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Applying Multi-Criteria Decision-Making to the Technology Investment Decision-Making Process

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Abstract

Department of Defense (DoD) activities are pursuing innovative solutions to communication and electromagnetic warfare challenges, especially for contested electromagnetic (EM) environments. Candidate technologies suitable for this environment are in a state of near-constant change. Current approaches for selecting these technologies for investment of limited resources can be inconsistent and based on subjective assessments and biased decision-making processes. Decision-makers require a structured and objective approach to technology selection and investment decision-making. Multi-Criteria Decision-Making (MCDM) methods provide this structured, consistent, and repeatable approach (Georgiadis et al., 2013).

To improve return on investment (ROI) of increasingly limited resources, candidate technologies and associated enabling products must be objectively evaluated against relevant measurable criteria. Implementing MCDM methods as part of the technology investment decision-making process increases consistency, objectivity, and repeatability of the process, leading to increased ROI of limited resources.

To research applicability and value of MCDM to technology investment decisions, this paper focuses on technology evaluation within a single domain, Private Cellular Networks, for use in U.S. and mission partner tactical operations. A decision framework for Private Cellular Network technology investment decision-making is presented to serve as a model for larger and more complex technology investment decisions using MCDM methods.

Introduction

Organizations within the DoD are engaged in capability modernization initiatives where potential candidate technologies and their enabling products are in a state of near-constant change. These technologies span multiple technical and operational domains to include wireless and cellular communications, Electro-Optical (EO), Free Space Optics (FSO), Low Earth Orbit (LEO) satellite communications, and other means of electronic information transmission, receipt, processing, and storage. In this highly complex, dynamic environment, often the approach to identifying, evaluating, and selecting technologies for investment of scarce resources is inconsistent and largely based on subjective assessments and decision-making processes. In this environment characterized by rapid technology evolution and capability enhancement, decision-makers require a structured and objective approach to technology selection and resource investment decision-making.

To improve return on investment (ROI) of limited resources, candidate technologies and associated enabling products should be objectively evaluated against relevant measurable criteria. A structured decision-making model enables development of relevant criteria against which candidate technologies and enabling products can be assessed. Implementing multi-criteria decision-making (MCDM) methods as part of the technology investment decision-making process increases consistency, objectivity, and repeatability of the process leading to increased ROI of limited resources.

Research Issue Statement

Current approaches to identifying, evaluating, and selecting emerging technologies for investment of scarce resources can be inconsistent and based largely on subjective assessments and unstructured decision-making processes. To ensure that technology investment decisions are properly aligned to organizational goals and objectives, decision-makers require a structured and objective approach to technology selection and investment decision-making.

Research Questions

The research introduced in this paper focuses on answering the following questions regarding technology investment decision-making:

- Can appropriate technology investment decision criteria be identified?
- What technology investment decision criteria can be appropriately quantified?
- How can technology investment decision criteria be quantified?
- Can statistical analysis be used to accurately develop weighted decision criteria?
- Can the technology investment decision-making process be made more objective, consistent, and repeatable?

Multi-Criteria Decision-Making

Multi-Criteria Decision-Making (MCDM) is a method to help decide when there are multiple alternatives, with each alternative having several characteristics and attributes (Yoon & Hwang, 1995). MCDM methods are sufficiently flexible for application to simple decision-making scenarios with binary decision alternatives as well as complex, multi-criteria, multi-alternative scenarios. MCDM is well-suited for technology investment decisions because those decisions routinely include criteria that must be identified, weighted, and compared to generate priority rankings for each decision alternative.

Methodology

The five phases in the proposed research methodology presented in this paper are briefly described in the following paragraphs and shown in Figure 1.

Phase 1, Preliminary Investigation, focuses on capability gaps identified by a Capability-Based Assessment (CBA) or similar activity. Phase 1 produces the problem statement and research objectives. It also produces the research questions whose answers help mitigate or close gaps in technology investment decision-making processes.

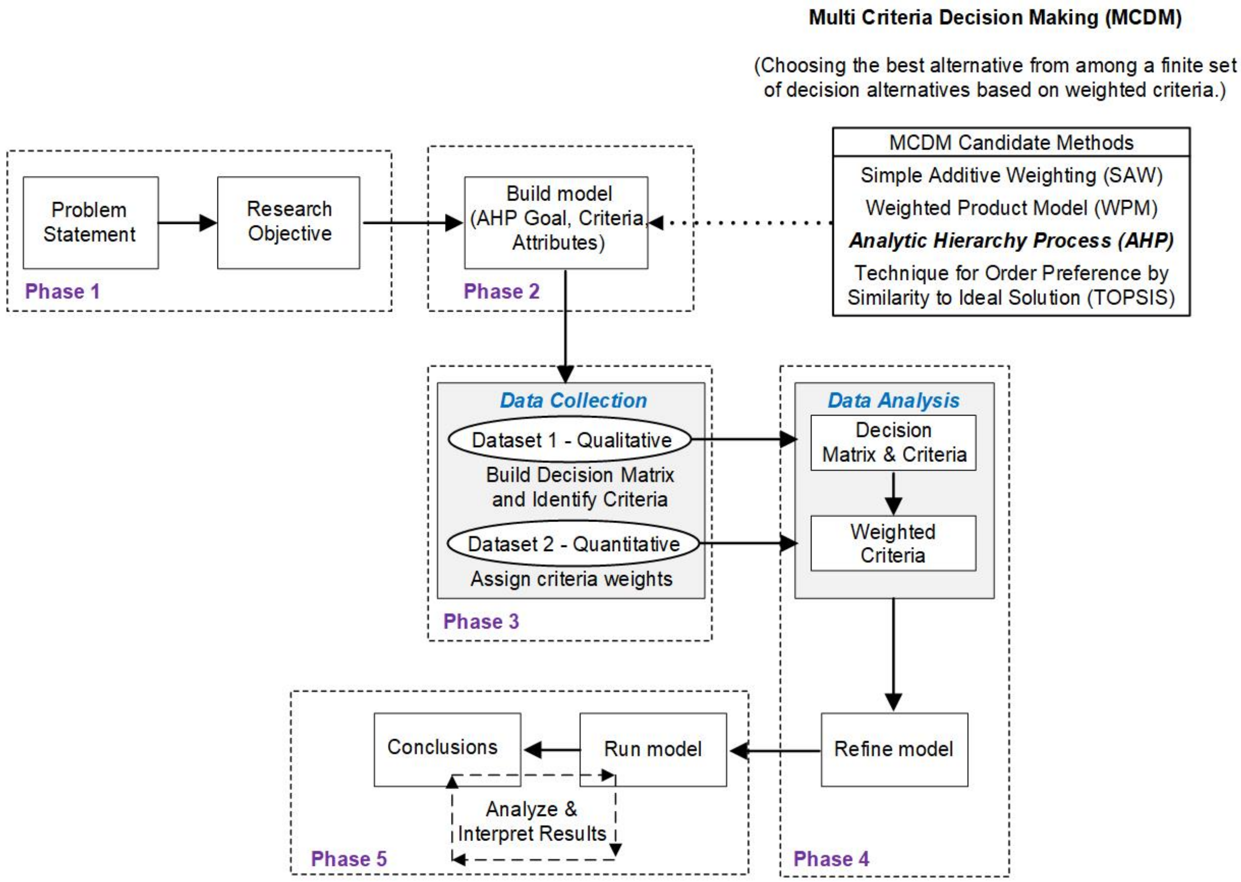

Figure 1. Methodology Map

Phase 2, Initial Model Development, focuses on the problem statement, research objectives, and research questions formulated during Phase 1. Outputs from Phase 1 research are used to build the initial version of the MCDM model to include identifying the Goal, Criteria, and Criteria Attribute components of the MCDM model. The decision model goal is the selection of the most appropriate technology and enabling a product consistent with organizational objectives, areas of greatest need, and highest possible ROI.

During Phase 2, several candidate MCDM methods were considered for applicability to the technology investment decision-making environment. Analytic Hierarchy Process (AHP) was selected as an appropriate MCDM method for the technology investment decision-making environment because of its ability to consider a set of evaluation criteria and a set of alternative options, from which the most appropriate decision can be made. Another factor in selecting AHP is that it is a “fast and understandable method for people who are not familiar with multi-criteria decision support methods” (Tscheikner-Gratl et al., 2017).

Phase 3, Data Collection, focuses on qualitative and quantitative data relevant to the decision environment. Qualitative and quantitative data on candidate technologies and enabling products must be collected to support development of the decision matrix, decision criteria, decision weights, and decision alternatives used in the model.

Phase 4, Data Analysis and Model Refinement, focuses on analyzing collected data to refine model components and relationships proposed in the initial model.

Phase 5, Model Run and Results, is where the decision model is run using as input the qualitative and quantitative data analyzed in Phase 4. The analyzed data is input into the model to calculate decision criteria weights using AHP. Decision criteria weights are tested for consistency using Saaty's Random Index before use as the basis for generating a ranked order of decision alternatives (Saaty, 1980).

Multi-Criteria Decision-Making Methods

Several MCDM methods exist and have been applied to a wide range of decision-making scenarios. Each MCDM method has strengths and weaknesses relative to the decision-making environment for which its application is considered.

A short description of frequently used MCDM methods is provided in the following paragraphs.

- Weighted Sum Model (WSM): WSM is designed for single-dimensional decision-making problems. WSM is a value-measurement MCDM method with criteria assigned a weight to represent relative importance for comparison to other decision criteria (Tscheikner-Gratl et al., 2017). Simple in design and application, WSM is not well-suited for multi-dimensional decision-making problems such as technology investment decisions because of its limitations for addressing multiple decision criteria scenarios (Triantaphyllou et al., 1998).
- Weighted Product Model (WPM): WPM is like WSM but uses multiplication rather than addition to calculate the sum for each decision alternative. WPM is suitable for single dimensional decision-making problems where the solution sought is that with the largest value relative to the other candidate solutions. WPM is not well-suited for multi-dimensional decision-making problems such as technology investment decisions because of its limitations for addressing multiple decision criteria scenarios (Triantaphyllou et al., 1998).
- Simple Additive Weighting (SAW): SAW is based on simple addition of scores assigned to different criteria associated with accomplishing the goal of the decision-making process. Though SAW calculations are simple and do not require complex computer algorithms, the results produced with SAW do not always realistically reflect the complexity of the multi-criteria technology investment decision-making process (Adriyendi, 2015).
- Technique for Order Preference by Similarity to Ideal Solution (TOPSIS): TOPSIS is an MCDM method based on the concept that the alternative chosen should be the one having the shortest distance from the ideal solution and furthest distance from the negative ideal solution. The ideal and negative ideal solutions are unique to the decision that must be made and can be based on quantitative or qualitative factors. TOPSIS is a calculation-intensive MCDM method whose proper application is dependent on accurate identification of ideal and negative ideal solutions (Gavade, 2014).
- Analytic Hierarchy Process (AHP): AHP decomposes complex MCDM problems into hierarchical relationships between decision criteria and their attributes. AHP allows the decision-maker to view the decision in terms of a hierarchy of criteria. AHP is a value-measurement MCDM method with criteria assigned a weight to represent its relative importance for comparison to other decision criteria (Tscheikner-Gratl et al., 2017). AHP considers qualitative and quantitative criteria when building decision criteria and developing criteria weights. AHP's framework for establishing relationships between goals, criteria, criteria attributes, and decision alternative weights makes it well-suited to the technology investment decision-making process.
- The MCDM methods briefly described previously share common components for intent, design, and application discussed in the following section.

Multi-Criteria Decision-Making Components

Though different in design and application to decision-making scenarios, MCDM methods share several common characteristics, as described here (Mocenni, 2018):

- The decision context must be identified. The decision that must be made, the decision-maker, and key contributors are identified as the first step in the MCDM process (Department for Communities and Local Government, 2009).
- Decision options are identified before being assessed or evaluated for suitability. Decision options are eventually assessed against weighted decision criteria as the MCDM process is applied. Decision options can be the selection of the most appropriate solution or elimination of one or more candidate solutions from further evaluation and consideration.
- Independent decision criteria are identified. The decision criteria should be independent of each other to avoid introducing inconsistencies in the criteria weighting results. The relevance of the criteria to each identified option is also identified. The decision criteria are those factors against which potential solutions are evaluated for acceptance or rejection (Vargas, 2010).
- Weights are developed for each of the decision criteria to establish the relative importance of the criteria when evaluated against each other. The weights can be developed through qualitative methods, quantitative methods, or a combination of both methods. Decision criteria weights are applied during the evaluation of potential solutions to create a rank order of all evaluated solutions. Subject Matter Expert input is a critical component of developing credible criteria weights.
- Each potential solution, or decision alternative, is assessed against criteria and assigned a value using criteria weights.
- Options are rank ordered to help the decision-maker either select one option or eliminate one or more options from further consideration.

Figure 2 shows MCDM components and their relationships in helping the decision-maker reach an evidence-based selection from available alternatives.

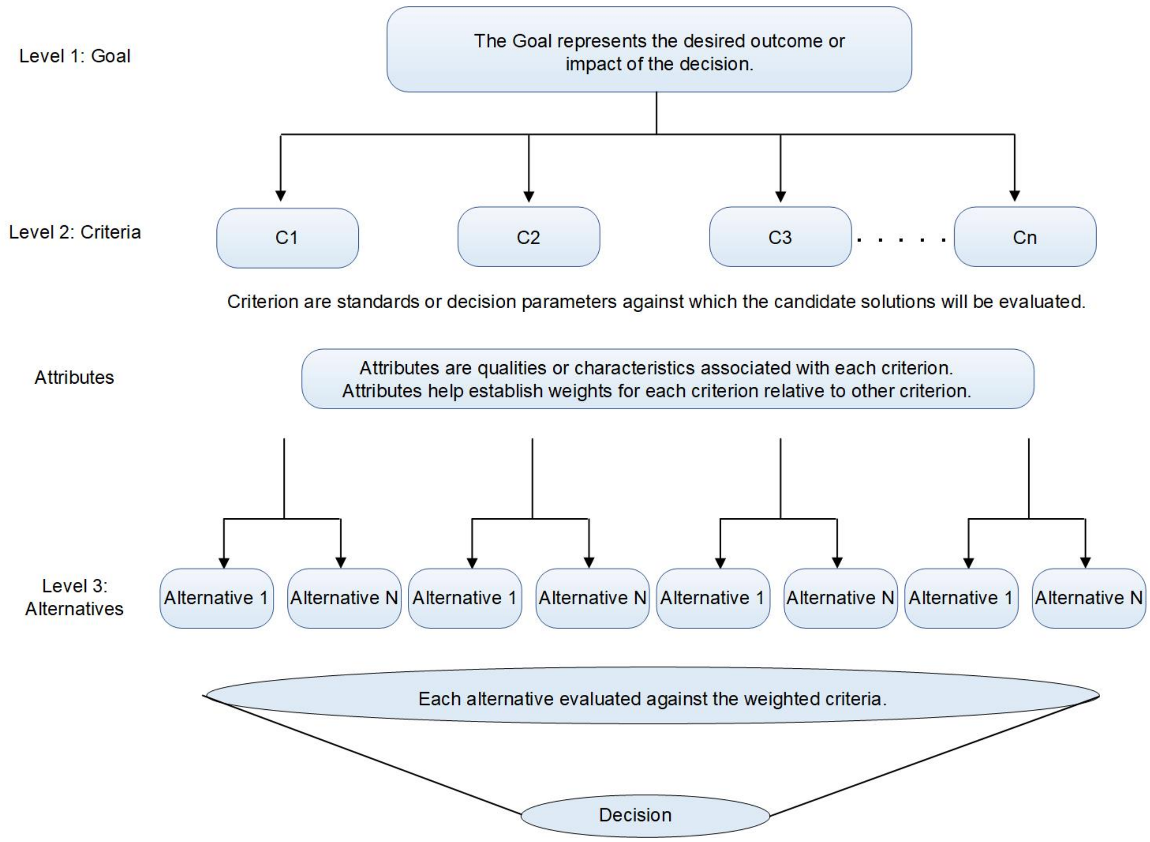

Figure 2. MCDM Components, Levels, and Relationships

Applying Multi-Criteria Decision-Making Methods to Decision-Making Processes

Since MCDM methods incorporate computational tools to weight and assess decision options, they are well-suited for application to complex, multi-dimensional decision-making scenarios such as technology investment decision-making.

The goal of a decision-making process is to provide the decision-maker with the ability to investigate the future and to make the best possible decision based on past and present information and future predictions (Georgiadis et al., 2013). MCDM methods accomplish this goal by considering quantitative data, qualitative data, and expert judgment to assess and rank decision options from which the decision-maker can select the most appropriate option.

MCDM methods integrate quantitative and qualitative data analysis as components of the decision-making process. MCDM methods align closely, and are appropriately applied, to a decision-making process with the following characteristics (Foote, 2010):

- Decision objectives are identified. A decision results from comparing one or more alternatives against one or more criteria relevant to the decision-making environment.
- Decision options available to the decision-maker are identified.
- Decision criteria upon which the decision will be made are identified. The decision criteria are independent of one another.
- Decision criteria weights are developed for use in evaluating and comparing decision alternatives. The weights are developed using a combination of quantitative and quantitative data sources. Expert judgment provided by subject matter experts is a critical success factor in determining a criterion’s weight relative to other decision

criterion. Qualitative subject matter expert judgments are transformed into numerical values (quantitative data) using a pairwise comparison scale (Saaty, 1980).

- Decision options are evaluated against the weighted criteria. Each option is evaluated against the weighted decision criteria independent of other decision options.
- Decision options are rank ordered to help the decision-maker either choose the most appropriate alternative or to eliminate one or more alternatives from further consideration.
- A decision is made by selecting the most appropriate alternative from among all ranked alternatives.

By integrating quantitative and qualitative data analysis into the decision-making process, MCDM methods strengthen the technology investment decision-making process by

- Removing subjectivity in decision criteria weight assignments.
- Improving documentation and communication of all components of the decision-making process. MCDM methods facilitate documentation and communication between the decision-maker and stakeholders impacted by the decision.
- Calculating and analyzing the decision criteria weights and alternative rankings to generate an audit trail for future analysis or refinement as appropriate.
- Providing a platform for sensitivity analysis and "What-If" studies

The technology investment decision-making process is a multi-criteria environment where MCDM methods can be applied to identify decision goals, identify decision criteria, develop decision criteria weights, and assess available options against the weighted criteria to help the decision-maker select the most appropriate option.

The next section of the paper presents a case study for applying a selected MCDM method, Analytic Hierarchy Process, to the decision-making process for investing resources to pursue Private Cellular Network Technology and enabling products.

Case Study: Applying Analytic Hierarchy Process to Investment Decision-Making for Private Cellular Network Technology

AHP is a structured MCDM method well-suited to organize and analyze complex decisions. AHP uses qualitative and quantitative data as critical components of the decision-making process. In AHP, decision alternatives are identified along with criteria relevant to each decision alternative. AHP reduces complex decisions to a series of pairwise comparisons, which allow the decision-maker to establish priorities to support the decision-making process. AHP establishes weights for decision criteria, which are then applied to evaluate and prioritize decision alternatives (Mocenni, 2018).

Because of its ability to create a decision hierarchy identifying the decision objective, decision criteria, decision criteria weights, and decision alternatives, AHP is well-suited to technology investment decision-making processes. Relevant qualitative and quantitative data can be collected from technical research, subject matter expert judgment, formal testing, or capability demonstration events.

Figure 3 shows the MCDM components and levels presented in Figure 2 tailored to the decision-making process for determining appropriateness of Private Cellular Network technology as an investment initiative.

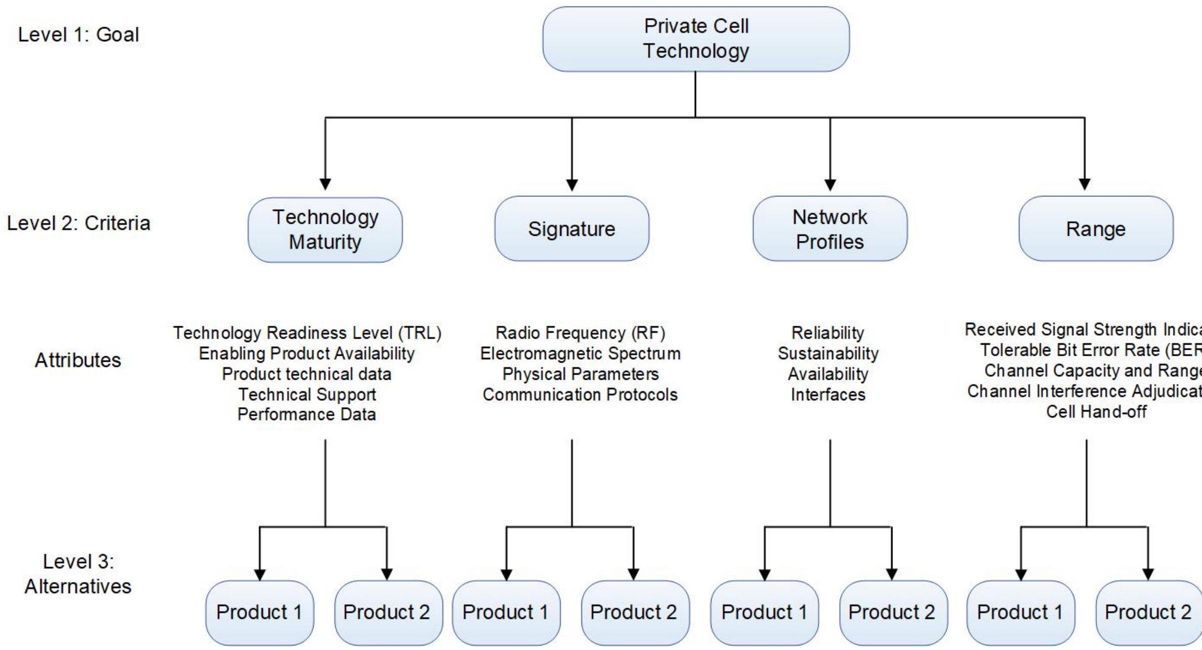

Figure 3. Applying AHP to the Private Cell Technology Investment Decision-Making Process

For the Private Cellular Network Technology case study, the Goal, which represents the desired outcome or impact of the decision, is to make an investment decision on pursuing the technology and, if yes, identifying the most appropriate material solution.

Decision Criteria for the Private Cellular Network Technology Case Study are Technology Maturity, Signature, Network Profile, and Range. These criteria are the standards or measurements against which the decision will be made and candidate solutions will be evaluated. The four Criteria provide sufficient depth and granularity to define the technology and to differentiate candidate enabling products if the decision is made to pursue this technology as an investment initiative.

The Attributes listed for each criterion are qualities or characteristics associated with that criterion. Attributes add depth and identify characteristics of interest to help establish weights for each criterion. Attributes can focus on technical, operational, security, cost, supportability, or other characteristics that help describe the criteria.

In the Private Cellular Network Technology Case Study, Decision Alternatives are a binary yes or no decision to pursue the technology and a multi-criteria decision to evaluate candidate enabling products. Two candidate material solutions, Product 1 and Product 2, are shown as decision alternatives in Figure 3. These two material solutions will be evaluated against the weighted criteria established by AHP's Pairwise Comparison Matrix shown in Figure 4.

It is important to note that a Doctrine, Organization, Training, Material, Leadership and Education, Personnel, Facilities and Policy (DOTMLPF-P) analysis should be performed prior to pursuing a material solution to mitigate or close a capability gap. The DOTMLPF-P Analysis will determine if a non-material or material approach is required to mitigate or close a capability gap. The technology under consideration, and the products that realize the technology's capability, are material solutions to mitigating or closing the capability gap.

Qualitative and quantitative data are used to establish criteria weights, which are applied to rank order the decision alternatives of Product 1 or Product 2.

The qualitative data component of the AHP model identifies decision criteria and associated attributes in the Criteria component of the AHP hierarchy structure. Qualitative data can be collected from technical research and subject matter expert judgment. Figure 4 shows how Saaty's (1980) Pairwise Comparison Scale is used to translate qualitative verbal judgments to quantitative numeric values.

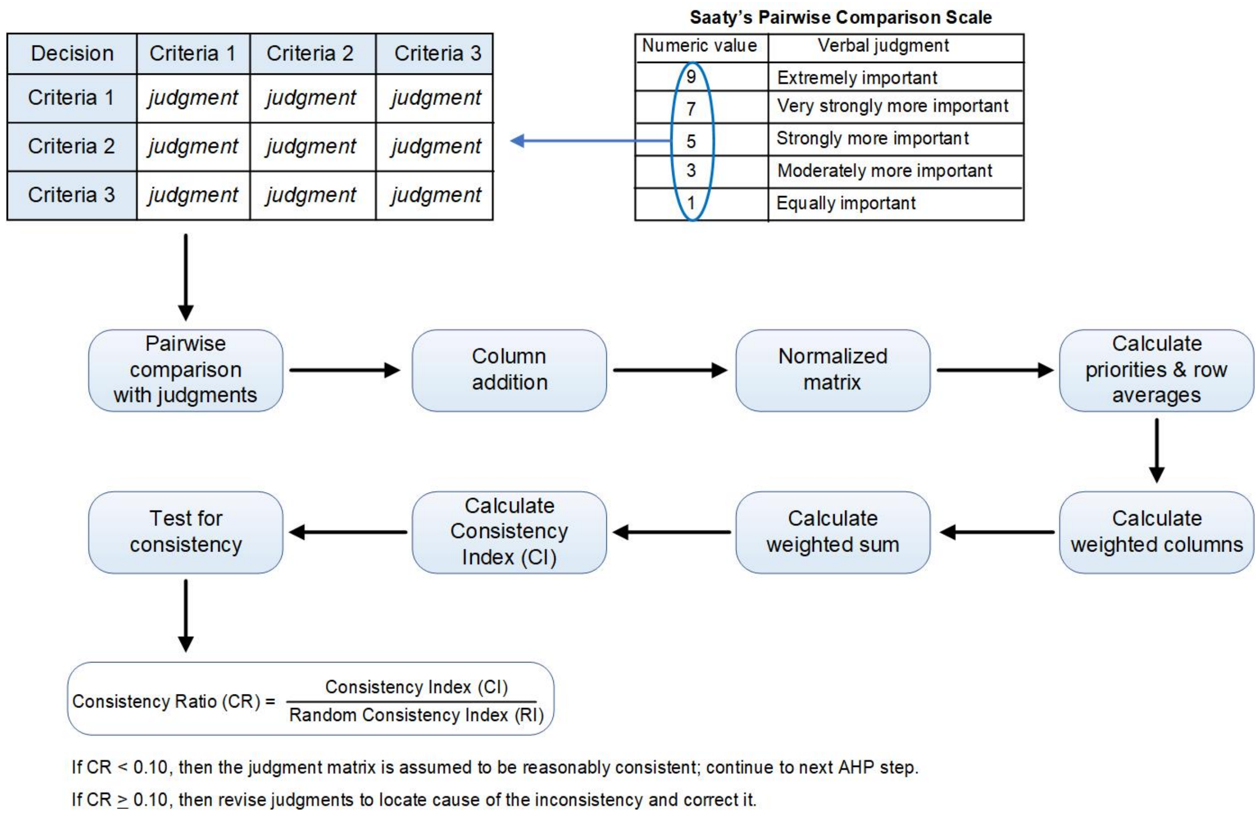

Figure 4. Developing Decision Criteria Weights Using Pairwise Comparison

The criteria weights developed through Saaty's (1980) Pairwise Comparison Scale are tested for consistency as the final step in the pairwise comparison. The Consistency Ratio (CR) compares the Consistency Index (CI) of the Subject Matter Expert–generated judgment matrix against the consistency index of a random matrix (RI). The random matrix is one where judgments have been entered randomly and therefore are expected to be highly inconsistent. The RI is the average consistency index of 500 randomly populated matrices. As shown in Figure 4, if the Consistency Ratio is < 0.10, the judgment matrix is assumed to be reasonably consistent and is acceptable for use in the AHP model (Saaty, 1980).

With criteria weights established and verified for consistency against the Random Index, the Product 1 and Product 2 material solutions can be evaluated against the weighted criteria.

Figure 5 shows the final steps in the Case Study, which produce a rank ordered list of decision alternatives from which the decision-maker can select.

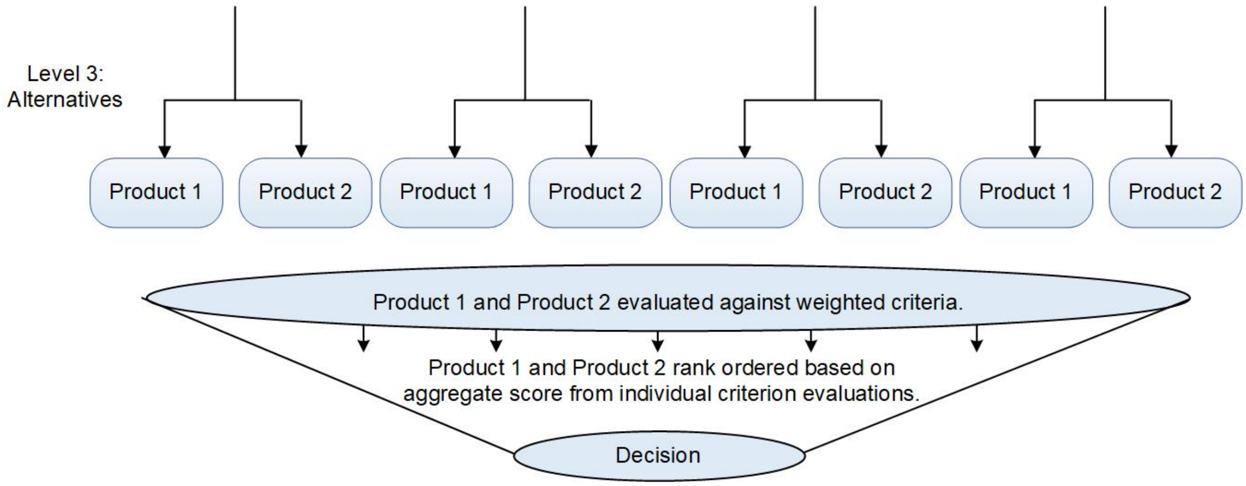

Figure 5. Applying Criteria Weights to Decision Alternatives

Evaluating Product 1 and Product 2 against the weighted criteria produces an aggregate score that can be used to rank order the decision alternatives. In the Private Cellular Network Technology Case Study, there are only two products from which the decision-maker can select. Though the number of decision alternatives can be sufficiently larger than shown in the Case Study, the AHP process steps and application are consistent with the two-decision alternative Private Cellular Network Technology Case Study.

Findings

Key findings from MCDM method research and selection, model development, decision criteria research, and criteria weighting are presented in the following paragraphs.

- Criteria identification and weighting are heavily influenced by the quality of subject matter expert judgment. Pairwise comparisons used to translate qualitative data to quantitative data can be influenced by the breadth and depth of knowledge and experience of subject matter experts providing the qualitative assessments.
- Decision criteria should be limited to those that clearly enable differentiation of decision alternatives. As the number of criteria increases, the difference in their respective weights becomes increasingly smaller and potentially less meaningful.
- The criteria may be sensitive to unique characteristics of the environment in which the technology and enabling product is intended to operate. Criteria and associated attributes must be considered in the context of the environment in which the technology or product will operate. Criteria with absolute measurements, such as weight or cost, are less susceptible to operating environment influences than more dynamic criteria such as electromagnetic spectrum and channel interference criteria.
- An Acceptance Threshold should be established as a value that must be equaled or exceeded for any decision alternative to be selected. Determining an Acceptance Threshold for selecting one of the decision alternatives can help avoid the scenario where even the highest ranked alternative fails to perform in a manner that mitigates the targeted capability gap.
- The mission owner’s risk tolerance can impact the choice between decision alternatives. Risk tolerance is based on the mission owner’s assessment of the impact if the technology and enabling product fail to perform as expected. Different mission owners

can have different risk tolerances when addressing suitability of similar technologies and products for investment decisions.

- The MCDM approach to technology investment decisions is not a substitute for a formal Analysis of Alternatives (AoA) and subsequent formal source selection evaluations. However, the MCDM approach proposed in this paper is well-suited to rapid capability testing and fielding as a first step in large-scale system evaluations and investment decisions.
- Improvement in the ROI for technology initiatives attributed to applying MCDM methods is difficult to measure until a robust body of data is collected and analyzed. The ROI for applying MCDM methods should include factors such as cost avoidance of pursuing technologies that do not mitigate or close capability gaps, pursuing technologies that have no measurable contribution to mission success, and pursuing technologies for which enabling products do not yet exist.

Conclusion and Practical Application

The MCDM model presented in this paper meets the proposed research objectives and answers the research questions. The MCDM model can produce a consistent and repeatable technology investment decision-making process that removes subjectivity and decision-maker bias, either intended or unintended, from the decision-making process. The structured and objective approach to technology selection and investment decision-making ensures that technology investment decisions are properly aligned to organizational goals and objectives.

The application of MCDM methods to technology investment decision-making researched and summarized in this paper removes inconsistency and subjectivity from that decision-making process. Removing inconsistency and subjectivity results in a reduced level of risk potentially introduced to mission success by adopting technology and enabling products that fail to perform as required in the anticipated operating environment. The decision support model presented in this paper, based on the AHP MCDM method, can be applied by organizations pursuing technology-based solutions to their most critical operational challenges and capability gaps.

References

Adriyendi. (2015). Multi-attribute decision making using simple additive weighting and weighted product in food choice*. International Journal of Information Engineering and Electronic Business*, *6*.

Department for Communities and Local Government. (2009). *Multi-criteria analysis: A manual.* http://www.communities.gov.uk

Foote, K. E. (2010). *An introductory overview to multi criteria evaluation.* https://www.colorado.edu/geography/foote/2010/Methodology_Norlund_final.ppt

Gavade, R. (2014, November 20). Multi-criteria decision making: An overview of different selection problems and methods. *International Journal of Computer Science and Information Technologies*.

Georgiadis, D. R., Mazzuchi, T. A., & Sarkani, S. (2013). Using multi-criteria decision making in analysis of alternatives for selection of enabling technology. *Systems Engineering, 16*(3).

Mocenni, C. (2018, June 7). *The analytic hierarchy process*. http://www.dii.unisi.it/~monecci/Note_AHP.pdf

Saaty, T. L. (1980). *The analytic hierarchy process: Planning, priority setting, resource allocation*. McGraw-Hill International Book Company.

Triantaphyllou, B., Shu, B., & Ray, T. (1998). Multi-criteria decision making: An operations research approach. *Encyclopedia of Electrical and Electronics Engineering*, *15*.

Tscheikner-Gratl, F., Egger, P., Rauch, W., & Kleidorfer, M. (2017). Comparison of multi-criteria decision support methods for integrated rehabilitation prioritization. *Water*.

Vargas, R. V. (2010). *Using the analytic hierarchy process (AHP) to select and prioritize projects in a portfolio* [Paper presentation]. PMI® Global Congress 2010—North America, Washington, DC.

Yoon, K. P., & Hwang, C.-L. (1995). *Multiple attribute decision making: An introduction*. Sage Publications.

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