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Quantifying, Visualizing, and Tracking Capability Gaps

Kamel, Magdi, N.; Gallup, Shelley

Monterey, California. Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

QUANTIFYING, VISUALIZING, AND TRACKING CAPABILITY GAPS

by

Dr. Magdi N Kamel

Dr. Shelley Gallup

January 2022

Distribution Statement A: Approved for public release; distribution is unlimited

Prepared for: Navy Warfare Development Command (NWDC)
This research is supported by funding from the Naval Postgraduate School, Naval Research Program (PE 0605853N/2098)
NRP Project ID: NPS-21-N123-A

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE ***(DD-MM-YYYY)*** 15-01-2022	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** ***(From-To)*** Jan 2021 – Jan 2022

4. TITLE AND SUBTITLE
Quantifying, Visualizing, and Tracking Capability Gaps

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0605853N/2098

6. AUTHOR(S)
Kamel, Magdi, N
Gallup, Shelley

5d. PROJECT NUMBER
NPS-21-N213-A; W0A35

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Naval Postgraduate School
1 University Circle
Monterey, CA 93943

8. PERFORMING ORGANIZATION REPORT NUMBER
NPS-IS-22-002

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Naval Postgraduate School, Naval Research Program
Navy Warfare Development Command (NWDC)

10. SPONSOR/MONITOR'S ACRONYM(S)
NRP; NWDC

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NPS-IS-22-002; NPS-21-N213-A

12. DISTRIBUTION / AVAILABILITY STATEMENT
Distribution Statement A: Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Gap Analysis, Data Visualization, Risk Assessment

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
U	U	U	UU	43	Kamel, Magdi, N
					19b. TELEPHONE NUMBER ***(include area code)*** 831-656-2494

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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NAVAL POSTGRADUATE SCHOOL
Monterey, California 93943-5000

Ann E. Rondeau
President

Scott S. Gartner
Provost

The report entitled "Quantifying, Visualizing, and Tracking Capability Gaps" was prepared for Commander, U.S. Navy Warfare Development Command (NWDC) and funded by the Naval Postgraduate School, Naval Research Program (PE 0605853N/2098).

Distribution Statement A: Approved for public release; distribution is unlimited.

This report was prepared by:

Dr. Magdi Kamel
Associate Professor

Dr. Shelley Gallup
Research Associate Professor

Reviewed by:

Alex Bordetsky, Chairman
Information Sciences

Released by:

Kevin B Smith
Dean of Research

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ABSTRACT

While there are numerous sources of information/knowledge that identify warfighting capability gaps and/or provide recommendations to close gaps and/or provide new/improved capabilities to the fleet, there is no comprehensive system, and responsible entity, that captures all that information in one place to provide a clear and concise picture of progress being made, or not made, to close identified gaps and/or provide a capability. To address this problem, we developed a methodology based on Multi-Criteria Decision Analysis (MCDA) methods to calculate and visualize a capability gap score at any given point in time to depict capability gap resolution progress based on substantiated real-time information. In this effort we expand the framework used to evaluate capabilities by adding new elements and sub-elements to the framework and extend the MCDA methodology by incorporating different models for calculating the capability gap score. These models include the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP). The goal is to develop a comprehensive methodology to 1) support prioritization of capabilities based on hard data, 2) provide a clear and concise picture of progress being made, or not made, to close identified gaps and/or provide a capability, and 3) support the creation of a central repository for organizations to distribute pertinent information.

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A. BACKGROUND

Commander, Naval Surface and Mine Warfighting Development Center (SMWDC) is tasked to provide oversight, alignment, synchronization, and end-to-end assessment of Warfare Improvement Programs (WIP) for mission areas under the cognizance of the Surface Type Commander. The WIP process is the formal framework for capturing, vetting, and prioritizing Fleet capability needs to improve readiness and optimize resources for Navy forces in the execution of Combatant Commander (CCDR) tasking (Commander U.S. Pacific Fleet, 2013). For each mission area, SMWDC HQ is responsible to ensure a WIP Fleet Collaborative Team (FCT) is constituted to participate in events that inform development of annual output products. Each WIP conducts Executive Working Groups (EWG) in Q1 and Q2 and a Symposium in early Q3 of the current Fiscal Year Program Objective Memorandum (POM) cycle. A SMWDC HQ N8/9 endorsed ranking tool is utilized throughout the WIP cycle to aid in objective prioritization of capability gaps. Annual Capability Area Assessment (CAA) is a collaborative effort led by the EWG Chair with the support from the FCT working group leads and the Warfare Development Center. Intel briefs and FCT updates received during EWG one and two help inform creation of the CAA and ultimately provide the "homework" or supporting documentation, for prioritization of capability gaps. Each Capability Area Owner (CAO) briefs their CAA and IPCL to SMWDC N00. The CAA report serves as the basis for the development of the current WIP cycle IPCL through the efforts put forth in the WIP Symposium (Commander, Naval Surface and Mine Warfighting Development Center, 2018).

B. RESEARCH OBJECTIVE

In a previous research effort, we developed a methodology based on Multi-Criteria Decision Analysis (MCDA) methods to calculate and visualize a capability gap score at any given point in time to depict capability gap resolution progress based on substantiated real-time information. In this effort we extend the MCDA methodology by expanding the framework used to evaluate different capabilities and incorporating different models for calculating the capability gap score. These models include the Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and. The application of this methodology would provide decision makers with objective information to 1) support prioritization of capabilities based on hard data, 2) provide a clear and concise picture of progress being made, or not made, to close identified gaps and/or provide a capability, and 3) support the creation of a central repository for organizations to distribute pertinent information.

C. APPLICATION OF MULTI-CRITERIA DECISION ANALYSIS TO GAP ANALYIS

In a previous effort, we proposed using Multi-Criteria Decision Analysis (MCDA) to calculate a capability gap score for a given priority at a given point in time. MCDA is both an approach and a set of techniques, with the goal of providing an overall ordering of alternatives, from the most preferred to the least preferred. The alternatives may differ in the extent to which they meet several criteria, and no one alternative will be best meet all criteria. In addition, some conflict or trade-off is usually evident amongst the criteria. MCDA is a way of looking at complex problems that are influenced by many decision criteria, breaking the problem into more manageable pieces to allow data and judgements to be brought to bear on the pieces, and then reassembling the pieces to present a coherent overall picture to decision makers. This method serves as an aid to thinking and decision making, but not to making the decision (Department for Communities and Local Government, 2009).

In the case of capabilities gap analysis, the criteria represent the factors that affect a gap (e.g., doctrine, organization, materiel, funding, etc.) and the alternatives are the priorities as specified by the Prioritized Capability Lists. Weights are specified for each factor to reflect their relative importance and are assigned by subject matter experts individually and collectively. Each priority is evaluated periodically (e.g., quarterly) with respect to each factor and a score is assigned according to an appropriate scale. A total score for each priority is then calculated and visualized using an appropriate MCDA model to produce a capability gap score.

To implement the proposed approach, the following tasks need to be completed:

1. Identifying a comprehensive list of factors and sub-factors that determine a capability gap using a suitable capability management framework. The factors are the measures of performance by which the capabilities will be evaluated. These may include such factors as: doctrine, organization, training, materiel, funding, policy, etc. These factors can be grouped in a hierarchy of high-level factors and low-level sub-factors and so on.
2. Rating capabilities on each factor using an appropriate scale. For example, a scale from 1 to 5 could be used for the funding factor where 1 indicates considerable funding cuts and 5 indicates full funding availability for the priority at a given point in time. Similar scales would be developed for the other factors such as doctrine, organization, training, materiel, etc.
3. Assigning weights to the identified factors to reflect their importance. This could be based on methods that range from individual assessments to models that achieve consensus among groups of subject matter experts.
4. Calculating an overall priority gap score by combining the weights and ratings for each of the alternatives using a suitable MCDA model. These models include Weighted Sum Model (WSM), Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP) (Parlos, 2000).
5. Conducting a sensitivity analysis to reveal how different weights or preferences affect the capability gap score. Sensitivity analysis provides a means for examining the extent to which vagueness about weights and preferences or disagreements between evaluators makes any difference to the final overall results.
6. Visualizing the capability gap score across time to provide a clear and concise picture of progress being made, or not made, to close identified gaps on the identified factors.

1. Identifying Factors that Determine a Capability Gap

A capability is typically assessed and managed with regard to several dimensions or integrative elements. Therefore, it would be helpful to use a capability management framework that incorporates these dimensions as a basis for developing a capability gap score at a given point of time.

For example, The US military analyses its capabilities in the dimensions of "DOTMLPF", as defined in The Joint Capabilities Integration Development System, or JCIDS Process, being: Doctrine, Organization, Training, Materiel, Leadership, Personnel and facilities (DOTMLPF-P, n.d.). NATO uses a similar acronym, DOTMLPF-I, the "I" stand for "Interoperability": the ability to be interoperable with forces throughout the NATO alliance. The UK Ministry of Defense uses a similar framework, known by the acronym TEPID-OIL, that includes the following dimensions: Training, Equipment, Personnel, Information, Concepts and Doctrine, Organization, and Infrastructure. Although Interoperability is not mentioned specifically in the framework, The UK Ministry of Defense cites Interoperability as an overarching theme that must be considered when any Defense capability is being addressed. The Australian Defense Organization also analyses its capabilities in similar dimensions, known as Fundamental Inputs to Capability, and include Command and Management, Organization, Major Systems, Personnel, Supplies, Support, Facilities, Collective Training, and Industry. The dimensions identified by these frameworks must be integrated and managed within a defined or constraining financial envelope to develop and sustain a capability: a deficiency in any one adversely impacts the whole.

In this effort we will use an extended and expanded Department of Defense DOTMLPF framework that include, in addition to the elements of the framework, a Funding and a Policy element as the factors that determine a capability gap. Here is an example of how the dimensions of DOTMLPF would be used in determining the state of capability gap at a given point in time:

- Doctrine: Is there a doctrine describing the way we fight using the capability?
    - CONOPS: Is there a concept of operations for the capability?
    - System Specific: Is there a system specific doctrine for capability?
    - Navy-Wide: Is there a navy-wide doctrine for capability?
    - Detailed Design: Is there a detailed design for the capability?

- Organization: Do we have the organization for using the capability to fight? (e.g., divisions, air wings, Marine-Air Ground Task Forces (MAGTFs), etc.)
    - Direct Support: Is there a funded and established direct support organization for the capability?
    - Indirect Support: Is there indirect support from Fleet/Force and other supporting organizations specific to the capability?
- Training: Do we have tactical training to use the capability? (e.g., basic training to advanced individual training, various types of unit training, joint exercises, etc.)
    - Formal Training: Is there formal training for the capability?
    - Informal Training: Is there an informal training for the capability?
    - OJT: Is there uniformed expertise to support on-the-job training for the capability?
- Materiel: Do we have all the technology and "stuff" necessary to equip the forces so they can use the capability effectively?
    - Autonomous/Automation: Does the capability have full autonomy/automation?
    - Sensing: Is there a full range of sensing to support the capability?
    - Reliability: Does materiel of capability have a high degree of reliability?
    - Tactical Relevance: Is there high maturity on payloads delivering tactical capability?
    - Communication/C2: Is the communication/C2 architecture fully established for capability?
- Leadership and education: Do we have leaders to lead the fight using the capability from squad leader to 4-star general/admiral?
    - Advocacy: Is there strong advocacy from leadership for capability?
    - Level of Knowledge: Is there a high level of knowledge of the capability among leadership?

- Personnel: Do we have qualified people to use the capability for peacetime, wartime, and various contingency operations?
  - OPNAV N1 Support: Is there strong personnel support from OPNAV N1 for the capability?
  - Billets: Are there established billets to support capability?
- Facilities: Do we have the facilities (e.g., real property; installations and industrial facilities to support the capability?
  - R&D/Lab: Is there R&D/lab support for the capability?
  - Shipyard Availability: Is there shipyard availability to support capability?
  - Basing (CONUS): Is there established CONUS basing for the capability?
  - Basing (OCONUS): Is there established OCONUS basing for the capability?
  - Maintenance: Is there established maintenance facilities for the capability?
  - Operations Center: Is there an operation center to support the capability?
  - Updates & Upgrades: Is there a plan for updates & upgrades for capability?
- Funding: Do we have adequate level of funding to sustain development for the current period?
  - DoD: Is there adequate funding to support capability?
  - Congressional: Is there congressional appropriated and authorized funding to support capability?
- Policy: Do we have clear policies to support the capability
  - Fleet/Navy Policy: Is there a fleet/navy policy to support capability
  - National: Is there a national policy to support the capability?

Figure 1 shows the proposed extended and expanded DOTMLPF framework used in this research to evaluate a capability score.

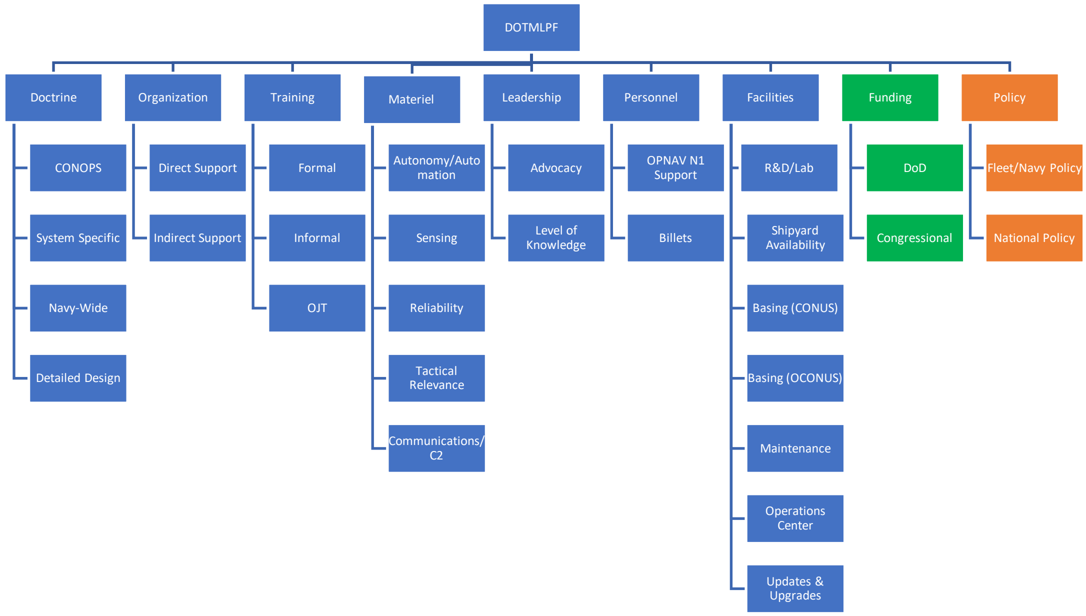

Figure 1. Expanded DOTMLPF framework

2. Rating Capabilities on Identified factors

This step rates the preference of each capability against the identified factors. This can be accomplished using a relative or fixed preference scale. In a relative preference scale, the scale is anchored at its ends by the most and least preferred capability. For example, using a one to five scale, the most preferred alternative is assigned a preference rating of five, and the least preferred, a rating of one. Ratings are assigned to the remaining capabilities so that differences in the numbers represent differences in strength of preference. These are relative judgements comparing differences in consequences, and they are often easier for people to make than absolute judgements. The resulting ratings represent the relative strength of preference; a relative preference scale is particularly appropriate for comparing several capabilities at the same time.

If capabilities are evaluated against criteria serially, a fixed preference scale is more appropriate. In a fixed preference scale, the lowest value on a given criterion might be defined as the lowest preference that would be given to a capability. The highest value could be defined as the maximum feasible value that could be given to a capability — this would require imagining and defining a hypothetical capability as a top-scorer.

a. Normalization/Standardization

Different rating scales could be used to rate capabilities against identified factors. In this case, we need to bring uniformity to the ratings by normalizing them. Normalization converts rating values to a scale that ranges between 0 and 1.

We identify two main types of factors: beneficial and non-beneficial factors, also known as cost factors. Non-beneficial factors are those factors where lower values are desired (e.g., price), while beneficial factors are those factors where higher values are desired. We discuss below several methods for normalization.

(1) Linear Normalization

The formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_{ij}}{X_{ij}^{Max}}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on rating j, and X_j^{Max} is the maximum rating of factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = 1 - \frac{X_{ij}}{X_{ij}^{Max}}$$

(2) Linear Normalization – Method II

For this version of linear normalization, the formula for calculating a standardized rating for a beneficial factor is similar to that of the previous version:

$$\bar{X}_{ij} = \frac{X_{ij}}{X_{ij}^{Max}}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on rating j, and X_j^{Max} is the maximum rating of factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_j^{Min}}{X_{ij}}$$

Where X_j^{Min} is the minimum rating of factor j.

(3) Linear Normalization – Max/Min Method

The formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_{ij} - X_j^{Min}}{X_j^{Max} - X_j^{Min}}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on factor j, X_j^{Max} is the maximum rating of factor j, and X_j^{Min} is the minimum rating of factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_j^{Max} - X_{ij}}{X_j^{Max} - X_j^{Min}}$$

(4) Linear Normalization – Sum Method

In this method, the formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_{ij}}{\sum_{i=1}^{m} X_{ij}}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{1/X_{ij}}{\sum_{i=1}^{m} 1/X_{ij}}$$

(5) Vector Normalization

In this method, the formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = 1 - \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}}$$

(6) Enhanced Accuracy Normalization

In this method, the formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = 1 - \frac{X_j^{Max} - X_{ij}}{\sum_{i=1}^{m}(X_j^{Max} - X_{ij})}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j, X_{ij} is the rating of alternative i on factor j, and X_j^{Max} is the maximum rating of factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = 1 - \frac{X_{ij} - X_j^{Min}}{\sum_{i=1}^{m}(X_{ij} - X_j^{Min})}$$

Where X_j^{Min} is the minimum rating of factor j.

(7) Logarithmic Normalization

In this method, the formula for calculating a standardized rating for a beneficial factor is as follows:

$$\bar{X}_{ij} = \frac{\ln X_{ij}}{\ln(\prod_{i=1}^{m} X_{ij})}$$

Where $\bar{X}_{ij}$ is the standardized rating for alternative i on factor j and X_{ij} is the rating of alternative i on factor j.

The formula for calculating a standardized rating for a non-beneficial factor is as follows:

$$\bar{X}_{ij} = 1 - \frac{1 - \ln X_{ij} \,/\, \ln(\prod_{i=1}^{m} X_{ij})}{m-1}$$

b. Which Normalization Method to Use

Selecting a normalization method is an important consideration for solving MCDM problems. Unfortunately, there are no hard and fast rules for selecting a normalization method for a given MCDM problem. However, we can make selections based on certain parameters such as the minimum and maximum normalized value and the difference (range) between the two.

For Linear Normalization method, the highest normalized value is 1 for beneficial factors and the lowest normalized value is 0 for non-beneficial factors. For Linear Normalization – Method 2, the highest normalized value for both beneficial and non-beneficial factors is 1, and for the Linear Normalization – Max/Min method, the highest normalized value is 1 and the lowest normalized value is 0 for both beneficial and non-beneficial factors. In the Linear Normalization – Sum method, the highest and lowest normalized values take on values other than 0 or 1, based on the percentage of the rating to the sum of all ratings. Similarly, the Vector Normalization method returns normalized values based on vector distance from origin and results in values other than 1 or 0 for the highest and lowest normalized values for both beneficial and non-beneficial factors. Enhanced Accuracy Normalization normalizes values similar to Linear Normalization – Method 2, thus the highest normalized value for both beneficial and non-beneficial factors is 1. However, the difference between the two approaches is that the range between the highest and lowest normalized values using Enhanced Accuracy is less than that of Linear Normalization. Finally, in Logarithmic Normalization the highest and lowest normalized values take on values other than 1 or 0. This is similar to Vector Normalization, but the range between the highest and lowest normalized values is narrower.

3. Assigning Weights to Identified Factors

Assigning weights to identified factors ensures that more important criteria have a greater impact on the final decision. These weights can be assigned subjectively by individual subject matter experts or collectively among a group of subject matter experts either directly or through pairwise comparison using the Analytic Hierarchy Process (AHP). Common scales used are one to three, one to five, one to ten, one to one-hundred, and zero to five. Each scale has its own merits, but one to ten seems to be the most common and is the one that we use for this effort. Other scale options include the one, four, nine scale or the one, three, nine scale, which forces people to decide if something is very important, somewhat important, or not important.

Weights can be assigned objectively using the method of “swing weighting.” This method is based on comparisons of differences (swings) between capability preferences. In making weight assignments, evaluators consider the difference in ratings between the least and most preferred capability, and how much they care about the difference. If the difference in ratings among the capabilities on a given criterion is small, that criterion would receive a low weight.

Implementing the swing weighting method with a group of subject matter evaluators can be accomplished by using a “nominal-group technique.” First, the one criterion with the largest swing in preference is identified. With few criteria, this can usually be found quickly with agreement from evaluators. With many criteria, a binary pairwise comparison of all criteria for preference swings may be necessary. The one criterion with the largest swing in preference is assigned the highest weight (e.g., five). This criterion becomes the standard to which all other criteria are compared in a four-step process:

1. Another criterion is chosen, and all evaluators are asked to write down, without discussion, a weight that reflects their judgement of its swing in preference comparted to the standard. For example, if the criterion is judged to represent two-fifth the swing in value of the standard, then it should be assigned a weight of two.
2. Evaluators reveal their judgement weights to the group and the results are recorded on a flip chart as frequency distribution.
3. Evaluators who gave extreme weights, high and low, are asked to explain their reasons to the group and a general group discussion follows.

4. Following the discussion, a subset of evaluators makes the final determination of the weight of the criterion under discussion. This subset usually consists of the decision maker, those representing the decision maker, or senior participants whose perspectives on the issues enable them to take a broad view.

The setting of weights raises the question of whose preferences count the most, and the choice may ultimately be political, and/or depend on the context. However, it should be noted that a broadly satisfactory criterion should reflect the informed preferences of people as a whole, to the extent that these preferences and the relative importance of the criteria can be expressed in numbers. Therefore, the process of determining weights is fundamental to the effectiveness of this approach. If there is not a consensus, then it might be best to take two or more sets of weights forward in parallel, for agreement on choice of alternatives can sometimes be agreed even without agreement on weights. Even if this does not lead easily to agreement, explicit awareness of the different weight sets and their consequences can facilitate the further search for acceptable compromise.

4. Calculating a Capability Gap Score Using an Appropriate Model

This step calculates an overall gap score for each capability from the ratings and the weights developed in the previous steps. There are several models to calculate an overall score. They include Weighted Sum Model (WSM), Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP). We describe these models in the following sections:

a. Weighted Sum Model (WSM)

The Weighted Sum Model is the best-known MCDA method for evaluating several alternatives in terms of several decision criteria and is the method we recommend for this effort. Suppose that a given MCDA problem consists of n decision criteria with m available alternatives. Furthermore, let us assume that all the criteria are benefit criteria, that is, the higher the values are, the better it is. Next suppose that w_j denotes the relative weight of importance of the criterion C_j and x_{ij} is the score of alternative A_i when it is evaluated in terms of criterion C_j. Then, the total (i.e., when all the criteria are considered simultaneously) score of alternative A_i, denoted as $A_i^{WSM\text{-score}}$, is defined as follows:

$$A_i^{WSM\text{-score}} = \sum_{j=1}^{n} w_j \, x_{ij}$$

The best alternative then is the one that yields the highest total score value.

Consider a decision problem with three alternatives A_1, A_2, A_3 and three decision criteria C_1, C_2, C_3 as shown in Table 1. The weight of criteria is 1, 2, and 3 respectively. Each alternative is scored on each criterion as shown in the following table.

Table 1. Decision problem criteria and alternatives

		C_1	C_2	C_3
	Weights	*1*	*2*	*3*
Alternatives	A_1	3	2	1
	A_2	3	1	3
	A_3	3	2	2

The total score of Alternative A_1 ($A_1^{WSM\text{-}score}$) is calculated as follows:

$$A_1^{WSM\text{-}score} = 3 \times 1 + 2 \times 2 + 1 \times 3 = 10$$

Similarly, we get:

$$A_2^{WSM\text{-}score} = 14 \text{ and } A_3^{WSM\text{-}score} = 13$$

Thus, the best alternative is alternative A_2 because it has the highest WSM score of 14. Furthermore, these numerical results imply the following ranking of these three alternatives: $A_2 > A_3 > A_1$ (where the symbol ">" stands for "preferred over").

b. The Weighted Product Model (WPM)

The Weighted Product Model (WPM) is similar to the WSM. The main difference is that it uses multiplication instead of addition.

$$A_i^{WPM\text{-score}} = \prod_{j=1}^{n} {x_{ij}}^{w_j}$$

Consider the decision problem of the previous section. The total score of Alternative A_1 ($A_1^{WPM\text{-}score}$) is calculated as follows:

$$A_1^{WPM\text{-}score} = 3^1 \times 2^2 \times 1^3 = 12$$

Similarly, we get:

$$A_2^{WPM\text{-}score} = 81 \text{ and } A_3^{WPM\text{-}score} = 96$$

Thus, the best alternative is alternative according to this method is A_3 because it has the highest WPM score of 96. Furthermore, these numerical results imply the following ranking of these three alternatives: $A_3 > A_2 > A_1$ (where the symbol ">" stands for "preferred over").

c. Weighted Aggregated Sum Product Assessment (WASPAS)

The Weighted Aggregated Sum Product Assessment (WASPAS) combines both WSM and WPM using a weighting factor λ as shown in the formula below:

$$A_i^{WASPAS\text{-}score} = \lambda A_i^{WSM\text{-}score} + (1-\lambda) A_i^{WPM\text{-}score}$$

Note that $A_i^{WASPAS\text{-}score} = A_i^{WSM\text{-}score}$ when $\lambda = 1$ and $A_i^{WASPAS\text{-}score} = A_i^{WPM\text{-}score}$ when $\lambda = 0$.

Consider the decision problem of the previous section and using a value $\lambda = 0.5$, the total score of Alternative A_1 ($A_1^{WASPAS\text{-}score}$) is calculated as follows:

$$A_1^{WASPAS\text{-}score} = 0.5 \times 10 + (1-0.5) \times 12 = 11$$

Similarly, we get

$$A_2^{WASPAS\text{-}score} = 47.5 \text{ and } A_3^{WASPAS\text{-}score} = 54.5$$

Thus, the best alternative is alternative according to this method is A_3 because it has the highest WASPAS score of 54.5. Furthermore, these numerical results imply the following ranking of these three alternatives: $A_3 > A_2 > A_1$ (where the symbol ">" stands for "preferred over").

d. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is based on the concept that the best alternative should have the shortest distance, i.e., Euclidean distance, from the ideal solution. This is accomplished by constructing a weighted normalized matrix, identifying the ideal best and ideal worst weighted normalized value for each criterion, calculating the Euclidean distance from the ideal best and ideal worst for each alternative, and calculating a performance score based on the Euclidean distances. Alternatives are then ranked based on the performance score.

The formula for calculating the Euclidean distance from the ideal best value is as follows:

$$S_i^+ = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^+\right)^2\right]^{0.5}$$

and the formula for calculating the Euclidean distance from the ideal worst value is as follows:

$$S_i^- = \left[\sum_{j=1}^{m} \left(V_{ij} - V_j^-\right)^2\right]^{0.5}$$

where $V_j^+$and V_j^- are the ideal best and ideal worst weighted normalized values for criterion j.

The performance score P_i for each alternative is calculated using the following formula:

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-}$$

Table 2: Euclidean distances and performance scores shows the weighted normalized matrix, Euclidean distances from ideal best and ideal worst, performance scores, and ranking of each alternative for our example.

Table 2. Euclidean distances and performance scores

		C$_1$	***C***$_2$	***C***$_3$				
	Weights	*1*	*2*	*3*	S_i^+	S_i^-	P_i	***Rank***
Alternatives	***A***$_1$	0.5774	1.3333	0.8018	1.60357	0.66667	0.29366	3
	A$_2$	0.5774	0.6667	2.4054	0.66667	1.60357	0.70634	1

	***A*$_3$**	0.5774	1.3333	1.6036	0.80178	1.04274	0.56532	2

The best alternative is alternative according to this method is A_2 because it has the highest performance score. Furthermore, these numerical results imply the following ranking of these three alternatives: $A_2 > A_3 > A_1$ (where the symbol ">" stands for "preferred over").

e. Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a well known MCDM method. It is used to help decision makers assign weights of criteria and ratings of alternatives through pairwise comparison rather than assigning weights and ratings directly to criteria and alternatives.

The process of using AHP is as follows:

1. The decision problem is represented as a hierarchy (tree) consisting of the decision goal as the root of the hierarchy, the criteria for evaluating the alternatives as levels (branches) of the hierarchy, and the alternatives for achieving goal as lowest level (leaves) of the hierarchy
2. The elements of the hierarchy are analyzed by comparing them to one another two at a time. The criteria are pairwise compared against each other for importance with respect to goal, and the alternatives are pairwise compared against each other for preference with respect to criteria
3. The comparisons are processed mathematically, and weights and ratings are derived for each node
4. A final decision is made based on the results of this process

5. Conducting a Sensitivity Analysis

Sensitivity analysis examines the extent to which vagueness about the inputs or disagreements between people makes a difference in the final overall results. First, interest groups can be consulted to ensure that the model includes factors affecting capability gaps that are of concern to all the stakeholders and key players. Second, interest groups often possess differing views regarding relative importance of the factors, and of some ratings, though weights are often the subject of more disagreement than ratings. Using the model to examine how the capability gap scores might change under different rating or weighting systems can show, though their order may shift, that two or three capabilities always have the highest scores. If the differences between these best capabilities under different weighting systems are small, then accepting either option can be associated with little loss of overall benefit. This is usually not apparent in the ordinary thrust of debate between interest groups, given that they focus on their differences, as opposed to the many factors on which they agree. Third, sensitivity analyses can begin to reveal ways in which capabilities might be improved; in fact, there is a potentially useful role for sensitivity analysis in helping to resolve disagreements between interest groups.

6. Visualizing Capability Score Gaps across Time and Factors

Capability gap scores across time can be visualized using a variety of graphs and charts. Figure 2 is a radar chart that shows factor (dimension) scores by quarter for a given capability.

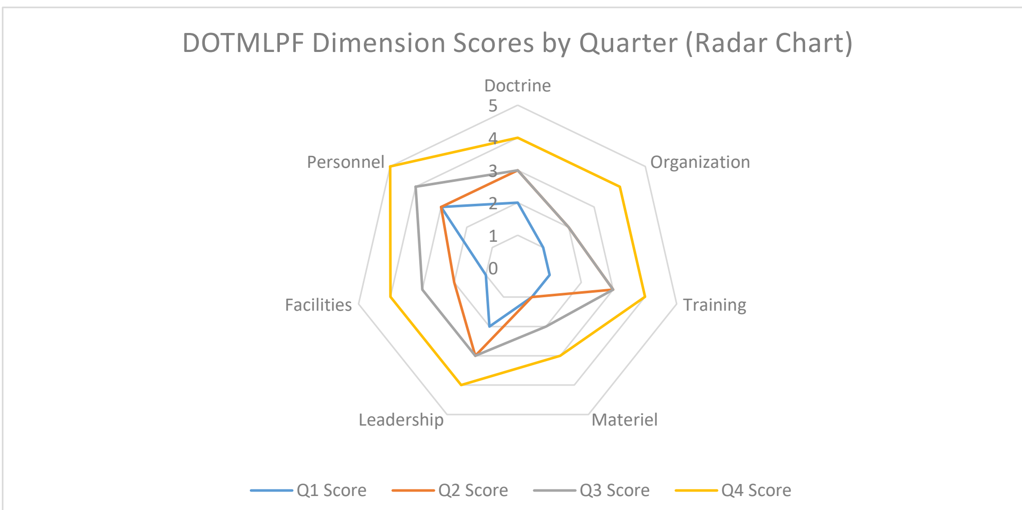

Figure 2. Dimension scores by quarter for a capability

Figure 2 is a line chart that depicts factor (dimension) scores by factor for a given capability.

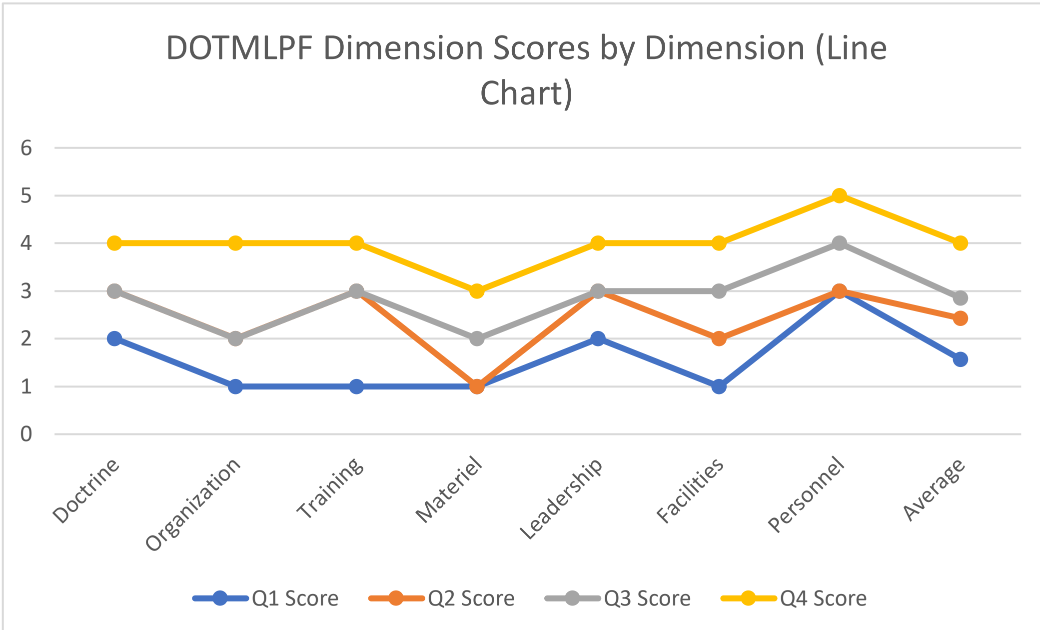

Figure 3. Dimension scores by dimension for a capability

Figure 3 depicts a proof-of-concept dashboard for displaying capability gap scores by capability, year, quarter, and factor. A dashboard is a type of graphical user interface which provides at-a-glance views of key performance indicators (KPIs) relevant to a particular objective. In this case the KPI is the capability gap score across time and dimensions. A dashboard is linked to a database that allows the display to be constantly updated thus providing a near real time progress report of capability gap progress.

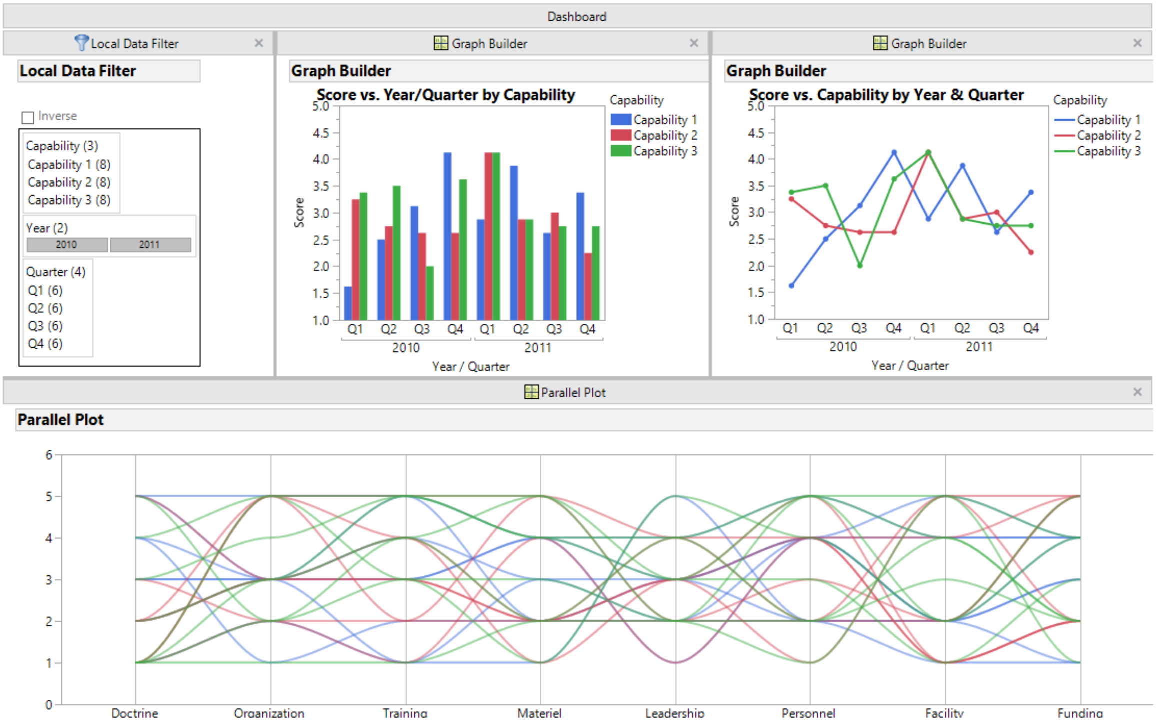

Figure 4. IPCL visualization dashboard

D. APPLICATION OF METHODOLOGY TO THREE CAPABILITES (PROGRAMS)

In this section we apply the developed methodology to three programs representing three capabilities. These programs are fictitious but are based on actual programs of records.

1. Mission Scenario

Our peer nations in Asia have enhanced their capabilities, which could create an anti-access, area denial (A2/AD) situation in the Indo-Pacific Sea lanes of communications (SLOC). In particular, the Chinese Navy has the capability to threaten Taiwan, target US Fleet assets with precision long-range missiles, and use other means to take control of the "first Island Chain"—meaning shipping and defense in this area. In peacetime, an increasing force by the Chinese Navy and shore-based assets would create a *fait accompli*, meaning that when those forces are able to overwhelm US and allied forces, the US Fleet and Joint forces will be unable to push back, making it impossible to project dominance. In other words, it will be too late to act.

At the moment, the U.S. has too few combat ships to prevent this scenario. Specifically, the Arleigh Burke class DDG's are very expensive, and their primary role is to defend a carrier battle group or an expeditionary battle group. Some are used in freedom of navigation operations (FONOPS), but they are constrained by the reality of distributed maritime operations with too few assets. Also, as the US and allies move from a phase 0 to phase 1 operational stance, these capital ships will move out of range of the sea- and land-based long-range precision surface to surface missiles.

a. Program A

Although autonomy may hold promise to address the challenges presented above, achieving true autonomy will take time. Experimentation with programs that attempt to achieve full autonomy has shown promise, but a long way to being truly autonomous, apart from a battle group. What is missing is an armed autonomous platform, yet we are not ready to jump directly towards this capability. We need an intermediate step, and this is where Program A proposes to accomplish by developing a potentially useful platform. The platform would combine current capabilities for autonomy, such as navigation in avoiding collisions (COLGRES) and control of the internal shipboard functions, with a small but tactically and technically savvy crew. Given these capabilities, and armed with its own long-range missiles, we would then have a force forward already inside the first island chain. These 1000-ton vessels, with a crew of 15, would carry 10 long-range missiles. They would have long range engagement against shore-based missile batteries and sea-launched long-range missiles as their primary mission. Instead of piling numerous missions on one vessel, each platform would have its primary mission and one secondary (ASW, AAW, ASUW) mission. This distributes capabilities and as these vessels spread out, and combined with other platforms, create a "Pack" which would greatly increase the adversary's targeting problem. These vessels would use littoral hiding, hiding within commercial fishing fleets, EW capabilities, and stealth technology, making targeting with certainty very difficult.

By having this force forward, we have then a deterrent force, which is able to face the Chinese *fait accompli.* The intended cost of these vessels is less than $100 million; the cost of a new DDG is around $4 billion. Simply put, for the price of one DDG, we can create a new and lethal class of vessel with first- and second-strike capability.

b. Program B

This program's goal is to develop a completely autonomous vessel. Its fundamental capability is as a sensor that can be dispersed over long ranges, while avoiding other vessels and obeying international rules of the road. Though still considered a prototype, a fleet staff has been commissioned to work out issues around homeporting, command and control, and tactical employment when in company with a battle group. A concept of operations draft has been created as a living document while program difficulties emerge and are worked through. To date, these vessels are not being deployed with manned units, but still being employed in exercises and experiments. There are multiple ways in which autonomy is being employed in the US Navy. A complimentary program involving a small but permanently embarked crew on an armed vessel is also being developed and holds potential for an advanced small combatant in the "gray zone." A concept of operations, engineering drawings and innovations in enhanced autonomy allows for a dialog to occur between the ship's intentions engine and the captain of the vessel to create the best possible plan given the current situation.

c. Program C

This program's emphasis is an unmanned vessel operating autonomously and carrying vertical launch or other types of missiles. This program requires a manned vessel to act in supervisory control of any weapons release decision. Advocates claim this can also be accomplished from long distances, such as a command center on land. However, it introduces the need for resilient and consistent command and control, something that cannot be guaranteed after hostilities begin. In addition, it is likely a highly monitored target for advisory land based or warship-based missiles. A concept of operations for the proposal has not been published, and the engineering design has not been finalized. Thus, other questions stemming from the DOTMLPF cannot be answered.

2. Application of the Capability Gap Methodology Steps

In the following sections, we apply the first four steps of the methodology developed in this effort to calculate a current capability gap score for the three programs described in the previous section. We also visualize the results using sample graphs and charts.

a. Identifying the factors that determine the capability gap

We use the expanded DPOTMLPF framework developed in Section C.1 to evaluate the three programs described in the previous section. For this analysis, we focus on evaluating the capabilities on the elements at the highest level of the hierarchy (i.e., Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities, Funding, and Policy).

b. Rating capabilities on identified factors

We use a fixed preference scale, from one to ten, to rate the current state of the three programs on the expanded DOTMLPF factors. These ratings were assessed subjectively by subject matter experts familiar with each program. Table 3 shows the current ratings of each program against the elements of the expanded DOTMLPF framework. A justification was provided for each rating as well, but not included in this write up. Note that ratings for the three programs were provided at the highest level of the DOTMLPF hierarchy. Ideally ratings should be provided at the lower levels of the hierarchy to provide a more granular assessment of these programs.

Table 3. Ratings of the three programs on the elements of the expanded DOTMLPF

	Doctrine	Organization	Training	Materiel	Leadership	Personnel	Facilities	Funding	Policy
Program A	5	2	1	2	3	1	1	1	1
Program B	2	4	1	2	6	3	3	2	1
Program C	4	4	2	3	6	4	3	3	2

c. Assigning weights to identified factors

This step assigns weights to identified factors and sub-factors of the DOTMLPF framework to ensure that more important factors have a greater impact on the final decision. These weights were assigned through consensus by subject matter experts on a scale from one to ten. Table 4 shows the weights and normalized weights as assigned by the SMEs to the highest level of the expanded DOTMLPF hierarchy.

Table 4. Weights and normalized weights of expanded DOTMLPF factors

	Doctrine	Organization	Training	Materiel	Leadership	Personnel	Facilities	Funding	Policy
Weights	2	5	7	9	4	7	4	10	8
Normalized Weights	*0.04*	*0.09*	*0.13*	*0.16*	*0.07*	*0.13*	*0.07*	*0.18*	*0.14*

d. Calculating a capability gap score

This step calculates an overall capability gap score by constructing a weighted matrix and using the methods discussed in Section C.4 to calculate a capability gap score. Table 5 shows the weighted decision matrix and Table 6 shows the capability gap score using the WSM, WPM, and WASPAS methods.

Table 5. Weighted decision matrix

	Doctrine	Organization	Training	Materiel	Leadership	Personnel	Facilities	Funding	Policy
Weights	2	5	7	9	4	7	4	10	8
Normalized Weights	*0.0357*	*0.0893*	*0.1250*	*0.1607*	*0.0714*	*0.1250*	*0.0714*	*0.1786*	*0.1429*
Program A	0.1786	0.1786	0.1250	0.3214	0.2143	0.1250	0.0714	0.1786	0.1429
Program B	0.0714	0.3571	0.1250	0.3214	0.4286	0.3750	0.2143	0.3571	0.1429
Program C	0.0357	0.1786	0.1250	0.1607	0.2857	0.2500	0.0714	0.1786	0.1429

Table 6. Capability gap scores using different MCDA methods

	WSM Score	WPM Score	WASPAS Score
			λ = 0.5
Program A	1.54	1.36	1.45
Program B	2.39	2.07	2.23
Program C	1.43	1.28	1.35

For the above scenario, the best capability gap score is for Program B across the three methods. The capability gap score for Program B indicates that about 20 - 24% of the capability gap is closed and about 76 - 80% of the gap remains to be closed across the elements of the framework. Note that the ranking of the programs is identical across the three methods.

e. Visualizing capability gap scores

Results of the analysis can be visualized using a variety of graphs and charts. Figure 5 is a line chart depicting the current performance scores of each element of the expanded DOTMLPF framework for each program. Figure 6 is a radar chart that depicts the same information but in a different representation. These charts are combined into a dashboard to provide decision makers with an at-a-glance view of the status of each program across time and elements of the DOTMLPF framework.

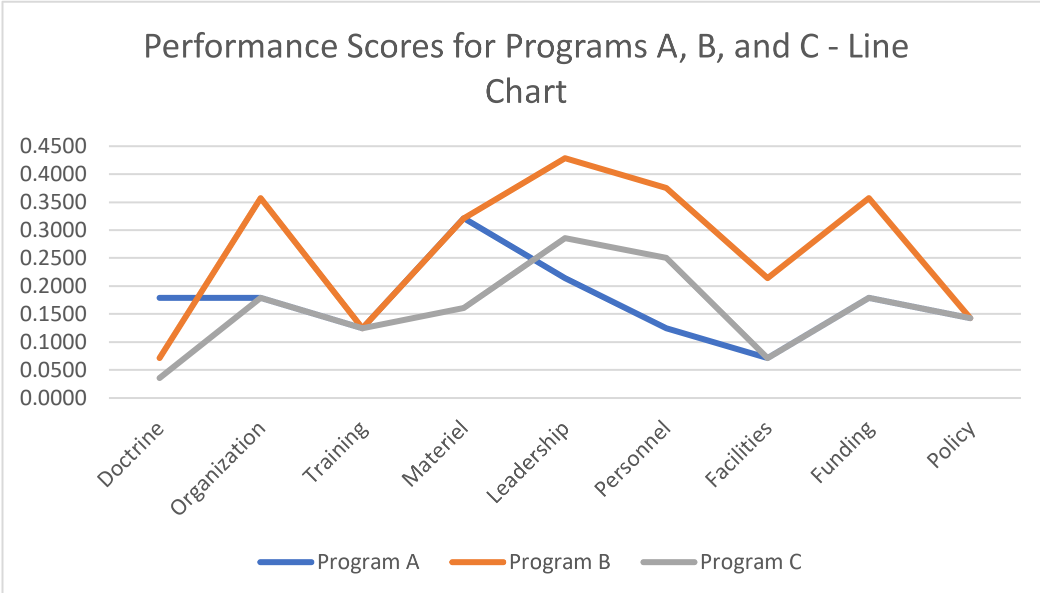

Figure 5. Performance scores for Programs A, B, and C - line chart

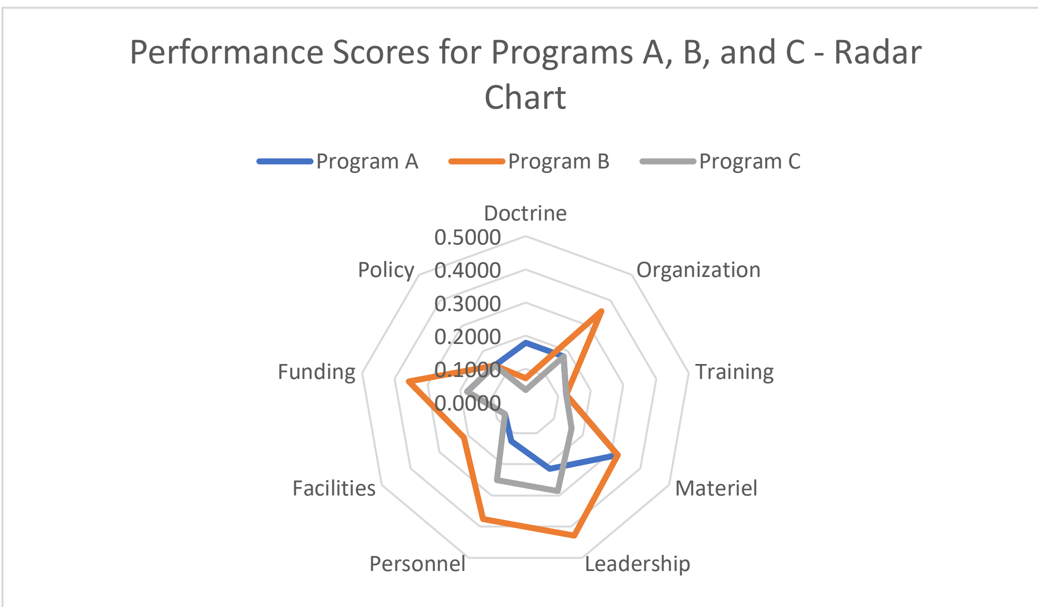

Figure 6. Performance scores for Programs A, B, and C - radar chart

E. SUMMARY AND CONCLUSIONS

In this research effort, we extended the MCDA methodology, developed in a previous effort for calculating capability gap scores, by incorporating different models for combining factor weights and capability ratings to calculate a capability gap score. These models include the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Weighted Aggregated Sum Product Assessment (WASPA), the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Analytic Hierarchy Process (AHP). We also expanded and extended the DOTMLPF framework used to evaluate capabilities by adding new elements and sub-elements to the framework. We applied the developed methodology to a scenario of three programs to demonstrate the viability and applicability of the approach.

The goal of the effort is to develop a comprehensive methodology that would enable Navy leadership to have a clearer picture of what has been accomplished, what remains to be done, who has action, and the critical path to closing the gap and/or delivering a capability.

F. FUTURE WORK

For future research efforts, we recommend continuing to refine the Doctrine, Organization, Training, Materiel, Leadership and Education, Personnel, and Facilities (DOTMLPF) capability management framework by adding new and/or modifying existing elements and sub-elements as appropriate. We also recommend applying the proposed methodology to several real-life capability scenarios and visualize the resulting gap scores across time and framework factors. Finally, we recommend developing a comprehensive dashboard, with a rich set of graphs and charts, to provide decision makers with an at-a-glance view of the status of each program across time and elements of the DOTMLPF framework.

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