Application of Multi-Criteria Decision Analysis in Requirements Definition for Prioritization of Stakeholder Elicitation

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Dedication

Dedicated to my wife, Christina (thank you for your patience, love, and companionship in this journey); my mother, Judy (fulfilling your premonition when I was a toddler); and my brother Mike (I'm sorry I couldn't finish in time; you were and always will be an inspiration to us all).

Abstract

Application of Multi-Criteria Decision Analysis in Requirements Definition for Prioritization of Stakeholder Elicitation

This paper presents the results of research that uses several Multi-Criteria Decision Analysis (MCDA) methods for stakeholder-input prioritization during requirements definition. Developing a comprehensive requirements document is a complex task. Stakeholder inputs are a key factor for the development of an efficient and effective requirements document. Gathering and processing these inputs can be daunting and doing so often leads to injecting subjectivity of the requirements analyst. The challenges of complexity and subjectivity can be effectively addressed by prioritizing, justifying, and documenting each requirement. For this work, the research used stakeholder inputs from a Mobile Ad Hoc Network (MANET) operational scenario as a case study. The research proposes a novel consecutive approach, where MCDA algorithms are used in stages and feed further MCDA algorithms in succession to prioritize stakeholder elicitations. The research demonstrates that this approach reduces the level of subjectivity introduced into the requirements definition by the definer of the requirements.

Keywords: Requirements definition, Multi-Criteria Decision Analysis (MCDA), stakeholder prioritization, AHP, TOPSIS

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List of Acronyms

AHP	Analytic Hierarchal Process
AoA	Analysis of Alternatives
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
FFBD	Functional Flow Block Diagram
FMV	Full Motion Video
GAO	Government Accountability Office
IDEF	Integrated Definition charts
INCOSE	International Council of Systems Engineers
JCIDS	Joint Capabilities Integration and Development System
JUONS	Joint Urgent Operational Needs Statement
KPP	Key Performance Parameter
MACO	Maritime Accelerated Capabilities Office
MANET	Mobile Ad Hoc Networking
MAUT	Multi-Attribute Utility Theory

MCDA	Multi-Criteria Decision Analysis
MNS	Mission Needs Statement
PLI	Position Location Information
Promethee	Preference Ranking Organization Method for Enrichment of Evaluations
QFD	Quality Function Deployment
RDC	Rapid Development of Capability process
RPED	Rapid Prototyping, Experimentation and Demonstration
RVTM	Requirement Verification and Traceability Matrix
SAW	Simple Additive Weighting
SECNAV	Secretary of the Navy
SWaP	Space Weight and Power
TOPSIS	Technique of Order Preference in Ideal Solution
WSM	Weighted Sum Model

List of Symbols

r	Requirement
i	Alternative
m	Number of alternative
j	Criteria
n	Number of criteria
w_j	Weight of criterion
a_{ij}	Decision matrix with *i* as row and *j* as column
a_j^{max}	Maximum of the criteria in row of decision matrix
a_j^{min}	Minimum of the criteria in row of decision matrix
r_i	Summation of element in row *i*
R_i	Aggregated sum of best alternative requirement
p_i	Normalized priority element
p_{ij}	Normalized decision matrix
P_i	Aggregate by summing weighted product of normalized decision matrix
r_{ij}	Normalized matrix using the distributive normalization method
u_j^+	Maximum valued element in column

u_j^- Minimum valued element in column

R+ "Ideal" requirement (TOPSIS)

R^- "Anti-ideal" requirement (TOPSIS)

p_i^+ Maximum of normalized decision matrix

p_i^- Minimum of normalized decision matrix

d_j^+ Euclidean distance to "ideal"

d_j^- Euclidean distance to "anti-ideal"

C_j Closeness coefficient to ideal

1 - Introduction

Developing clearly defined requirements is an early key to success. The Joint Capabilities Integration and Development System (JCIDS) is the formal Department of Defense (DoD) procedure for acquisition requirements definition, defense program-evaluation criteria, and next-generation acquisition requirements development across the four military services (OSD-JCS, 2015). However, according to the Government Accountability Office (GAO), requirements-definition issues have been the common denominator in failures for the last several decades, resulting in schedule slip, cost overruns, and an ineffective product for end users (GAO, 2012) (GAO, 2015) "In other words, requirements are insufficiently defined at program start; when their full consequences are realized, trade-offs are harder to make—cost increases and schedule delays become the preferred solutions" (p. 12) (GAO, 2015). Specifically, the GAO noted that the DoD could benefit from prioritizing requirements (GAO, 2011). The International Council of Systems Engineers (INCOSE) Systems Engineering Handbook describes the normal life cycle of a system, from concept, design, and implementation through operations and disposal. The concept-development portion of the system's life cycle, where requirements are defined, is described as only eight percent of the total life cycle (Haskins, 2011). Dr. Georgiadis asserts that less than two percent of a life cycle effort includes requirements definition and analysis of alternatives (AoA), saying the "effect of this initial two percent effort should never be underestimated as it greatly affects what happens during the rest of the ninety-eight percent of the life cycle efforts" (Georgiadis, Mazzuchi, & Sarkani, 2013). Simply stated, what is fed into the

requirements-definition process has a dramatic impact on the outcome and success of a system. The pie chart shown in Figure 1, derived from the INCOSE Handbook and Dr. Georgiadis's data, demonstrates the disparity of effort in developing such important parts of the systems engineering life cycle.

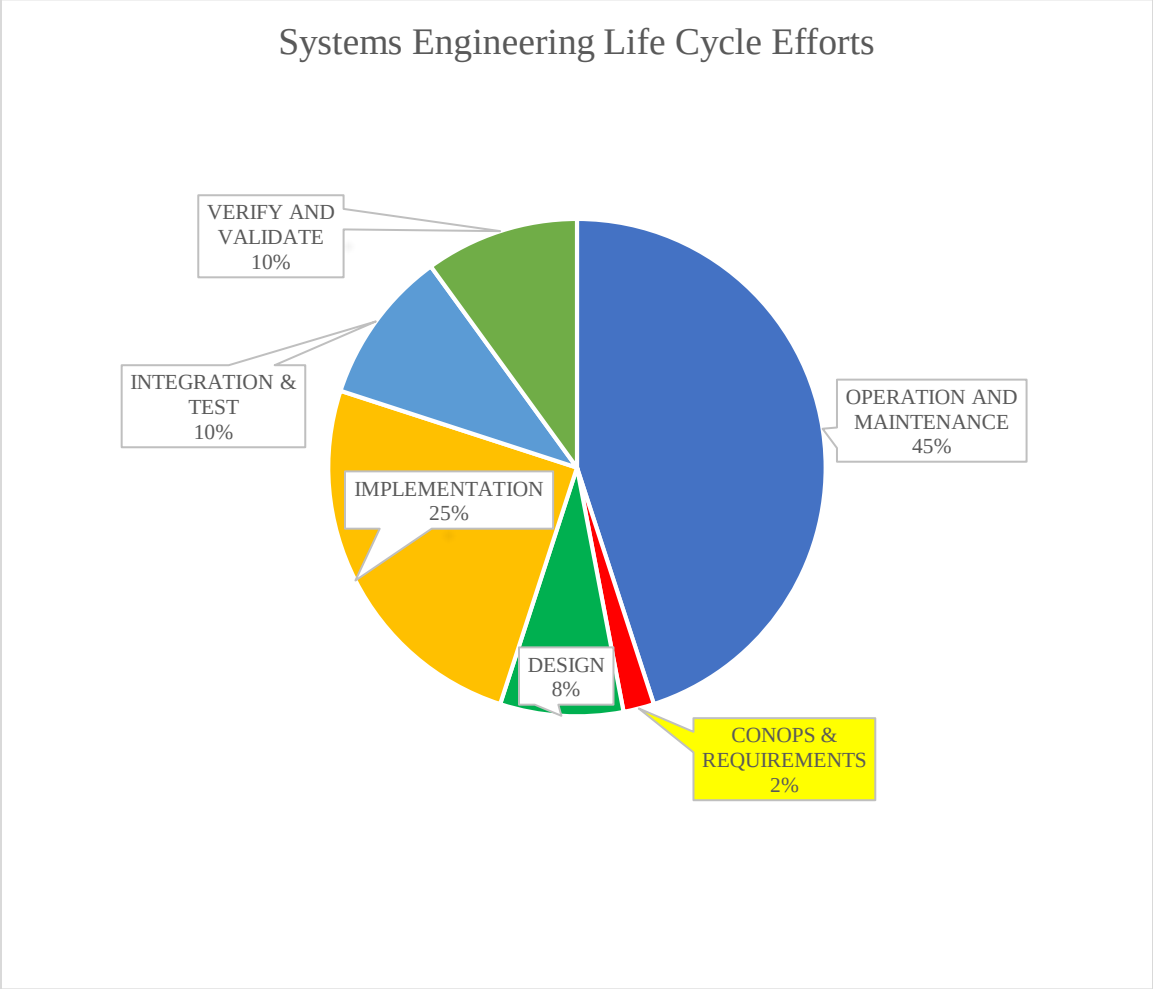

Figure 1. Systems engineering life cycle efforts

1.1 Research Question

Each requirement should be defined in terms of a needed capability and not in terms of a preconceived solution (Sage, 2009). Several modeling tools have been developed, including Quality Function Deployment (QFD), functional flow block diagrams (FFBD), Integrated DEFinition (IDEF) charts, and N-squared charting (p.86) (Blanchard & Fabrycky, 2011), the use of which can complicate the problem of organizing the data itself. Specifically, smaller, rapid, and dynamic systems may not require approaches as complex as Quality Function Deployment (Hooks & Farry, 2001) or the Department of Defense Architecture Framework (DoDAF) (OSD-DCI, 2010) to define their requirements. The formality and adherence to set requirements-development and systems-engineering protocols are dependent on the sophistication of the system, the organizational needs, and the effort to be accomplished; the process should be tailored to the specific system. Adding to this complexity are inputs from multiple stakeholders, rapidly changing technology, scope change or mission drift, and overload of potential vendor solutions. It is crucial to accurately capture stakeholder needs and translate them into an operational form that engineers and program managers can use throughout the system life cycle.

Prioritization of these stakeholder inputs provides options for managing requirements, mitigating risks in system changes, scheduling, additional resourcing, and cost dependencies while guiding architecture and design trade-offs (Hooks & Farry, 2001). Developing a comprehensive requirements document is a complex task, and justification of the value of each requirement is critical to the creation of a useful and

effective requirements document. The task is to translate the stakeholder's needs to definitions that can be utilized by the system implementation, design, logistics teams, or community to follow. With the prevalence of the poor practices described in requirements-writing texts (Sage, 2009), we suggest that *each requirement must earn its place in the defining document* and that subjectivity of the requirement definer can be minimized by using mathematically based data analysis in the prioritization and decision-making process. Thomas Saaty discusses objectivity and inserting subjectivity:

> Using judgements has been considered to be a questionable practice when objectivity is the norm. But a little reflection shows that even when numbers are obtained from a standard scale and they are considered objective, their interpretation is always, I repeat, always, subjective. We need to validate the idea that we can use judgements to derive tangible values to provide greater credence for using judgements when intangibles are involved (p. 85) (Saaty, 2008).

Multi-Criteria Decision Analysis (MCDA), also known as Multi-Criteria Decision Making (MCDM), is becoming more prevalent in the systems engineering community and has been used in many areas for prioritization and trade space analysis. MCDA will be discussed in the literature research section and used in the case study. This is a suggested alternative or additional tool for use in the requirements-definition process in a dynamic, rapid integration environment, and the intent of this alternative is to reduce subjectivity of the requirement analyst from being inserted into requirements development.

1.2 **Background**

Expedited requirements development is necessary for rapid technology integration with aggressive schedules, as seen in programs such as the Secretary of the Navy (SECNAV) Accelerated Acquisition Process for the Rapid Development, Demonstration and Fielding of Capability governing the handling of urgent and emergent needs (SECNAV, 2016). The two paths for fielding capability to the fleet through this process are (1) Rapid Prototyping, Experimentation and Demonstration (RPED) and (2) the Maritime Accelerated Capabilities Office (MACO). RPED is an approach to fast-track the development, fielding, and assessment of prototypes to demonstrate solutions to capability needs, inform concepts of operations and requirements development, and inform acquisition and resource planning. RPED also, if necessary, provides limited fielding until a formal program can be established and a full system acquired. RPED initiatives are not formal acquisition programs but may be used to support urgent-needs processes when a suitable materiel solution cannot be identified through the service's urgent-needs process.

RPED replaced the "Speed to Fleet" process (CNO, 2015). In layman's terms, RPED is the path taken to address urgent and emergent needs when requirements are not completely understood, and no government or industry solution exists. MACO is an acquisition program for which schedule is a priority and for which there are known requirements and an existing materiel solution. MACO uses the Rapid Development of Capability (RDC) process to leverage commercial off-the-shelf, government off-the-shelf, non-developmental solutions, or an engineering modification to an existing

capability to provide a solution for an urgent need. RDC also accelerates the delivery of existing programs of record. All approaches are intended to deliver a solution within 24 months or less, a quick turnaround considering it can take decades to get a new weapon system, aircraft, or ship to operators in the fleet (GAO, 2015).

In the DoD, requirement inputs often come from Mission Needs Statements (MNS) or Joint Urgent Operational Needs Statements (JUONS). Stakeholder queries of the actual operators are used less often, but they are valuable because they can translate directly from an operational stakeholder rather than being filtered through the lengthy process and bureaucracy of creating official documents such as MNS and JUONS.

This movement toward rapid integration and execution of systems to the operational stakeholder makes solid requirements definition not only more significant to the success of the system but also more difficult to complete in a short time frame, especially since we were already rushing requirements definition. Further development of requirements is necessitated by situation complexity and the influence of dynamic environments in requirements elicitation. Effective requirements elicitation can only be achieved when the requirements-elicitation process is compatible with the complexity of the situation (i.e., degree of uncertainty, ambiguity, emergence, etc.) (Katina, Keating, & Jaradat, 2014).

1.3 Research Objective

Large-scale projects often take years to develop requirements documents. For example, the Jordanian Emergency Operations Center in Amman requirements document entailed a two-year development process that included Erlang studies of phone habits throughout the country, a home address system, and dispatch protocol procedures (Hammed, 2006). Modeling requirements with available software is effective; however, modeling can be time and resource consuming, and it can take a significant level of expertise to develop valid models. Reasons for poorly written requirements include lack of experience, unclear justification, hidden agendas, and poor or inadequate communication on the part of the development team (Hooks & Farry, 2001).

Our research proposes the use of MCDA algorithms to process stakeholder inputs to develop mathematically based solutions for prioritization of stakeholder needs. The case study uses a unique *consecutive approach*, where algorithms are used in stages and feed successive MCDA algorithms to prioritize stakeholder elicitations where requirement-definer subjectivity was required to be inserted into requirements. This approach demonstrates the flexibility of MCDA to address a data set from a questionable survey. The consecutive approach can be used for greater clarity of the processed data—for example, if the variables seem too near to be prioritized or if requirements conflict with each other (Mariza Dewi, 2014). Our case study uses the consecutive MCDA algorithms calculations from previously processed data to satisfy a missing variable need (e.g., the AHP local priority used as weighting). Using a related variable from the same

questionnaire to fill a necessary variable gap makes it unnecessary for the requirements writer to insert a subjective number. This approach gives more validity to the process, as demonstrated in the case study.

The three objectives of this research study are to identify MCDA algorithms and methods as follows: First, conduct a literature review for selection of MCDA algorithms that have a history in the requirements-definition domain. Second, identify a distinctive technique for using more than a singular MCDA approach for processing requirements data. Finally, conduct a case study using the multiple-MCDA approach on an existing operator stakeholder data set, using data from one algorithm process to feed a consecutive process in prioritizing the requirements.

1.4 Purpose

Excessively formalized procedures, with minimal contribution, can greatly impact the system progress, costs, and schedule (Haskins, 2011). This is especially true for rapid prototyping and rapid integration initiatives that identify technology candidates that may not be at full maturity, but which address high-priority capability gaps whose requirements are not otherwise being met with existing technology or fielded systems (SECNAV, 2016). This dynamic environment creates a challenge for the requirements-definition team because of changing scope or external constraint conditions that are subject to change and are often ambiguous. Translating needs from non-technical or

operationally focused stakeholders into requirements that can be validated and verified is a common challenge in the community.

1.5 Hypothesis Statement

The hypothesis for the approach is that the application of MCDA algorithms to prioritize stakeholder inputs in a multi-algorithm approach will remove the subjectivity of the requirement definer interpreting the data by inserting engineering and substantiating requirements decisions with mathematical rigor.

1.6 Significance

The need to deliver new technologies to the fleet at a rapid pace, combined with the fiscal constraints of sequestration, makes decision-making critical. This research emphasizes the importance of selecting specific criteria from stakeholder inputs and establishing priorities in requirements alternatives to develop the optimum alternative set. The research also demonstrates the strength of using MCDA algorithms to prioritize stakeholder needs and remove requirement-definer subjectivity from the process. The objectives of this research are to examine MCDA algorithms used to aid requirements-definition decision makers in prioritizing data and producing informed decisions. The

algorithms' computations should be simple, executable on readily available software, and easily demonstrated graphically. The following predominant MCDA algorithms were considered for relevance in the approach: Simple Additive Weighting (SAW), Analytic Hierarchal Process (AHP) (Saaty, 1980), Multi-Attribute Utility Theory (MAUT) (Keeney & Raiffa, 1976), and Technique of Order Preference Similarity in the Ideal Solution (TOPSIS) (Yoon, 1980).

This proposed method is not intended to be a comprehensive approach or an authoritative decision mechanism but is meant to provide a tool for guiding decision-making in the requirements-definition process, as well as to further the discussion of utilizing MCDA in requirements engineering. This research was motivated by Sheard's discussion of complex adaptive systems and finding "strange attractors" in the chaos of the complexity of systems engineering (Sheard, 2009)—and also by Dr. Farry and Hooks' book on writing requirements (Hooks & Farry, 2001). This is also an extension of Dr. Georgiadis's work discussing the use of MCDA on AoAs as part of the systems engineering process (Georgiadis, Mazzuchi, & Sarkani, 2013) (Georgiadis, 2013). We chose a few representative MCDA algorithms with a history in the stakeholder analysis realm. These algorithms should be effective but not overly complex for a requirements writer. The proposed method is applicable to both simple and complex requirements development, providing enough engineering and mathematical rigor that the process will produce robust results without requiring high-end software and years of analysis.

2 - Literature Review

2.1 **Requirements**

"Requirements exist whether you discover them or not, and whether you write them down or not" (p.1) (Robertson & Robertson, 2013). Decades of research have gone into requirements definition, and it has become its own engineering discipline. Sources for gathering requirements include existing products, stakeholder focus groups or questionnaires, and operational needs. Gathering the data points is a beginning step of the requirements-definition process (requirements elicitation). Once gathered, the data can appear daunting for writing a useable document. The literature review and research focus on prioritizing this data.

2.1.1 Definition

A commonly used definition of a requirement is the IEEE version (IEEE, 1998):

1) A condition or capability needed by a user to solve a problem or achieve an objective, or
2) A condition or capability that must be met or possessed by a system or system component to satisfy a contract, standard, specification or other formally imposed document.

Requirements can be viewed as functional and performance statements that capture stakeholder demands. Understanding requirements requires domain knowledge

that balances a stakeholder's viewpoint on what a system needs to do with what is practically implementable.

> At the top of the hierarchy are the mission's requirements, which relate to the needs associated with the missions or activities which are important to one or more group of stakeholders. These mission requirements typically involve interaction of several systems. . . . Mission requirements represent stakeholder preferences for the increased ability to perform their activities with the introduction of the system in question (p.30) (Buede, 2009).

Domain knowledge, which also contains rules and assumptions about the system's operating environment, offers a practical means to identify inconsistencies and overlaps in requirements that may arise from the competing objectives and/or different stakeholder preferences (Nguyen, Vo, Lumpe, & Grundy, 2014). Stakeholder requirements define and constrain the performance parameters that the system engineers develop into engineering requirements. (Buede, 2009) (Pohl, 2010)

Requirements can be classified as mandatory requirements or trade-off requirements. Mandatory requirements use words such as "shall" or "must" and are often written as key performance parameters (KPP) in the DoD contracting arena. Trade-off requirements state conditions that would satisfy stakeholder wants, using words such as "should," and are described as goals. Each of these distinctions in requirements is often described with the "objective" to be met and the "threshold" to be reached (but which is not critical to the success of the system). "Tradeoff requirements should be evaluated with multi-criterion decision-making techniques because none of the feasible alternatives is likely to optimize the criteria" (p. 217) (Sage, 2009). Our research approach for the

application of selected MCDA algorithms is developed to assist in prioritizing and reducing subjectivity of the requirement-defining process.

Two other categories for requirements are customer requirements, which are stakeholder questionnaire based, and derived requirements, developed from the more technically worded customer requirements document. Requirements development includes (1) eliciting, analyzing, validating, and communicating stakeholder needs, (2) transforming customer requirements into derived requirements, (3) allocating requirements to architecture elements, hardware, software, test, and interface elements, (4) verifying requirements, and (5) validating the set of requirements. (Bahill & Henderson, 2005)

While there is much literature on the subject, Table 1 lists a few commonly referred qualities or attributes that make a good requirement (Grenn, Sarkani, & Mazzuchi, 2014) (Davis, 2005)(Stuckey, Sarkani, & Mazzuchi, 2017) (Haskins, 2011) (Robertson & Robertson, 2013) (Kotonya & Sommerville, 2002) (Katina, Keating, & Jaradat, 2014) (Buede, 2009). Sage and Rouse have a list of 25 (Sage, 2009).

Realistic	Can be met within the cost and schedule constraints of the program
Achievable	The implementing designer should have the expertise to achieve the requirement
Correct	Represents something necessary for the system to be built and the satisfaction of some need
Understandable	Has a requirement whose meaning is easily comprehended by stakeholders with minimal explanation
Complete	Captures everything that is intended with not to-be determined or resolved
Verifiable	Is written to enable cost-effective verification
Validated	Is necessary for building the right system for user needs
Traceable	Is allocated and linked to all other supporting requirements at higher and lower levels
Unambiguous	Has only one possible interpretation
Consistent	Is not in conflict with other requirements
Precise	Has numeric quantities that are accurate and specific to an appropriate level
Concise	Communicates the information using as few words as possible
Design independent	Enables flexibility in the design process by defining what is necessary, not how it should be designed or implemented
Annotated	Documents necessity and relative importance
Not redundant	Does not state information more than once without good reason

Table 1. Short list of attributes for good requirements (Grenn, Sarkani, & Mazzuchi, 2014) (Haskins, 2011)

The attribute "Realistic" is similar to "Achievable," which, although already fairly established (Haskins, 2011), has received recent attention for study (Stuckey, Sarkani, & Mazzuchi, 2017). This can, however, lead to the already too-common practice of writing

requirements to a preconceived or existing solution, and we need to consider the "Design Independent" attribute while not conflicting with "Achievable" or "Realistic."

"Traceable" done well is one of the top ways to prevent late-stage delivery failures. It suggests complexity because of the need to track multiple levels of requirements definitions. Modeling with common systems engineering software such as CORE©, Rhapsody©, or a SySML©-compliant standard software can be useful for organizing the functional requirements tracing. However, a certain level of expertise and experience with the software is recommended or it can become unwieldly and tax already strained resources of the development team. The Requirements Verification Traceability Matrix (RVTM) suggested by the INCOSE (Haskins, 2011) is a simple, useful tool for tracing and tracking requirements, and it should be an early consideration when developing the requirements-definition process.

On lists of attributes, "Necessary" is usually at the top. The INCOSE handbook notes that "every requirement generates extra effort in the form of processing, maintenance and verification. Only necessary requirements should be written. Unnecessary requirements are of two varieties: (1) unnecessary specification of design, which should be left to the discretion of the designer, and (2) a redundant requirement covered in some other combination of requirements" (p.78) (Haskins, 2011). "Gold Plating" is a term used in the DoD for nonessential features or unnecessary requirements that lead to higher costs. One of the pillars of our hypothesis is that each requirement should earn its place in the document, because redundant requirements all too often lead to conflict within the document.

2.1.2 Stakeholder Elicitation

Stakeholders can be defined as anyone having a vested interest in the system, seen or unseen (Banville, Landry, Martel, & Boulaire, 1998). In our case study, they are defined as owners, sponsors, maintainers, logisticians, architects, and the end user or operator. All stakeholders have subjectivity related to their own knowledge base, experience, and professional opinion. This subjectivity, when aggregated and organized, creates the necessary synergy that gives value to the stakeholder elicitation process. The subjectivity that is not wanted is from the requirements analyst performing the aggregation of the data and defining the end requirement definition. Dr. Davis discusses the pros and cons (p.45) (Davis, 2005):

> *Pro's of elicitation:* Not doing elicitation is like saying, "I am not going to find out from my customers what they need." But the reason we build software is to solve the real problems. And we can only solve them if we understand those problems. If you do not do elicitation, requirements changes during development are likely to be more insidious and more persistent, and you run the risk of building the wrong system. A wrong system results in unhappy users and unsatisfied customers—not to mention a product that is not used by the intended users, that does not provide an adequate return on investment, and that will not sell. For me, building the wrong system is the ultimate "project failure."
>
> *Con's of elicitation:* It could take a long time to meet stakeholders and learn their needs. So, doing elicitation may result in a delay to the delivery. If you spend excessive effort doing elicitation, the project inception will be unduly delayed and the product will be delivered late.

The trade-off is in risk, time, and resources to gather and interpret the stakeholder's point of view, which may be why it is not a common practice in risk-averse government requirements-development organizations.

Gathering knowledge from this base has been referenced with three different names: stakeholder elicitation, consumer preferences, and preference elicitation. Dwayne Phillips refers to it as "learning the requirement" (Phillips, 2010). Stakeholder elicitation, a core function in requirements engineering, determines relevant sources and identifies and develops requirements from these sources (Pohl, 2010). Pohl describes three methods of stakeholder requirement elicitation through interviews, surveys, and observations. Our case study uses a survey or stakeholder questionnaire; therefore, our application of MCDA will focus on prioritizing specific data and its format. Phillips suggests a combined survey and interview process to gather data from stakeholders (Phillips, 2010). Saaty provides a common 1–9 measurement scale used in his Analytic Hierarchal Process for pairwise comparison (Saaty, 2008) and in the QFD structure.

There are numerous techniques discussed on prioritizing requirement elicitation, from index cards (Robertson & Robertson, 2013) to automating or modeling stakeholder elicitation (Zdravkovic & Svee, 2015). Consolidating and developing metrics to validate requirements (Nikou, Mezei, & Sarlin, 2015) are like our MCDA approach. The scope of this research, with the case study, focuses on operator stakeholder inputs and prioritization.

2.2 MCDA Methodologies

Multi-Criteria Decision Analysis was first developed in the early 1960s. It has grown into a popular family of algorithms used for the multi-dimensional decision-

making process (comparing apples to oranges). MCDA has been used in many areas of systems engineering, including analysis of alternatives (Georgiadis, Mazzuchi, & Sarkani, 2013), management and human resources (Forman & Gass, 2001), and nonfunctional requirements definition (Mariza Dewi, 2014). Dr. Salado's body of work in trade space analysis encompasses a larger scope of study (Salado & Nilchiani, 2015) (Salado & Nilchiani, 2015) (Salado & Nilchiani, 2015) but includes requirements definition in his Adaptive Requirements Prioritization and uses TOPSIS as its analytic basis (Salado & Nilchiani, 2015). Concurrent or parallel execution MCDA approaches for developing more stable requirements (or redundant models) for sensitivity analysis have been suggested in the literature (Georgiadis, Mazzuchi, & Sarkani, 2013) (Karsak, Sozer, & Alptekin, 2003). However, most often, the literature on requirements definition uses a single algorithm for requirements analysis (Mariza Dewi, 2014) (Salado & Nilchiani, 2015).

The following are three common steps in utilizing a decision-making technique involving numerical analysis of alternative criterion such as MCDA (Triantaphyllou, Shu, Sanchez, & Ray, 1998):

(1) Establish criteria and relevant alternatives

(2) Assess numerical measures to importance weights of each criterion and to the performance of the alternatives on each criterion

(3) Assess non-linearity associated with system considerations when selecting MCDA methodology.

Dr. Georgiadis suggests a fourth step:

(4) Utilize MCDA model for ranking each alternative (Georgiadis, 2013)

The following sections discuss some of the more popular MCDA algorithms, although only TOPSIS and AHP were applied to the case study data. SAW would not be appropriate for the multi-dimensional data set, and MAUT requires survey questions and weighting more focused on functionality.

2.2.1 Simple Additive Weighting (SAW)

The Simple Additive Weighting (SAW) model, also known the Weighted Sum Model (WSM) is one of the most well-known MCDA approaches (Fishburn, 1967). It is appropriate for single-dimensional situations (simply stated, when all data are expressed in the same units: apples to apples).

Choosing the best quality of a requirement *r*, suppose there are *m* number of alternatives designated as *i*, and *n* number of decision criteria designated as *j*. We denote the relative importance, or weight, of the criterion *j* with w_j. The first step is populating the decision matrix a_{ij}. Consider *i* as rows and *j* as columns.

Next, normalize with either the higher-is-better value, such as speed or bandwidth, being more important, by dividing the elements in the column by the maximum of the column, for each row, as in formula (1-1).

$$r_j = \frac{a_{ij}}{a_j^{max}},\ i = 1,2,\dots,m \text{ and } j = 1,2\dots,n \qquad (1\text{-}1)$$

For smaller value being more important, such as cost or weight, divide each element in the column by the lowest element in the column for each row (1-2).

$$r_{ij} = \frac{a_j^{min}}{a_{ij}},\ i = 1,2,\dots,m \text{ and } j = 1,2\dots,n \qquad (1\text{-}2)$$

The best alternative requirement is the one that maximizes R_i (using the capital letter to designate the aggregate sum) in equation (1-3). The weights w_j are expected to sum to one.

$$(1)\ R_i = \sum_{j=1}^{n} w_j\, a_{ij} \text{ for } i = 1, 2\dots, m \qquad (1\text{-}3)$$

The additive utility assumption is where the total value of each alternative is equal to the sum of the products given in equation (1-3).

2.2.2 Analytic Hierarchal Process (AHP)

Analytic Hierarchal Process (AHP) was developed by Saaty (Saaty, 1980). AHP uses a simple four-step process to rank alternatives using pairwise comparison with optional consistency-check and sensitivity-analysis steps (recommended but not required). AHP is already a common tool among requirements definers who use a defined process. AHP uses subjective inputs for pairwise comparison; therefore, it can be used in a multi-dimensional scenario, but the algorithm structure is similar to SAW.

There are multiple published methods for prioritization using AHP, approximation, eigenvalue, and geometric mean. The AHP approximation is a common method that only requires additions and averages, which can easily be accomplished in Excel. The eigenvalue method uses a vector instead of a weight variable. Working with vectors can become complicated to the novice without an AHP-specific software package. AHP also has a logarithmic least square, or geometric mean method, which is used to avoid the left-right rank reversal. (Ishizaka & Nemery, 2013) For the sake of simplicity, this paper uses the approximation method that does not require special software and can easily be accomplished with basic spreadsheet manipulation.

Often, the most difficult issue is structuring the problem for pairwise comparison for prioritizing requirements. An example is in describing the concept of communication plan, or C4 in the DoD vernacular, and how it can become complicated rather quickly with just the basic criteria space, weight, and power (SWaP). Then adding frequency

bands and data types as different levels of alternatives becomes graphically complex, as shown in Figure 2.

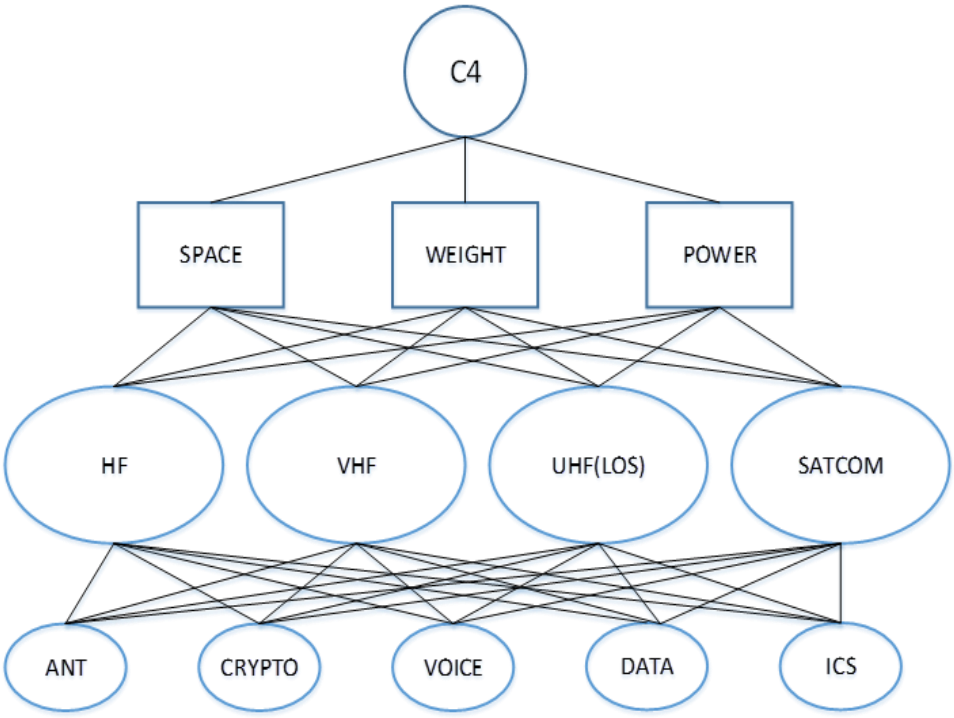

Figure 2. C4 complication description

We describe "C4" as the top goal. Space, weight, and power are criteria that can affect length of mission, load on the operator, and bulk of equipment that needs to be carried. Other criteria, such as frequency band, have effects on power consumption, antenna size, bandwidth constraints; basically, all are interconnected. Generally, organizing the criteria into local alternatives for pairwise comparison is an effective first step.

Prioritizing these elements is done by applying a score that ranks the importance of the criterion or alternative in the decision process. The AHP process, as described by Ishizaka (p 16) (Ishizaka & Nemery, 2013), has three types of priorities that have to be calculated:

- Criteria priority: importance of each criterion with respect to top goal.
- Local alternative priority: importance of an alternative with respect to one criterion.
- Global alternative priority: using the criteria and local alternative priorities, the global alternative priority ranks alternatives with respect to all criteria and the overall goal.

For the algorithm, let us suppose again, choosing the best quality of a requirement *r*, that there are *m* number of alternatives designated as *i* and *n* number of decision criteria designated *j*. We denote the relative importance, or weight, of the criterion *j* with w_j. The first step is populating the decision matrix a_{ij}. Consider *i* as rows and *j* as columns.

(1) Summation of the elements of the decision array *a* in a row *r*, with alternative *i*, and criterion *j*:

$$r_i = \sum_i a_{ij} \qquad (2\text{-}1)$$

(2) Normalization of the sum, where p is the normalized priority element by dividing each element in row r_i by the sum of the elements of the row:

$$p_i = \frac{r_i}{\sum_i r_i} \qquad (2\text{-}2)$$

Priority calculations for local priority, or a subset or level of questions in the survey, are ranked by priority with the normalized sum data. They can be ranked against other subsets to determine the global priority for overall goal with simple aggregation:

(3) Aggregate by summation of weighted product:

$$P_i = \sum_j w_j \, p_{ij} \text{ i=1,2…, m} \qquad (2\text{-}3)$$

P_i is the global priority of alternative i, p_{ij} is the local priority with regard to criterion j, and $w_j$is the weight or stakeholder's suggestion of importance of the criterion j. (Ishizaka & Nemery, 2013)

SAW and AHP are very similar algorithms, as seen in equations (1-3) and (2-3); however, AHP uses subjective inputs from stakeholders and can be used in a multi-

dimensional or different unit scenario, where SAW requires actual values of the same unit.

2.2.3 Technique of Order Preference Similarity in the Ideal Solution (TOPSIS)

Technique of Order Preference Similarity in the Ideal Solution was developed by Yoon in 1980 (Yoon, 1980). TOPSIS requires a minimal number of inputs from the end user or operator and has an output that is easy to understand and graphically display. Fundamentally, the best option entails the shortest distance to the calculated "ideal solution" and the furthest from the "anti-ideal," as shown in Figure 3. TOPSIS is best when multi-dimensional choices would be difficult to visualize. Consider comparing apples to oranges, but with the ability to distinguish Granny Smith, MacIntosh, and Fuji apples from Valencia or blood oranges. TOPSIS has been used widely in decision-analysis problem sets (Behzadian, Otaghsara, Morteza, & Ignatius, 2012) and trade space analysis (Salado & Nilchiani, 2015). TOPSIS is also the subject of focused studies used in requirements conflict resolution (Mariza Dewi, 2014) (Salado & Nilchiani, 2015).

TOPSIS has five basic steps. Although slightly more complex than AHP, TOPSIS can still be implemented in a spreadsheet without special software: (1) populate the requirements survey data and develop a normalized decision matrix, (2) weight the normalized decision matrix, (3) calculate "ideal" and "anti-ideal" solution, (4) determine the Euclidean distance from anti-ideal and closeness to ideal, (5) rank preferences and choose solution. Graphically displaying the results is very helpful. The normalization of

data and calculations of ideal and anti-ideal remove the issue of multiple scales used in our case study stakeholder questionnaire. (Ishizaka & Nemery, 2013)

The decision matrix a_{ij} is populated by n alternatives i with respect to m criteria j, where $i = 1 \ldots, \text{m}$ and $j = 1 \ldots., \text{n}$. With TOPSIS, there are several ways to process normalization of the data:

The *distributive normalization method* divides each data point by the square root of the sum of each squared element in a column in normalized matrix constructing matrix d_{ij}:

$$d_{ij} = \frac{a_{ij}}{\sqrt{\sum_{j=1}^{n} a_{ij}^2}} \; for \; j = 1, \ldots., n \; and \; i = 1, \ldots., m \qquad (3\text{-}1)$$

However, a similar process was used in the previous two examples for normalization and was therefore used in our case study for consistency. The *ideal normalization method* divides each data point by the highest value, if the ideal is a maximum, or by the lowest value, if minimized, to construct the normalized matrix r_{ij}.

(1) For maximum ideal, divide each element in the column by the maximum valued element in the column u_j^+:

$$r_{ij} = \frac{a_{ij}}{u_j^+} \; for \; j = 1, \ldots., n \; and \; i = 1, \ldots, m \qquad (3\text{-}2)$$

(2) For minimum ideal, divide each element in the column by the minimum valued element in the column u_j^- :

$$r_{ij} = \frac{a_{ij}}{u_j^-} \; for \; j = 1, \ldots, n \; and \; i = 1, \ldots, m \qquad (3\text{-}3)$$

The weighted normalized decision matrix p_{ij} is constructed by multiplying the normalized scores r_{ij} by the weights w_i.

$$p_{ij} \; = \; w_i \cdot r_{ij} \qquad (3\text{-}4)$$

Depending on the data, the "ideal" requirement R+ can either be a maximum (3-5), as in speed or bandwidth, or a minimum (3-6), such as cost.

$$R^+ = (p_i^+ \ldots, p_{m)}^+ \; where \; p_i^+ = \max(p_{ij}) \quad (3\text{-}5)$$

$$R^- = (p_i^- \ldots, p_{m)}^- \; where \; p_i^- = \min(p_{ij}) \quad (3\text{-}6)$$

Calculate the *distance for each point to the ideal* d_j^+ with Euclidean distance:

$$d_j^+ = \sqrt{\sum_i (p_I^+ - p_{ij})^2}, j = 1, \ldots, m \qquad (3\text{-}7)$$

The *distance to anti-ideal* d_j^-:

$$d_j^- = \sqrt{\sum_i (p_I^- - p_{ij})^2}, j = 1, \ldots, m \quad (3\text{-}8)$$

Finally, we calculate a *closeness coefficient* to the ideal C_j for each action (always between 0 and 1, with the preference closer to 1, independent of the scales):

$$C_j = \frac{d_j^+}{d_j^+ + d_j^-} \qquad (3\text{-}9)$$

The current issue in application of TOPSIS is subjective weighting if such considerations are not requested in the stakeholder query. The case study is such an example of not having weighting considered in the questionnaire. The consecutive approach discussed in the methodology section suggests a mitigation for the weighting issue.

Figure 3 is a graphical example of the TOPSIS using R+ as the ideal requirement, R- as the negative ideal requirement, and R1 and R2 as examples of requirements that in other MCDA tests are close in comparison, similar to requirement deconfliction efforts (Salado & Nilchiani, 2015).

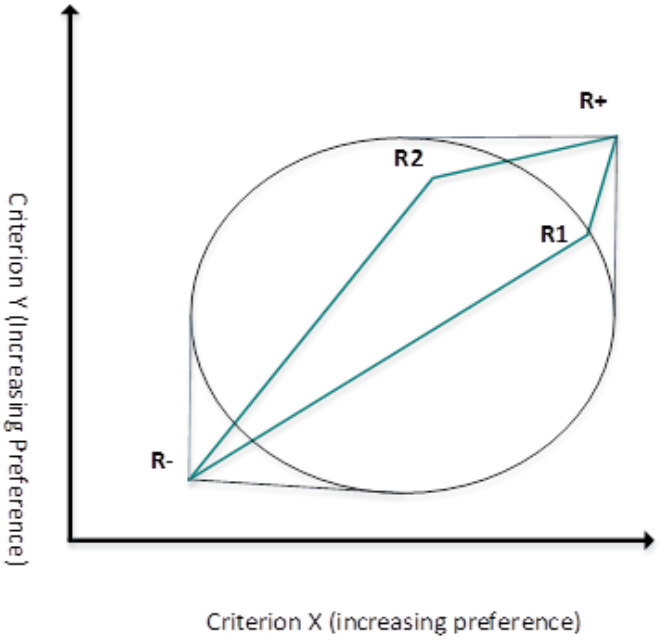

Figure 3. Example of TOPSIS graphically displaying closeness to positive idea requirement R+ and distance from negative ideal requirement R-

As mentioned, most literature research is in using MCDA in the requirements-definition process approach with a singular algorithm, which has its benefits. This research discusses a multi-algorithm approach. Table 2 is a graphic display of alternative approaches, pros and cons discussed in the literature research.

MCDA Algorithm Approach	Singular SAW	Singular AHP	Singular MAUT	Singular TOPSIS	Concurrent SAW, AHP, TOPSIS	Consecutive SAW, AHP, TOPSIS
Comparison Type	Simple additive comparison	Pairwise comparison	Pairwise comparison	Multi attribute comparison	Comparison of models	Integrating models
Comparison Approach	Mathematical weighting	Geometric mean recommended for survey comparison	Utility function for comparison	Closeness to ideal and distance from anti-ideal	Compare rankings from different approaches	Using data from previous models
Pros	Very basic, may require some subjectivity for interpretation	Normalized data removes issue of different scales, less subjectivity	Utility function removes subjectivity	Precise comparison, excellent for conflict resolution	Stable models, similar to sensitivity analysis	Remove subjectivity, holistic approach
Cons	Stakeholder query must be solid and well thought through	Requires less flexibility in stakeholder query	Requires functional inputs from stakeholder	Weighting variable needs to be provided, can introduce subjectivity	Stakeholder data needs to be precise, can introduce subjectivity	Slightly more complex than singular method

Table 2. Comparison of proposed approach to prior research

3 - Methodology

The goal of the methodology is to reduce the level of subjectivity introduced by the requirements definers. Literature research identified two MCDA algorithms—AHP and TOPSIS—that will be used to prioritize the stakeholder inputs. These algorithms are applied to an existing operator stakeholder data set. AHP is used for prioritization of a set of questions. TOPSIS is used for requirements de-confliction or clearer separation of the stakeholder requirements. The stakeholder questionnaire does not request a weight of importance, only ranking of priorities. AHP being applied to the first section, questions 1–3 of the questionnaire will assume equal importance. The weight variable *w* will equal 1. Results from the AHP process are utilized as a weighting variable in the TOPSIS process, since the weighting variable was not available in the case study query. The hypothesis for the approach is that using MCDA algorithms to prioritize stakeholder inputs in a multi-algorithm approach will remove the subjectivity of the requirement definer interpreting the data. Figure 4 demonstrates a flow chart of the process described, from building the decision matrix, developing basic priorities, and using inputs from AHP in the TOPSIS calculation as the weight variable.

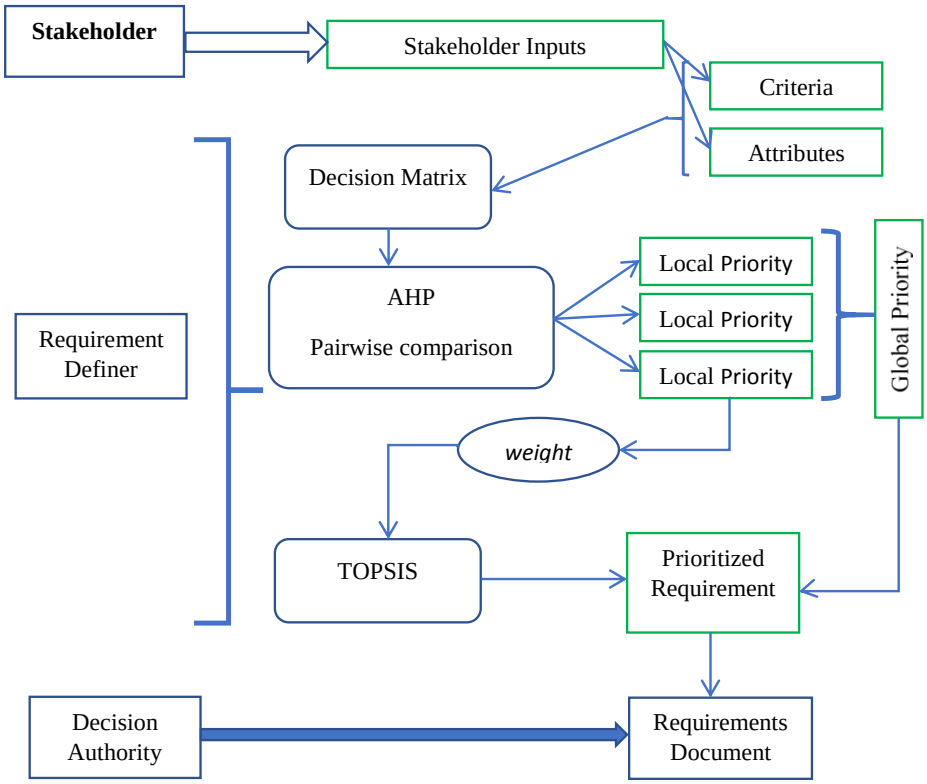

Figure 4. Flow chart of case study stakeholder priority using MCDA with AHP data in TOPSIS model

3.1 Case Study

This case study was chosen to verify the potential benefits of MCDA in a rapid approach to prioritize stakeholder needs into functional requirements. The subject of this case study is Mobile Ad Hoc Networking (MANET), an IP-based system that passes data over radio frequency. MANET systems were developed from Defense Advanced Research Projects Agency (DARPA) Packet Radio Network in 1972. MANET does not

rely on a preexisting solid architecture. It has evolved into a self-forming, self-healing mobile system that does not rely on central control or management of its network links, making it a very agile, quick-to-deploy IP layer 2 infrastructure (Cengiz, 2010). With this versatility, MANET has gained popularity in the Department of Defense and Department of Homeland Security (DHS) (Anjum, Noor., & Anisi, 2015) for high-profile security events: political conventions, major sporting events, and formal state visits. Applications include transmitting chemical, explosive sensor, position, and health telemetry for operators (Buller, Tharion, & Yokota, 2015); relaying full motion video (FMV) on robots; and communicating with first responders entering hazardous areas during response to natural and manmade disasters (Jonkey, 2016).

3.2 Data Set

Several recent stakeholder queries of federal government agency operators in the field have been collected to prioritize the operational attributes of MANET devices. These data sets are not published in academic journals but are used in government acquisition contracts or classified operations; therefore, an academic citation is not available.

The queries of operational use, such as environment (urban or rural), length of mission, and type of data being passed (FMV, biometric telemetry, sensor warning, etc.) can be translated into physical requirements of the device such as power requirements, battery life, weight, and chemistry. Environment and bandwidth are a tradeoff in terms

of frequency agility. For example, a communication channel to convey data in confined indoor and urban environments, such as shipboard or in subway tunnels, is subject to frequency effects in such an environment. Higher frequencies have different surface reflectivity characteristics than lower frequencies (Liang Chi Shen, 1987) and will have different wave propagation efficiencies. Radio waves tend to bounce off walls made of steel in ships and tunnels. Weight is a significant issue for any device to be carried by an already-overburdened operator. Space, weight, and power are common attributes that determine man-portable equipment in the field. What variables affect those specific attributes should drive requirements prioritization in communications.

3.3 General Stakeholder Query Information

The source of data used in this case study is a stakeholder query performed for a government agency that has operators in every state and territory in the United States. The stakeholder questionnaire for this case study was submitted to operational subject matter experts with MANET experience. The questionnaire was sent via email to operational units across the United States. The data were gathered in an Excel spreadsheet. There were no demographics taken of the experience level of the respondents. The data were analyzed by arithmetic mean, median, and number of responses in each attribute rank category. The process gave an overview of what was a priority to the stakeholder; however, no mathematical basis, other than averaging, was

used to determine the stakeholder-need priorities. This created subjectivity of the requirement writers interpreting the data.

The operator community familiar with MANET systems provided seventeen survey responses. The stakeholder query requested the operators rank importance of operational type variables; however, it made use of inconsistent scales for inputs in separate sections of the stakeholder query. For example, in the first section, users prioritized environment from one to four, with number one being most important. In the second section, the survey scales were inverted, with five being most important. The last two questions ask the stakeholder to rate from one to ten. These inconsistent scales make prioritizing and linear arithmetic analysis challenging for the requirements-definition team. The team of requirements definers used the basic arithmetic mean of the inputs to prioritize the stakeholder inputs, and important decisions were made from this simplistic approach. The changing of scales and failure to compensate mathematically by normalizing the data, a fundamental step in any MCDA process, resulted in the insertion of subjectivity during the interpretation of the data. The different scales for ranking makes it difficult to plot the data to determine if it is normal. However, through the data-gathering method, the data can be assumed to be a normal distribution. Aggregating with the geometric mean instead of arithmetic mean removes the issue of different scales (Saaty, 1977). Also, Saaty suggests, since the data came from stakeholders across the country, a geometric mean instead of an arithmetic mean for aggregation of data points (Saaty, 1980) is a better option for aggregating stakeholder inputs. Applying MCDA to

the data, even simply normalizing the data to compare different scales, would have improved the original requirements-definition process based on this data.

3.4 Methods: MCDA Discussion

The MCDA algorithms for the case study (AHP and TOPSIS) were chosen for their multi-dimensional aspects and the variations in the scales used for different types of operational and technical data gathered from the stakeholder questionnaire. SAW is appropriate for single-dimensional situations, but it is not appropriate for comparing the multi-dimensional aspects of data types. The flawed questionnaire structure of the case study data provides an opportunity to show the power of MCDA to recover data from a poorly formulated stakeholder query.

3.4.1 AHP

AHP structures the problem according to a hierarchy, where the top element is the end requirement's goal or overarching need. The second level represents the criteria and the third level the alternatives, as shown in Figure 4. (See Appendix A for the survey questions.) The data in level two comes from the survey's first question, which asks what environment the system is likely to be operated in. The stakeholder is asked to rate the most critical environment from one to four, one being the highest priority. Level three is from question two of the survey that prioritizes operational communication

protocol that is most likely to be used during operations. Level three will be defined as a Technical Local Priority during the AHP process.

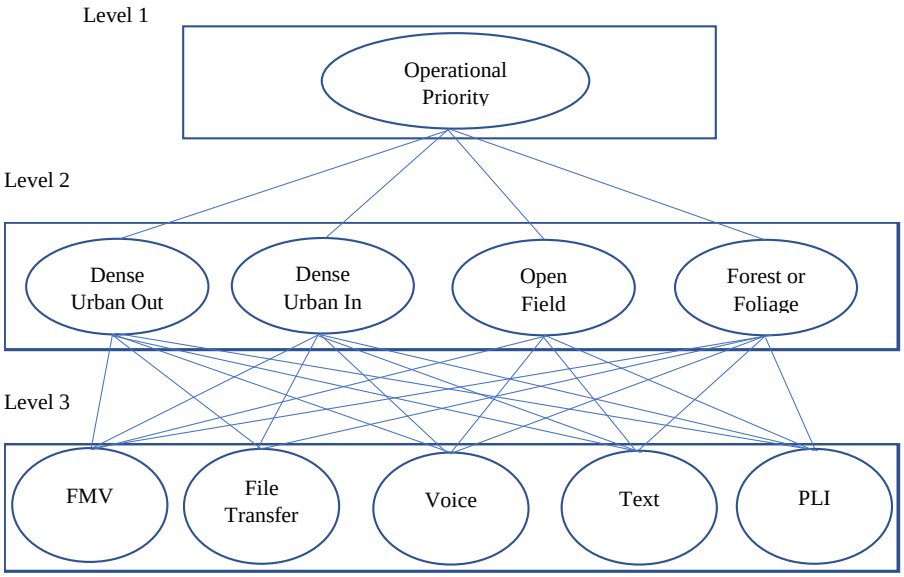

Figure 5. Traditional representation of hierarchy, using elements from case study

The case study used separate MCDA algorithms in processing the operator stakeholder input data: "Type of operational environment: Forest (dense canopy), open field, dense urban outdoors (city), dense urban indoors (high rise or subway)." This type of question can affect the rest of the field in the trade space for prioritization of needs. Other questions that may affect operational parameters include application types such as full motion video (FMV), voice communications, text-chat, and Position Location Information (PLI).

As shown in Table 3, the AHP process begins with populating the decision array with data from the stakeholder query, which was aggregated using geometric mean, as suggested for analyzing stakeholder inputs from separate locations (Saaty, 1980). Note the arithmetic mean was used by the team originally to analyze the data.

Raw Data	Geometric Mean
Dense Urban Environment - Outdoors	1.89
Dense Urban - Indoors	1.33
Open Field	2.88
Forest or Heavy Foliage	3.48

Table 3. The environmental local priority is defined from geometric mean of raw data from question 1 of the stakeholder query

Environment variables from the data were selected as a local priority group, since the type of environment dominates frequency effectiveness, range, and power consumption. The "critical application" question from the stakeholder query is used for a more technically oriented local priority group. Transmitting and receiving data such as full motion video (FMV), voice, and sensor data determine bandwidth and processing time, affecting power consumption and frequency band requirement. Power and

frequency RF technology affect critical variables such as weight, chemistry of battery, and processor speed.

Normalizing the data with formulas (2-1) and (2-2), shown in Table 4, has the global priority normalized by dividing each row by the column variable.

Environmental local priority	Dense Urban Environment -	Dense Urban - Indoors	Open Field	Forest or Heavy Foliage
Dense Urban Environment - Outdoors	1.00	1.42	0.66	0.55
Dense Urban - Indoors	0.70	1.00	0.46	0.38
Open Field	1.52	2.17	1.00	0.83
Forest or Heavy Foliage	1.83	2.61	1.21	1.00

Table 4. Populate the decision matrix and normalize

The AHP approximation method was applied by taking the sum of the rows and dividing each of the elements by the sum of the column (shown in Table 5). The approximation method is a common method that only requires additions and averages, which can easily be accomplished in Excel. Since the aggregation of the data was accomplished with the geometric mean, Saaty's suggestion for data processing should be satisfied.

Defining Environment Priority	Dense Urban Environment - Outdoors	Dense Urban - Indoors	Open Field	Forest or Heavy Foliage	approximate process (average)	
					Sum of Column	Normalized
Dense Urban- Outdoors	1.0000	1.4247	0.6580	0.5453	3.6279	0.1978
Dense Urban - Indoors	0.7019	1.0000	0.4619	0.3827	2.5465	0.1388
Open Field	1.5198	2.1652	1.0000	0.8287	5.5136	0.3006
Forest or Heavy Foliage	1.8340	2.6128	1.2068	1.0000	6.6536	0.3628
				Sum of Row	18.3416	

Table 5. Environment priority definition approximation method

Note that “Dense Urban - Indoors” is the top environmental local priority with the lowest score (0.1388), where in this section of the stakeholder query, one means top priority. The second step in our example is to define the technical local priority using the same AHP approximation method in Table 6.

Defining Technical priority	Position Location Information (PLI)	Text Chat	Voice	File transfers	Full-Motion-Video	approximate process (average)	
						Sum of Column	Normalized
Position Location Information (PLI)	1.0000	0.6440	1.2696	0.9399	1.2328	5.0863	0.1927
Text Chat	0.6440	1.0000	1.9715	1.4595	1.9144	6.9894	0.2648
Voice	1.2696	0.5072	1.0000	0.7403	0.9711	4.4882	0.1700
File transfers	0.9399	0.6852	1.3508	1.0000	1.3117	5.2876	0.2003
Full-Motion-Video	1.2328	0.5224	1.0298	0.7624	1.0000	4.5474	0.1723
					Sum of Row	26.3987	

Table 6. Defining technical local priority approximation method

Note that “Voice” is top technical local priority (0.1700).

Finally defining the global priority, we aggregate the data using formula (2-3) with pairwise comparison shown in Table 7. The top priorities are highlighted in yellow.

Defining Global Priority	Position Location Information (PLI)	Text-chat	Voice	File transfers	Full Motion Video
Dense Urban Environment - Outdoors	0.0389	0.0514	0.0336	0.0396	0.0336
Dense Urban - Indoors	0.0273	0.0361	0.0236	0.0278	0.0236
Open Field	0.0591	0.0782	0.0511	0.0601	0.0511
Forest or Heavy Foliage	0.0713	0.0943	0.0617	0.0726	0.0617

Table 7. Aggregate of local and global priorities

The results show that voice (0.0236) and full motion video (0.0236) in enclosed urban environments are the key attributes.

3.4.2 TOPSIS

Further analysis into the data can be prioritized using the AHP priorities as focal points along with physical parameter information that affects bandwidth management, frequency, encryption, and processor power. The number of channels, embedded technology, and ability to monitor information types at the command level were chosen as examples of attributes from the stakeholder query data set. In the consecutive approach for populating the decision matrix, local priority data from the FMV, voice, file transfer, Position Location Information (PLI), and text capabilities were chosen as weight variables. Bandwidth and frequency considerations are an important question in a

MANET discussion and can be directly correlated to the number-of-channels discussion. For example, bandwidth of a voice channel is significantly less than that of a high-definition full motion video stream, and PLI is a very small data burst, which may seem more valid than number of channels.

Using weights from AHP and feeding the necessary variables in the TOPSIS process is the key to our consecutive-approach concept. TOPSIS, which uses closeness to an ideal and distance from anti-ideal, is chosen for a more precise ranking process than AHP pairwise comparison.

The TOPSIS decision matrix was populated with data pulled from different parts of the query structure (see Table 8). Central Command Monitor: FMV (18D), Voice (29), Data (13C), PLI (25G). Embedded capability: FMV (18), Voice (17), Data (sensor) (13D), Text-chat (13B), PLI (25G).

Channels are based off notes (not shown in questionnaire) from a recent high profile operation discussing 24 channels. FMV number of channels is from question (9B) discussing number of video streams of 3.57, which would require four channels. Sixteen Voice channels are from operational requirement. Large Data is split into two channels. PLI and Text-chat are small data bursts and get one channel each.

TOPSIS Decision Matrix	Channels	Embedded Capability	Central Command Monitor
Full Motion Video	4	4.29	4.39
Voice	16	3.88	4.72
Data	2	3.61	3.99
PLI	1	3.00	4.00
Text-chat	1	2.74	4
max	16.00	4.29	4.72

Table 8. TOPSIS decision matrix

The *ideal normalization* for the simple data set, using formula (3-2) by dividing each element by the max in the row, shown in Table 9.

TOPSIS Ideal Normalized	Channels	Embedded Capability	Central Command Monitor
Full Motion Video	0.2244	1.0000	0.9301
Voice	1.0000	0.9044	1.0000
Data	0.1250	0.8415	0.8453
PLI	0.0625	0.6993	0.8475
Text-chat	0.0625	0.6387	0.8475

Table 9. Ideal normalized matrix with weights from AHP

The normalized elements are multiplied by the weights (3-4), as shown in Table 10 (this data comes from Table 6 in the AHP process). The weighted matrix is developed by multiplying each element by the weight, shown in Table 11.

TOPSIS Ideal Normalized	AHP weights
Full Motion Video	0.1723
Voice	0.1700
Data	0.2003
PLI	0.1927
Text-chat	0.2648

Table 10. Weights from AHP process for local priority

TOPSIS Weighted	Channels	Embedded Capability	Central Command Monitor
Full Motion Video	0.0387	0.1723	0.1602
Voice	0.1700	0.1538	0.1700
Data	0.0250	0.1685	0.1693
PLI	0.0120	0.1347	0.1633
Text-chat	0.0165	0.1691	0.2244

Table 11. TOPSIS weighted matrix

The weighting in TOPSIS is a discussion of stakeholder inputs in most cases. Using the AHP data from previous local priority calculations lessens the risk of the requirement writer inserting subjectivity. The "ideal" can be provided in three ways: (1) assumed as maximum of the data set, (2) assumed as one (or zero for anti-ideal), or (3) provided by the stakeholder (Ishizaka & Nemery, 2013). This example assumes maximum is the "ideal" and minimum is "anti-ideal" in each row.

TOPSIS Weighted	Channels	Embedded Capability	Central Command Monitor	Ideal (max row)	Anti-Ideal (min of row)
Full Motion Video	0.0387	0.1723	0.1602	0.1723	0.0387
Voice	0.1700	0.1538	0.1700	0.1700	0.1538
Data	0.0250	0.1685	0.1693	0.1693	0.0250
PLI	0.0120	0.1347	0.1633	0.1633	0.0120
Text-chat	0.0165	0.1691	0.2244	0.2244	0.0165

Table 12. Ideal and Anti-Ideal calculations

The Euclidean distance to the "ideal" formula (3-7) is calculated in Table 13, and the distance to Anti-Ideal formula (3-8) is shown in Table 14. Only four decimal places are shown for consistency in the tables.

Distance to Ideal	Channels	Embedded Capability	Central Command Monitor
Full Motion Video	0.0179	0.0000	0.0001
Voice	0.0000	0.0003	0.0000
Data	0.0208	0.0000	0.0000
PLI	0.0229	0.0008	0.0000
Text-chat	0.0432	0.0031	0.0000
$d_i^+=[(\Sigma A_j^+-A_{ij})^2]^{1/2}$	0.3236	0.0643	0.0120

Table 13. Determine Euclidean distance to ideal

Distance to Anti-Ideal	Channels	Embedded Capability	Central Command Monitor
Full Motion Video	0.0000	0.0179	0.0148
Voice	0.0003	0.0000	0.0003
Data	0.0000	0.0206	0.0208
PLI	0.0000	0.0151	0.0229
Text-chat	0.0000	0.0233	0.0432
$d_{i-}=[(\Sigma A_j-A_{ij})^2]^{1/2}$	0.0162	0.2771	0.3193

Table 14. Determine Euclidean distance from Anti-Ideal

Finally, relative closeness to the ideal solution was calculated with formula (3-9). This distance ranked the priority, as shown in Table 16. The top priority is highlighted in yellow.

Distance Coefficient Relative distance to Ideal	Channels	Embedded Capability	Central Command Monitor
C*= di+/(di++di-)	0.9522	0.1884	0.0364
Rank	3	2	1

Table 15. Calculate relative closeness to ideal solution

As we can see from the prioritized requirements in our example, monitoring from a central command center ranked highest among the question set for priorities. Being able to see full motion video, locate personnel, and monitor voice traffic by the operational commanders is critical in many large tactical and disaster situations. The Boston Marathon incident, Osama bin Laden operation, Super Bowl, and political national conventions are examples of successful operations in part because of FMV.

4 - Results

4.1 Sensitivity Analysis

Sensitivity analysis is performed to test the robustness of the data-selection process. As discussed earlier, sensitivity analysis can be performed in MCDA by parallel algorithm comparison, where MCDA processes are completed and compared on the same data for a "more stable model" (Georgiadis, Mazzuchi, & Sarkani, 2013) (Georgiadis, 2013) (Ishizaka & Nemery, 2013). The rankings from our stakeholder-query MCDA processing were compared to the rankings of the geometric mean and arithmetic mean (the method the original stakeholder query group chose) to ensure no significant deviations. Only the rankings from the AHP results were compared, because the stakeholder query has identical scales. The arithmetic mean is only valid when the scales are identical. The geometric mean can be valid when the scales differ. The environmental local priorities rankings are shown in Table 17 and technical local priorities rankings in Table 18. The top priorities are highlighted in yellow.

Sensitivity Analysis Environmental priority	Arith Mean	Rank	Geo Mean	Rank	AHP	Rank
Dense Urban - Outdoors	2.06	2	1.89	2	0.20	2
Dense Urban - Indoors	1.50	1	1.33	1	0.14	1
Open Field	3.06	3	3.06	3	0.30	3
Forest or Heavy Foliage	4.00	4	3.56	4	0.36	4

Table 16. Sensitivity-analysis example for environmental local priority

Sensitivity Analysis Technical priority	Arith Mean	Rank	Geo Mean	Rank	AHP	Rank
PLI	2.88	3	2.52	3	0.1927	3
Text-chat	4.13	5	3.91	5	0.2648	5
Voice	2.38	2	1.98	1	0.1700	1
File Transfer	3.00	4	2.68	4	0.2003	4
Full Motion Video	2.31	1	2.04	2	0.1723	2

Table 17. Sensitivity-analysis example for technical local priority

The rankings for the environmental local priorities are identical, which is to be expected with the urban indoor stakeholder inputs naming this as top priority more than

the other choices. Ranking the technical local priority using the geometric mean and MCDA data over the arithmetic mean approach produces a slight difference, but this still demonstrates a stable model.

4.2 MCDA Effectiveness

The case study is a basic example of applying MCDA algorithms to a dynamic and complex requirements-definition effort. The original team used the most basic mathematics of the arithmetic mean to prioritize the stakeholder data in the project the case study is based on. Having multiple scales and not normalizing the data for comparison between sections demanded the requirements definers insert their own relative importance of the requirements across the questions. Using MCDA allowed comparison and prioritization of requirements with the objectivity of a mathematical basis. Designing a stakeholder questionnaire for MCDA algorithms, with proper scaling techniques and a consistent process of aggregating the stakeholder data, would have significantly reduced the necessity for interpretation of the data by the requirements-writing team.

The consecutive approach in Section 3, using AHP-prioritized data from a global priority and feeding into the TOPSIS requirement for a weighting variable, may have resulted from such a poorly designed stakeholder questionnaire. However, this demonstrates the flexibility of using MCDA in a dynamic requirements-definition scenario. Although established frameworks and tools represent a holistic approach on

requirements elicitation and prioritization, the literature supports the need to consider dynamic environment and system complexity (Katina, Keating, & Jaradat, 2014).

5 - Discussion

The Departments of Defense and Homeland Security need to direct significant attention at developing requirements documents for large- and small-scale rapid-prototyping efforts. Investing the time and funding to elicit inputs from stakeholders and objectively prioritizing the data during the first two percent of the system life cycle will have significant cost, schedule, and resource advantages in future governmental development and acquisition efforts.

6 – Conclusion

This paper describes a unique approach that minimizes the insertion of subjectivity by prioritizing stakeholder priorities in a consecutive execution of MCDA algorithms. In our case study, two MCDA models (TOPSIS and AHP) were chosen for their simplicity of execution to demonstrate that the prioritization process does not need to be complex, and that the decision-making process can have a mathematical basis.

Issues with the case study questionnaire process were significant and avoidable. The questionnaire authors apparently developed the survey without fully understanding how the data would be compared and the elements prioritized between questions. The original data were processed by the government requirements-definition team using a very basic arithmetic mean, which does not account for the differing scales in the stakeholder query. This required the team to make major assumptions interpreting the data, thereby inserting subjectivity into the process.

The following are issues with the case study questionnaire process:

- not using a standard scale (e.g., 1–5 or 1–10) throughout the questionnaire
- inverting the scales from 1–4 importance in Section 1 to 5–1 importance in Section 2 and 1–10 importance for the last two questions
    - confuse the stakeholder answering the questionnaire
    - make mathematical comparison problematic

- processing the data using arithmetic mean only, where geometric mean is recommended by Saaty for questionnaires over large geographic areas
- not normalizing the data for comparison between sections
- not interviewing stakeholders but using a blanket email request, a few interviews could calibrate the email.

The goal of this research was to identify a more robust and objective method of prioritizing stakeholder inputs for writing requirements to reduce subjectivity in the requirements-definition process. Literature research demonstrated MCDA is generally known to the requirements community. The implementation is either singular (Mariza Dewi, 2014) (Salado & Nilchiani, 2015) or used in concurrent processes (Georgiadis, Mazzuchi, & Sarkani, 2013). This case study demonstrated a unique approach to interpreting data inherently prone to subjective interpretation and prioritization.

The MCDA approach improved the process by

- normalizing the data to compare between stakeholder inputs given on different scales
- establishing a decision matrix for prioritization
- using geometric mean for aggregation of data points from widely scattered stakeholders
- using an established algorithm (AHP) for pairwise comparison

- Using TOPSIS for requirement deconfliction and more substantial granularity in comparison

Recommendations for future surveys using a multi-algorithm approach to stakeholder queries would be as follows:

- Consider what algorithms might be used as questions are written
- Use standard scale of 1–9, as recommended by literature review (p. 17) (Ishizaka & Nemery, 2013)
- Interview stakeholders with standard questionnaire instead of blanket mail attempt (Davis, 2005)
- Consider Requirements Verification Traceability Matrix (RVTM) approach for traceability or simple modeling of functions (Haskins, 2011)

The first step in any MCDA algorithm is to normalize the data, which would have allowed for comparative ranking across the different scales. Choosing AHP for initial prioritization and TOPSIS for more detailed definition is more effective than an arithmetic mean or singular algorithm application.

In our example, using the previously calculated priority from AHP as the weight calculation in the TOPSIS algorithm contributes to prioritizing other requirements. Otherwise, not having the information in stakeholder inputs would require subjective interpretation by the requirements writer. The consecutive approach was not used in

actual practice on the data set; therefore, an empirical verification of improvement to the process was not made in real-world results. But the example shows a valid prioritization process that uses data from within the requirements prioritization process to feed the next stage of data calculations. This removed the subjectivity of analytic judgement in selecting a weight value for the TOPSIS calculation.

The consecutive MCDA concept may also be useful in feeding the more complex DoDAF and QFD structured processes by prioritizing, weighting, or adding mathematical value to a subjective input to the modeling. This is a topic for future research. MCDA models such as Multi-Attribute Utility Theory (MAUT) and Preference Ranking Organization METHod for Enrichment of Evaluations (Promethee) should also be studied with the same consecutive approach.

In the end, stakeholder elicitation and prioritization are key factors in writing solid requirements documents vital to the success of a system's entire life cycle. The methodology demonstrated here efficiently minimizes added subjectivity in interpreting with stakeholder inputs. This reduces the time to deploy newer technologies to the field and ensures more effective deployment. Discussions about using MCDA algorithms to ensure requirements earn their place in the defining document with objective and mathematically based justification should continue.

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Appendix A. Stakeholder Input Data

The following pages are the sanitized survey data, without names, personal information, locations, and notes.

The data is not published online. The questionnaire results are the actual data points that were used by the requirements-writing team.

Question Number	Question	Sub Question																	Average	Median
1A	Please place in order from 1 to 4 the most critical environments for EZW (MANET) mission support (1 being the most critical).	Dense Urban Environment - Outdoors	1	1	2	1	1	3	2	2	2	2	2	2	3	2	3	4	2.06	2.00
1B		Dense Urban - Indoors	1	3	1	2	2	1	1	1	1	1	1	1	1	1	2	4	1.50	1.00
1C		Open Field	5	2	3	3	3	4	4	4	3	3	3	3	2	4	1	2	3.06	3.00
1D		Forest or Heavy Foliage	4	4	4	4	4	2	3	3	4	4	4	4	4	3	4	2	3.56	4.00
2A	Please place in order from 1 to 5 the most critical application types for EZW (MANET) mission support (1 being the most critical).	Shared Position Location Information (PLI) (e.g. ATAK)	1	3	4	1	3	3	3	4	5	3	3	3	5	1	1	3	2.88	3.00
2B		Text Chat	2	5	5	5	5	5	4	5	3	4	5	5	4	2	5	2	4.13	5.00
2C		Voice	1	1	3	3	4	1	5	2	2	1	1	1	2	5	2	4	2.38	2.00
2D		File transfers	1	4	1	2	1	4	2	3	4	4	4	4	3	3	4	4	3.00	3.50
2E		Full-Motion-Video	3	2	2	4	2	2	1	1	1	2	2	2	1	4	3	5	2.31	2.00
																			Average	Median
3A	Please write in the maximum acceptable delay (in seconds) for each application/traffic type when being transmitted over the EZQ MANET. Write INDEF if delay is not a concern (for example, if video is only used for intelligence gathering vice being immediately actionable).	Shared Position Location Information (PLI) (e.g. ATAK)	30	15	30	INDEF	3	10	10	5	30	5	10	1	INDEF	4	1	2	11.14	7.50
3B		Text Chat	30	15	60	INDEF	3	10	2	5	10	2	don't wan	1	INDEF	2	20	INDEF	13.33	7.50
3C		Voice	0	0	10	1	1	5	0	1	5	0	0	1	1	1	1	2	1.81	1.00
3D		File transfers	30	30	0	1	indef	60	5	5	30	15	15	10	1	5	INDEF	2	14.93	7.50
3E		Full-Motion-Video	60	2	2	INDEF	1	5	10	5	5	0	0	5	1	3	1	3	6.87	3.00
																			Average	Median

																			Average	n
4	For voice traffic over the MANET, select the minimum critical level of voice quality for mission support. Voice quality must meet:	1. Bad: Difficult to hear in most situations (static and low volume) 2. Poor: Some static and volume issues, but easily understood in quiet settings 3. Fair: Quality issues do not impede reception of message in most situation 4. Excellent: Received voice is	3	3	2	3	3	2	3	4	3	4		4	4	3	3	3	3.13	3.00
																			Average	Median
5	What is the maximum acceptable time between location updates for each user to push their PLI (in other words, how often should a user device push location updates to the network). This is often set high for slow moving sources (such as a user walking) to conserve bandwidth, or set low for fast moving	Maximum PLI update interval in seconds		15	60	10	15	30	60	15	30	10	10	30	10	*300	30	10	23.93	15.00
																			Average	Median
6A	Please write in the maximum expected distance between two EZW devices in each environment.	Dense Urban Environment	5	0.2	0.25	1	1	1	1	0.5	1	0.06	1	0.5	1	0.25	0.5	0.5	0.92	0.75
6B		Open Field	25	0.5	1	3	5	3	3	1	2	LOS	1	1	1	3	1	2	3.50	2.00
6C		Forrest or Heavy Foliage	10	0.2	0.25	3	3	2	1	0.5	1	0.06	0.25	0.5	0.25	2	1	1	1.63	1.00
7A	Please write in the maximum expected mission distance in each environment (mission distance at its widest point).	Dense Urban Environment	25	5	3	2	1	2	1	10	1	10	1	50	1	10	2	0.5	7.78	2.00
7B		Open Field	25	10	3	3	3	3	1	10	2	10	1	10	1	2	10	2	6.00	3.00
7C		Forest or Heavy Foliage	25	5	0.5	5	2	2	1	10	1	10	0.25	10	1	5	1	1	4.98	2.00
																			Average	Median
8A	Please write in the minimum required and ideal runtime on battery for each EZW device.	Minimum	15	4	8	12	8	72	8	3	8	12	12	8	8	3	8	6	12.19	8.00
8B		Ideal	20	12	24	24	12	80	12	8	12	24	24	72	12	12	16	8	23.25	14.00
																			Average	Median
9A	Please write the minimum required and ideal number of Full Motion Video (FMV) streams on the MANET at any single time for mission support.	Minimum	3	2	2	1	1	3	1	1	6	3	1	1	1	3	1	1	1.94	1.00
9B		Ideal	5	5	4	1	2	12	3	2	8	4	1	5	2	25	3	2	5.25	3.50

																			Average	Median
16	For streaming video over the MANET, select the minimum critical level of video quality for mission support. Video quality must meet:	Low quality: Frame rate: 1-10 fps Resolution: < 320x480 (VHS) Medium quality: Frame rate: 15 fps Resolution: 720x480 (DVD High Quality: Frame rate: 30 fps Resolution: > 1280 x 720 (HD) Very High Quality:Frame rate: 30 fps	3	2	3	2	3	2	2	2	3	4	3	2	3	2	2	2	2.50	2.00
																			Average	Median
11A	Please write the maximum acceptable weight and size of the body worn EZW device	Maximum Weight (pounds)	3	5	1	10	5	5	5	16	2		2.5	3	*30	10	5	8	5.75	5.00
11B		Maximum Size	8-10 TALL X 4-5 WIDE X 3-5 THICK WITHOUT	size of Harris Unity	4x1.5x3.5 or 21cu in	8"x8"x2" ?	12 in X 12 in	15 inches	12X12	size of Unity/ motorola handheld	4"X3"		1800 RADIO	3" x 8" x 4" W x H x L	2FT	5 x 5 x 5	3 x 3 x 3	less than 12 inches		
Section 2. Rate the Importance of MANET system capabilities and human factors **1 Not required. No value added to mission.** **2 No effect on mission but provides value added.** **3 Enhances mission.** **4 Greatly enhances mission.** **5 Mission critical.** **NIA Please enter NA if you are unsure.**																				
This section can be used to weight criteria for the demonstration																			Average	Median
12	Network Performance	Network performance - the ability to support a minimum of 30 simultaneous users and utilizing a variety of network services	5	4	4	3	5	4	3	4	4	4	3	4	4		5	4	4.00	4.00
13	Basic network services	Basic network services					5												5.00	5.00
13A		a. Support for Web browsing without timeouts or delays that impact page	3	5	3	5	3	3	4	2	5	4	4	2	4		4	4	3.67	4.00
13B		b. Support for near real-time chat	4	3	2	3	4	2	3	3	3	2	1	4	3		5	2	2.93	3.00
13C		c. Support for large file transfers without delay caused by	5	3	4	4	2	3	4	5	4	3	3	4	4		4	4	3.73	4.00
13D		d. Support for sensor data (biometric, biochemical, etc.) transmission in near real-time	5	4	2	4	4	3	3	5	4	5	4	5	4		1	5	3.87	4.00
13E		e. Remote robot control over the MANET with streaming video	5	3	2	2	NA	NA	4	3	4	4	4	5	3		2	4	3.46	4.00
14	Range	14. Range for connectivity between two MANET devices	4		3	5	4	4	5	5	4	5	4	4	5		5	4	4.36	4.00
15		15. Ability to extend the range of the network through multiple hops in a daisy chain configuration (also known as string-of-pearls)	5	5	5	5	5	4	5	5	4	5	4	4	5		5	4	4.67	5.00
16	Out-of-net notification	Feedback or indication that the MANET device is in-net or out-of-net other than loss of connectivity		5	4		5	5	5	5	4		5	5	4		5	4	4.67	5.00
16A		Visual indication that the radio is in-net or out-of-net	3	5	3	4	5	3	5	5	4	4	5	5	4		5	4	4.27	4.00
16B		Audible indication that the radio is in-net or out-of-net	5	4	2	4	5	3	3	5	4	3	5	5	4		2	4	3.87	4.00

17	Voice	17. Voice Communication as an embedded feature of the MANET	5	4	3	4	4	2	3	4	4	4	5	5	3		5	5	4.00	4.00
18	Full Motion Video	Ability to support streaming full motion video (FMV)	2.5				4		5	5	5				5				4.42	5.00
18A		a. Near real-time streaming FMV over the MANET (Near real-time is immediately actionable video vice stored video for intelligence gathering)	2.5	5	3	3	4	4	5	5	4	5	5	5	4	3	4	4	4.09	4.00
18B		b. Support for multiple streams of FMV	2.5	4	3	2	2	3	4	3	5	2	5	2	4	2	2	4	3.09	3.00
18C		c. Support for high frame rate (30+fps) or high resolution (720p+) FMV	2.5	4	4	2	3	3	4	3	5	4	5	4	4	1	3	4	3.47	4.00
18D		d. A central location or command has access to view streaming video	4	5	4	4	5	5	4	5	5	4	5	4	4	3	5	5	4.44	4.50
18E		e. All users on the MANET have access to view streaming video	2.5	3	2	3	4	2	4	5	5	2	1	3	4	2	4	5	3.22	3.00
19	Antennas	19. Antennas should be removable/replaceable	5	4	4.5	4	5	4	5	2	4	4	4	3	3	4		4	3.97	4.00
20	EMP/HEMP	20. High altitude electromagnetic pulse (EMP/HEMP) protection	2.5	2.5	1	2	2	4	3	2	4	2	1	1	3	3	2	2	2.31	2.00
21	Encryption	21. Encryption Level and Classification (minimum FIPS 140-2)	3	4	2	4	3	5	3	1	4	2	5	2	4	3	5	3	3.31	3.00
22	Frequency bands	22. Support for frequency ranges other than the common public 2.4-2.5 GHz	5	5	4	4	4	3	3	5	4	3	5	4	4	5		5	4.20	4.00
22A		a. Modular or swappable radios in the device to support multiple frequency bands on the fly	2.5	3	2	4	4	4	3	3	4	3	5	5	3	4	5	5	3.72	4.00
22B		b. Support for DoD specific	4	4	4	3	4	4	3	4	4	3	5	5	3	4	4	5	3.94	4.00
22C		c. Ability to change frequencies/channels during a mission	5		2	3	4	4	3	3	4		5	5	4	2	5	5	3.86	4.00
22D		d. Maximum amount of time a frequency change should take during a mission (Please circle best choice in minutes)	2	3	4	3	1		5	2	1	3	1	5	1	3	3	4	2.73	3.00
23	RF jamming	Resistant to RF jamming techniques	3.5	4	2	5	4	1	5	4	4	5	5	2	3	4	3	4	3.66	4.00
24	SWAP	Low size and weight as worn on the body with ancillaries	5	5	3	5	4	1	4	5	4	5+	5	5	4	4	5	3	4.13	4.00
25	Features of the MANET	25. Embedded features of the MANET device other than as data				4	4	1	4		4			2	4				3.29	4.00
25A		a. Video encoding in the device	3.5	3	2	3	4	1	4	4	4	1	5	3	4	2	3	4	3.16	3.25
25B		b. Integrated computer with OS (for hosting mapping tools, custom applications,	4.5	2	1	4	3	1	4	3	4	1	5	4	3	3	3	3	3.03	3.00
25C		c. Ability to tether existing voice radios, and extend that voice through the network to other tethered voice radios	4	3	1	3	4	1	4	4	4	2	5	4	4	4	5	4	3.50	4.00
25D		d. Serial interfaces (for sensors, data input, or control signals)	5	4	2	4	5	1	4	4	4	3	1	5	4	4	5	4	3.69	4.00
25E		e. USB interfaces (for sensors and accessories)	5	4	2	4	5	1	4	4	4	3	1	5	4	5	5	4	3.75	4.00
25F		f. Direct WiFi (802.11) access to the backbone MANET (vice attaching an access point via Ethernet)	5	4	2	4.5	5	1	4	3	4	4	5	3	5	5	3	4	3.84	4.00
25G		g. Position Location Information (PLI) or Situation Awareness (SA) as a feature of the radio (radio transmits its location and heading onto the network	4	5	3	4	5	2	4	5	4	3	5	5	3	5	5	4	4.13	4.00
25H		h. Ethernet ports for connection of Ethernet enabled devices	5		4		5	1	4	4	4	3	1	4	4	4	3	4	3.57	4.00
25I		i. How many ports are required per radio (Please circle best choice)	1.5	2	2	3	2	3	2	1	2	2	2	5	2	3	2	2	2.28	2.00

26	Intrusion protection (environmental)	26. Intrusion protection from water and dust (minimum IP66)			5	5	5	4	4	5	4	5			5	5		4	4.64	5.00
26A		a. Submersible to more than 1 m in water (IP68)	3	5	4	3	4	4	4	2	4	5	5	4	4	5	5	4	4.06	4.00
27	Batteries	27. Device should be battery powered					5		5	5	5				5			5	5.00	5.00
27A		a. Snap-on/Snap-off battery in a similar style to MBITR or PRC-152 is acceptable	5	4	3	5	5	4	3	5	4		5	1	4	NA	5	5	4.14	4.50
27B		b. Internal batteries, or proprietary form factors not used with other radios, is acceptable	2	2	3	3	4	3	3	2	4		1	5	4	NA	5	4	3.21	3.00
27C		c. Power interface to accept standard military and commercial batteries is acceptable	5	4	3	3	4	4	4	4	5		5	3	4	5	5	4	4.13	4.00
28	HMI	28. Human Factors and Human-Machine Interface (Snag hazards, button locations,	5	5	3	4	4	4	4	3	4		3	5	4	NA	3	4	3.93	4.00
Section 3. For each item below, answer each question on a scale of 1 to 10:																				
																			Average	**Median**
29	29. In order to support missions in challenging RF environments, tradeoffs from the MANET may be necessary. On a scale of 1 to 10, rate what is the most critical information transmitted over the MANET for mission success when operating at the maximum expected distance (Data	1 = Voice is most critical if weighed against the impact to data 5 = Both are equally important 10 = Data is most critical if weighed against the impact to Voice	5	2	10	8	8	3	5	5	8	1.5	5	5	4	7	5	3	5.28	5.00
																			Average	**Median**
30	30. In order to support missions in challenging RF environments, tradeoffs from the MANET may be necessary. On a scale of 1 to 10, select the tradeoff with the	1 = Decrease the Range (Distance) to improve Bandwidth (Throughput) 10 = Decreasing the Bandwidth (Throughput) to improve Range (Distance)	4	6	6	5	7	5	5	6	3	7	7	7	5	6	7	7	5.81	6.00
	Changes made	If a range was provided, the maximum value was used for the calculations.																		
		operators such as >, <, ±, were removed																		
		If the answer gave two numbers such as 1\2, 3\4, then it was converted to a N.5. 1\2 = 1.5, 2\3 = 2.5, etc.																		
		"Immediate" was changed to 0 to represent no delay in voice																		

Appendix B. Excel working tables for different normalization techniques

AHP

Defining the Environmental properties using both the approximate and geometric mean processes for normalizing the data. As we can see the results of each technique are very close, although not identical.

Defining Environment Priority	Dense Urban Environment Outdoors	Dense Urban - Indoors	Open Field	Forest or Heavy Foliage		approximate process (average)		geometric mean process (geometric mean normalized)	
						AVG	Normalized	GEOM	Normalized
Dense Urban Environment -	1.0000	1.4247	0.6580	0.5453		3.6279	0.1978	0.8455	0.1978
Dense Urban - Indoors	0.7019	1.0000	0.4619	0.3827		2.5465	0.1388	0.5935	0.1388
Open Field	1.5198	2.1652	1.0000	0.8287		5.5136	0.3006	1.2850	0.3006
Forest or Heavy Foliage	1.8340	2.6128	1.2068	1.0000		6.6536	0.3628	1.5507	0.3628
					Sum of Row	18.3416		4.2748	

Defining Technical priority	Shared Position Location Information (PLI) (e.g. ATAK)	Text Chat	Voice	File transfers	Full-Motion-Video	approximate process (average)		geometric mean process (geometric mean normalized)	
						AVG	Normalized	GEOM	Normalized
Shared Position Location Information (PLI) (e.g.	1.0000	0.6440	1.2696	0.9399	1.2328	5.0863	0.1927	0.9892	0.1965
Text Chat	0.6440	1.0000	1.9715	1.4595	1.9144	6.9894	0.2648	1.2882	0.2559
Voice	1.2696	0.5072	1.0000	0.7403	0.9711	4.4882	0.1700	0.8572	0.1703
File transfers	0.9399	0.6852	1.3508	1.0000	1.3117	5.2876	0.2003	1.0267	0.2040
Full-Motion-Video	1.2328	0.5224	1.0298	0.7624	1.0000	4.5474	0.1723	0.8725	0.1733
					Sum of Row	26.3987		5.0339	

TOPSIS

The two normalization processes for TOPSIS discussed are the Distributive and the Ideal normalization. There are differences in the processes, but the results are the same. The Ideal normalization is demonstrated in the body of the paper.

Distributive Normalization: start with decision matrix and then square the elements in the matrix

Decision Matrix	Channels	imbedded capability	Central command monitor
Full Motion Video	3.59	4.29	4.39
Voice	16.00	3.88	4.72
Data	2.00	3.61	3.99
PLI	1.00	3.00	4.00
text	1.00	2.74	4.00
max	16.00	4.29	4.72

The elements are squared, and the sum of the squares is determined, Σx_{ij}^2

The bottom row is the square root of the sum of the squared elements, $(\Sigma x_{ij}^2)^{1/2}$

normalize matrix	Channels	imbedded capability	Central command monitor
Full Motion Video	12.8881	18.4041	19.2721
Voice	256.0000	15.0544	22.2784
Data	4.0000	13.0321	15.9201
PLI	1.0000	9.0000	16.0000
text	1.0000	7.5076	16.0000
Σx_{ij}^{2}	274.8881	62.9982	89.4706
$(\Sigma x_{ij}^{2})^{1/2}$	16.5797	7.9371	9.4589

The normalized elements are multiplied by the weights. The Ideal solution is the maximum element in the column, and the anti-ideal is the minimum.

Weighted elements	Channels	imbedded capability	Central command monitor		Weights from AHP
Full Motion Video	0.0373	0.0931	0.0799		0.1723
Voice	0.1641	0.0831	0.0848		0.1700
Data	0.0242	0.0911	0.0845		0.2003
PLI	0.0116	0.0728	0.0815		0.1927
text	0.0160	0.0914	0.1120		0.2648
Find Ideal Solution	0.1641	0.0931	0.1120		
find negative ideal soltuion	0.0116	0.0728	0.0799		

Calculating distance to ideal (see Table 14), anti-ideal (Table 15) and coefficient of closeness (Table 16) are the same in both instances.