for Rapid Decision Making in Complex Multi-Task Time-Critical Environments"    January 2009.

### 3.1 Executive summary

This report documents a research project focused on developing a protocol for assessing trust in virtual teams. Much of the existing literature on trust in virtual teams includes case study reports. These ethnographic approaches provide rich detail of work-team interactions, and provide valuable documentation of barriers encountered by virtual teams, as well as strategies that seem to facilitate teamwork in virtual settings. The goal of this effort was to adapt effective strategies observed in natural settings for use in a controlled experiment that would allow for manipulation and more precise examination of the effectiveness of these strategies. Two specific strategies, termed “Break-the-Ice” and “Situation Awareness Calibration” were used as interventions in this study.

Fourteen three-member teams navigated a simulated military domain (Virtual Battlespace I) to complete 14 logistics tasks. Seven teams were instructed to perform the interventions and the other seven teams performed the tasks without being instructed to do so. As part of the scenario, commanders were faced with a choice between trusting team members or anonymous intel data. Following the completion of all missions, a 38 question survey (combination of 5 previously validated surveys) was administered to assess the trust between the teammates.

Perhaps the most surprising finding was that participants in the study failed to demonstrate the levels of distrust reported in prior research (cites). One possible explanation for this is that gamers may develop strategies to assess team members and establish trust quickly. This is in contrast to studies of trust in virtual teams in business settings or among students working on group projects.

No significant difference in level of trust was observed between the control and experimental groups. Additional research is needed to explore whether the rapid development of trust is specific to the gaming community. An alternate explanation is that other factors such as the scenario, duration of team interaction, etc. simply did not evoke sufficient engagement to generate feelings of distrust reported elsewhere.

The project was a success in developing a protocol for studying trust in virtual teams in a controlled environment. In spite of the fact that no significant differences were found between the experimental and control groups, several important contributions were realized:

- *Variability in trust scales.* Trust measurement scales validated in different settings evoked reports of high levels of trust, with the exception of an instrument developed by Jian, Bisantz, & Drury (2000). The Jian et al survey (2000) evoked reports of distrust in team members such as deceptiveness, suspicious intent/action, lack of integrity, and unreliability. Additional research is needed to explore differing levels of sensitivity across the surveys.
- *Protocol for studying trust.* This study adapted strategies from measuring trust from the trust-in-automation literature and the interpersonal trust literature. From the trust-in-automation research tradition, we incorporated a forced choice in which the commander had to choose whether to trust his teammates or an anonymous intel report. In addition, we adapted surveys used to assess trust-in-automation as well as interpersonal trust.
- *Balance of control.* As with any laboratory study, the design of this experiment involved the weighing of a number of tradeoffs. A highly-engaging war game used in order to engage participants. While the high-level of flexibility allowed for an engaging scenario, it also allowed participants to deviate from the script and perform unrelated actions. Controlling the experiment too tightly will likely distort the team dynamics being studied, while not enough control makes it difficult to interpret findings.

## Introduction

Many sense and respond logistics (SRL) tasks are completed by distributed teams. It is important to identify and understand the human aspects of collaborative decision making to ensure that the tasks are completed successfully. The first phase of this research identified a need for more research in the area of trust development on virtual teams (Hill, Davis, Vohra, Militello, Bowman, Bowers, 2006). This report documents a study designed to evaluate the effect of two possible trust facilitating interventions (Break-the-Ice, and Situation Awareness Calibration) on trust for virtual teams.

### 3.2 Objectives

The primary objective of this study was to investigate the effects of the two previously mentioned interventions on the development of trust between teammates performing sense and respond logistics tasks. The interventions involved the teammates sharing biographical information prior to beginning the logistics tasks (Break-the Ice) and the commander performing the situation awareness calibration every ten minutes.

### 3.3 Experimentation

Prior to data collection at Wright State University, a small scale pilot study was performed in collaboration with University of Dayton Research Institute (Militello, Bowers, Gripper, 2007). The methodology utilized for this pilot study was slightly modified and used as a framework for the present study. The facility used for the pilot study allowed for individual offices for each player. During testing at WSU, each player was located in the same room. The room was partitioned off to avoid players viewing their teammate's screens and the players were not allowed to talk to each other. This negated the need for cell phones and reduced the physical workload on the second investigator.

The following sections outline the experimentation used for data collection at Wright State University.

#### 3.3.1 *Instrumentation*

The software applications used for the research included Virtual Battlespace One (VBS 1) as a test bed, Platypus to distribute surveys, and ScreenShot Magic version 3.0. The hardware consisted of three OmniTech ClientPro PC computers equipped with Pentium IV processors and Microsoft Windows XP Professional, and three 17-inch monitors with areas set to 1280 by 1024 pixels. The input devices used were three standard keyboards and three two-button optical wheel mice. The commander of the experimental group was provided a digital desktop clock to help him/her determine accurate times to perform the situation awareness calibrations. The study was conducted in the AMOS Laboratory at Wright State University.



### 3.3.2 Scenario

There were no changes to the scenario used in the pilot study conducted with UDRI. Its impetus was to have logistics teams of three people complete a number of SRL tasks in a manner that the effects of the potential trust facilitating interventions could be observed. The teams comprised of a commander and two soldiers (alpha and bravo). During experimentation, the commander was only able to view a real time map of the area that displayed the location of friendly units and possible hostiles (See Figure 4 below). Both soldiers were only able to view the three dimensional environment they were operating in (Figure 5 below). The soldiers did not have access to the real time map. To allow for scripting some of the interaction, the bravo soldier was played by a confederate.

The location of the scenario was the imaginary island of Al-Almar. On this island, the team was in preparation for the increase of coalition forces in the area. Their task was to inventory equipment available in different locations of the island.



Figure 4. Real Time Map Available to Commander



Figure 5. Example Views of Soldiers

At specific times during the scenario, the commander was given missions that needed to be disseminated to the ground soldiers. Each mission included orders for one soldier to locate and report quantities of assets at a particular location. Intelligence data was provided with the missions as well as reminders of the criticality of the mission. Some of the intelligence data was designed to be in conflict with what the soldiers would be able to account for. This introduced circumstances where the commander would have to decide if they would trust the intelligence reports or their teammates. The commander was cautioned of the inexperience and likelihood of his soldiers to get confused when using the terrain map and identifying some of the equipment. It was also stressed that it was the responsibility of the commander to report the most accurate information available whether it was from the intelligence reports provided with the missions or the responses from the soldiers.

### 3.3.3 Participants and Team Development

The experimental data were collected from 28 Wright State University students ages 18 - 31. Of the 28 participants, 13 were native English speakers and 15 speak English as a second language. All participants were required to have experience with first-person shooter games prior

to their participation in the study. An online screening survey developed using Platypus was used to determine experience. We were unable to recruit a sufficient number of expert gamers to complete this study. Thus, the experience level of the player's was variable, but was balanced across groups. Of the 28 players, 8 were novice to computer gaming, 13 had intermediate gaming experience, and 7 were experts. Teams of two were formed primarily based on the availability of the participants and the experimenters. Each team's "method of play" was alternated between experimental and control groups (i.e., the first team was a control group and the second team was an experimental group). There were only 2 teams that played with two expert players (one in the control group and one on the experimental group). Participants were compensated for taking part in the study and for completing all missions effectively and efficiently.

#### *3.3.4 Procedures*

The basic procedure for each team included providing consent to participate, going through a training exercise, assignment to a role (commander or soldier based on performance during training exercise, i.e., those who did not maneuver well were assigned to commander role), and experimental procedures. The following sections provide more details on the training exercise and experimental procedures. Both the experimental and control groups received the same training.

##### *Training*

During the training phase, each participant was given time to familiarize themselves with the game and to learn various maneuvers necessary to complete the scenario. Game play instructions (Appendix A) and a key map (Appendix B) were provided during the training and available for reference throughout the testing period.

The game play instructions were designed to walk the commander and alpha soldier through a tutorial that demonstrated the following: (1) how to communicate with other teammates using the chat tool in VBS 1, (2) how to look around the environment, and (3) how to perform basic movements of the characters and vehicles. The tutorial ended with the participants getting into a vehicle and using the map to get to the airport. Once they reached the airport and exited their vehicle, training was over and the experimental test was set up. The key map was given as a quick reference to the keyboard functions.

## Experimental Procedures

Following the training session, the participants were told that the game would take a few minutes to begin and to wait quietly. During this time the commanders of the experimental teams were given the situation awareness (SA) calibration sheet (Appendix C) to review. This document detailed the importance of the calibration and instructs the participant to perform the SA calibration approximately every 10 minutes. Also during this waiting period, the Bravo soldier (e.g, the confederate) of the experimental group began the “Break-the-Ice” intervention by initiating an informal chat-based in exchange. The control group was not exposed to either intervention and sat quietly during this time.

After about five minutes of "game set-up/intervention set-up" time, the commanders and the alpha soldiers of both the experimental and control groups were given their respective packets of information. The commander's packet included an information sheet (Appendix D), resource checklist (Appendix E), and an example mission order (Appendix F). The information sheet outlined the nature of the mission, role of the commander, information about the team, an explanation of mission orders and mission reports, and how to use the resource checklist. The commander's information sheet also relayed the inexperience and chances of confusion of his ground soldiers. The experimenter answered any questions on how to fill out the resource checklist and the contents of the example mission order. Once the commander read through the all of the packet materials, they were instructed to type “I am your new commander. I will be issuing you orders from now on.” This communication was the initiation of the game.

The alpha soldier was given an information sheet (Appendix G) that outlined the nature and goals of the scenario, the role of the alpha soldier, and instructions to avoid enemy contact. In addition, the alpha soldier was given a US Army reference sheet (Appendix H) and an enemy forces reference sheet (Appendix I) for quick reference of friendly and enemy forces and equipment during game play. They were instructed to watch their screen for further instructions from the commander. Once the game was initiated, the commander was given a total of 14 mission orders at previously determined times (Appendix J) to disseminate to his teammates. After all missions were completed, the participants were asked to fill out the trust surveys online. Following the surveys, all team members were brought together and debriefed.

### 3.4 Data analysis

Each participant in the commander role filled out the resource checklist. There were discrepancies between the intelligence reports that came with the mission orders and what resources were at the locations for four of the missions. For example, the sixth mission for the Bravo soldier was to count tanks at Djebel Gabr. The intelligence report alerts the commander that there are 4 tanks there, but on the ground, there are only 2. The commander had to decide if s/he would trust the intelligence reports or their teammates. A frequency table was generated for the control and experimental groups based on the responses on the resource checklist (Table 14). It was considered trust in the teammate if the commander reported anything other than what was on the intelligence report. From the data provided, the commanders from both the groups in general reported the eyes on counts, (or trusted their teammates more than the intelligence reports). A chi-square analysis showed no significant differences between the groups ( $\chi^2$  ratio = 0.133, p-value = 0.72).

Table 14. Frequency Table for Assessment of Commander's Trust of Teammates

Control Teams				
Trust	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Team Mates	24	85.71	24	85.71
Intelligence Reports	4	14.29	28	100
Experimental Teams				
Team Mates	23	82.14	23	82.14
Intelligence Reports	5	17.86	28	100

Next, t-tests were used to analyze the survey assessments for the teams. The survey used for team trust assessment was a conglomerate of four scales that have been validated in previous research. The questions were given with a seven point likert scale response mode ranging from strongly agree (1) to strongly disagree (7). Table 15 shows each question, and its source. The statistical data analysis was performed on the differences between the responses from the experimental groups to the responses from the control groups. These results are discussed in the categories described in the source and purpose column of Table 15. In addition, to the questions

listed, respondents were also encouraged to record their impressions of the session and examples of events that influenced their trust in their teammates. These results are discussed as well.

Table 15. Synopsis of Team Trust Assessment Questionnaire

	Question	Source and Purpose
1	If I had my way, I wouldn't let the other team members have any influence over issues that are important to the team mission	“Measures of Trust”  Jarvenpaa, & Leidner, 1999  *adapted from Mayer, Davis, Shoorman, 1995
2	I would be comfortable giving the other team members complete responsibility for the completion of the mission	
3	I really wish I had a good way to oversee the work of the other team members	
4	I would be comfortable giving the other team members a task or problem which was critical to the mission, even if I could not monitor them	
5	Members of my team show a great deal of integrity	“Trust”  Jarvenpaa, S. & Leidner, D., 1999  *adapted from Pierce Sommer, Morris, Fridegar, 1992
6	I can rely on those with whom I work on this team	
7	Overall, the people on my team are very trustworthy	
8	We are usually considerate of one another's feelings in this team	
9	The people on my team are friendly	
10	There is no team spirit in my group	
11	There is a noticeable lack of confidence among the people on my team	
12	We have confidence in one another on this team	
13	I feel like I belong to this team	“Perceived Team Cohesion”  Bollen & Hoyle, 1990
14	I feel like I am a member of this team	
15	I see myself as part of this team	
16	I am pleased about being on this team	
17	I am happy to be a part of this team	
18	Of the teams I have played with, this team is one of the best	
19	Members of this team are deceptive	“Trust in Systems”  Jian, Bisantz, Drury, 2000
20	Members of this team behave in an underhanded manner	
21	I am suspicious of team members intent, actions, or outputs	
22	I am wary of other team members	
23	A team members actions led to harmful or injurious outcome in the game	
24	I have confidence in the members of this team	
25	The members of this team provide a sense of security	
26	This members of this team have integrity	

27	This members of this team are dependable	
28	The members of this team are reliable	
29	I can trust the members of this team	
30	I am familiar with the members of this team	
31	Members of this team are primarily interested in their own welfare	“Interpersonal Trust”  Larzelere & Huston, 1980
32	There are times when members of this team cannot be trusted	
33	Members of this team are perfectly honest and truthful with me	
34	I feel that I can trust the members of this team completely	
35	The members of this team are truly sincere in their promises	
36	I feel that members of this team do not show me enough consideration	
37	Members of this team treat me fairly and justly	
38	I feel that members of this team can be counted on to help me	

### 3.4.1 Statistical Data Analysis

The first category of questions relate to measures of trust. Table 16 shows the mean and standard deviation of the responses for the commander, alpha soldier and the team for the control and experimental groups. To compare the differences between the groups, t-tests were performed on the experimental and control groups. The columns labeled “p-value” show the results for each question for the scale. There were no statistical differences between the responses for the control and experimental groups. Overall, the participants were not comfortable giving influence or responsibility to their teammates. In terms of overseeing the team, it was felt that the activity of overseeing was important but not a necessity even for critical conditions.

Table 16. Descriptive and Statistical Results for "Measures of Trust" Scale

Question	Commander			Alpha			Team		
	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value
	Con.	Exp.		Con.	Exp.		Con.	Exp.	
1) If I had my way, I wouldn't let the other team members have any influence over issues that are important to the team mission	1.86 (1.21)	1.71 (1.11)	0.82	2.00 (1.15)	2.00 (1.41)	1.00	1.93 (1.14)	1.86 (1.23)	0.87
2) I would be comfortable giving the other team members complete responsibility for the completion of the mission	4.29 (2.43)	5.71 (1.98)	0.25	6.57 (1.13)	5.71 (2.36)	0.40	5.43 (2.17)	5.71 (2.09)	0.73
3) I really wish I had a good way to oversee the work of the other team members	2.43 (1.90)	1.86 (1.86)	0.58	2.00 (1.15)	1.57 (1.13)	0.50	2.21 (1.53)	1.71 (1.49)	0.39
4) I would be comfortable giving the other team members a task or problem which was critical to the mission, even if I could not monitor them	1.29 (0.49)	1.14 (0.38)	0.55	2.14 (1.35)	1.57 (1.13)	0.41	1.71 (1.07)	1.36 (0.84)	0.34

The second scale was developed to assess the perceived trustworthiness of the team members. Table 17 provides the mean, standard deviations, and the t-test results of the responses. There were no statistically significant differences between the groups for this scale. The respondents recorded relatively high levels of integrity, reliability, and trustworthiness as their perceptions of their teammates. They also felt that their teammates were considerate of each other, but not friendly and showed fairly low team spirit. Another interesting find from this scale was that there was a noticeable lack of confidence in the actions of the teammates, but an overall confidence in each other.



Table 17. Descriptive and Statistical Results for "Trustworthiness" Scale

Question	Commander			Alpha			Team		
	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value
	Con.	Exp.		Con.	Exp.		Con.	Exp.	
5) Members of my team show a great deal of integrity	1.86 (1.46)	1.57 (0.79)	0.66	2.00 (1.15)	2.43 (1.62)	0.58	1.93 (1.27)	2.00 (1.30)	0.88
6) I can rely on those with whom I work on this team	1.86 (0.90)	1.71 (1.50)	0.83	1.86 (1.21)	2.00 (1.41)	0.84	1.86 (1.03)	1.86 (1.41)	1.00
7) Overall, the people on my team are very trustworthy	1.43 (0.79)	1.86 (1.86)	0.59	1.71 (0.95)	1.71 (1.50)	1.00	1.57 (0.85)	1.79 (1.63)	0.67
8) We are usually considerate of one another's feelings in this team	1.71 (0.95)	1.43 (0.53)	0.51	2.14 (1.46)	2.14 (1.35)	1.00	1.93 (1.21)	1.79 (1.05)	0.74
9) The people on my team are friendly	6.71 (0.49)	5.43 (2.07)	0.16	5.00 (2.38)	5.00 (2.00)	1.00	5.86 (1.88)	5.21 (1.97)	0.38
10) There is no team spirit in my group	2.00 (0.82)	1.57 (1.13)	0.43	2.57 (1.27)	2.00 (1.41)	0.44	2.29 (1.07)	1.79 (1.25)	0.27
11) There is a noticeable lack of confidence among the people on my team	1.43 (0.79)	2.00 (1.83)	0.47	1.29 (0.76)	1.86 (1.21)	0.32	1.36 (0.74)	1.93 (1.49)	0.22
12) We have confidence in one another on this team	1.00 (1.14)	2.00 (2.24)	0.35	2.14 (2.27)	1.29 (0.76)	0.37	1.64 (1.65)	1.64 (1.65)	1.00

The results from the "Perceived Cohesiveness" survey are listed in Table 18. Again, there were no statistically significant differences between the experimental and control groups. In general, high levels of cohesion were observed on the teams, both experimental and control, even though the sense of belonging was somewhat lower than the other measures of cohesion.

Table 18. Descriptive and Statistical Results for "Perceived Cohesion" Scale

Question	Commander			Alpha			Team		
	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value
	Con.	Exp.		Con.	Exp.		Con.	Exp.	
13) I feel like I belong to this team	5.43 (2.30)	6.00 (1.83)	0.62	4.86 (2.48)	5.71 (1.80)	0.47	5.14 (2.32)	5.86 (1.75)	0.37
14) I feel like I am a member of this team	1.71 (1.11)	1.57 (0.79)	0.79	2.57 (1.72)	2.29 (1.60)	0.75	2.14 (1.46)	1.93 (1.27)	0.68
15) I see myself as part of this team	1.57 (0.79)	1.57 (0.79)	1.00	1.86 (1.21)	1.86 (1.07)	1.00	1.71 (0.99)	1.71 (0.91)	1.00
16) I am pleased about being on this team	1.43 (0.79)	2.14 (1.77)	0.36	1.57 (0.98)	1.71 (1.11)	0.80	1.50 (0.85)	1.93 (1.44)	0.35
17) I am happy to be a part of this team	1.57 (0.53)	1.29 (0.49)	0.32	2.00 (1.91)	1.86 (1.21)	0.87	1.79 (1.37)	1.57 (0.94)	0.63
18) Of the teams I have played with, this team is one of the best	2.14 (1.46)	2.86 (2.54)	0.53	2.00 (1.29)	1.71 (1.11)	0.67	2.07 (1.33)	2.29 (1.98)	0.74

The "Trust in Systems" scale was created to evaluate how much trust a person has in a system or automation. The questions have been slightly modified to assess trust in virtual teams. The mean, standard deviation, and t-test results are presented in Table 19 below. There were no statistically significant differences between groups here as well. The participants here felt that their teammates were deceptive, and had suspicious intent or actions, but they did have confidence in each other. Here it was also recorded that the team had little integrity, was unreliable, and unfamiliar with each other. The responses were almost neutral on the subjects of team security and team trust.

Table 19. Descriptive and Statistical Results for "Trust in Systems" Scale

Question	Commander			Alpha			Team		
	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value
	Con.	Exp.		Con.	Exp.		Con.	Exp.	
19) Members of this team are deceptive	1.57 (1.13)	2.57 (2.07)	0.29	1.29 (0.49)	2.14 (1.35)	0.15	1.43 (0.85)	2.36 (1.63)	0.08
20) Members of this team behave in an underhanded manner	2.86 (2.48)	5.00 (2.77)	0.43	4.71 (1.11)	5.14	0.66	4.29 (2.20)	5.07 (2.16)	0.35
21) I am suspicious of team members intent, actions, or outputs	1.71 (0.95)	1.57 (0.79)	0.76	1.71 (1.11)	1.71 (1.50)	1.00	1.71 (0.99)	1.64 (1.15)	0.86
22) I am wary of other team members	1.57 (1.13)	1.86 (1.86)	0.74	1.43 (0.79)	2.14 (1.35)	0.25	1.50 (0.94)	2.00 (1.57)	0.32
23) A team members actions led to harmful or injurious outcome in the game	1.57 (0.79)	1.43 (0.53)	0.70	1.57 (1.13)	1.86 (1.86)	0.74	1.57 (0.94)	1.64 (1.34)	0.87
24) I have confidence in the members of this team	2.71 (2.21)	3.00 (1.73)	0.79	3.14 (0.90)	2.43 (1.51)	0.31	2.93 (1.64)	2.71 (1.59)	0.73
25) The members of this team provide a sense of security	3.00 (2.08)	2.14 (1.07)	0.36	3.57 (1.62)	2.86 (2.27)	0.51	3.29 (1.82)	2.50 (1.74)	0.25
26) This members of this team have integrity	4.43 (2.51)	6.14 (1.86)	0.17	5.86 (1.68)	5.57 (2.15)	0.79	5.14 (2.18)	5.86 (1.96)	0.37
27) This members of this team are dependable	3.14 (1.95)	3.00 (2.08)	0.90	2.71 (2.06)	2.43 (2.30)	0.81	2.93 (1.94)	2.71 (2.13)	0.78

28) The members of this team are reliable	6.43 (1.13)	5.86 (1.86)	0.50	5.43 (2.70)	5.43 (2.44)	1.00	5.93 (2.06)	5.64 (2.10)	0.72
29) I can trust the members of this team	2.14 (1.86)	3.14 (1.95)	0.35	2.57 (1.72)	2.57 (1.51)	1.00	2.36 (1.74)	2.86 (1.70)	0.45
30) I am familiar with the members of this team	5.00 (2.00)	5.71 (1.98)	0.51	6.29 (1.25)	4.71 (1.80)	0.09	5.64 (1.74)	5.21 (1.89)	0.54

The final scale used was developed to determine “Interpersonal” trust. Table 20 shows the descriptive statistics and the t-test results. None of the differences in the responses between the experimental and control groups were significant. The overall responses for these measures showed positive ratings of interpersonal trust. Players did not observe selfish behaviors during play and felt that their teammates were trustable, honest, considerate, fair and reliable.

Table 20. Descriptive and Statistical Results for "Interpersonal Trust" Scale

Question	Commander			Alpha			Team		
	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value	Mean (std. dev.)		p-value
	Con.	Exp.		Con.	Exp.		Con.	Exp.	
31) Members of this team are primarily interested in their own welfare	5.71 (2.21)	5.57 (1.99)	0.90	6.29 (1.89)	6.29 (1.89)	1.00	6.00 (2.00)	5.93 (1.90)	0.92
32) There are times when members of this team cannot be trusted	6.43 (1.13)	5.86 (1.86)	0.50	5.57 (2.15)	6.29 (1.50)	0.49	6.00 (1.71)	6.07 (1.64)	0.91
33) Members of this team are perfectly honest and truthful with me	2.00 (1.00)	1.71 (1.11)	0.62	3.86 (2.12)	3.00 (2.00)	0.45	2.93 (1.86)	2.36 (1.69)	0.40
34) I feel that I can trust the members of this team completely	2.00 (1.41)	1.57 (0.79)	0.50	1.86 (1.07)	2.86 (1.86)	0.25	1.93 (1.21)	2.21 (1.53)	0.59
35) The members of this team are truly sincere in their promises	0.49 (1.57)	6.29 (0.95)	0.07	6.14 (1.21)	5.86 (1.68)	0.72	5.50 (1.51)	6.07 (1.33)	0.30
36) I feel that members of this team do not show me enough consideration	4.29 (1.98)	6.00 (1.83)	0.12	5.71 (2.21)	6.00 (1.00)	0.76	5.00 (2.15)	6.00 (1.41)	0.16
37) Members of this team treat me fairly and justly	1.29 (0.49)	1.14 (0.38)	0.55	2.14 (1.57)	1.57 (0.79)	0.41	1.71 (1.20)	1.36 (0.63)	0.34
38) I feel that members of this team can be counted on to help me	1.43 (0.79)	1.71 (1.15)	0.67	2.29 (1.89)	1.43 (1.13)	0.84	1.86 (1.46)	1.57 (1.28)	0.59

### 3.4.2 Qualitative Analysis

Along with the likert scale questions discussed in the previous section, participants were asked to provide specific examples of events or actions that influenced their trust in their teammates. Table 21 summarizes the responses for this question. In the table, each row represents a team. The responses here point to a relationship between the quality of the communication and trust rather than the quantity of the communication and trust. This was especially evident with the commanders of the experimental teams 2, 6 and 10 and control commanders of teams 5 and 7. It was also observed from these teams' commanders (2, 6, and 10) that when the soldiers took their time to complete missions, it had a positive effect on their trust of the soldiers. Another trend drawn from these responses was the relationship between trust and the teammate's readiness to help other members of the team. Most of the alpha soldiers stated actions and events regarding either the commander or the bravo soldier helping them to navigate the game or complete missions as events that influenced their trust. Negative comments are also listed in Table 21 that point to the helpfulness of team mates being positively correlated with trust.

Table 21. Commander and Alpha Soldier's Examples of Events or Actions that Influenced Their Trust in Their Teammates

#	Control Commander's	Control Alpha's
1	"I would perform better when I do the role a second time; more time is required for me to get a hang of the game".	"When near the end, I was confused with the map and everyone was helping me to figure out where to go, I felt like I'm part of the team".
3	"Bravo was on par and fast. He stuck with all his missions, and had success. Strong trust in him but unfortunately he found a few AI in the desert and was terminated repeatedly which removed him from the game. Alpha missed the 3rd mission order which I typed at least twice and therefore we had to do it at the end of the game. He had a few issues with remembering orders. Trust with him was lower than with Bravo."	"Bravo was sent to assist me in times of trouble".
5	"When I had told them earlier to report in when they made it to a waypoint and then they did, that let me know that they were serious about getting the mission done and that I could trust them to do their job."	"The commander was quick to give me my orders once I reached a destination, which let me trust that he knew what he was doing".
7	"I trusted both of my team members. When the Intel they	"I did not see collective team

	gathered was different from the Intel gathered by the satellite, I had them double check. But other than that, I trusted them”.	work; we just followed the individual orders respectively though I didn’t complete them”.
9	“When Alpha was in trouble bravo went to pick him up despite of where he was. Both of them worked as a team”.	“When I asked for help, the team responded”.
	<b>Experimental Commander’s</b>	<b>Experimental Alpha’s</b>
2	“Both teams were responsive and clear, and this made me trust both, they also seemed to take the necessary time to complete a full count, and so I went with their reports”.	“While pinned down under enemy fire, the commander did nothing to aid me. Instead, Bravo traveled to my aid”.
4	No Response	“Bravo came to pick me up when I got stuck”.
6	“Well, Bravo was never injured, so that made me trust him a bit more. Also, he seemed more likely to be able to give counts quickly and accurately. Alpha was more detailed orientated, which was nice, but cost some delays at time”.	“Bravo drove out to pick me up when I was injured”.
8	“When Alpha was in trouble and not able to get out from one site due to enemy firing, Bravo was ready to help him out. In fact, on many occasions I interchanged their tasks so as to get the mission done as early as possible”.	“When my hummer broke down, Bravo helped me”.
10	“Confirmation after completing missions increases my trust as well as time spent performing the mission successfully. My team was evenly effective”.	“The commander did not always respond to my reporting, so I was unsure if he was receiving my orders. As a result, I constantly repeated myself”.

### 3.5 Discussions and conclusions

This project was a success in developing a new paradigm for studying trust development in virtual teams. Although no significant differences were found between the control and experimental groups, there were a number of contributions and significant findings. Some major contributions of the research include:

- Trust measurement scales from different domains can be used for evaluating virtual team trust.
- A good benchmark protocol for the study of trust in virtual teams was developed and ways to refine it were observed during implementation of this study.
- Balance of control in both the scenario and instructions is important to the reliability of results.

Subjective surveying is the most common method of measuring trust. There are a number of scales that have been developed for various environments and relationships including trust in

systems, team cohesion, and interpersonal trust. This research has shown that these scales, though developed and used in other domains, can be successfully used in evaluating trust in virtual teams. The scale developed for trust in systems (Jian, Bisantz, Drury, 2000) was the only one that seemed to have evoked slightly different reactions from respondents. The questions from this scale were developed empirically and were more direct in nature. These types of questions may provide a better look into the constructs of trust to provide a more in depth analysis of trust in virtual teams. It was demonstrated here that a combination of types of scales can be advantageous in looking at the multifaceted concept of trust.

Trust in virtual teams is a very complex area of research that requires a very detailed protocol, especially in a gaming environment. As the protocol for this study was developed and executed, some important requirements were determined. First, without face-to-face interaction, we anticipate that we will need to develop longer scenarios with more interactions between team members to observe distrust and trust development in ad hoc virtual teams as reported elsewhere in the literature. Also, our participants were compensated for their time but seemed not invested in the task. Gamers can be considered more competitive in nature and if using this type of platform and participants, the stakes should be higher to produce more personal investments in the tasks along with the final results. Thus a protocol for using games as a test bed for studying trust in virtual teams should include a balanced combination of high stakes and necessities to rely on teammates.

It was also observed that a balance of control is a definite necessity. For this type of research, there is a need for a mix of real world interactions with some control. This control is what makes this a complex area of research, but the delicacy of it can make it even more difficult to obtain accurate results. Too little or too much control can have major implications on the findings. As the data collection procedures progressed, the importance of the balance of control and real world interaction became more evident, especially in terms of instructions given and the scenario. Both instructions and the scenario have influence on the real world aspects of the experience. Too much control in the scenario will compromise the real world characteristics of the process and too much or too little control in the instructions can lead to players getting off course. The balance of control for these two must be taken into consideration to get reliable interactions and results.



In summary of the research findings, a chi-square analysis on the responses from the resource checklists showed no significant differences in the control and experimental commander's trust of their teammates ( $p\text{-value} = 0.72$ ). During testing, it was observed that some of the control commanders performed the SA calibration by instinct. It is possible that this is one reason why there are no differences between the groups. Both groups trusted their teammates over the intelligence reports more than 80% of the time (85.71% for the control group and 82.14 for the experimental group).

The survey questions were analyzed using t-tests. Again, the differences between the control and experimental participants were not significant although there were a number of interesting findings from the survey. There was a relatively high level of trust for both groups.

The first set of questions was pulled from a survey from (Jarvenpaa, & Leidner, 1999). The responses here showed that the players were not completely comfortable giving influence or responsibility to their teammates and felt that overseeing was important but not necessary. There seems to be trust in the teams but with hesitation.

The next group of questions looked at perceived trustworthiness of the teams. The respondents reported high levels of integrity, reliability and trustworthiness in their teammates. There was also a displayed confidence in the overall teams, but the teammates noticed a lack of confidence among the individuals on the team. In other words, even though individuals on the teams did not show a lot of confidence in themselves and their abilities, the overall view of the team was not affected by it.

In terms of team cohesion, both the control and experimental team members felt unified and somewhat pleased to be on the team. The sense of belonging was not readily observed in the survey responses for either of the groups. An alpha soldier stated that they did not see collective teamwork and that they just followed individual orders. This could explain some of the lack of sense of belonging to the team. Some participants may have felt that they were on a team in a sense that they were working together to complete the missions but not necessarily interrelated to the team. There was a question on the previous scale about team spirit. There was some agreement among teams that there was no team spirit.

The next scale was the modified "trust in systems" scale. There responses were somewhat conflicting with those in some of the other scales. Both groups reported levels of deception, suspicious intent and actions, little integrity, little reliability and little familiarity with each other.

The final scale measured interpersonal trust. The ratings here were relatively high for interpersonal trust. Overall, both groups felt that their teammates were, trustable, honest, considerate, fair and reliable.

When asked to provide examples of events or actions that influenced their trust in their teammates, the players listed comments that led to the possible relationship between the qualities of communication over the quantity. An alpha soldier was criticized for being more detailed oriented (Experimental Team 6) which caused time delays, whereas the bravo soldier of the same team responded quickly and accurately was trusted more. Also, the alpha soldiers tended to relate assistance from teammates with their trust of them. Commanders on the other hand, seemed to relate trust to how long it took to complete missions. When soldiers took their time to complete missions, commanders felt like they were more “committed” to the missions.

Another major observation from this study was that though the trust ratings were relatively high, these particular interventions seemingly had little effect on the development of trust on the teams. High levels of trust reported by participants in this study are surprising given findings from studies of trust in virtual teams in the workplace. These prior studies suggest that trust is generally slow to develop and particularly fragile when team members do not get an opportunity to interact face-to-face (Burgoon et. al., 2003; Jarvenpaa & Leidner, 1999). Wainfan and Davis (2004) summarize their extensive review of the literature with these words: “[in virtual teams] participation is reduced, along with interpersonal factors such as perceptions of other collaborators, cohesiveness, persuasiveness, cooperation, and leadership emergence. Virtual groups are more likely to attribute others’ behavior less generously, to dispositional rather than situational factors.” (p. 61). Our study did not support this previous finding. We speculate that in the gaming culture, participants tend to be more strategically inclined. The strategies employed here seemed to be conducive to building trust in teammates quickly.

In terms of the game, there were several bugs that were discovered during play. The players could only view 3 lines of the chat log at a time and could not scroll up if they missed something. If one player was engaged in conversation with another and the third team member responded to a mission, it was often missed (the third team member had no way of knowing if their response was recorded unless the commander somehow acknowledged it) and the third player would have to repeat themselves. This could be addressed by having some type of transcribing mechanism in a separate window for the commanders to scroll through. Also, there

were some complaints on the sensitivity of the mouse as related to controlling vehicles and issues of skill needed when driving the vehicles.

### 3.6 Recommendations for future work

There is a need for further research into trust development on virtual teams. This study is a good benchmark for potential future work investigating issues of trust in virtual teams using computer based games. Here, we looked between the experimental and control groups to see the influence of the interventions. It would be interesting to analyze the trust development within the teams and roles. This could give a measure of direction of trust development. For instance, is trust development related to the role of the team members? It may be that those in leadership tend to trust more or less than those that they lead. This could involve more roles and relationships than commander and ground soldier and thus larger teams. This type of study would produce more interactions upon which to rate trust in different team members. Also, the differences between populations (specifically military versus civilian) should be explored. There may be aspects of training that may influence the levels and development rates of trust that military participants possess.

One of the shortcomings of this research was that the scenario may have been too short. The duration of the task could be manipulated to ensure that team members interact with each other and have time to assess teammates and develop clearer impressions of the team. This may be key to observing the desired variability in distrust/trust levels. This could be done with multiple trials of the same teams.

There were no significant differences between the groups for these interventions. Several researchers have proposed a number of other mitigation strategies for virtual teams. Some of these could be identified as candidate trust facilitating interventions for virtual teams in future studies as well.

This study has revealed a very worthwhile area of research. Many SRL tasks are completed virtually by remote teams. This research area can provide baseline requirements for tools and procedures to allow for effective completion of these types of tasks.

### 3.7 References

- Bollen, K.A., Hoyle, R.H. (1990). Perceived Cohesion: A conceptual and empirical examination. *Social Forces*, 69(2), 479-504.
- Burgoon, J. K., Stoner, G. M., Bonito, J. A., & Dunbar, N. E. (2003). *Trust and deception in mediated communication*. Proceedings of the Hawaii International Conference in Systems Science, Kona, HI.
- Hill, R., Davis, J., Vohra, H., Militello, L.G., Bowman, L., Bowers D. (2006). Human Aspects of Sense and Respond Logistics. Technical Report for contract F33615-99-D6. Fairborn, OH: Wright State University.
- Jarvenpaa, S.L, and Leidner, D.E. (1999). Communication and trust in global virtual teams. *Organizational Science*, 10(6), 791-815.
- Jian, J., Bisantz, A.M., Drury, C.G. (2000). Foundations for an empirically determined scale of trust in automated systems. *International Journal of Cognitive Ergonomics*, 4(1), 53-71.
- Larzelere, R.E.and Huston, T.L. (1980). The Dyadic Trust Scale: Toward understanding interpersonal trust in close relationships. *Journal of Marriage and the Family*, 42(3), 595-604.
- Mayer, R.C., Davis, J.H., Schoorman, F.D. (1995). An integrative model of organizational trust. *Academic Management Review*, 20(3), 709-734.
- Militello, L.G., Bowers, D., Gripper, M. (2007). Trust in Virtual Teams Pilot Study Report. Technical Report for contract SA050416/FA95500 510182.
- Pearce, J., Sommer, S., Morris, A., Fridegar, M. (1992). A configurational approach to interpersonal relations: profiles of workplace social relations and task interdependence. Working Paper #OB92015 Graduate School of Management, University of California, Irvine.
- Wainfan, L., & Davis, P. K. (2004). *Challenges in Virtual Collaboration: Videoconferencing, audio conferencing, and computer-mediated communications*. Santa Monica, CA: RAND Corporation.

## 3.8 Appendixes

### 3.8.1 Appendix A—Gameplay Instructions

Welcome to the Virtual Teams Study. All participants will receive \$10 for taking part in this study. Teams that complete all the missions effectively and efficiently will receive an **additional \$10** at the completion of the study. **Please read these and other instructions carefully to increase your chances of obtaining the additional \$10.**

To your right you will find a key map, which list the functions each key is used for within the VBS 1 simulation. The following will walk you through a brief tutorial, which will allow you to better familiarize yourself with the game. This is a brief tutorial and should take no longer than 10 minutes to complete. Please read though and familiar yourself with the game in a timely fashion.

#### Team Communication:

To communicate with your team press **/**. Once you have typed your message, simply press **ENTER** to send your message to your teammates.

There are also several chat channels, which can be selected by using the comma ( , ) and period ( . ) keys. During this study it is not necessary to change the channel you are speaking in, but if you accidentally change the channel you can use the comma and period to get back to the default channel, which is the **SIDE CHANNEL**.

If at any time you have a question during this tutorial, simply send a message saying “Help” and someone will come to answer your question.

Type, “I have begun the training” now.

Looki  
ng

#### around the environment:

To begin, move the mouse cursor around. The mouse is used to control your view, the direction you are moving in, and to steer vehicles. To look up, move the mouse forward, to look down, move the mouse backward. To turn your view left or right, or to steer a vehicle to the left or right, simply move the mouse in that direction.

Try looking around the environment now.

#### Basic Movement:

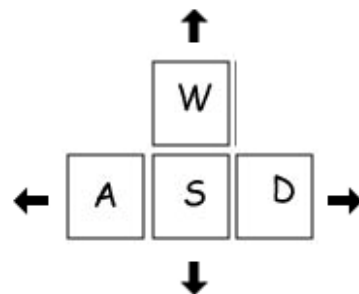
Movement is done with the **W**, **A**, **S**, **D** keys, similar to most First-Person Shooters. **W** will move your character forward or accelerate your vehicle; **S** will move your character backward, stop your vehicle, or if held, move your vehicle in reverse. **A** will make your character side step to the left, or turn your vehicle to the left. **D** will make your character side step to the right, or turn your vehicle to the right.

When driving a vehicle, it is recommended that you use the mouse to steer, as the **A** and **D** keys can sometimes be unresponsive. To run, simply press **E**, or hold the **SHIFT** key while pressing **W**. This method also works when driving a vehicle, and will make you accelerate beyond the normal driving speed.

There are also several standing positions your character can take, such as crouching or going prone (laying down). To crouch, simply press **Q**, to stand up again, press **Q** once more. To go prone, press **Z**, and press **Z** again stand up.

Try out the movement controls now.

Vehic



**le Use:**

To enter a vehicle, walk up to the driver side door and a menu will appear in the bottom right corner. In this menu you are presented with several options including:

- get in the vehicle as the driver (get in as driver),
- ride as a passenger (ride in back),
- enter the gunner positions (get in as gunner).

Using the bracket keys ( [ and ] ), you can move the selector through the list of choices available in the list. Once you have highlighted the position you wish to enter in a given vehicle, press **ENTER** on the keyboard to enter that position. If for any reason this menu does not appear, simply press one of the bracket keys and it should appear. When inside a vehicle, coming to a stop or pressing one of the bracket keys will bring up the commands menu in the bottom right corner. To exit a vehicle, highlight the “get out” option, and press **ENTER** on the keyboard.

Some vehicles contain weapons and items such as grenades and binoculars. These items are considered off limits to your squad, and removing them from vehicles will result in a mission failure.

Once you are inside a vehicle, you can press the **ENTER** key on the **Number Pad** to switch to a third-person view. This view makes driving certain vehicles much easier, and can be used at your own discretion.

Enter one of the humvees in your area and try out these controls now. When you are comfortable with the controls and driving within the game, drive to the airport and exit the vehicle.

This  
comple  
es the  
VBS 1

familiarization. When you have driven to the airport and exited your vehicle please wait for further instructions.

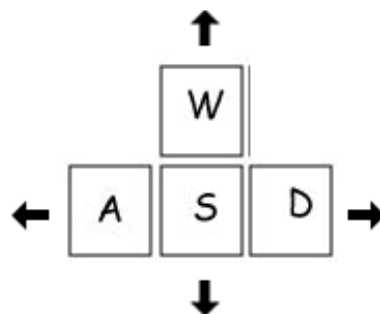
### 3.8.2 Appendix B—Key Map

#### **Team Communication**

<u>Key</u>	<u>Action</u>
/	Opens the chat dialogue where you can type what you want to say
enter	Sends the communication you just typed to all in the channel used
. (period)	Changes chat channel

#### **Basic Movement**

<u>Key</u>	<u>Action</u>
W	Move forward
S	Move backward
A	Step left
D	Step right
E	Run forward
Q	Move to a crouched position
Z	Press once to go prone (lay down) / press again to stand up
ENTER (on numpad)	Changes view perspective from 1 <sup>st</sup> person to 3 <sup>rd</sup> person.
M	Brings up the map



#### **Vehicle Use**

<u>Key</u>	<u>Action</u>
W	Accelerate
E	Fast accelerate
S	Brake / continue holding to move in reverse
A	Turn left
D	Turn right
Mouse	Look where you wish to drive and the car will turn

#### **Command Menu**

<u>Key</u>	<u>Action</u>
[	Cycle upwards through items in command menu
]	Cycle downwards through items in command menu
Return	Select highlighted item in command menu

### 3.8.3 Appendix C—Situation Awareness Calibration

It is key that the teams maintain a shared awareness of the current situation throughout the scenario. Each player will have information that the others do not. In order to work effectively as a team, it is important that each player convey key information to the others, while avoiding overloading communication channels with extraneous chat.

In this scenario, you will be asked to use a *situation awareness calibration* strategy to facilitate information sharing without overloading communication channels. Approximately every 10 minutes the commander will state current mission goals for each soldier, and ask each soldier to report on current status on assigned mission, enemy activity, and any other elements that put the mission at risk. In addition, team members are encouraged to share information about the situation and the mission outside of the scheduled *situation awareness calibration* if they believe others on the team need the information immediately.

The commander should initiate a situation awareness calibration approximately every 10 minutes. Soldiers should expect to respond to the commander's questions every 10 minutes.

#### **Situation Awareness Calibration procedure**

1. Commander states current mission goals
2. Commander asks the following questions of each soldier:
  - 2.1 What is your current status?
  - 2.2 Is your mission clear?
  - 2.3 Have you seen any indication of enemy activity?
3. Each soldier provides commander information about anything encountered that might affect the mission.

Please  
note  
, in  
addi-  
tion  
to  
the  
*situa-  
tion*

*awareness calibration*, any team member may share information at any time if they believe other members need the information to complete the mission.



### 3.8.4 Appendix D—Commander Information Sheet

#### **Background**

The neighboring island of Al-Almar was recently taken over by the head of the military, Miyindi Amin. Coalition forces from several countries are moving equipment and supplies to the neighboring island of Andaman. You are among the forces that have already arrived on Andaman that are helping prepare the military buildup that will be required to take back Al-Almar. The Americans have amassed several regiments on the island already, and are now inventorying equipment and units to ensure that all of the necessary items are in position.

#### **Your Role**

In this scenario you will be playing the role of the Commander of a logistics squad consisting of two soldiers, Alpha and Bravo. As the commander, it is your responsibility to assign missions to both soldiers, keep records of units available, and ensure that enough units are present on the island for the upcoming conflict. You will receive Mission Orders from headquarters sporadically, and it is your responsibility to ensure that your soldiers complete the tasks accurately and in a timely fashion.

It is important for you to remain in your logistics role, as you and your team are not properly equipped to be members of a combat unit. It is critical that coalition forces avoid escalating hostilities in the area. Any hostile actions initiated by you or your logistics team members will be considered a mission failure.

#### **Your Team**

The soldiers you are working with have recently deployed and are extremely inexperienced. They may have difficulty following the terrain using the provided map, and recognizing the equipment they are asked to report on. It is critical that you, as commander, provide accurate information up the chain regarding resources available. You must decide whether the intel provided with the mission or the eyes-on-report from the alpha and bravo soldiers is most reliable.

#### **Reports**

Attached to each Mission Order is a Mission Report. These reports will be sent back to headquarters, along with your final count of units, to determine what resources are needed. Mission Reports also have a space for additional information. In this area you are free to write down any mission critical information that may be reported to you during the course of a mission, such as enemy contact. See the attached sheet for an example of how to fill out a Mission Report.

#### **Mission Checklist**

Along with the example Mission Report, you will also find attached to the back of this document your Resource Checklist. This document is to be used by you throughout the scenario to keep track of equipment and supplies. In the “Accounted For” column you will indicate the number of each unit type accounted for. In the “Number Requested” column you will indicate the number of additional units requested (if any) to meet the mission needs. After the scenario is complete, you will turn in the Resource Checklist, with your final counts for equipment and the number of units you still need to meet the mission goals.

#### **Begin Play**

After you have reviewed the example Mission Report and feel comfortable with your position as commander, send a message to your team stating “I am your new commander, I will be issuing you orders from now on.” Once you have done this Mission Orders will begin to arrive.

### 3.8.5 Appendix E—Resource Checklist

Unit Type	Accounted For	Total Needed	Number Requested
Fuel Truck		2	
Ammo Truck		3	
Troop Truck		1	
Bradley Fighting Vehicle		4	
Tank		6	
Helicopter		4	
Soldier		45	
Anti-Tank Soldier		6	
Medic		6	
Officer		1	
Humvee		3	
Ambulance		2	

Use this form to track resources throughout the scenario. This page will be turned in at the end of the scenario with your finally tally count.

### 3.8.6 Appendix F—Example Mission Order

Order 0

SEND BRAVO SQUAD TO DJEBEL GABR

MISSION: COUNT NUMBER OF HUMVEES PRESENT AT DJEBEL GABR. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS SIX HUMVEES CURRENTLY PRESENT IN THE TOWN.

### 3.8.7 Appendix G—Alpha Soldier Information Sheet

The neighboring island of Al-Almar was recently taken over by the head of the military, Miyindi Amin. Coalition forces from several countries are moving equipment and supplies to the neighboring island of Andaman. You are among the forces that have already arrived on Andaman that are helping prepare the military buildup that will be required to take back Al-Almar. The Americans have amassed several regiments on the island already, and are now inventorying equipment and units to ensure that all of the necessary items are in position.

In this scenario you will be playing the role of soldier Alpha, who is part of a team of logistics support staff. You and your teammates are responsible for locating and verifying intelligence reports on the number of units or pieces of equipment that are on the island. When you receive a mission from your commander, drive to the stated location, perform the mission task, report back your findings to the commander, and then wait for further orders.

It is important to remember that you are not equipped to engage enemy contacts. If for any reason you come in contact with an enemy, it is best to leave the area as quickly as possible. It is critical that coalition forces avoid escalating hostilities in the area. Any hostile actions initiated by you or any other members of your logistics team will be considered a mission failure.

3.8.8 Appendix H—Us Army Reference Sheet

**U.S. Army Reference Sheet**

**Tank**



**Fuel Truck**



**Humvee**



**Troop Transport**



**Helicopters**



**AT Soldier**



**Medic**



**Pilot**



**Soldier**



**Dignitary**



3.8.9 *Appendix I—Enemy Reference Sheet*

**Enemy Forces Reference Sheet**

**Soldier**



**Officer**



**Patrol Boat**



### *3.8.10 Appendix J—Mission Orders And Delivery*

#### Order 1

SEND ALPHA SQUAD TO DAR AL-HARB

MISSION: COUNT NUMBER OF FUEL TRUCKS PRESENT IN DAR AL-HARB.  
ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWO FUEL TRUCKS CURRENTLY  
PRESENT IN THE TOWN.

#### Order 1

SEND BRAVO SQUAD TO HARG

MISSION: COUNT NUMBER OF AMBULANCES PRESENT IN HARG.  
ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWO AMBULANCES  
CURRENTLY PRESENT IN THE TOWN.

#### Order 2

SEND ALPHA SQUAD TO HARG

MISSION: COUNT NUMBER OF AMMO TRUCKS PRESENT IN HARG. ONE  
AMMO TRUCK MUST BE RETURNED TO THE AIRPORT. ACCURATE COUNT  
IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS THREE AMMO TRUCKS  
CURRENTLY PRESENT IN THE TOWN.

#### Order 2

SEND BRAVO SQUAD TO THE NORTH OF DAR AS-SUTH

MISSION: COUNT NUMBER OF TANKS PRESENT IN DAR AS-SUTH.  
ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWO TANKS CURRENTLY  
PRESENT IN THE TOWN.

Order 3

SEND ALPHA SQUAD TO THE SADH OUTPOST.

MISSION: COUNT NUMBER OF SOLDIERS PRESENT AT THE SADH OUTPOST. WE MUST ALSO KNOW THE NUMBER OF ANTI-TANK SOLDIERS PRESENT AMONG THE SOLDIERS AT THE OUTPOST. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

ONCE ALL SOLDIERS HAVE BEEN ACCOUNTED FOR, A FUEL TRUCK PRESENT AT THE OUTPOST NEEDS TO BE TRANSPORTED TO DJEBEL GABR.

INTEL: RECENT SATELLITE IMAGERY SHOWS FIFTEEN SOLDIERS, WITH THREE ANTI-TANK SOLDIERS AMONG THEM CURRENTLY PRESENT IN THE TOWN.

Order 3

SEND BRAVO SQUAD TO MUT

MISSION: COUNT NUMBER OF SOLDIERS PRESENT IN MUT. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWENTY-SIX SOLDIERS CURRENTLY PRESENT IN THE TOWN.

Order 4

SEND ALPHA SQUAD TO DJEBEL GABR.

MISSION: COUNT NUMBER OF HELICOPTERS AND HUMVEES PRESENT IN DJEBEL GABR. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS THREE HELICOPTERS AND THREE HUMVEES CURRENTLY PRESENT IN THE TOWN.

Order 4

SEND BRAVO SQUAD TO THE SADH OUTPOST

MISSION: COUNT NUMBER OF OFFICERS PRESENT AT THE SADH OUTPOST. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS ONE OFFICER CURRENTLY PRESENT IN THE TOWN.

Order 5

SEND ALPHA SQUAD TO DJEBEL GABR.

MISSION: TRANSPORT A SOLDIER TRUCK FROM DJEBEL GABR TO MUT. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS ONE TRANSPORT TRUCK CURRENTLY PRESENT IN THE TOWN.

Order 5

SEND BRAVO SQUAD TO DAR AL-HARB

MISSION: COUNT NUMBER OF BRADLEY FIGHTING VEHICLES PRESENT AT DAR AL-HARB. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS FOUR BRADLEY FIGHTING VEHICLES CURRENTLY PRESENT IN THE TOWN.

Order 6

SEND ALPHA SQUAD TO MUT.

MISSION: COUNT THE NUMBER OF MEDICS PRESENT IN MUT. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS FIVE MEDICS CURRENTLY PRESENT IN THE TOWN.

Order 6

SEND BRAVO SQUAD TO DJEBEL GABR

MISSION: COUNT NUMBER OF TANKS PRESENT AT DJEBEL GABR. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS FOUR TANKS CURRENTLY PRESENT IN THE TOWN.

TOP PRIORITY MISSION REQUEST

A C130 HAS JUST CRASHED OUTSIDE OF MUT. SEND ALPHA SQUAD TO CHECK FOR SURVIVORS.

MISSION: SEARCH FOR SURVIVORS AT THE CRASH SITE. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: THERE IS NO INTEL AT THIS TIME.

Order 7

SEND BRAVO SQUAD TO THE NORTH OF DAR AS-SUTH

MISSION: FIND AND PROTECT THE DIGNITIARIES OUTSIDE OF DAR AS-SUTH.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWO DIGNITIARIES CURRENTLY PRESENT IN THE TOWN.

Order 7

SEND ALPHA SQUAD TO THE NORTH OF DAR AS-SUTH.

MISSION: LOCATE, COUNT, AND GUARD THE DIGNITIAIRES PRESENT OUTSIDE OF DAR AS-SUTH. ALPHA SQUAD MUST MEET UP WITH BRAVO SQUAD AND GUARD THE DIGNITIES. ACCURATE COUNT IS CRUCIAL TO MISSION SUCCESS.

INTEL: RECENT SATELLITE IMAGERY SHOWS TWO DIGNITIARIES CURRENTLY PRESENT IN THE TOWN.



**Delivery times**  
Time

Order Number for Alpha and Bravo

	1 Alpha, 1 Bravo
4:00	2 Alpha
5:30	2 Bravo
10:00	3 Alpha
11:10	3 Bravo
14:20	4 Bravo
16:20	5 Bravo
16:30	4 Alpha
18:20	5 Alpha
19:40	6 Bravo
22:00	6 Alpha
23:20	IMMEDIATE MISSION
25:20	7 Bravo
27:40	7 Alpha

#### **4 Research Task # 4**

### **Developing and Evaluating Operationally Robust Forecasting Techniques in Military Logistics**

#### **Submitted By**

M.D. Rossetti, Ph.D., (PI)

E.A.Pohl, Ph.D., (Co-PI)

Mehemt Miman, Ph.D., (Graduate Research Assistant)

Vijith Varghese., Ph.D. Candidate, (Graduate Research Assistant)

Department of Industrial Engineering

University of Arkansas

4207 Bell Engineering Center

Fayetteville, AR 72701

#### **Papers and Presentation:**

Rossetti, M. D., Varghese, V., Miman, M., and Pohl E. (2008) “Simulating Inventory Systems With Forecast Based Policy Updating”, Proceedings of the 2008 Winter Simulation Conference, S. J. Mason, R. Hill, L. Moench, and O. Rose, eds., Piscataway, New Jersey: Institute of Electrical and Electronic Engineers.

Varghese, V. and Rossetti, M. D. (2008) “A Parametric Bootstrapping Approach to Forecast Intermittent Demand”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada.

Varghese, V. and Rossetti, M. D. (2008) “A Classification Approach for Forecasting Intermittent Demand”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada.

Miman, M., Rossetti, M. D., Varghese, V., and Pohl E. (2008) “An Object-Oriented Framework for Analyzing VARIMETRIC Systems”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada

Varghese, V. and Rossetti, M.D. “A Meta Forecasting Methodology for Large Scale Inventory Systems with Intermittent Demand”, submitted to the 2009 Industrial Engineering Research Conference.

Varghese, V., Miman, M., Rossetti, M.D., Pohl, E. “Evaluating Forecast Based Policy Updating in Spare Part Inventory Systems”, in preparation

#### **Dissertation (Related)**

Vijith Varghese, “Intermittent Demand Forecasting Techniques for Large Scale Inventory Systems”, in progress expected May 2009

## 4.1 Executive Summary

The purpose of this task is to develop new forecasting techniques that can be readily applied within the military context (especially sparing forecasts), evaluate the effectiveness of those techniques, and to examine their operational effects within a supply chain setting. A new technique call MCARTA was developed and shown to be better than other known techniques for intermittent demand based on extensive empirical testing. A number of competing metrics were examined for comparing forecasting techniques. In addition, a simulation environment was developed to allow the evaluation of the effects of using different forecasting techniques within multi-echelon spare parts networks.

The forecasting of logistics demand (inventory requirements, transportation loads, etc.) has been a perennial problem for military logisticians. While many of the forecasting methods used in commercial practice can be utilized in a military setting, military logistical requirements have characteristics that necessitate the development of specialized or unique forecasting techniques. While cost is always a concern, the operational metrics in military supply chains are very different than in a commercial setting. In a military planning situation, it is the ability to complete the mission, which is paramount. Standard methodologies for evaluating forecasting techniques involve fitting models to historical data and selecting the parameters of the models and the “optimal” technique based on minimizing forecasting error. Previous research by the PI and co-PI for the Navy (“*Evaluation of Intermittent Forecasting Techniques*”) and Air Force (“*C/KC-135 Weapon System Stockage Policy and MICAP Avoidance Analysis*”) has indicated a number of problems that need to be addressed:

- Intermittent demand that is generated within spare part modeling contexts is extremely difficult to forecast and existing techniques remain inadequate.
- Should different forecasting models be used for each and every item or can a standard set of techniques be identified that are operationally robust across the supply chain? For example, when forecasting part demand, it becomes computationally problematic to fit an optimal forecasting model to hundreds of thousands of items. Can preprocessing techniques be developed that are strong predictors of the most operational robust technique?
- No standardized methodology exists for evaluating the effectiveness of forecasting techniques within an operational context. Such a methodology would assist military planners in evaluating whether or not it is worth improving the forecasting in a certain area and then in selecting the most operationally robust forecasting technique.

The task was divided into four sub-topics: 1) new intermittent demand forecasting, 2) new metrics for evaluating forecasts, 3) new methods of applying techniques to large scale inventory systems, and 4) operational effects of inventory systems with forecast based policy updating.

## 4.2 The MCARTA Technique for Intermittent Demand Forecasting

### 4.2.1 *Problem/Background*

Intermittent demand is characterized by demand data that has many time periods with zero demands. It is hard to model intermittent demand by conventional distributions. Intermittent demand is commonly found in military supply network among reparable spare parts. The availability of spare parts that depends on the accuracy of forecast, affects the mission accomplishment in military. The purpose of this research is to develop an intermittent demand forecasting technique named MCARTA based on a Markov Chain model and ARTA algorithm. The first part of this research investigates the best parameter settings for the MCARTA technique. In the second part of the research, various intermittent forecast techniques are compared with MCARTA and the robustness of each of the forecasting techniques under the various demand scenarios were investigated. The other forecasting techniques considered for the research are simple exponential smoothing, moving average, cumulative average, Croston, Syntetos, and naïve forecast 1 (NF1).

### 4.2.2 *Methods, Assumptions, and Procedures*

MCARTA is a bootstrapping approach for making a forecast estimate. It requires estimates for the parameters (called the statistical parameters of MCARTA): probability of non-zero demand after zero demand, probability of non-zero demand after non-zero demand, mean of non-zero demand, variance of non-zero demand and lag 1 correlation coefficient of non-zero demand.

Based on the transition probabilities a binary generator is created, in which the zero represents zero forecast estimates and one represents non-zero forecast estimates. At each time

index, the underlying model is a Markov chain. With the decision made by the binary generators, MCARTA will generate non-zero forecast estimates. The nonzero forecast is generated based on the ARTA (Autoregressive to Anything) algorithm with an underlying non-zero positive distribution (e.g. Poisson, Negative Binomial, Binomial, etc.) selected based on the mean and the variance of the non-zero demand.

For the experiments, demand series that are representative of intermittent demand were generated and forecasts made at different parameter levels of MCARTA. At the end of the run, the different forecast errors (MAD, MSE, mean unbiased absolute percentage error, relative mean absolute error, and mean absolute scaled error) are estimated; bias and variance are also computed. The demand scenario is replicated and the forecast errors, bias and variance at each replication measured. The best parameter settings of MCARTA were selected using a multiple comparison with the best approach based on forecast errors. The bias and the variance were statistically analyzed and inferences made on the statistical quality of the forecast estimates of the best MCARTA. The research also discusses an intermittent demand generator which generated demand according to user specified levels of demand characteristics. The demand generator is based on Batch – on/off algorithm. We considered 40 different levels of demand scenarios.

#### 4.3 Results and Discussion

The best MCARTA settings were selected based on forecast errors. A bootstrap size of 1000 is recommended along with the use of the mean of bootstrap sample as the bootstrap estimator. The whole demand series should be used to estimate the statistical parameters of MCARTA. The best settings of updating the statistical parameters selected were: update the

statistical parameter continuously and the ARTA matching may be turned off. The bias and the variance of the best MCARTA were statistically analyzed. The MCARTA appears to have low bias, and was shown to have statistically similar bias properties as the next best technique due to Syntetos(). We also see that the bias of MCARTA and the Syntetos are statistically equal. The variance of MCARTA is lower compared to that of the Syntetos technique. These properties of MCARTA qualify it not only as a very competent intermittent demand forecasting technique but also as one of the best. In addition, it is seen that the new demand generator is efficient and can be fully controlled by the user, which is another contribution of the research.

Using multiple comparisons with the best, based on MAD, relative mean absolute error, and mean absolute scaled error, MCARTA is clearly the best intermittent forecasting technique. Also, based on MSE and mean unbiased absolute percentage error, MCARTA is as competent as the best technique. It can be inferred from this result that MCARTA is robust across different demand scenarios. The performance the forecasting techniques across specific demand scenarios was also investigated. We observed the demand scenarios that represent the erratic demand, intermittent demand, slow demand, bursty demand, and that of an US Navy inventory system that holds reparable spare parts with intermittent demand. We observed that in most of the cases MCARTA was the best technique and other cases MCARTA is as competent as the best technique. All these comparisons are based on each of the forecast error metrics.

#### 4.4 The Effects of Forecasting Techniques on the Operational Performance Measures of an Inventory System

##### 4.4.1 *Problem/Background*

Traditionally, in a real inventory system the policy may be updated based on the forecast estimates and the forecast error from a forecasting technique selected by inventory managers. There are several research studies that justify that the selection of the forecasting technique affects the operational performance measures (OPM) of the inventory system. This motivated the investigation of whether there is a relationship between forecast error (FE) and OPM.

Using the forecast estimate and forecast error inventory managers model the lead time demand distribution (LTDD). Inventory optimization models that depend on the approximate LTDD are used to set policy parameters. Approximations occur during this process because an assumed family of distributions (e.g. Neg-binomial) is used for the lead time demand and also owing to the estimation of the mean and variance of the lead time demand distribution. How well the approximate lead time demand distribution fits the actual lead time demand distribution is critical to how well the planned for parameter settings allow for the inventory model performance to match the actual operational performance. Thus, rather than use forecast error to select the forecasting technique, a metric based on the goodness of the approximate lead time demand distribution should be used. This research investigates a new performance metric for picking the best forecasting technique.

##### 4.4.2 *Methods, Assumptions, and Procedures*

A  $(r, Q)$  inventory system which encounters intermittent demand was simulated for the research. The demand arrives and it is filled. The system requests replenishment and the



replenishments are fulfilled with a delay. The demand during the lead time of replenishment is captured. At the end of the run, the empirical LTDD is built. Meanwhile, during the run, forecasts are made based on the relevant forecasting technique: MCARTA, SES, MA, CA, Croston, Syntetos, and NF1. The forecast technique makes a forecast for the next period. At the end of the run, we observe the next period forecast which is an estimate for the demand per unit time (DPUT). At the end of the run, we estimate the variance of the forecast via the mean squared error, an estimate for the variance of the DPUT. This is matched with the first 2 moments of the hypothesized LTDD. The hypothesized LTDD is also built based on next period forecast estimate and the actual variance from the observed LTD. The goodness of fit of the hypothesized LTDD from each forecast technique is compared with the empirical LTDD. The goodness of fit is measured based on Kullback-Leibler (KL) divergence measure, Anderson Darling test statistics, Kolmogorov Smirnov test statistics and sum of squared error. We study the relationship between forecast error and these metrics via the Kendall's Tau correlation coefficient.

#### *4.4.3 Results and Discussion*

Preliminary research shows that based on the LTDD metrics, MCARTA is as competent as other forecasting techniques.

## 4.5 A Meta Forecasting Methodology for Large Scale Inventory Systems with Intermittent Demand

### 4.5.1 *Problem/Background*

This research presents a meta-forecasting approach for recommending the most appropriate forecasting technique for an intermittent demand series based on a multinomial logistic regression classifier. The meta-forecaster is based on a mapping between a demand attribute space and the best forecasting technique. The demand attribute space is based on the estimates from the demand series of the following attributes: probability of non-zero demand after zero demand, probability of non-zero demand after non-zero demand, mean demand, demand variance, lag 1 correlation coefficient of demand, mean interval between non-zero demands, variance of interval between non-zero demands and lag 1 correlation coefficient of the interval between non-zero demand and. Based on the mapping, the best forecasting technique for an unknown demand vector can be predicted. Given the demand series, the demand attributes are estimated and then the classifier is used to predict the best forecasting technique.

### 4.5.2 *Methods, Assumptions, and Procedures*

The demand attribute space for the meta-forecaster is generated using a normal to anything (NORTA) approach, where each of the demand attributes are generated based on a marginal distribution that is representative of the demand attributes of intermittent demand scenarios and at the same time are correlated. Thus, a comprehensive representation for the demand attribute space that is representative of the intermittent demand was created for testing. For each demand vector, demand is generated and forecasts are made according to the relevant forecasting technique and using a multiple comparison with the best technique, the best

forecasting technique is selected. The resultant data are divided for training and testing. The training data is trained based on multinomial logistic regression and subsequently tested.

#### *4.5.3 Results and Discussion*

In a pilot study, a meta-forecaster was developed where the best forecasting technique was selected based on MAD. This meta-forecaster was tested. The results indicate an accuracy rate of 70.87% for the recommended best forecasting technique; and an 87.94% accuracy rate for the recommended top two forecasting techniques.

### **4.6 Forecast based inventory policy updating**

#### *4.6.1 Problem/Background*

The primary objective of this research is to provide a baseline analysis of the effect of various forecasting techniques on the effectiveness of METRIC/VARI-METRIC based sparing models. This is achieved via a simulation approach. This paper presents an object oriented framework that facilitates modeling inventory network that holds repairable spare parts whose METRIC/VARIMETRIC approximation (by which policies are updated) is driven by forecast estimates. Through the simulation approach questions regarding the choice of the forecasting technique and the frequency of updating the policy, especially in non-stationary demand scenarios are addressed. The research also recommends an appropriate forecasting technique for this class of systems. This research discusses how the framework can be used to develop simulation models through which these questions can be addressed.

#### 4.6.2 *Methods, Assumptions, and Procedures*

The research considers the robustness across several supply-chain configurations of which each supply chain configuration are distinct by the number of bases and the number of items. Each item has its characteristic budget, demand pattern and demand rate and its corresponding unit cost, reparability at each location, repair delay and shipping delay. At each supply chain configuration, different scenarios were considered each in which a different forecasting technique is assigned to all the bases and all the items. Each of the scenarios is compared with a base scenario in which the corresponding supply chain is optimized based on the best forecasting technique. We assumed that the best forecasting technique is based on the demand rate function that the user assigned to that item in the simulation model. Hence comparing each forecasting technique to best forecasting technique, the forecasting technique that is most close to the best forecasting technique across the different supply chain configuration will be robust. The supply chain configuration generator is another contribution of this research.

#### 4.6.3 *Results and Discussion*

In a pilot study, whose results are published in Rossetti et.al (2008) we showed the ease in which the modeling can be done. The results also showed how the user can observe the improvement in operation performance measures of the supply chain when the forecasting techniques and the policy updating frequencies are changed.

#### 4.7 References

1. Rossetti, M. D., Varghese, V., Miman, M., and Pohl E. (2008) “Simulating Inventory Systems With Forecast Based Policy Updating”, Proceedings of the 2008 Winter Simulation Conference, S. J. Mason, R. Hill, L. Moench, and O. Rose, eds., Piscataway, New Jersey: Institute of Electrical and Electronic Engineers
2. Varghese, V. and Rossetti, M. D. (2008) “A Parametric Bootstrapping Approach to Forecast Intermittent Demand”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada.
3. Varghese, V. and Rossetti, M. D. (2008) “A Classification Approach for Forecasting Intermittent Demand”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada.
4. Miman, M., Rossetti, M. D., Varghese, V., and Pohl E. (2008) “An Object-Oriented Framework for Analyzing VARIMETRIC Systems”, Industrial Engineering Research Conference Proceedings, May 17-21, 2008, Vancouver, Canada
5. Varghese, V. and Rossetti, M.D. “A Meta Forecasting Methodology for Large Scale Inventory Systems with Intermittent Demand”, submitted to the 2009 Industrial Engineering Research Conference

6. Varghese, V., Miman, M., Rossetti, M.D., Pohl, E. “Evaluating Forecast Based Policy Updating in Spare Part Inventory Systems”, in preparation

## **Integrated Distribution Planning and Forecasting for Medical Logistics**

### **Submitted By:**

Scott J. Mason, Ph.D. (PI)  
Heather L. Nachtmann, Ph.D. (Co-PI)  
Edward A. Pohl, Ph.D. (Senior Personnel)  
Selin Celikkol (Graduate Research Assistant)  
Jun Jia (Graduate Research Assistant)  
Yasin Unlu (Graduate Research Assistant)  
Troy Long (Undergraduate Research Assistant)  
Sarah Brotherton (Undergraduate Research Assistant)

Department of Industrial Engineering  
University of Arkansas  
4207 Bell Engineering Center  
Fayetteville, AR 72701

### **Papers and Presentations:**

Mason, S.J., 2006, AFOSR-PS13: Integrated Distribution Planning and Forecasting for Medical Logistics, Logistics Management Institute, Virginia.

Mason, S.J., 2006, Informal Briefings at Medical Materiel Executive Agent ROC Drill, Defense Logistics Agency, Fort Belvoir, Virginia.

Mason, S.J., 2007, Integrated Distribution Planning and Forecasting for Medical Logistics, U.S. Army Medical Research & Materiel Command's Telemedicine & Advanced Technology Research Center (TATRC), Fort Detrick, Maryland.

Mason, S.J., Nachtmann, H.L., Pohl, E.A., 2008, Integrated Distribution Planning and Forecasting for Medical Logistics, INFORMS Annual Meeting, Washington, D.C.

Mason, S.J., Pohl, E.A., 2008, Military and Medical Logistics at the University of Arkansas, Defense Medical Logistics Academic Forum, Gaithersburg, Maryland.

## 5.1 Executive Summary

All organizations operate in an atmosphere of uncertainty. Despite this fact, decisions must be made that affect the future of the organization. This is particularly true in proactive logistics environments such as medical logistics, as current demands at on-going medical facilities, such as patient care, required medicines, and blood/plasma usage must be carefully met/managed in the face of unexpected events, such as natural disasters, humanitarian aid efforts, and military mobilizations. Per USTRANSCOM, “there is a lack of collaborative distribution planning ... for optimizing the end-to-end distribution process.” In this project, we develop a multi-commodity flow model for military medical logistics materiel distribution. The main characteristics which we consider include inventory holding and initial storages, storage and commodity flow restrictions and the supply of commodities between any identified facilities. Using actual data gathered from medical supplies being requested in USAMM-SWA, we analyze the Class VIII supply chain from prime vendor locations in the US all the way to a hospital in Kuwait. Our experimental results suggest that transportation efficiencies can be gained via lateral supply transshipments across supply chain network nodes and appropriate inventory management policies. While our initial experiments are not meant to be conclusive, there is evidence that, pending transportation asset availability, optimized planning and distribution can help to decrease the number of required deliveries for class VIII materiel in theater.



## 5.2 Introduction

All organizations operate in an atmosphere of uncertainty. Despite this fact, decisions must be made that affect the future of the organization. This is particularly true in proactive logistics environments such as medical logistics, as current demands at on-going medical facilities, such as patient care, required medicines, and blood/plasma usage must be carefully met/managed in the face of unexpected events, such as natural disasters, humanitarian aid efforts, and military mobilizations. Although new forecasting techniques, software, and powerful desktop computing platforms can empower managers to utilize very sophisticated data analysis techniques, these “opportunities” for making effective forecasts are often missed due to a variety of factors, such as poor communications among/between logistics network partners, improper/insufficient training/personnel expertise, and primary reliance on historical data/trends, to name only a few.

As “distribution and transportation organizations must collaboratively plan both force movement and sustainment activities,” (USTRANSCOM Priority 2 document), the need exists for effective planning/forecasting capabilities to be in place to plan for future events while simultaneously being able to plan/replan and coordinate the transportation of materiel and other goods for activities occurring in a much more immediate time frame. These methodologies must be able to effectively accommodate “products” that may have a finite shelf (useful) life and specific due dates at which time it needs to be delivered to the appropriate customer.

While many researchers have conceptually and/or theoretical decoupled planning and scheduling in academic papers, these two important areas often are very dependent on one another. Individual planning scenarios for achieving one or more objectives of interest each make their own (potentially unique) demand on system resources. Unfortunately, current

operations/commitments can and often do have a significant (potentially adverse) effect on the feasibility of planning scenarios. Per USTRANSCOM, “there is a lack of collaborative distribution planning ... for optimizing the end-to-end distribution process.” Further, “Medical Transportation Managers are not able to synchronize load movement with available air capacity when scheduling loads.”

In this project, we developed a multi-commodity flow model which captures many characteristics of network design problems. The main characteristics which we consider include a planning horizon, inventory holding and initial storages, storage and commodity flow restrictions and the supply of commodities between any identified facilities (production plants, warehouses, distribution centers, etc.). We are able to bring a solution for large size of problems due to the complexity of the provided model. In particular, more useful insights on these design decisions are gained along with the progress in more understating the nature of the problem. In the current state of art, we consider any flow which is possible between facilities and between stages (echelons). Although commodity flow is possible in any direction between facilities, it is only defined for one direction between stages. This network structure is illustrated in Figure 6.

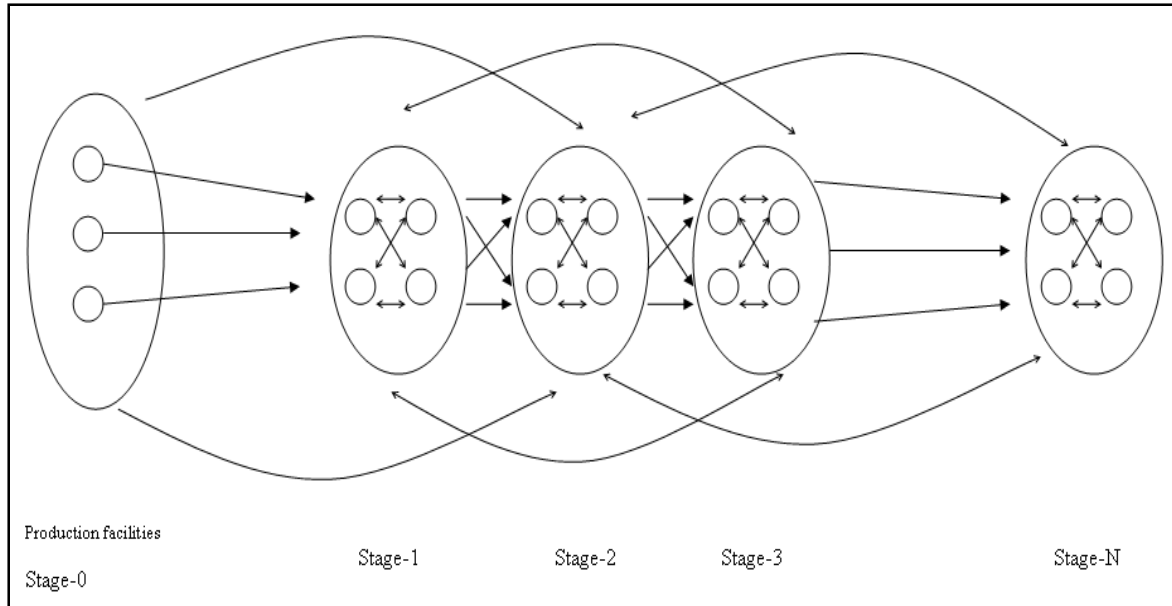


Figure 6. Example Supply Chain Network

### 5.3 Background Discussions and Motivation

During this project, research team members have met with numerous Department of Defense and support personnel in the Washington DC area and various organizations/locations, such as the Defense Logistics Agency (DLA), the Logistics Management Institute (LMI), the US Army's Telemedicine and Advanced Technology Research Center (TATRC), and prime vendor Owens & Minor to learn more about military medical logistics and the Class VIII supply chain.

From these interactions, it was suggested we focus our research efforts on supply channel replenishment and distribution from US-based prime vendor locations to European and Asian supply and distribution centers. In addition, forward-deployed teams and combat hospitals were to be a major area of focus, given the current operations of the Class VIII supply chain during Operation Enduring Freedom and Operation Iraqi Freedom (Figure 8). With this supply chain network in mind, we set forth to develop optimization-based solution methodologies for planning the distribution, transshipment, and delivery of key Class VIII materiel items.

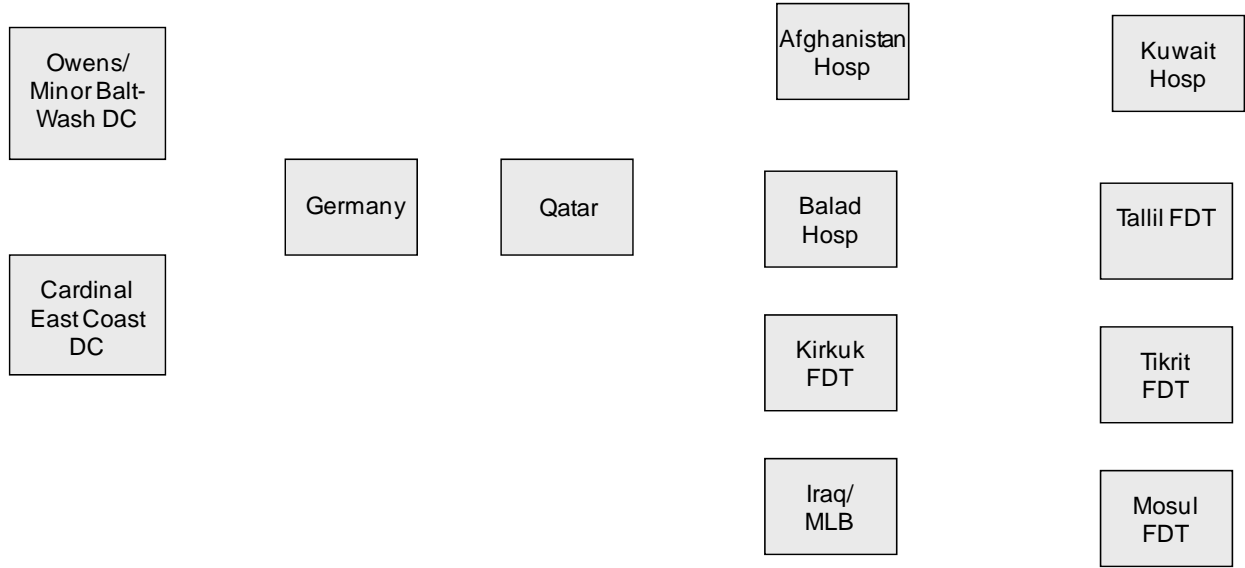


Figure 7. Prime Vendor-Driven Supply Chain Network of Project Focus

#### 5.4 Mathematical Model for Class VIII Materiel Distribution

##### 5.4.1 Sets

$N$	Set of facilities
$V_\rho$	Set of facilities at stage $\rho$
$K$	Set of products
$T$	Set of time periods

##### 5.4.2 Parameters

$d_j^{p,t}$	Demand of product $p$ at facility $j$ at time period $t$
$c_{ij}^m$	Transportation cost of product flow from facility $i$ to facility $j$ by transportation flow $m$
$s_j^{p,t}$	Initial storage of product $p$ at facility $j$ at time period $t$
$h_j^p$	Unit inventory holding cost of product $p$ at facility $j$
$u_i$	Upper bound of inventory amount at facility $i$
$n$	Number of stages

### 5.4.3 Variables

$f_{ij}^{p,t}$  Amount of product ( $p$ ) flow from facility  $i$  to facility  $j$  at time period  $t$ .

$I_j^{p,t}$  Inventory of product  $p$  at facility  $j$  at time period  $t$ .

### 5.4.4 Model Formulation

Total transportation costs and inventory holding costs are of interest in terms of current performance metrics. The following objective function (1) minimizes the sum of total transportation costs and holding costs.

$$\min \sum_i \sum_j \sum_p \sum_t c_{ij} f_{ij}^{p,t} + \sum_p \sum_j \sum_t h_{pj} I_j^{p,t} \quad (1)$$

As a main constraint we consider the following equality which satisfies conservations of flows at any facilities. We can consider flow in commodities as initial storages and goods which are transferred from some other facilities in the same stage or facilities in previous stages. On the other hand, flow out commodities can be thought of as goods which are transferred to some other facilities in the same stage or facilities in succeeding stages. Finally specified net amount for the corresponding facility constitutes of the net demand and the inventory levels. In this manner, we introduce the following two constraints (2 and 3).

$$\sum_{\rho=1}^{\rho=q} \sum_{i \in V_\rho \cup V_q \setminus \{j\}} f_{ij}^{p,1} + s_j^{p,1} = d_j^{p,1} + \sum_{\tau=q}^{\tau=n} \sum_{k \in V_\tau \cup V_q \setminus \{j\}} f_{jk}^{p,1} + I_j^{p,1} \quad q = 0,1,2,3,\dots,n \quad j \in V_q \quad p \in K \quad (2)$$

$$\sum_{\rho=1}^{\rho=q} \sum_{i \in V_\rho \cup V_q \setminus \{j\}} f_{ij}^{p,t} + s_j^{p,t} + I_j^{p,t-1} = d_j^{p,t} + \sum_{\tau=q}^{\tau=n} \sum_{k \in V_\tau \cup V_q \setminus \{j\}} f_{jk}^{p,t} + I_j^{p,t} \quad q = 0,1,2,3,\dots,n \quad j \in V_q \quad p \in K \quad t \in \{2..l\} \quad (3)$$

Constraint (2) and (3) are required that total flow-in amount is equal to total flow-out amount. For initial period (constraint (2)), there are no inventory amount flow-in. An upper bound is considered for the inventory, which is ensured by the constraint set (4), while constraint sets (5) and (6) are variable type restriction constraints.

$$I_i^{p,t} \leq u_i \quad i \in N, \quad p \in K, t \in T \quad (4)$$

$$I_i^{p,t} \geq 0 \quad i \in N, \quad p \in K, t \in T \quad (5)$$

$$f_{ij}^{p,t} \geq 0 \quad i, j \in N, \quad p \in K, t \in T \quad (6)$$

## 5.5 Experimental Study

With the assistance of US military personnel at the Army Medical Department (AMEDD), we collected the following list of the top 20 highest demanded Class VIII products (lines) at the United States Army Medical Materiel Center-Southwest Asia (USAMMC-SWA) sourced by a prime vendor (Figure 9). In Figure 9, each Class VIII line is described and assigned an associated ID # for use in all subsequent experimentation and model explanations.

Figure 10 displays a hypothetical monthly representation of actual annual demand levels by Class VIII item type at each supply chain location (site). In each case, AMEDD personnel provided the research team with actual annual demand values that were subsequently distributed across the twelve model time periods of interest in a random manner. Next, from-to travel times were determined by the research team using Internet references and AMEDD personnel validation (Figure 11). This transportation matrix is expressed in terms of the number of hours required to travel between any two sites. This information is important in the model as a surrogate measure for transportation cost  $c_{ij}^m$ .

<b>Line</b>	<b>ID</b>
PAD_PREP_ALCOHOL_100S	1
BANDAGE_GAUZE_4.5"_1S	2
CATHETER_IV_ANGIO_1S	3
TAPE_SURGICAL_ADH_4S	4
BANDAGE_ELAS_4IN_10S	5
ADHESIVE_TAPE_1IN_12S	6
GLOVE_LT_PF_LG_100S	7
ADHES_TAPE_SILK_2IN_6S	8
NEEDLE_HYPO18GX1.5_100	9
BANDAGE_ELAS_3IN_10S	10
SPHYGMOMANOMETER_AD_1S	11
SYRINGE_HYPO_5CC_100S	12
ADHESIVE_SKIN_DERM_12S	13
SYRINGE_HYPO_20CC_40S	14
SYRINGE_HYPO_10CC_100S	15
GLOVES_SURG_7.5__100S	16
SPONGE_4X4_TRAY_1280S	17
BANDGE_COBAN_5X1_30S	18
PAD_PREP_ALC_MED_200S	19
BANDAGE_37X37X52IN_1S	20

Figure 8. Top Class VIII Lines at USAMMC-SWA Sourced by Prime Vendor

The initial amount of inventory for each Class VIII item available from prime vendor suppliers was calculated by summing up all required demand by item type, then evenly splitting this demand across the two prime vendor locations (Table 22). Next, in order to stop the optimization model from simply bulk shipping all required demanded items in the first model period, we are required to model the maximum amount of inventory that could be stored at any site in any model time period (Table 23). The values in Table 23 were computed after examining the demand levels by supply chain location, although other methods of determining these values will also work in our model.

Table 22. Annual Demand for Top 20 Class VIII Lines--Random Distribution by Month

Line	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
PAD_PREP_ALCOHOL_100S	1474	1412	1103	1121	2486	1834	1706	2327	1405	3170	1845	2410
BANDAGE_GAUZE_4.5" _1S	198	294	432	762	1672	593	662	343	9224	19309	3242	5017
CATHETER_IV_ANGIO_1S		3	13	5		18	33	37	33	243	19	18017
TAPE_SURGICAL_ADH_4S	131	424	181	386	347	669	325	607	399	482	317	427
BANDAGE_ELAS_4IN_10S	339	369	527	492	611	433	723	584	679	432	550	335
ADHESIVE_TAPE_1IN_12S	420	485	424	355	424	310	471	441	425	375	380	357
GLOVE_LT_PF_LG_100S	760	540	446	580	1080	833	1193	1300	869	1119	750	1113
ADHES_TAPE_SILK_2IN_6S	364	382	325	204	282	270	244	430	399	328	345	419
NEEDLE_HYPO18GX1.5_100	435	222	199	290	525	428	329	366	328	106	367	280
BANDAGE_ELAS_3IN_10S	497	136	266	264	310	246	287	319	292	185	280	391
SPHYGMOMANOMETER_AD_1S	493	97	119	158	119	234	119	99	120	104	218	55
SYRINGE_HYPO_5CC_100S	31	146	167	92	139	105	341	58	179	121	120	116
ADHESIVE_SKIN_DERM_12S	41	18	43	47	99	70	115	88	100	9	79	57
SYRINGE_HYPO_20CC_40S	77	113	106	39	169	88	118	101	136	102	165	124
SYRINGE_HYPO_10CC_100S	93	119	176	158	220	150	211	144	173	140	98	140
GLOVES_SURG_7.5_100S	33	73	58	58	107	75	118	104	112	38	176	90
SPONGE_4X4_TRAY_1280S	441	76	71	73	30	52	331	100	703	52	74	107
BANDGE_COBAN_5X1_30S	134	84	129	59	53	53	60	79	237	113	66	66
PAD_PREP_ALC_MED_200S	221	264	317	664	1062	1510	563	107	575	813	392	240
BANDAGE_37X37X52IN_1S	8599	9898	3226	3065	2988	9212	10904	9834	3783	970	6445	6936

Table 23. From/To Travel Time Matrix for Supply Chain Locations (Sites)

	Owens/Minor	Cardinal	Germany	Qatar	Afghanistan Hosp	Balad Hosp	Kirkuk FDT	Iraq/MLB	Kuwait Hosp	Tallil FDT	Tikrit FDT	Mosul FDT
Owens/Minor	0	6.55	37.68	52	67.48	60.05	60.64	61.78	65.21	64.02	61.05	59.72
Cardinal	6.55	0	43.28	45	69.79	63.88	63.1	64.37	67.79	66.5	64.02	62.21
Germany	37.68	43.28	0	12	31.89	21.4	20.55	21.56	24.97	23.02	21.2	19.61
Qatar	52	45	12	0	12.31	8	8.23	7.01	17.57	17.88	17.98	19.13
Afghanistan Hosp	67.48	69.79	31.89	12.31	0	14.1	14.02	14.25	12.91	13.5	14.16	14.7
Balad Hosp	60.05	63.88	21.4	8	14.1	0	2.54	0.62	3.16	3.5	0.86	1.95
Kirkuk FDT	60.64	63.1	20.55	8.23	14.02	2.54	0	1.54	4.72	3.1	0.68	0.94
Iraq/MLB	61.78	64.37	21.56	7.01	14.25	0.62	1.54	0	3.44	2.3	1.23	2.25
Kuwait Hosp	65.21	67.79	24.97	17.57	12.91	3.16	4.72	3.44	0	1.56	4.6	5.59
Tallil FDT	64.02	66.5	23.02	17.88	13.5	3.5	3.1	2.3	1.56	0	3.1	4.2
Tikrit FDT	61.05	64.02	21.2	17.98	14.16	0.86	0.68	1.23	4.6	3.1	0	1.15
Mosul FDT	59.72	62.21	19.61	19.13	14.7	1.95	0.94	2.25	5.59	4.2	1.15	0

Given these model inputs, our next step is to analyze this example problem instance using our optimization model. Our mixed-integer program is coded in AMPL and analyzed using CPLEX v10.1. The test case scenarios are run on a quad core, quad processor PC-based server with 128 GB of RAM. All runs produced feasible results in a fraction of a computational second,



as this problem falls into the class of assignment problems which can be resolved quite nicely using standard optimization software packages.

Table 24. Initial Inventory for Top 20 Class VIII Lines by Prime Vendor

<b>Line</b>	<b>Owens/Minor</b>	<b>Cardinal</b>
1	13375	13375
2	25048	25048
3	11052	11052
4	2817	2817
5	3644	3644
6	2920	2920
7	6349	6349
8	2395	2395
9	2325	2325
10	2083	2083
11	1161	1161
12	969	969
13	459	459
14	802	802
15	1093	1093
16	625	625
17	1266	1266
18	679	679
19	4036	4036
20	45516	45516

Table 25. Assumed Maximum Total Inventory by Site

Owens/Minor	15000
Cardinal	15000
Germany	8800
Qatar	8500
Afghanistan Hosp	6844
Balad Hosp	6878
Kirkuk FDT	6779
Iraq/MLB	6980
Kuwait Hosp	6569
Tallil FDT	6556
Tikrit FDT	6628
Mosul FDT	6619

Figure 9 displays the model's transportation cost-optimal solution for ID 1 of the 20 Class VIII lines, 'Pad Prep Alcohol 100S.' The values on each arc indicate the quantity of the item to be shipped. In order to both meet some period one demand levels and to supply network locations with inventory for subsequent periods, the optimization model recommends a large initial shipment from prime vendor Owens & Minor to Germany (USAMMC-E), which is subsequently sent both to Qatar and Mosul. The Qatar shipment is then destined for other supply locations as described in Figure 9.

Notice that the optimal model solution in Figure 9 determines that shipment from Qatar to Iraq/MLB to the Balad hospital is preferred to a direct shipment from Qatar to the Balad hospital. This is most probably related to transportation economies of scale while considering holding costs and/or demand levels at each site. By allowing this sort of lateral transshipment within the same echelon of the supply chain, our optimization model is able to exploit all possible transportation and distribution options in order to find a globally optimal solutions for the Class VIII transportation distribution problem.

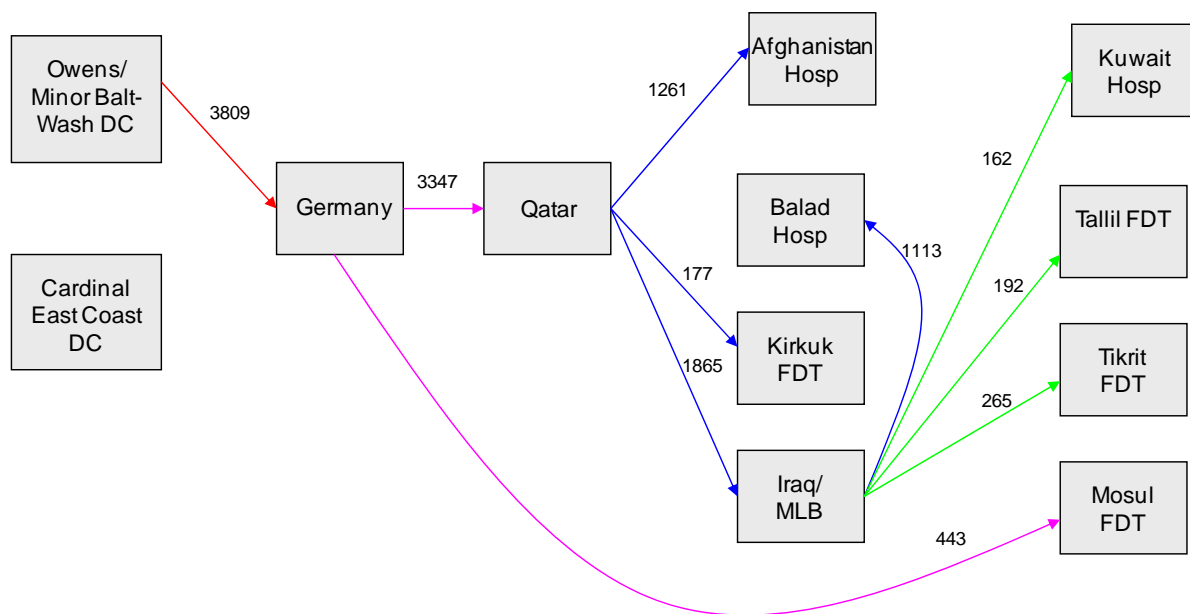


Figure 9. Time Period 1 Model Solution for Line 1 'Pad Prep Alcohol 100S'

Building upon the example model results displayed in Figure 9, Table 26 displays the resulting projected total inventory levels by site by month over the model horizon. The effects of both initial deliveries and ongoing demand consumption of items can be seen in the figure in terms of increasing and decreasing inventory levels, respectively.

Table 26. Projected Periodic Inventory Levels for Line 1 ‘Pad Prep Alcohol 100S’ by Site

	Month											
	1	2	3	4	5	6	7	8	9	10	11	12
<b>Owens/Minor</b>	5107	4148	3234	2500	2500	2188	1291	1291	1263	724	410	0
<b>Cardinal</b>	13375	13375	13375	12755	10583	8785	5782	4851	4289	3021	0	0
<b>Germany</b>	0	0	0	50	0	0	607	0	0	0	0	0
<b>Qatar</b>	0	0	0	0	0	0	0	0	0	0	1157	0
<b>Afghanistan Hosp</b>	1158	1059	982	904	730	602	483	320	222	0	0	0
<b>Balad Hosp</b>	966	825	715	603	354	171	0	0	0	0	241	0
<b>Kirkuk FDT</b>	0	0	0	0	0	0	1338	1059	890	510	289	0
<b>Iraq/MLB</b>	6980	6268	6186	6041	5724	2659	2599	2568	1738	0	0	0
<b>Kuwait Hosp</b>	0	0	0	0	202	0	760	504	349	0	0	0
<b>Tallil FDT</b>	0	0	0	0	0	1120	898	595	412	0	313	0
<b>Tikrit FDT</b>	0	0	0	0	330	0	0	0	0	0	0	0
<b>Mosul FDT</b>	212	0	0	373	0	0	0	211	0	0	0	0

## 5.6 Conclusions and Future Research

In this project, we developed a multi-commodity flow model which captures many characteristics of network design problems. The main characteristics which we consider include a planning horizon, inventory holding and initial storages, storage and commodity flow restrictions and the supply of commodities between any identified facilities (production plants, warehouses, distribution centers, etc.). As all organizations operate in an atmosphere of uncertainty and decisions must be made that affect the future of the organization, our proposed optimization-based transportation and distribution approach for Class VIII materiel can be a viable way for military decision makers to act/react to changing network conditions.

In the future, the results of our optimization model may be used to help set target inventory levels by Class VIII item type and/or by site such that inventory replenishment can be done more cost effectively. Further, anticipatory actions for dealing with potential network node changes/closures can be evaluated using this optimization framework as the model can easily be solved in a ‘what if’ scenario mode by simply changing the AMPL data files to represent the desired network configuration under study. The transportation matrix should be reevaluated and updated, with a large (“big M”) value being input for any transportation routes/links that do not exist in practice. Finally, additional granularity into the demand resolution at each node in each period could be added to allow the model to solve more realistic problem instances, rather than the example instance the was based on an abstraction of actual demand values for a whole year.

## 6      **Research Task #6**

### **An Auction-Based Framework for Resource Allocation in Disaster Relief Operations**

#### **Submitted By:**

Nebil Buyurgan, Ph.D., (PI)  
Alp Ertram, Ph.D., (Graduate Research Assistant)  
Alejandro Mendoza, Ph.D. Candidate (Graduate Research Assistant)

#### **Papers and Presentations:**

Ertem, M.A., Buyurgan, N., Pohl E.A.,(2008) Bid construction in resource allocation via auctions for supply chain management, Submitted to the Journal of Logistics.

Ertem, M.A., Buyurgan, N., Rossetti, M.D.,(2008) Multiple buyer procurement auctions framework for humanitarian supply chain management, Submitted to International Journal of Physical Distribution and Logistics Management.

A. Mendoza, and N. Buyurgan., “A Laboratory Environment For Radio Frequency Identification (RFID) Technology Education,” Institute of Industrial Engineers (IIE) Annual Conference, May 2006, Orlando, FL.

N. Buyurgan, “Real-Time Manufacturing System Control with RFID Technology,” 35th International Conference on Computers and Industrial Engineering, June 19-22, 2005, Istanbul, Turkey.

N. Buyurgan and J. R. Chimka, “AutoID Technology for Real-Time Manufacturing System Control,” Institute of Industrial Engineers (IIE) Annual Conference, May 14-18, 2005, Atlanta, GA.

N. Buyurgan and A. Mendoza, “Creating A Laboratory Learning Environment for RFID Education,” Decision Sciences Journal of Innovative Education, In Print for 2008

N. Buyurgan, M. A. Ertem, and J. R. Chimka, “Read Rate Analysis of Radio Frequency Identification Systems for Business Applications,” International Journal of Radio Frequency Identification Technology and Applications, Vol. 1, No. 2, pp. 147-163, 2007.

#### **Dissertation:**

Ertem, M,A (2008) Procurement auctions-based framework with announcement options for resources allocation in disaster relief operations. Doctoral Dissertation, University of Arkansas.

Mendoza, A. (In-progress) An analysis for real-time decision making with imperfect RFID data. Doctoral Dissertation, University of Arkansas.

## 6.1 Executive Summary

This task aimed to increase the understanding and knowledge of disaster relief management within the contexts of managing the limited resources. Specifically, the problem addressed in this research is the inefficiency in resource allocation for disaster relief procurement operations. The research activities focused on understanding the resource allocation problems considering different dimensions. A holistic, intuitive, and reconfigurable procurement auctions-based framework for effective resource allocation was developed in which auctioneers and bidders compete amongst each other in multiple rounds of the procurement auction. In decentralized and chaotic disaster relief environment the developed model offers a systematic approach to allocate resources effectively. In this alternative model unique system parameters were introduced and tested in order to utilize all available resources on-hand. These parameters include substituting the required/demanded items by other on-hand items and allowing partially fulfilled demands (i.e. allowing the amount of shipped item being less than required/demanded) to satisfy a portion of them. Moreover, procedures to handle urgency of the demands and sorting them were addressed in the framework. Using these system characteristics of a disaster relief environment, the framework is verified by simulation and optimization techniques.

## 6.2 Introduction

The occurrence of natural disasters is increasing especially in the last two decades. 225 natural disasters were recorded on a yearly average between 1987 and 1997, whereas the same figure almost doubled between 2000 and 2006 [8,13]. This number reached to 414 in 2007 [13]. The property damage from Hurricane Katrina in 2005 alone was estimated about \$96 billion; the residential damage was approximately 300,000 homes [16]. Thousands were left injured or missing in Indonesia, India, Sri Lanka and Thailand after tsunamis in 2004 and the earthquake in China this year. It was very difficult or impossible for many homeless victims to reconstruct their shattered lives. The crucial questions are how responsive and prepared we are to these types of tragedies and how we respond when they occur.

Disaster relief management domain is distributed and has a decentralized structure due to: (1) the domain is geographically distributed, (2) relief efforts typically require separate independent organizations, and (2) each organization has unique business processes to perform particular tasks [17]. Organizations (e.g., local governments, the United Nations, and non-governmental organizations etc.) in this environment reveal autonomous characteristics in order to achieve their own goals. They are usually self-centered with specific decision-making mechanisms and expertise and often times they are reluctant to release their process information. They typically have less formalized internal and external information and communication systems. Thus, the knowhow gained by one organization cannot be transferred to others easily. Moreover, every disaster relief operation is treated in unique ways and there is no standard means of operations used by those organizations.

### 6.3 Methods, Assumptions, and Procedures

Given that local resources are vital in the first few days after a disaster strikes, they should be utilized efficiently to supply the needs of the victims immediately. Additionally, procurement activities should be performed according to the specifics of disaster relief operations in the long run. The framework proposed for disaster relief operations here fits well both into the immediate response with local resources and also the long-term procurement activities from local and global suppliers. The main idea is to introduce some auction design parameters and decision making logic that would facilitate the procurement activities.

The procurement auctions considered in this research have multiple auctioneers and multiple bidders. The bidder parties can be identified as warehouses, suppliers, or manufacturers of the auctioned items in a disaster relief environment, whereas the auctioneer parties represent the disaster locations which send appeals for the items. The auction process is given in Figure 10.



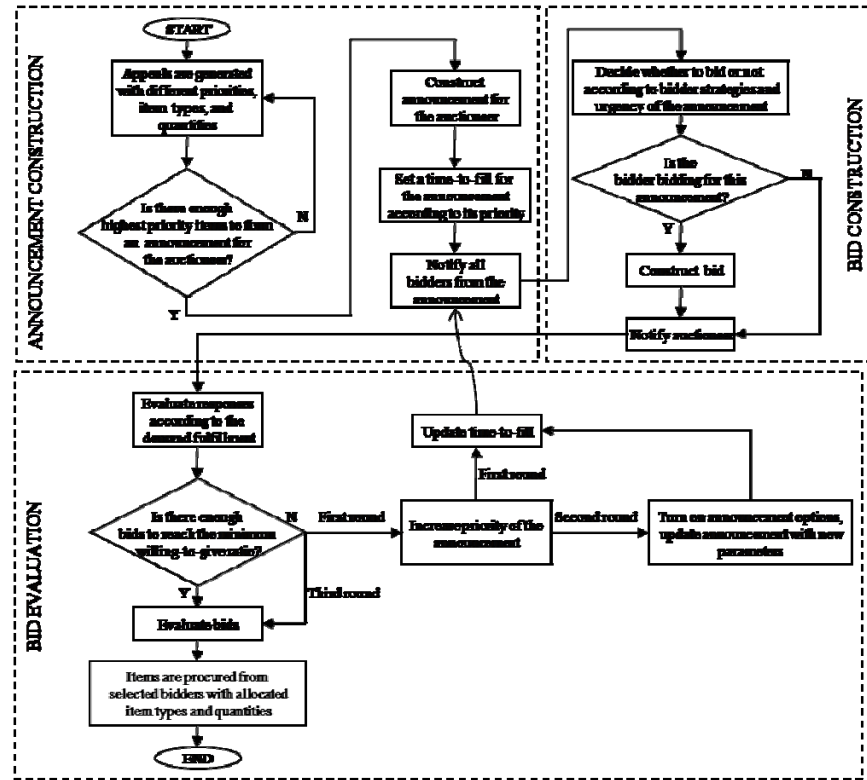


Figure 10. Procurement Auctions Framework

As seen in Figure 10, in the announcement construction phase, the auctioneer accumulates incoming demands and releases announcements based-on a predefined count threshold for *priority of items* (i.e., a certain number of highest priority items). Demands for different items arrive to auctioneers as appeals for relief supplies. These demands are then bundled according to the announcement construction criterion. When there are enough demands to form an announcement, it is announced. The auctioneer accumulates demands to benefit from the economies of scale in the procurement process. The bid construction phase receives an announcement, compares demanded items with on hand inventory quantities, and their associated values. The value of an item corresponds to its age and condition. Using this information, bidders (suppliers) determine the quantities and mix of their bids with the aim of minimizing the current asset value of offered items. In the bid evaluation phase, bid quantities

and their associated asset values are maximized by a general multidimensional knapsack problem (MDKP). Details of the framework will be explained in separate sections. The following considerations are made in the auction process:

- When an auction is finalized, the procured items from the bidder to the auctioneer are considered to be shipped and consumed.
- Without loss of generality, there is only one substitute for each item and two or more order substitutes (i.e., substitute of a substitute) are not allowed.
- An announcement cannot have the original item and the substitute item at the same time.

The auctioneer is responsible for setting the stage for the auction. An auctioneer can offer two announcement options in the announcement construction phase. These are substitution and partial fulfilment options. These options are proposed in order to fulfill the demand of the disaster locations as much as it is possible with the current inventories of bidders. If the substitution option is preferred by the disaster locations, then these unsolicited donations will get a chance to be used instead of causing stocking costs. Substitute item options are given to the bidder to give the opportunity to bid on the item even if it does not have the original quantity. The partial fulfilment option enables better usage of supplier inventories, and the value of the item gives a means to humanitarian organizations to evaluate the supplies.

The priority of items is included in the framework to improve the linkage between the disaster locations and suppliers. Three levels of priority are used in the proposed framework. The first level indicates urgent-immediate distribution, the second level indicates low priority distribution, and the third level indicates non-priority items. The ease of logistics concept attempts to take into account of the differences among suppliers in terms of convenience in geographical or topographical access to the disaster location. During disasters, essential

infrastructure like highways, roads and bridges are usually destroyed. The ease of logistics parameter is considered in three levels. The suppliers having better ease of logistics are favoured in the bid evaluation.

### 6.3.1 *Announcement construction phase*

In the *announcement construction phase*, appeals for items are declared with item types, quantities and priorities. Each item type has a priority, an integer from the interval [1,3] (with one being the highest priority). When a certain quantity threshold is reached for the highest priority items, the decision for partial fulfilment and substitution options is taken and the announcement is constructed. *Time-to-fill* for the announcement is defined as the waiting time of the announcement before receiving any response from bidders. An upper bound for time-to-fill was selected as 24 time units (e.g., hours, etc.), because the assessment happens within the first 24 hours after the disaster strikes [15]. The *weighted priority* (*WP*) of the announcement is used in extrapolating from [1,3] priority interval to [1,24] time unit interval using  $[time\ to\ fill = 1 + (weighted\ priority - 1) \times 23/2]$ . Note that higher priority announcements have a shorter time-to-fill.

### 6.3.2 *Bid construction phase*

In the bid construction phase, bidders need to decide whether to bid or not on the announcement. This decision is based on the urgency of the announcement and the bidding strategy that the bidder follows. If the announcement is urgent, the bidder by-passes its bidding strategy and constructs bid for the announcement. Otherwise, it checks whether its bidding strategy picks the upcoming announcement. If the announcement is chosen, then the bidder constructs the bid;

otherwise the bidder notifies the auctioneer with a null bid. Bidders make the comparison among announcements with three different strategies:

1. Bid to the announcement if it has the longest waiting time in the announcement queue.
2. Bid to the announcement if it has the highest fill rate (i.e., supplied amount / requested amount) with original item types.
3. Bid to the announcement if it is the most urgent (i.e., the lowest weighted priority).

These strategies are applied only when there are enough announcements (three announcements are taken without loss of generality) in bidder's agenda to compare. The first strategy aims to decrease the waiting time of announcements in the queue. The second strategy aims to better utilize on hand inventories and the third strategy gives importance to the priority of the items.

After a bidder decides to bid on an announcement, it uses an IP formulation to construct its bid. The decision in bid construction is whether to use substitute items or not while fulfilling the announcement with original items. A bidder may have choices of satisfying the demand with only original items, only substitute items, or a mix of those depending on its inventory on hand. The objective function used in bid construction is formulated as:  $\sum_j^m (X_j V_j + Y_j W_j)$ , where  $X_j$  is the original quantity bid,  $Y_j$  is the substitute quantity bid,  $V_j$  and  $W_j$  are the original and substitute values of the bidders' inventory for item  $j$  of the announcement having  $m$  items. The value of an item represents the asset value of the item depending its age and condition. The challenge here is whether to include substitutes and how much to include when it is allowed by the auctioneer party. The bids are divisible and all-or-nothing bids are not accepted, therefore suppliers are considered as willing to give the quantity that is allocated by the auctioneer at the same value as they offered for the whole quantity [14,18]. In the following formulation, if-then constraints and

inventory availability parameters are critical. If-then constraints are needed for the partial demand fulfilment and the substitution options. The inventory availability parameter aims to determine the inventory on hand. The index of items in an announcement in the IP formulation is represented by  $(j = 1, \dots, m)$ . The parameters and decision variables are given in Table 27.

Table 27 Parameters and decision variables in bid construction phase

Parameter	Definition
$Q_j$	original demand quantity for item type $j$
$I_j$	original quantity of type $j$ in bidder's inventory
$H_j$	substitute quantity of type $j$ in bidder's inventory
$V_j$	value of original type $j$ in bidder's inventory
$W_j$	value of substitute type $j$ in bidder's inventory
$P_j$	$\begin{cases} 1, \text{ if partial demand fulfillment is allowed for type } j \\ 0, \text{ otherwise} \end{cases}$
$S_j$	$\begin{cases} 1, \text{ if substitute type is allowed for type } j \\ 0, \text{ otherwise} \end{cases}$
$z_j$	$\begin{cases} 0, \text{ if inventory of bidder is greater than announced quantity for type } j \\ 1, \text{ otherwise} \end{cases}$
M	Big-M (i.e. a sufficiently large integer)
Decision Variables	
$X_j$	original quantity bid by the retailer
$Y_j$	substitute quantity bid by the retailer

The objective function is given as  $[\text{Min } \sum_j^m (X_j V_j + Y_j W_j)]$ . The constraints of the IP formulation are as follows:

$$\begin{array}{llll}
X_j + S_j Y_j \geq Q_j - M z_j & \forall j & X_j \geq P_j I_j - M(1 - z_j) & \forall j \\
Y_j \leq M S_j & \forall j & Y_j \geq S_j P_j H_j - M(1 - z_j) & \forall j \\
X_j \leq I_j & \forall j & X_j \geq 0 \text{ and integer} & \forall j \\
Y_j \leq H_j & \forall j & Y_j \geq 0 \text{ and integer} & \forall j
\end{array}$$

### 6.3.3 Bid evaluation phase

In the bid evaluation phase, the auctioneer collects responses from bidders and decides whether or not to send the announcement back to bidders for another round. Multi-round auctioning usually means the revision of the bid from suppliers [3]; on the other hand, the framework in this research introduces modification of announcements to get a higher fill rate in the upcoming rounds. In our framework, the willing-to-give ratio is important. The willing-to-give ratio is

defined as  $[(\text{total bid quantity}) / (\text{announcement quantity})]$ . This ratio is calculated for each item using all the bids. When there are enough bids to reach the predetermined willing-to-give ratio for all item types, then auctioneer evaluates the bids. If there are not enough bids, then the priority of the announcement is increased by a priority increase rate, time-to-fill is updated (i.e., decreased), and the announcement is sent back to the bidders for a second round. In the second round, if the willing-to-give ratio is still not reached, then the substitution and partial fulfilment options are turned on for the item types where they were not allowed before. Then, the priority of the announcement is increased, time-to-fill is updated, and the announcement is sent back to the bidders for a third round. If the willing-to-give ratio is still not reached, then the auctioneer evaluates the bids and becomes content with the available bids.

The bid evaluation phase chooses the suppliers to fulfil the announcement. The auctioneer might fulfil the announcement by only original items, only substitute items, or a mix of those depending on the bids received and the location of the bidders. The objective function used in bid evaluation is formulated as:  $\sum_i^n \sum_j^m \alpha_i (A_{ij} V_{ij} + B_{ij} W_{ij})$ , where  $A_{ij}$  is the original quantity of item  $j$  allocated to bidder  $i$ ,  $B_{ij}$  is the substitute quantity of item  $j$  allocated to bidder  $i$ , and  $V_{ij}$  and  $W_{ij}$  are the original and substitute values of the bidder  $i$ 's inventory for item  $j$  in an announcement having  $m$  items. Note that  $V_{ij}$  and  $W_{ij}$  are exogenous for the auctioneer and declared by the bidder in the bid construction phase. Here,  $\alpha_i$  represents the ease of logistics parameter for bidder  $i$ . The following formulation is a variation of the general MDKP [1]. The index of items in an announcement in the IP formulation is represented by  $(j = 1, \dots, m)$  and the index of bidders is represented by  $(i = 1, \dots, n)$ .

The objective function is given as  $[\text{Max } \sum_i^n \sum_j^m \alpha_i (A_{ij} V_{ij} + B_{ij} W_{ij})]$ . The constraints of the IP formulation are as follows:

$$\begin{array}{llll}
\sum_i^n (A_{ij} + B_{ij}) \leq Q_j & \forall j & A_{ij} \geq 0 \text{ and integer} & \forall i, j \\
A_{ij} \leq C_{ij} & \forall i, j & B_{ij} \geq 0 \text{ and integer} & \forall i, j \\
B_{ij} \leq D_{ij} & \forall i, j & & 
\end{array}$$

#### 6.3.4 Experimental Study

Proposed procurement auctions-based framework is evaluated with respect to different design parameters. A simulation model was used to generate different problem instances and to combine the three phases of the framework. The results of two sets of experiments are analyzed and presented here: the first set of experiments illustrates the effects of the environmental factors and the second set of experiments details the effects of different auction parameters with four special scenarios. The environmental and auction design parameters are depicted in Figure 11.

In Figure 11, environmental factors are given as (1) demand quantity distribution, (2) the ease of logistics, (3) value of the item, (4) inventory on hand, and (5) lead time. Auctioneer related parameters are given as willing-to-give ratio, and strategy threshold. The count threshold, priority increase rate, and bidder related parameter are given for the bidding strategy. In the following two sections environmental factors and auction design parameters are explained.

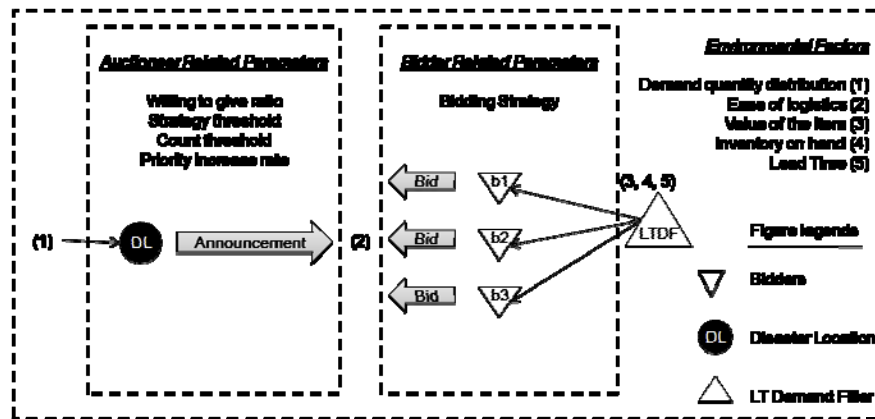


Figure 10. Experimental design factors

### 6.3.5 Environmental factors

The location and timing of a disaster determine some environmental factors which can be changed neither by the auctioneers nor by the bidders. These environmental factors affect the result of the procurement auctions, but are not an inherent part of the auction design. In an attempt to stabilize the environmental factors for the scenario analysis, a  $2^5$  full factorial design of experiments was performed with three bidders and one disaster location. One high and one low level was chosen from Table 28. Demands for different item types were generated using a Poisson distribution with a mean of 1 demand/time-unit. Each item type is equally likely to be demanded out of ten item types. One-thousand individual demands are generated with 30 replications. The quantity of each demand is a random variable which follows the demand quantity distribution. Each incoming demand quantity is added to its same item type in the bundle and the count threshold (200) is checked. If the threshold is met, then this bundle, which includes quantities for different item types, is announced. The demand quantity distribution depends on the severity of the damage in the disaster location. Ease of logistics is a constant factor relative to disaster locations and bidders, which is determined after the disaster strikes. Value of the item, inventory on hand, and lead time are determined by contractual terms between external lead time demand fillers and bidders. The  $S$  value represents the order up to level and the  $s$  value represents the reorder point, which is taken as ten for all bidders.

Table 288. Environmental Factors and Their Levels

Factor	Level	
	Low	High
Demand quantity distribution	U(1,50)	U(100,150)
Ease of logistics	33% of the bidders - 3	33% of the bidders - 1
	67% of the bidders - 1	67% of the bidders - 3
Value of the item	33% of the bidders - 100	33% of the bidders - 50
	67% of the bidders - 50	67% of the bidders - 100



Inventory on hand	33% of the bidders - 70	33% of the bidders - 30
	67% of the bidders - 30	67% of the bidders - 70
Lead Time	33% of the bidders – U(12, 72)	33% of the bidders – U(72, 120)
	67% of the bidders – U(72,120)	67% of the bidders – U(12,72)

One of the performance measures in humanitarian logistics is the quantity that is supplied out of the amount requested [5]. This metric is defined as the *fill rate*. A practical example for the fill rate can be given from a disaster relief operation after South Asia Earthquake on October 9th, 2005. The fill rate (i.e., appeal coverage) was 63% after the first week, 47% after the second week, 74% after a month, 91% after two months, and 93% after three months [5]. *Allocation share of bidders* is another performance measure, which defines the distribution of supplied items among bidders. When the results of the full factorial design are analyzed, the value of the item and ease of logistics factors have no effect on the fill rate. Other quantity related factors have an effect on fill rate. Inventory on hand and ease of logistics affect the bidder shares, where higher inventory on hand and higher ease of logistics increase the bidder's share. For the scenario analysis, middle levels from Table 28 were selected and remained unchanged during the remaining experiments. Demand quantity distribution was selected as U(50,100) for all disaster locations. The value of the item in a bidders' inventory is taken as 75, inventory on hand was set to 100 and ease of logistics was set to 2 for all bidders. The fill rate of the auctioneer with these middle levels is 0.59.

### 6.3.6 Auction design parameters

Auctioneer related parameters give flexibility to the auctioneers to adapt themselves to the changing settings of different disasters and different locations. Willing-to-give ratio determines the eagerness of the disaster location for demand satisfaction. Since resources are limited in a disaster relief environment, there might be cases where auctioneers need to be satisfied with a

certain amount. This concept is termed willing-to-give because it shows the willingness of the bidders to bid on an announcement. The strategy threshold is a safety factor for disaster locations where the below threshold levels by-pass bidder strategies in urgent announcements and oblige bidders to bid on the announcement. Count threshold determines the number of highest priority items and the timing of an announcement. Priority increase rate determines the rate to increase the priority between multiple rounds. We assume that the tolerance of the disaster location decreases with increasing rounds. Bidding strategy gives flexibility to bidders whether to bid or not. Table 29 summarizes the special scenarios to analyze these auction parameters.

Table 29. Four scenarios to evaluate different auction design parameters.

Scenario	Bidders	Auctioneers	Performance measure	Target design parameter
1	- No decision on whether to bid or not - Construct bid to every announcement	- Evaluate all the bids. - Single Round	- fill rate - announcement queue	- Base case for multiple disaster locations - Count threshold
2	-Decide to bid or not -3 bidders-strategy 1 -3 bidders-strategy 2 -3 bidders-strategy 3	- Evaluate all the bids. - Single Round - Count threshold same for all auctioneers (400)	- fill rate - allocation share among bidders -announcement queue	- Effect of bidder decision making and bidding strategies - Strategy threshold
3	- No decision on whether to bid or not - Construct bid to every announcement	-Decide to evaluate bids -Multiple rounds -Count threshold same for all (400) -Strategy threshold same for all (1.7)	- fill rate -announcement queue	-Effect of auctioneer decision making -Effect of multiple rounds -Willing to give ratio
4	-Decide to bid or not -3 bidders-strategy 1 -3 bidders-strategy 2 -3 bidders-strategy 3	-Decide to evaluate bids -Multiple rounds -Count threshold same for all (400) -Strategy threshold same for all (1.7) -Wiling-to-give same for all (0.7)	- fill rate - allocation share among bidders -announcement queue	-Effect of auctioneer decision making and bidder decision making combined -Effect of multiple rounds -Priority increase rate

The experiments in Table 29 are performed with three auctioneers and nine bidders. Only the target design parameters are altered in each scenario. After the target design parameter is analyzed, it remained unchanged in later scenarios. The first scenario is the base case for the multiple auctioneers setting. In the second scenario, bidding strategies are introduced. The third scenario introduces multiple rounds, and the fourth scenario evaluates bidding strategies and multiple rounds together. The fill rate, the allocation share among bidders and the announcement queue characteristics are used as the performance factors [4]. An announcement queue holds all the announcements that an auctioneer has requested.

The objective of the first scenario is to examine the effect of multiple disaster locations and count threshold on fill rate. Neither bidders nor the auctioneers have decision making logic; bidders bid to every announcement and auctioneers get whatever they are given. This scenario is like a single round sealed-bid auction. The results are given in Table 30. It can be concluded that total number of announcements, number of announcements in the announcement queue and fill rate decreases with increasing count threshold levels. With one auctioneer and three bidders, the fill rate was 0.59 compared to the 0.71 fill rate with three auctioneers and nine bidders in experiment one. This increase can be explained by the pooling of different bidder inventories. A count threshold was selected as 400 for future scenarios with a fill rate of 0.61.

Table 300. First scenario results

Experiment	Auctioneer	Count threshold	Fill rate	Total Number of Ann.s	Average Time an Announcement Spends in Queue	Average Number of Announcements in Queue
1	1	200	0.71	104.67	11.20	1.17
	2	200	0.71	104.67	11.18	1.16
	3	200	0.71	104.67	11.24	1.17
	1	200	0.73	104.67	11.20	1.17

2	2	400	0.61	55.93	11.76	0.65
	3	600	0.51	38.37	12.06	0.46
3	1	400	0.61	56.63	11.82	0.67
	2	400	0.61	55.93	11.76	0.65
	3	400	0.61	56.00	11.82	0.66

The second scenario examines the effect of bidder decision making, bidder strategies, and strategy threshold. Three out of nine bidders all behave according to one bidding strategy. In this analysis, the strategy threshold is altered. This scenario is like a single round sealed-bid auction with increased governance on the bidder side. The results are given in Table 31. Urgency increases by decreasing levels of weighted priority ( $WP$ ) and bidder strategies are by-passed for an urgent announcement. Since  $E[WP] = 2$ , probabilistically less number of announcements fall into below threshold levels. It can be seen that lower levels for strategy threshold give bidders more freedom of not bidding, therefore fill rate decreases. The third bidding strategy emphasizes announcements with higher weighted priority; consequently bidders 7-9 have the highest shares in the allocation. Bidders using the second bidding strategy outperform the bidders with the first bidding strategy, because the second bidding strategy picks the announcements with higher fill rate. The announcement queue shows similar characteristics in this scenario when compared with the first scenario having the 400 count threshold level. A strategy threshold of 1.7 was selected for the last two scenarios for all auctioneers.

Table 311. Second scenario results

Experiment	Auctioneer	Strategy threshold	Fill rate	Sum of Bidders 1-3 Share	Sum of Bidders 4-6 Share	Sum of Bidders 7-9 Share
1	1	1.5	0.04	0.07	0.22	0.71
	2	1.5	0.05			
	3	1.5	0.04			
2	1	1.5	0.04	0.14	0.26	0.61
	2	1.7	0.12			
	3	1.9	0.30			

3	1	1.7	0.10	0.12	0.24	0.64
	2	1.7	0.12			
	3	1.7	0.12			

The third scenario examines the effect of multiple rounds, auctioneer decision making, and willing-to-give ratio. In this scenario, bidders do not have bidding strategies. During multiple rounds of auctioning, the auctioneer alters the parameters of the announcement to reach higher fill rates. In each round when the willing-to-give ratio is not reached, for the items having  $WP > 2$ , priority is increased by the *priority increase rate*. For instance, an item with 2.2  $WP$  would have 2.1  $WP$  after one round of auction with a 0.1 priority increase rate. In the third scenario, the priority increase rate is taken as 0.1 for all auctioneers. The results are given in Table 32. Fill rates jumped substantially to closer values to 1.0. Since the willing-to-give ratio is related to bidder strategies, it shows a slight effect on fill rates. If the willing-to-give ratio is increased, fill rates slightly decrease. Altering the willing-to-give ratio changes the number of announcements resolved in each round. If the willing-to-give ratio is increased, it pushes the announcements back to the later rounds. The number of resolved announcements in the second round is the least, which shows that announcement options do not change the decision of sending the announcement back to the bidders. The average time that an announcement spends in the queue and the average number of announcements in the queue almost doubled. It can be concluded that auctioneers wait more in order to reach the higher fill rates in later rounds. The willing-to-give ratio was set to 0.7 for the last scenario.

The fourth scenario examines the combined effects of bidder and auctioneer decision making in multiple rounds with priority increase rate. This scenario includes all the design parameters that are proposed. Priority increase rate works together with strategy threshold to by-pass the bidder strategies. The results are given in Table 33. If priority is increased by 0.5 between rounds, then bidder strategies are by passed and bidders are obliged to bid, which leads to higher fill rates. If priority is increased by 0.1 between rounds, then bidders might decide not to bid, which decreases fill rate. If the priority increase rate is smaller, more announcements are pushed to later rounds to be resolved. When auctioneers use different priority increase rates as 0.1, 0.1 and, 0.5, respectively, the third auctioneer with 0.5 does not reach to the high fill rate when they all use 0.5. If the auctioneers use 0.5, 0.5, and 0.1, respectively, the third auctioneer with 0.1 does not have a fill rate as low as when they all use 0.1. The higher priority increase rate makes announcements spend less time in the queue and enable higher fill rates to be reached. The bidder shares change significantly. Lower priority increase rate makes first bidding strategy more powerful, whereas, bidders with the second bidding strategy get more shares with a higher priority increase rate.

In order to compare different scenarios in terms of fill rate, the experiments on which the later scenarios built were selected. The third experiment from the first, second, and third scenarios, and the first experiment from the last scenario were examined. The average fill rates of auctioneers and the announcement queue characteristics are shown in Table 34. The first scenario reaches a 0.61 fill rate, whereas in the second scenario, fill rate decreases substantially, because most of the bidders choose not to bid and auctioneers do not have a means to compel them to bid. These two scenarios have the least time spent and number in announcement queue. The third scenario introduces auctioneer decision making in multiple rounds, and if the

auctioneer is not satisfied with what has been bid, it sends the announcement back to the bidders. This allows more time for the bidders to replenish their inventory and gives priority to the second and third round announcements in the announcement queue. As a result, announcements spend more time in the queue, but reach the highest fill rate. This might be unrealistic, because bidders do not have the decision to bid or not. In the fourth scenario, although the time an announcement spends in the queue increases, it reaches a higher fill rate than the first and the second scenario.

Table 32. Third Scenario Results

Exp.	Auctioneer	Willing-to-give ratio	Fill rate	Average Time an Ann. Spends in Queue	Average Number of Ann.s in Queue	Total Number of Ann.s	Number of Resolved Ann.s	First Round Resolved	Second Round Resolved	Third Round Resolved
1	1	0.5	0.9992	22.63	1.27	56.63	54.80	9.87	0.53	44.40
	2	0.6	0.9994	22.38	1.24	55.93	54.17	9.27	0.47	44.43
	3	0.7	0.9996	22.56	1.25	56.00	54.43	8.03	0.60	45.80
2	1	0.6	0.9994	22.66	1.27	56.63	54.80	9.50	0.70	44.60
	2	0.6	0.9996	22.43	1.24	55.93	54.17	9.23	0.43	44.50
	3	0.6	0.9996	22.62	1.25	56.00	54.43	8.23	0.30	45.90
3	1	0.7	0.9994	22.64	1.27	56.63	54.80	9.37	0.57	44.87
	2	0.7	0.9999	22.39	1.24	55.93	54.17	8.93	0.40	44.83
	3	0.7	0.9998	22.65	1.26	56.00	54.43	8.03	0.53	45.87

Table 333. Fourth Scenario Results

Exp.	Auctioneer	Priority Increase Rate	Fill Rate	Average Time an Ann. Spends in Queue	Average Number of Ann.s in Queue	Total Number of Ann.s	Number of Resolved Ann.s	First Round Resolved	Second Round Resolved	Third Round Resolved	Sum of Bidders 1-3 Share	Sum of Bidders 4-6 Share	Sum of Bidders 7-9 Share
1	1	0.1	0.803	33.13	1.85	56.63	54.80	3.43	0.47	50.77	0.71	0.22	0.07
	2	0.1	0.829	32.85	1.81	55.93	54.17	3.93	0.50	49.70			
	3	0.1	0.796	33.04	1.82	56.00	54.43	3.63	0.57	50.17			
2	1	0.5	0.970	28.34	1.58	56.63	54.90	3.80	2.70	48.40	0.38	0.43	0.18
	2	0.5	0.971	28.11	1.55	55.93	54.47	4.23	2.77	47.47			
	3	0.5	0.968	28.43	1.57	56.00	54.63	3.83	2.00	48.80			
3	1	0.1	0.856	33.13	1.85	56.63	54.67	3.47	0.47	50.73	0.59	0.30	0.11
	2	0.1	0.876	32.86	1.81	55.93	54.10	3.67	0.77	49.67			
	3	0.5	0.875	28.54	1.58	56.00	54.67	3.50	2.30	48.87			
4	1	0.5	0.923	28.51	1.59	56.63	54.90	3.27	3.07	48.57	0.49	0.36	0.15
	2	0.5	0.924	28.36	1.56	55.93	54.47	3.63	2.67	48.17			
	3	0.1	0.915	33.09	1.83	56.00	54.37	3.43	0.53	50.40			

Table 344. Comparison of Four Scenarios

Scenarios	Fill Rate	Time in Q	Number In Q
First	0.61	11.80	0.66
Second	0.11	11.80	0.66
Third	1.00	22.56	1.26
Fourth	0.81	33.01	1.83

#### 6.4 Results and Discussion

Since humanitarian supply chains have unique characteristics when compared to corporate supply chains, the environment should be understood before assessing the contribution of a framework. In the first phase of experimental study, environmental factors were conceived and they are kept as constants in the second phase. This approach enabled an examination of the auction design parameters proposed in this research within reasonable environmental conditions. Each scenario focused on a different parameter to represent the effect of that particular parameter.

The framework includes some design parameters which can easily be implemented in disaster relief operations. It is shown in the experimental study that the priority of items and weighted priority of a bundle affect the fill rate of an announcement. Bundling of items hasn't



been studied in the literature as much as the single indivisible item case [9]. Ease of logistics and announcement options can be used in software like HELIOS to reach higher efficiency in resource allocation. Bidder and auctioneer decision making introduced competition among bidders and among auctioneers, which is the practical case in procurement operations.

The framework is not intended to find the market-clearing price using each party's valuations of each item type; rather, we focus on the item type and quantity allocation from the sellers to the buyers. The exploratory research [10] serves the purpose of conceiving the specifics of disaster relief logistics. The framework proposed in this research is a quantitative and holistic model that can be used to address the specific needs of disaster relief logistics.

The network-flow models [2,11,19] are narrowly focused and usually deal with vehicle routing and allocation of specific resources, whereas our proposed framework is holistic (from demand creation to the fulfilment of the demand) as well as modelling the procurement activity with an auction. Resource allocation problems are typically solved in the literature [6,7,12] for equipments, vehicles, and reusable supplies. The framework here provides alternative methods for consumable supplies; therefore, it does not have the scheduling components that are found in other models.

## 6.5 Conclusions

A simulation-based procurement-auction framework is presented in this research to address the inefficiencies of humanitarian supply chains. In humanitarian supply chains, multiple disaster locations appeal for relief items at the same time in an area where supplier resources are limited. The specific design characteristics of disaster relief procurement activities are incorporated into the *Announcement Construction*, *Bid Construction* and *Bid Evaluation* phases of the framework.

Disaster locations are considered as auctioneers and suppliers are considered as bidders. Auctioneers compete to one another in multiple rounds of the procurement auction. The holistic framework in three phases is unique not only in procurement auction literature, but also in disaster relief logistics. The value notion plays a balanced role in the framework, since the bid construction phase minimizes the value, but the bid evaluation phase maximizes the value. The use of the value notion helps suppliers to dispose of the old items more effectively in the bid construction phase and helps the disaster location to get better conditioned items in the bid evaluation phase.

Disaster locations are given the right to reject the bids when they do not fulfil a certain portion of the appeal list. When disaster locations are not satisfied, they send a revised announcement to the suppliers. Disaster locations have substitution and partial fulfilment options while sending the announcement. Together with quantity, item type and priority information; the announcement options give a complete representation of the appeals list. Multiple rounds auctions usually require bids to be updated in each round, but the framework in this research allows disaster locations to revise the announcements. Priority of announcement is connected to the waiting time of an announcement. Multiple round auctioning helped disaster locations to increase their fill rate.

Suppliers are better evaluated with the ease of logistics parameter, which gives importance to the suppliers that have easy access to the disaster location. Suppliers are given the right to use bidding strategies when the announcement is not urgent. The balance with urgency in disaster relief operations and supplier preferences are accomplished with some threshold levels. Some bidding strategies performed well in certain settings, which leads to the conclusion that these strategies should be disaster specific.



## 6.6 References

1. Akcay Y, Li H and Xu SH (2007). Greedy algorithm for the general multidimensional knapsack problem. *Annals of Operations Research* 150: 17 – 29.
2. Barbarosoglu G, and Arda Y (2004). A two-stage stochastic programming framework for transportation planning in disaster response. *Journal of the Operational Research Society* 55(1): 43 - 53.
3. Beamon BM (2004) Humanitarian relief chains: Issues and challenges, in: *Proceedings of the 34th International Conference on Computers and Industrial Engineering*, November 14-16, 2004, San Francisco, CA, USA.
4. Beamon BM and Balcik B (2008). Performance measurement in humanitarian relief chains. *International Journal of Public Sector Management* 21(1): 4-25.
5. Davidson AL (2006). Key performance indicators in humanitarian logistics. Master's thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.
6. Fiedrich F, Gehbauer F and Rickers U (2000) Optimized resource allocation for emergency response after earthquake disasters. *Safety Science* 35(1-3): 41-57.
7. Gong Q and Batta R (2007). Allocation and reallocation of ambulances to casualty clusters in a disaster relief operation. *IIE Transactions* 39(1): 27 – 39.
8. Jap SD (2007). The impact of online reverse auction design on buyer-supplier relationships. *American Marketing Association* 71: 146 – 159.
9. Klemperer P (2004). *Auctions: theory and practice*. Princeton University Press, Princeton, NJ.
10. Kovacs G, Spens KM (2007). Humanitarian logistics in disaster relief operations. *International Journal of Physical Distribution and Logistics Management*, 37(2): 99-114.
11. Ozdamar L, Ekinci E, and Kucukyazici B (2004). Emergency logistics planning in natural disasters. *Annals of Operations Research*, 129: 217-245.
12. Qiao J, Jeong D, Lawley M, Richard JPP, Abraham DM and Yih Y (2007). Allocating security resources to a water supply network. *IIE Transactions* 39(1): 95 – 109.
13. Scheuren JM, de Waroux OP, Below R, Guha-Sapir D and Ponserr S (2008). *Annual Disaster Statistical Review: Numbers and Trends 2007*, Accessed 15 July 2008, <http://www.emdat.be/Publications/publications.html>
14. Schvartzman LJ and Wellman MP (2007). Market-based allocation with indivisible bids. *Production and Operations Management* 16(4): 495 – 509.
15. Thomas A (2003). Humanitarian logistics: enabling disaster response. Accessed 15 July 2008, <http://www.fritzinstitute.org/PDFs/WhitePaper/EnablingDisasterResponse.pdf>.
16. White House Report (2006). The federal response to Hurricane Katrina-Lessons learned. Technical report.
17. Wolf ES, Sanchez SM and Goerger NC (2003). Using Agents to Model Logistics. Technical report. ADA418397, Naval Postgraduate School, Monterey, CA
18. Wurman PR, Walsh WE, and Wellman MP (1998). Flexible double auctions for electronic commerce: theory and implementation. *Decision Support Systems* 24: 17 – 27.
19. Yi W, Ozdamar L (2007). A dynamic logistics coordination model for evacuation and support in disaster response activities. *European Journal of Operational Research* 179: 1177 – 1193.

## 7      **Research Task #7**

### **Comparing Maintenance Policies for Single-Unit, Markovian Systems**

#### **Submitted By:**

C.Richard Cassady, Ph.D. (PI)

Nagi Gebraeel, Ph.D. (Co-PI)

E. A. Pohl, Ph.D. (Co-PI)

Yisha Xiang, Ph.D. Candidate, (Graduate Research Assistant)

Suzan Alaswad, Ph.D. Candidate, (Graduate Research Assistant)

Kelly Sullivan, M.S., (Graduate Research Assistant)

Coby Durham, (Undergraduate Research Assistant)

Dia St. John, (Undergraduate Research Assistant)\

Department of Industrial Engineering

University of Arkansas

4207 Bell Engineering Center

Fayetteville, AR 72701

#### **Papers and Presentations:**

Xiang, Y. and C.R. Cassady (2007). "Comparing Scheduled and Condition-Based Maintenance Policies for Single-Unit Systems Operated in Markovian Environments", *IIE Annual Conference and Exhibition 2007 Proceedings*.

Xiang, Y. and C.R. Cassady (2007). "Time to Failure Behavior under a Stochastic Deterioration Model", *Proceedings of the Annual Reliability and Maintainability Symposium*.

#### **Dissertation (Related)**

Xiang, Y., "Evaluation of Alternative Maintenance Paradigms for Single-Unit Systems Operated in Markovian Environments" (Expected May 2009)

## 7.1 Executive Summary

We consider a single-unit system operating in a Markovian environment such that the instantaneous rate of degradation of the system is determined by the current state of the environment. The system fails when its cumulative degradation passes a threshold. We utilized a discrete-event simulation model to mimic the deterioration and failure of the system and fit a time to first failure distribution to the simulated data. A numerical experiment is used to evaluate the quality of the fit for multiple sets of system parameters. The goodness of fit test results indicate a three-parameter Weibull distribution as a reasonable estimate for the system. We extend this concept into the study of a system with a Weibull random variable threshold. The corresponding fit tests indicate a Weibull distribution to be a reasonable estimate. We then develop and compare an age-replacement policy and a condition-based maintenance policy based on the Weibull approximation. The condition-based plan is found to be the more cost efficient option.

## 7.2 Introduction

A repairable system (RS) is a unit of equipment which can be restored to an operating condition through maintenance actions after experiencing a failure. Maintenance actions include those intended to delay system failure and those taken in response to failure. These maintenance actions can be classified into three categories: routine maintenance, corrective maintenance, and preventive maintenance. Routine maintenance consists of the daily actions performed on the system to ensure proper system performance. Corrective maintenance includes actions performed as a response to failure. Preventive maintenance actions are intended to delay system failure.

Preventive maintenance can be further divided into two categories: scheduled maintenance and predictive maintenance.

Using a perfect predictive maintenance approach, preventive maintenance would be performed only when absolutely necessary and avoiding all failures. Singpurwalla [2] presents stochastic failure time models based on failure-causing mechanisms, like degradation and wear, which are fitting for a repairable system in a dynamic environment. Kharoufeh and Cox [1] present a model in which the system is operating in an environment represented as a continuous-time Markov Chain (CTMC). The rate of degradation of the system depends on the current state of the environment. The procedure analyzes the reliability and estimates the lifetime distribution of a RS operating in such an environment.

We explore the potential for approximating the mathematically complex time to failure and residual life distributions resulting from the Kharoufeh and Cox [1] approach with traditional time to failure distributions (e.g. Weibull) and construct age-based and condition-based policies to compare the economic performance of the RS under each policy. We extend this work by assuming the deterioration threshold which results in RS failure is a random variable with a Weibull distribution instead of a constant value. After constructing age and condition-based maintenance policies for this altered system, we evaluate and compare the cost per unit time of the repairable system under each policy.

### 7.3 Methods, Assumptions, and Procedures

#### 7.4 System definition

Consider a repairable system belonging to the type modeled by Kharofeh and Cox [1]. The system is operating in a stochastic environment which is modeled as a three-state, continuous time Markov chain.  $X(t)$  denotes the state of the environment at time  $t$ .  $X(t)$  is bound by the following two constraints: (1)  $X(t) \in \{-1, 0, 1\}$ , for all  $t \geq 0$ ; (2)  $X(0) = 0$ . The three states correspond to the following operating conditions for the system: state 0 is considered to be “nominal”; state  $-1$  is considered to be “less severe than nominal”; state 1 is considered to be “more severe than nominal.” Let  $q_{x,x'}$  denote the transition rate of the Markov chain from state  $x$  to state  $x'$  and  $p_{x,x'}$  represent the transition probability from state  $x$  to state  $x'$ , for all values of  $x \in \{-1, 0, 1\}$  and  $x' \in \{-1, 0, 1\}$  given that  $x \neq x'$ . In addition, let  $\nu_x$  denote the transition rate out of state  $x$  for all  $x$  in the set  $\{-1, 0, 1\}$ .

The system experiences stochastic deterioration, with the instantaneous rate of system deterioration dependent on the current state of the environment. Let  $r(X(t))$  describe the instantaneous rate of system deterioration at time  $t$ , for all  $t \geq 0$ . To better facilitate our definition of the instantaneous rate of system deterioration, we assume  $r(-1) \leq r(0) \leq r(1)$ .

Let  $Y(t)$  represent the cumulative deterioration of the system at time  $t, t \geq 0$ . Therefore,

$$Y(t) = \int_0^t r(X(u)) du.$$

The system fails for the first time when the cumulative deterioration ( $Y(t)$ ) is greater than or equal to the failure threshold ( $\psi$ ). Let  $T$  represent the time to first failure, therefore



$T = \min\{t : Y(t) \geq \psi\}$ . We initially assume  $\psi$  is a constant value and then that it is a random variable with a Weibull distribution, therefore  $T$  is a non-negative random variable.

### 7.5 Analysis of time to first failure for constant threshold

In order to generate the values of  $T$ , a discrete-event simulation model of the system was built. This model was constructed in Visual Basic, and begins with the system in state 0. The model mimics the transitions of the underlying Markov chain, ends when the cumulative deterioration is greater than or equal to the randomly generated failure threshold, and then outputs the time to first failure. The user inputs the number of replications that the model runs, the deterioration rates of each of the three states of the Markov chain, the transition rates of the Markov chain, and the deterioration failure threshold.

Considering a specific numerical example and visual inspection of the histogram formed from 1000 observations, the three-parameter truncated Weibull distribution was found to be a reasonable candidate for approximating the probability distribution of  $T$ . Under this assumption, the cumulative distribution function of  $T$  is initially approximated by

$$F(t) = 1 - \exp\left[-\left(\frac{t - t_{\min}}{\eta}\right)^\beta\right]$$

where

$$t_{\min} = \frac{\psi}{r(+1)}$$

and  $> 1$  and  $\eta > 0$ . Recognizing that  $T \leq t_{\max}$ , where

$$t_{\max} = \frac{\psi}{r(-1)}$$

an improved approximation of the cumulative distribution function of  $T$  is found to be

$$G(t) = \frac{F(t)}{F(t_{\max})} = \frac{1 - \exp\left[-\left(\frac{t - t_{\min}}{\eta}\right)^\beta\right]}{1 - \exp\left[-\left(\frac{t_{\max} - t_{\min}}{\eta}\right)^\beta\right]},$$

and the probability density function of  $T$  can be better approximated by

$$g(t) = \frac{dG(t)}{dt} = \frac{\frac{\beta}{\eta} \left(\frac{t - t_{\min}}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t - t_{\min}}{\eta}\right)^\beta\right]}{1 - \exp\left[-\left(\frac{t_{\max} - t_{\min}}{\eta}\right)^\beta\right]}.$$

Assuming the probability distribution of the data has cdf  $G(t)$ , the values of  $\beta$  and  $\eta$  can be estimated using the likelihood function

$$L(\beta, \eta) = \prod_{i=1}^n g(t_i)$$

and the log-likelihood function

$$\Lambda(\beta, \eta) = \ln(L(\beta, \eta)).$$

The estimation of  $\beta$  and  $\eta$  can then be obtained by simultaneously solving the following two equations:

$$\frac{\partial \Lambda(\beta, \eta)}{\partial \beta} = 0$$

$$\frac{\partial \Lambda(\beta, \eta)}{\partial \eta} = 0.$$

This optimization problem can be solved using the cyclic coordinate method of numerical search.

The final step in the analysis of the data is to utilize a Kolmogorov-Smirnoff (K-S) [3] test to compare the data to the approximate probability distribution. To conduct the test, 50 observations of  $T$  are sorted into ascending order, and the test statistic,  $\sqrt{n}D_n$ , is computed using

$$D_n^+ = \max_{1 \leq i \leq n} \left\{ \frac{i}{n} - \hat{G}(t_{(i)}) \right\},$$

$$D_n^- = \max_{1 \leq i \leq n} \left\{ \hat{G}(t_{(i)}) - \frac{i-1}{n} \right\},$$

and

$$D_n = \max_{1 \leq i \leq n} \{D_n^-, D_n^+\}.$$

The null hypothesis, that  $T$  is a random variable having a cumulative distribution function  $G(t)$  with parameters  $\hat{\beta}$  and  $\hat{\eta}$  is rejected if

$$\sqrt{n}D_n > C_{1-\alpha}^*$$

where  $C_{1-\alpha}^*$  is the critical value for a level of significance of  $\alpha$  and sample size  $n$ .

## 7.6 Analysis Of Time To First Failure For Random Variable Threshold

We used many of the same methods in the extension from a constant threshold to a random variable threshold. We found, through a numerical experiment and visual inspection of a 1000 observation histogram, that in this system  $T$  would be well approximated through the use of a Weibull probability distribution. The resulting cumulative distribution function is given by

$$F(t) = 1 - \exp \left[ - \left( \frac{t}{\eta} \right)^\beta \right]$$

for  $\beta > 1$  and  $\eta > 0$ , and the probability density function is

$$f(t) = \frac{\beta}{\eta^\beta} t^{\beta-1} \exp \left[ - \left( \frac{t}{\eta} \right)^\beta \right].$$

Utilizing the same method described previously, we find that estimates of  $\beta$  and  $\eta$  can be found by solving the following two equations simultaneously:

$$\frac{\partial \Lambda(\beta, \eta)}{\partial \eta} = \sum_{i=1}^n \left( \frac{t_i}{\eta} \right)^{\beta} \frac{\beta}{\eta} - n \left( \frac{\beta}{\eta} \right) = 0$$

$$\frac{\partial \Lambda(\beta, \eta)}{\partial \beta} = \frac{n}{\beta} + \sum_{i=1}^n \ln \left( \frac{t_i}{\eta} \right) - \sum_{i=1}^n \left( \frac{t_i}{\eta} \right)^{\beta} \ln \left( \frac{t_i}{\eta} \right) = 0.$$

The data is then subjected to a K-S test (as described previously) in order to compare it to the approximate probability distribution, the Weibull.

## 7.7 Age-Based Maintenance Policy

The approximate probability distribution on  $T$  can be used to develop an age-based PM policy for the RS. Instantaneous, perfect corrective maintenance is performed if the RS fails. If the RS operates without failure for  $\tau$  time units, then instantaneous, perfect preventive maintenance is performed. The cost of each corrective maintenance action is  $c_{CM}$  and the cost of each preventive maintenance action is  $c_{PM}$  such that  $0 < c_{PM} < c_{CM}$ . Since both CM and PM restore the RS to good as new condition, the maintenance of the RS can be modeled as a renewal process with renewal points at each maintenance occurrence. Let  $\mu(\tau)$  denote the expected duration of one cycle of the renewal process (duration of time between maintenance actions), under an age-based PM policy  $\tau$ . Then,

$$\mu(\tau) = \int_0^{\tau} t f(t) dt + \tau(1 - F(\tau)) \quad (21)$$

Let  $\rho(\tau)$  denote the expected value of the cost of each cycle of the renewal process under the same age-based policy. Therefore,

$$\rho(\tau) = c_{CM} F(\tau) + c_{PM} (1 - F(\tau)). \quad (22)$$

The long-run average maintenance cost per unit time ( $\gamma_{SM}(\tau)$ ) under the age-based PM policy is given by

$$\gamma_{SM}(\tau) = \frac{\rho(\tau)}{\mu(\tau)}. \quad (23)$$

In order to compute  $\gamma_{SM}(\tau)$  for any given  $\tau$ , numerical integration is required, followed by numerical search to find the value of  $\tau$  that minimizes the long-run cost.

## 7.8 Condition-Based Maintenance Policy

Assume the RS is one in which inspection can be used at any time to determine the current value of the cumulative deterioration. Instead of pursuing an age-based PM policy, we also consider a condition-based PM policy based on periodic inspection of the system. Instantaneous, perfect CM is performed if the system fails, and the cumulative deterioration  $Y(t)$  is observed at  $t = \delta, 2\delta, \dots (\delta > 0)$ . If the cumulative deterioration is greater than a certain threshold ( $\xi$ ) at any time of inspection, then the system undergoes instantaneous, perfect PM. The cost of each inspection is  $c_I$ , and is related to the costs of PM and CM by  $0 < c_I < c_{PM} < c_{CM}$ . In order to compare the two policies, we calculate  $\gamma_{CBM}(\delta, \xi)$ , the long-run average cost per unit time under the condition-based maintenance policy. In order to evaluate the average cost per-unit time, we developed a discrete event simulation model.

## 7.9 Results and Discussion

### 7.10 Constant Failure Threshold

Consider an example system such that  $r(-1) = 0.8$ ,  $r(0) = 1.05$ ,  $r(+1) = 1.25$ ,  $q_{-1,0} = 40$ ,  $q_{0,-1} = 35$ ,  $q_{0,+1} = 80$ ,  $q_{+1,0} = 45$ , and  $\psi = 1$ . The simulation model was used to generate 1000 observations on the time to first failure of the system. Following the methods described in the previous section, the resulting estimates of  $\beta$  and  $\eta$  are given by 4.0067 and 0.1421, respectively.

For this example, we utilized 50 observations in order to perform the K-S test and found that  $\sqrt{50}D_{50} = 0.811$ , which is less than  $c_{0.95}^* = 0.856$  when the sample size is 50 and  $\alpha = 0.05$ . This result indicates a failure to reject the null hypothesis, indicating that a claim could be made that the truncated three parameter Weibull distribution provides a reasonable fit to the data.

In order to generalize these results to a wider range of system parameters, we developed a larger numerical experiment. Assuming the failure threshold  $\psi = 1$ , the system degradation rates are drawn from uniform probability distributions as shown:

$$r(0) \sim U(0.8, 1.2)$$

$$r(-1) \sim U(0.25, 0.75) \times r(0)$$

$$r(+1) \sim U(1.5, 4) \times r(0),$$

and the transition rates are developed according to

$$\nu_0 \sim U(100, 150)$$

$$\nu_{-1} \sim U(1.5, 4) \times \nu_0$$

$$\nu_{+1} \sim U(1.5, 4) \times \nu_0.$$

Similarly, the transition probabilities are found according to

$$p_{-1,0} = \mathbf{1}$$

$$p_{+1,0} = \mathbf{1}$$

$$p_{0,-1} \sim U(0.25, 0.75)$$

$$p_{0,+1} = \mathbf{1} - p_{0,-1},$$

and the transition rate can be obtained from

$$q_{x,x'} = p_{x,x'} \nu_x$$

for all  $x = -1, 0, +1, x' = -1, 0, +1, x' \neq x$ .

This system was used to develop 10,000 experimental systems, each with 50 observations. For each data set, the parameters of the Weibull distribution were estimated and a K-S test was performed. The null hypothesis was rejected only 3289 times in 10,000 tests with  $\alpha = 0.05$ .

Consider an example system such that  $r(-1) = 0.6$ ,  $r(0) = 1$ ,  $r(+1) = 3.5$ ,  $q_{-1,0} = 40$ ,  $q_{0,-1} = 35$ ,  $q_{0,+1} = 80$ ,  $q_{+1,0} = 45$ , and  $\psi = 1$ . Suppose  $c_{CM} = 1$ ,  $c_{PM} = 0.8$ , and  $c_I = 0.02$ . The estimated Weibull parameters for this system are  $\beta = 2.8$ , and  $\eta = 0.23$ .

This system yields a recommended age-based preventive maintenance policy of  $\tau = 1.5$  and a recommended condition-based policy of  $\delta = 0.44$  and  $\xi = 0.46$ . Using 50 replications, each with a run length of 100 time units, we estimate  $\gamma_{SM}(1.5)$  and  $\gamma_{CBM}(0.44, 0.46)$ . According to these policies, the estimated average maintenance cost under the age-based policy is 2.85, and the estimated average maintenance cost under the condition-based policy is 2.10. This indicates an estimated savings of 26% through the usage of a condition-based approach over a scheduled approach.

#### 7.11 Random Failure Threshold

Consider the following example:  $r(-1) = 0.6$ ,  $r(0) = 1$ ,  $r(+1) = 3.5$ ,  $q_{-1,0} = 40$ ,  $q_{0,-1} = 35$ ,  $q_{0,+1} = 80$ , and  $q_{+1,0} = 45$ . Suppose the failure threshold is a Weibull random variable having a shape parameter of 2.5 and a mean of 1. The simulated model was executed with these inputs and 1000 observations on  $T$  were generated. The values of the Weibull parameters,  $\beta$  and  $\eta$ , were 2.291 and 0.607 respectively. For this example,  $\sqrt{50}D_{50} = 0.811$ . Choosing a level of significance of 0.05,  $C_{0.95}^* = 0.856$ . Since  $0.811 < 0.856$ , the null hypothesis fails to be rejected and the Weibull distribution appears to be a good estimate of the time to first failure.

To generalize these results to a wider range of parameters, we developed a numerical experiment. We generated 10,000 data sets of 50 observations each with failure threshold  $\psi$  distributed as a Weibull random variable with mean time to failure of one. The system degradation rates, transition values, and transition probabilities are shown below:

$$r(-1) \sim U(0.25, 0.75) * r(0)$$

$$r(0) \sim U(0.75, 1.25)$$

$$r(+1) \sim U(1.5, 4) * r(0)$$

$$v(-1) \sim U(1.5, 4) * v(0)$$

$$v(0) \sim U(100, 200)$$

$$v(+1) \sim U(1.5, 4) * v(0)$$

$$p_{-1,0} = 1$$

$$p_{+1,0} = 1$$

$$p_{0,-1} \sim U(0.25, 0.75)$$

$$p_{0,+1} = 1 - p_{0,-1}$$

and the transition rates for the system can be obtained by

$$q_{x,x'} = p_{x,x'} * v_x \forall x \in [-1, 0, +1], x \neq x'.$$

For each of the 50 data sets, Weibull distribution parameters were found and a K-S test was performed. At  $\alpha = 0.05$ , the null hypothesis was rejected only 1446 times, indicating a pass percentage of 85.54% and confirming the Weibull model as a good estimation of the time to first failure.

Continuing the example in which  $r(-1) = 0.6$ ,  $r(0) = 1$ ,  $r(+1) = 3.5$ ,  $q_{-1,0} = 40$ ,  $q_{0,-1} = 35$ ,  $q_{0,+1} = 80$ ,  $q_{+1,0} = 45$ , and the failure threshold modeled as a Weibull distribution with a mean time to failure of 1 and parameters,  $\beta$  and  $\eta$ , equal to 2.291 and 0.607 respectively, we develop maintenance policies with  $c_{CM} = 1, c_{PM} = 0.8$  and  $c_I = 0.02$ .



This system yields a recommended age-based preventive maintenance policy of  $\tau=0.814$  and a recommended condition-based preventive maintenance policy of  $\delta=0.666$   $\xi=0.579$ . A discrete event simulation model was used to run 50 replications of 100 time units. The age-based policy indicated an average cost per time unit of 4.64, and the condition-based policy yielded a cost per time unit of 4.08. These results indicate a possible savings of 13.73% by choosing a condition-based policy of an age-based policy.

## 7.12 Conclusions

In this study, we present an approach for the estimation of full lifetime distributions for single-unit systems operating in a Markovian environment. Our results indicate the this approach successfully provides a reasonable approximation of the time to first failure distribution when considering both constant value failure thresholds and random variable failure thresholds.

In addition, we develop age and condition-based preventive maintenance policies for single-unit repairable systems for both constant and random failure thresholds. Our experimentation provides evidence that there is cost reduction possible by shifting from a scheduled maintenance program to one based on condition-based maintenance.

## 7.13 Recommendations

Possible extensions to this research include the consideration of multi-unit systems to further generalize the results found. In addition, a model utilizing data that is only correlated to deterioration would provide a more realistic look into how well this approach to modeling overall system degradation would work in real-world situations.

## 7.14 References

- [1] Kharoufeh, J. P. and Cox, S.M., (2005) “Stochastic models for degradation-based reliability,” *IEEE Transactions*, Vol. 37, No. 6., pp. 533-542
- [2] Singpurwalla, N.D., “Survival in dynamic environments,” *Statistical Science*, Vol. 10, No. 1, 1995, pp. 86-103.
- [3] Law, A.M., Kelton, W.D., *Simulation Modeling and Analysis*, McGraw-Hill, 2000

## 8 Research Task #8

### Improved Outbreak Detection for Bio Terror Response Logistics

#### Submitted By:

Justin Chimka, Ph.D., (PI)  
Patricia V Cabrera-Arispe (Research Assistant)  
Lindsey C Walker (Research Assistant)  
Jia Zhou (Research Assistant)

Department of Industrial Engineering  
University of Arkansas  
4207 Bell Engineering Center  
Fayetteville, AR 72701

#### Papers and Presentations:

Chimka, J.R (2009). Gamma regressive individuals control charts for influenza activity, *Quality Engineering* 21(2): 182-189

Chimka, JR and LC Walker. Threshold autoregressive individuals control charts. Submitted to *Economic Quality Control*.

Chimka, JR and H Nachtmann (July 2006). Statistical process control for syndromic surveillance, *INFORMS Military Applications Society Conference* (Mystic)

Chimka, JR and J Zhou (November 2007). Theoretical errors for individual measurements motivated by models of flu activity, *INFORMS Annual Meeting* (Seattle)

Chimka, JR and J Zhou (November 2006). Statistical process control for syndromic surveillance, *INFORMS Annual Meeting* (Pittsburgh)

Zhou, J, PV Cabrera-Arispe and J.R Chimka (May 2006). Statistical process control for syndromic surveillance, *Industrial Engineering Research Conference* (Orlando)

#### PhD dissertation (related)

Zhou, J (2008). Theoretical errors and economic design for individual measurements

#### MS thesis (related)

Walker, LC (2007). Threshold autoregressive individuals control charts

## 8.1 Executive Summary

Statistical process control has been considered along with generalized linear models of influenza activity. Different combinations of distribution and link assumptions have been formally compared in order to choose one that would seem theoretically appropriate. Specificity of gamma regression-based individuals control charts for influenza activity has been estimated and compared to begin answering the important question: What are reasonable expectations about errors associated with outbreak detection?

Results include performance among gamma regression-based charts for laboratory data that is relatively near what one should expect from traditional process control. It is shown how more theoretically appropriate statistical quality control models of flu activity become increasingly specific and so useful in identifying non-seasonal outbreaks. And it is shared how this research is being applied in practice.

## 8.2 Introduction

High-profile disease outbreaks and the threat of terrorism have increased interest in public health surveillance systems for early outbreak detection (Buehler et al., 2004). Surveillance systems as defined by Centers for Disease Control and Prevention (CDC) collect and analyze morbidity and other data and facilitate timely dissemination of results to the appropriate decision-makers (Bravata et al., 2004). However, the issue of surveillance will be considered here as one of analysis and interpretation of health data. Also one may distinguish between what public health surveillance is syndromic and what is better known as spatial (Kleinman et al., 2004; Lawson and Kleinman, 2005). Syndromes are groups of symptoms that combine similar types of complaints, and surveillance generally refers to monitoring statistics for evidence of change. Spatial techniques are used to find clustering across a map.

Data used for illustration here will be that of influenza (flu) activity collected and reported by the Influenza Branch at CDC. Data of influenza-like illnesses (ILI) are of particular interest, because they include a variety of illnesses with similar clinical symptoms, including anthrax (Valleron and Vidal, 2002). For example, an anthrax outbreak might be detectable at first as an unusual increase in patients reporting emergency departments with respiratory symptoms (Reis and Mandl, 2003). Through acknowledging the importance of broader research into surveillance networks (Morse et al., 2003), programs (Yih et al., 2004), and systems (Widdowson et al., 2003; Paladini, 2004; Zhang et al., 2004; Dafni et al., 2004; Williamson and Hudson, 1999), the objective of the work described here has been to measure the specificity of combining statistical process control (SPC) and generalized linear models (GLM) for outbreak detection.

### 8.3 Methods, Assumptions, and Procedures

Let us assume that the objective for specificity should be that the probability of finding an outbreak in error is 0.0027, which is associated with traditional SPC. What we will find is that based on algorithms presented here, the probability 0.0027 would be a remarkable underestimate. And so we are left with what might be the most important question of this study: What are reasonable expectations about errors associated with outbreak detection?

In addition to results of an SPC-only approach there will be presented results about SPC applied to absolute values of residuals of both linear and gamma regression. Linear regression assumes a normal response, where its mean is a linear function of predictors. For gamma regression, we have assumed a gamma-distributed response where the natural logarithm of the mean is a linear function of predictors, which is also known as the log-gamma model (Hardin and Hilbe, 2001). Where  $y_i$  represents each observation of the response variable,  $x_i\beta$  is the linear combination of covariate values and associated parameters, and  $\phi$  is the scale required to produce standard errors following a gamma distribution, the log-likelihood function for the log-gamma model is

$$\sum_{i=1}^n \left[ \frac{y_i / \exp(x_i\beta) + x_i\beta}{-\phi} + \frac{\phi + 1}{\phi} \ln y_i - \frac{\ln \phi}{\phi} - \ln \Gamma\left(\frac{1}{\phi}\right) \right]$$

Stata statistical software has been used for this maximum likelihood estimation (StataCorp, 2005).

Regression models of lab data take as the response total isolates; predictors are number of labs reporting, total specimens tested, and dummy variables describing categories for virus and

region. Models of sentinel data take total ILI as a function of total patients, number of providers reporting and variables describing age and region. Again the flu activity data are collected in time (weekly).

In addition to the simple individuals control chart only approach, linear regression was chosen for its familiarity. A GLM philosophy led to choosing gamma regression. Each of five datasets was used to fit appropriate combinations of models assuming different response distributions and functions for their means. The distributions are gamma, negative binomial, normal, and Poisson; the functions are identity, inverse, and natural logarithm. Maximum likelihood among the combinations was found in every case to be what we have referred to as the gamma regression with log link.

#### 8.4 Results and Discussion

"The likelihood function is defined as the model taken as a function of the unknown parameter vector for the given observed value of  $y$ . A model that makes the observed data more probable is said to be more likely (Lindsey, 1997, p. 221)." An additionally chosen diagnostic here relies on the concept of Type I error that places more traditional goodness of fit squarely in the context of SPC. Further, "the study of residuals [for model checking] is generally only useful if the sample size is relatively small, at most 100 observations or so (Lindsey, 1997, p. 221)." Sample sizes here are between 1000 and 5000. Formal comparisons that led to the choice of log-gamma over other GLM were according to maximum log-likelihood. The relevant values appear in Table 35, and the reader can verify that the log-gamma model is consistently best fitting and so assumedly the most theoretically appropriate.

Table 35. Log likelihood Values Associated with Main Effects GLM given Reasonable

## Combinations of Distribution and Link

Distribution	Link	Lab 97-01	Lab 01-03	Sentinel 97-01	Sentinel 02-03	Sentinel 03-05
Gamma	Log	-971	-4785	-9060	-8198	-14,623
Gamma	Identity	-1.71E10	-3.30E9	-7.12E10	-3.87E10	-2.64E11
Neg. bin.	Identity	-18,011	-9852	-21,908	-15,500	-63,934
Neg. bin.	Reciprocal	-125,752	-71,112	-9217	-18,195	-50,008
Gaussian	Reciprocal	-23,597	-14,509	-11,002	-11,681	-18,271
Poisson	Identity	-68,277	-33,868	-108,741	-52,663	-236,853
Poisson	Reciprocal	-139,422	-97,876	-752,214	-266,397	-750,771

Moving ranges are correlated, but individual measurements are assumedly uncorrelated which contradicts what is known about time series. On the other hand, the individuals control chart is insensitive to small shifts that would seem advantageous to outbreak detection and requisite seasonality. Were it not interesting to compare process control of flu activity across model-based statistics, one might have chosen more theoretically appropriate methods such as  $P$  charts for proportions or ratios, as they have been called here.

Lab and sentinel data have been further separated for analysis according to how they have been collected over the years. Lab data collection changed somewhat during 2001, so lab datasets analyzed here are 1997-2001 and 2001-2003. Sentinel data collection changed at the end of 2001 and again in 2003, so sentinel results are for 1997-2001, 2002-2003, and 2003-2005. More recent lab data was not available at the time of this first analysis.

Table 36 gives example details of the log-gamma model for 2001-2003 lab data (log likelihood is -4785.334406). Baseline has virus is A (H1) and region is New England.



Table 35. Example Details of the Log-Gamma Model for 2001-2003 Lab Data

Total isolates	Coefficient	Standard error	Z
Specimens tested	0.0055275	0.0005708	9.68
Labs reporting	0.3397659	0.0350394	9.70
Virus is A (H3N2)	1.031436	0.182429	5.65
Virus is A (unknown)	1.229036	0.1750723	7.02
Virus is B	1.332141	0.1725199	7.72
Region is Mid-Atlantic	-2.708092	0.2797416	-9.68
Region is EN Central	-3.139738	0.3134402	-10.02
Region is WN Central	-2.943873	0.2942121	-10.01
Region is S Atlantic	-3.22848	0.2867831	-11.26
Region is ES Central	-1.226358	0.259689	-4.72
Region is WS Central	-2.024777	0.2757869	-7.34
Region is Mountain	-2.911517	0.3184262	-9.14
Region is Pacific	-2.939222	0.3056996	-9.61
Constant	-3.514507	0.3074684	-11.43

Find in Table 37 the following columns described left to right.

- 1) Lab and sentinel datasets and years included (column is “Dataset”)
- 2) Regional, weekly observations of different viruses and ages (column is “Number of Observations”)
- 3) Appropriate ratios and associated moving ranges simultaneously outside three sigma limits of individuals and moving ranges control charts (column is “SPC alone”)

- 4) Linear regression residuals and associated residuals simultaneously outside three sigma limits of individuals and moving ranges control charts (column is “Linear regress +”)
- 5) Gamma regression residuals and associated residuals simultaneously outside three sigma limits of individuals and moving ranges control charts (column is “Gamma regress +”)

The proportions of Table 37 in columns 3, 4, and 5 should be thought of as probabilities of Type I error or finding an outbreak in error.

Table 36. Probabilities of Finding an Outbreak in Error for SPC Alone, Linear Regress +, and Gamma Regress +

Dataset	Number of observations	SPC alone	Linear regress +	Gamma regress +
Lab 97-01	4784	0.0648	0.0364	0.0077
Lab 01-03	3060	0.0575	0.0386	0.0069
Sentinel 97-01	1494	0.0368	0.0375	0.0542
Sentinel 92-03	1872	0.0438	0.0342	0.0577
Sentinel 03-05	2556	0.0556	0.0376	0.0278

Among the lab data with respect to Type I error, there are consistent results: gamma regression with SPC outperforms, and SPC alone underperforms. There is no consistent result among sentinel data. Further, the outperforming gamma regression-based algorithm for lab data is the only one that is relatively close to the otherwise expected Type I error probability 0.0027. Type I errors associated with sentinel data are generally great perhaps because they are more subjective in nature. There would seem to be less measurement (human) error associated with lab data collection.

In the case of lab data one might imagine successively more theoretically appropriate models of flu activity "explaining away" more and more variation before moving to statistical

control charts. Imagine the models "pushing" more observations to be inside upper control limits or "pulling" those limits outside of more observations. In other words, we are moving to better fitting models of flu activity. First, with SPC alone we are controlling for denominators of the ratios charted, number of labs reporting, or total patients. As we move to regression-based SPC, we account for whatever else is available from the CDC, and within this framework: The gamma distribution might seem more appropriate than normal for absolute values of any kind; the natural logarithm as a function is presumably better here than the identity.

## 8.5 Conclusions

To finish on a note regarding strict application, I want to quote the U.S. Air Force Captain who oversaw the technical details of the research project described in this report:

Syndromic Surveillance Systems led by Dr Justin Chimka will offer benefits to the medical emergency response community and to the DOD by offering a framework to evaluate the effectiveness of surveillance systems in detecting the outbreak of specified illnesses. The procedures developed for testing U.S. surveillance data will be applied by AFRL/HEAL to influenza like data collected by Air Force Institute for Operational Health to aid the DOD Worldwide Influenza Surveillance Program study of identifying data that are unusable for outbreak reporting. (Air Force Research Laboratory, Jean-Claude Beasley, March 15, 2006)

## 8.6 Recommendations

In preliminary research for a follow up study, no different lab results were found among more recent datasets 2003-2004 and 2004-2005. Also, simple autoregressive models of lab data have not been found to interfere with aforementioned notions of what is good for lab-based surveillance. Sentinel data, on the other hand, have found in autoregressive models those that consistently outperform. So let us begin discussion of future work with hope for sentinel data of self-exciting autoregressive models or threshold autoregressive processes that do even more to account for serial correlation and seasonality. The addition of mathematical models of information processing such as artificial neural networks has also been considered.

Future work should include measurement of sensitivity and research into integrated models for broader bio-terror response logistics (Craft et al., 2005) and mitigation strategies for pandemic influenza (Germann, et al., 2006). Improved outbreak detection for bio-terror response logistics would positively affect medical materiel transportation forecasts, cognitive decision support for syndromic surveillance systems, and epidemic models for anticipatory and responsive support; that is, sense and respond operations, intelligence, and logistics.

Future data to be more systematically considered might include vaccine usage as a predictor, to further explain the variation in flu activity before representing what is left with control charts. There is interest in better understanding variation associated with OTC medication sales for public health surveillance (Goldenberg et al., 2002; Wagner et al., 2004).

However, what is most important at this time is thought to be the problem of estimating Type II error or sensitivity associated with our detection algorithms. Related problems facing the analyst would be the seemingly important gamma distribution and its computational intensity compared to the norm. Also, not only is there serial correlation in weekly series but covariance of individuals and moving ranges. Finally, future work with lab data might be most important to understanding variation of influenza A viruses, of which avian influenza or "bird flu" is a subtype. While both A and B viruses concern human health, only type A can cause pandemics.

## 8.7 References

Bravata, DM, V Sundaram, KM McDonald, WM Smith, H Szeto, MD Schleinitz and DK Owens, "Evaluating detection and diagnostic decision support systems for bioterrorism response," *Emerging Infectious Diseases* 10 (1), pp. 100-108 (January 2004)

Buehler, JW, RS Hopkins, JM Overhage, DM Sosin and V Tong, "Framework for evaluating public health surveillance systems for early detection of outbreaks," *MMWR Recommendations and Reports* 53 (RR-5), pp. 1-11 (May 7, 2004)

Craft, DL, LM Wein and AH Wilkins, "Analyzing bioterror response logistics," *Management Science* 51 (5), pp. 679-694 (May 2005)

Dafni, UG, S Tsoidras, D Panagiotakos, K Gkolfinopoulou, G Kouvatses, Z Tsourti and G Saroglou, "Algorithm for statistical detection of peaks," *MMWR Supplement* 53, pp. 86-94 (September 24, 2004)

Germann, TC, K Kadau, IM Longini Jr. and CA Macken, "Mitigation strategies for pandemic influenza in the United States," *PNAS* 103 (15), pp. 5935-5940 (April 11, 2006)

Goldenberg, A, G Shmueli, RA Caruana and SE Fienberg, "Early statistical detection of anthrax outbreaks by tracking over-the-counter medication sales," *PNAS* 99 (8), pp. 5237-5240 (April 16, 2002)

Hardin, JW, Hilbe, JM, *Generalized Linear Models and Extensions*, College Station, TX: Stata Press (2001)

Kleinman, K, R Lazarus and R Platt, "A generalized linear mixed models approach for detecting incident clusters of disease in small areas," *American Journal of Epidemiology* 159 (3), pp. 217-224 (February 1, 2004)

Lawson, AB and K Kleinman, *Spatial and Syndromic Surveillance for Public Health*, W Sussex, England: John Wiley and Sons (2005)

Lindsey, JK, *Applying Generalized Linear Models*, New York: Springer (1997)

Morse, SA, RB Kellogg, S Perry, RF Meyer, D Bray, D Nicholson and JM Miller, "Detecting biothreat agents," *ASM News* 69 (9), pp. 433-437 (2003)

Paladini, M, "Daily emergency department surveillance system," *MMWR Supplement* 53, pp. 47-49 (September 24, 2004)

Reis, BY, Mandl, KD, "Time series modeling for syndromic surveillance," *BMC Medical Informatics and Decision Making* 3 (2), (January 23, 2003)

StataCorp. 2005. *Stata Statistical Software*: Release 9. College Station, TX: StataCorp LP

Valleron, A-J, Vidal, JJ, "Timely redistribution of information for epidemiological surveillance and alert," *Proceedings of the AMIA 2002 Annual Symposium*, pp. 830-834

Wagner, M, J Pavlin, JC Brillman, D Stetson, S Magruder and M Campbell, "Synthesis of research on the value of unconventional data for early detection of disease outbreaks," *DARPA Bio-ALIRT Program final report* (October 2004)

Widdowson, M-A, A Bosman, E van Straten, M Tinga, S Chaves, L van Eerden and W van Pelt, "Automated, laboratory-based system using the internet for disease outbreak detection," *Emerging Infectious Diseases* 9 (9), pp. 1046-1052 (September, 2003)

Williamson, GD, Hudson, GW, "A monitoring system for detecting aberrations in public health surveillance reports," *Statistics in Medicine* 18, pp. 3283-3298 (1999)

Yih, WK, B Caldwell, R Harmon, K Kleinman, R Lazarus, A Nelson, J Nordin, B Rehm, B Richter, D Ritzwoller, E Sherwood and R Platt, "National bioterrorism syndromic surveillance demonstration program," *MMWR Supplement* 53, pp. 43-46 (September 24, 2004)

Zhang, X, R Fiedler and M Popovich, "A biointelligence system for identifying potential disease outbreaks," *IEEE Engineering in Medicine and Biology Magazine*, pp. 58-64 (January/February 2004)