Exploring the Design Space of an Electric Ship using a Probabilistic Technology Evaluation Methodology

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***Abstract*—With the advent of new technologies for electric ships, there is a need for a robust methodology to quantitatively evaluate their impact on the performance of a ship, while accounting for the uncertain nature of their parameters. To that end, this paper gives an overview of the Technology Identification, Evaluation, and Selection, or TIES, methodology as applied a 10kton surface combatant. This case study highlights the ability of TIES to aid in a broad exploration of the design space, by giving designers key tools that allow them to show in a traceable manner the tradeoffs involved in infusing technologies and making other design choices, as well as which designs best meet different sets of Figures of Merit. This ultimately allows decision-makers to determine what technologies or design choices to invest in to yield a ship with the performance parameters that will best serve the needs of its stakeholders.**

Keywords—set-based design, design space exploration, probabilistic methods, technology evaluation, ship design

I. INTRODUCTION

Given the complexity of the naval ship design process, a key issue traditionally faced by designers was the inability to easily explore the design space and analyze the possible effects of perturbing design parameters, often due to constraints in computational capacity. Thus, it is well known that there is a need for a more robust method to allow naval engineers to investigate more of the design space while maintaining more design freedom in the early stages [1][2].

Set-based design (SBD) is one example of a design paradigm that encourages naval engineers to conduct early exploration of the design space and hold off on making decisions until the tradeoffs were better understood, while also allowing for more design efforts to proceed in parallel [1][2]. Concurrently, with the rise in high-performance computing capabilities and advances in computational tools, such as Advanced Ship and Submarine Evaluation Tool (ASSET) and Smart Ship System Design (S3D), naval engineers are now able to generate and evaluate thousands of possible designs during these crucial early stages of the design process [1].

The advent of new ship technologies provides additional motivation for naval designers to be able to evaluate a large number of possible designs. This is because the performance and impacts of novel technologies tend to be modeled probabilistically, rather than deterministic, since the exact values for their parameters may not be fully known. In other words, in order to quantitatively evaluate the costs and benefits of applying new technologies to a ship design, it is necessary to have a robust methodology that can appropriately account for their inherent uncertainty.

This paper explores the use of a methodology known as the Technology Identification, Evaluation, and Selection (TIES) method on the naval ship design process. Section II of this paper details the TIES process. Section III details a case study that was done to demonstrate the benefits of TIES by expanding upon the 10kton study performed by Chalfant et al. Lastly, Section IV concludes the paper with a discussion of the merits of using TIES to augment SBD and avenues for future work.

The work done in this study was motivated by an on-going effort conducted by Georgia Tech and the Electric Ship Research and Development Consortium (ESRDC). That effort focuses on exploring the ship-wide effects of high-temperature superconducting (HTS) technologies using a joint ASSET-S3D simulation platform.

II. OVERVIEW OF THE TIES PROCESS

As the number of new technology alternatives and possible combinations of these alternatives increases, a robust methodology for evaluating the overarching systems impacts of these design alternatives is needed. The methodology used for this project was the Technology Identification, Evaluation, and Selection (TIES) method [3]. TIES is a multi-step process that enables decision makers to assess the trade-off between the costs and benefits of various design alternatives and technologies. Another advantage of the TIES method is that it provides a framework where technically feasible and economically viable alternatives can be identified with speed and accuracy.

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The steps of TIES applied to this problem are as follows:

1. Problem Definition – a customer need must exist, or a Request for Proposals (RFP) must be issued to drive the design of a new product. Requirements / performance metrics / Figures of Merit (FOMs) should also be defined.

2. Baseline Identification – determine the variant that will serve as the initial data point to which other variants will be compared.

3. Baseline Evaluation – determine the performance metrics of the baseline.

4. Technology Identification – perform due diligence research to determine possible technologies that could improve the performance of the designs, using a technology compatibility matrix to determine possible technology combinations.

5. Technology Evaluation – quantify the possible impacts of the technologies through the use of technology parameters, evaluate the impact of each technology through the use of a Modeling and Simulation (M&S) environment.

6. Technology Selection – use a multi-attribute decision-making (MADM) technique to select the best variant.

A key integral component of the TIES process is the need for a unified modeling and simulation environment that allows designers to rapidly evaluate each design alternative and quantify the impacts of technology infusions at each level. For naval applications, ASSET was the tool selected to fulfill this role, along with the related Rapid Ship Design Environment (RSDE) allowing for a large number of ships to be evaluated rapidly.

III. CASE STUDY: 10KTON SHIP

In order to demonstrate the effectiveness of the TIES methodology within the naval SBD paradigm, a case study was conducted. This case study built upon the work performed by Chalfant et al. [4] on quantifying the performance of a 10 kton electric ship along with quantifying the impacts of several technologies. The purpose for choosing this study to build upon was that it provides verified results to compare against and it supports on-going work conducted by members of this team and the ESRDC.

A. Problem Definition

The problem as originally defined the by Office of Naval Research (ONR) was to design a 10,000 metric ton integrated power system (IPS) surface combatant that achieved at a minimum the thresholds defined in Table 1 below [4]. These outputs of interest will be referred to as the figures of merit (FOMs) for the remainder of this case study.

Table 1. Ship Design Parameters [4]

Parameter	**Threshold**	**Objective**
Installed Power	95 MW	100 MW
Maximum Sustained Speed	27 kts	32 kts
Maximum Battle Speed	25 kts	30 kts
Cruise Speed	14 kts	16 kts
Range	3,000 nm	6,000 nm

In the context of an electric ship, battle speed is defined as the maximum sustained speed that can be obtained with weapons and sensors in their active states.

Along with the parameters identified in the table, the ship was also to be equipped with nominal representations of possible future weapon and sensor technologies, such as a railgun, laser, or phased-array radar, in addition to the normal armament. To model these more power-dense items, some rough nominal dimensions, weights, and power & cooling demands were added under SWBS group 711 in ASSET's payload and adjustments table [4].

B. Baseline Identification

The baseline ship was developed by the MIT Sea Grant team using ASSET 6.3.45.1; please refer to [4] for a more detailed documentation of the original baseline ship design. After the publication of that study, the baseline ship was updated in terms of manning and installed components for improved results. The hullform is based upon a destroyer-type hull that was modified to achieve the prescribed displacement [4]. In order to achieve the required installed power and speed requirements, three LM-2500+G4 engines at 29 MW each and three LM-500 engines at 3.7 MW each were selected, bringing the total installed power on the ship to 98 MW, with two 36 MW permanent magnet motors providing the propulsive power needed for movement [4]. The advanced weaponry and sensors were modeled on the ship by accounting for them in the Payload and Adjustments table within ASSET.

C. Baseline Evaluation

Table 2 shows the results from the single point ASSET synthesis run of the updated baseline ship. This table shows that the thresholds for power and the speeds are able to be met; however, the threshold range of 3,000 nm is unable to be obtained, as this initial design was only able to reach 2,471 nm.

Table 2. Baseline Results

Parameter	**ASSET Value**
Installed Power	98.1 MW
Maximum Sustained Speed	29 kts
Maximum Battle Speed	27 kts
Displacement	10,000 mt
Range	2,471 nm

In order to determine if the baseline configuration has the possibility of achieving the range threshold, the design space around the baseline needs to be explored. The first step in this process is to identify several design variable choices and vary them within a set range. For this study, the design variables were selected to be a set of weights of several SWBS groups, as shown in Table 3. The Baseline column refers to the value taken from the identified baseline ship, the lower bound is the baseline value modified by -5%, and the upper bound is the baseline value modified by +5%. The design range was selected to be +/-5% in order to capture uncertainties from any possible advancements in the existing technologies utilized on board the current generation of surface combatants. The choice of SWBS group weights as design variables was due to the constraints within RSDE and ASSET.

Table 3. Input Variables for Design Space Exploration

SWBS Group	Lower Bound (mt)	Baseline (mt)	Upper Bound (mt)
235	817	860	903
311	920.55	969	1017.45
321	158.175	166.5	174.825
324	215.745	227.1	238.455
456	115.425	121.5	127.575
711	173.85	183	192.15

These design variables were then loaded into RSDE, and, using the built-in Latin Hypercube function, 350 design points were generated. The outputs captured by RSDE were Endurance Range, Design Maximum Speed, Design Sustained Speed, and Usable Fuel Weight. The results of the RSDE runs were then loaded into a statistical software package, JMP, to further analyze the results.

Figure 1 shows a scatterplot matrix with the weight delta from the baseline (in metric tons) of each SWBS group on the x-axis, and the output variables on the y-axis. From this, it can be seen that due to the restriction of the design variables to only SWBS weight values, and the fact that the hullform, propulsive properties, and total displacement were held constant, the design maximum speed and sustained speed remain unaffected in this design space exploration. Future work will need to be conducted in order to determine the impacts of those design choices (hullform, propulsive motor properties, and displacement) on the FOMs. However, it can be seen that SWBS 311 and 235 are the primary drivers behind the design endurance range because those two SWBS groups had the highest baseline weights.

In order to more clearly see if any of the design points achieve the range goals, the Probability Density Function (PDF) of the endurance range can be plotted. This plot is shown in Figure 2. From this distribution, it can be seen that the mean range is 2,471 nm, which makes sense, since this was a design space exploration performed symmetrically around the baseline, so one would expect its value to fall in the middle of the distribution. Furthermore, one can see that the entirety of the PDF, including the box-and-whisker plot, falls below the 3000 nm threshold for range.

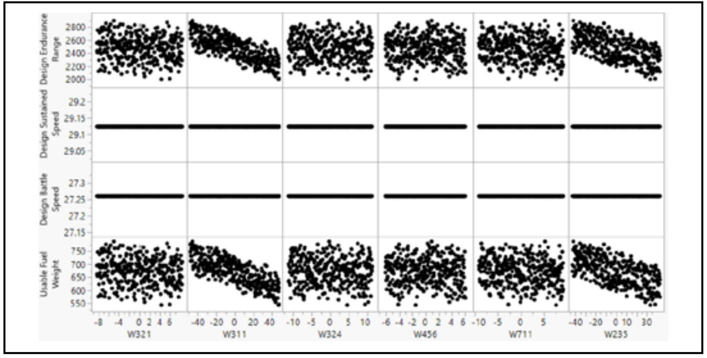

Figure 1. Scatterplot of the DSE

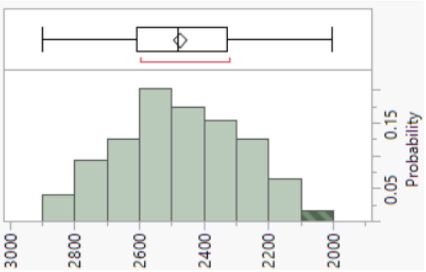

Figure 2. Probability Density Function of Endurance Range

Another way of viewing this information is, for each point represented in the PDF, one can take the 3000 nm threshold range, subtract the range of the design point to get the range difference below 3000 nm, which can then be transformed into a Cumulative Distribution Function (CDF), shown in Figure 3. This allows one to plainly view how many of the evaluated design points could possibly meet the 3,000 nm range threshold. As can be seen by the fact that the entirety of the range difference CDF falls above zero, there is a no probabilistic likelihood that any of the evaluated design points could achieve the 3,000 nm range threshold.

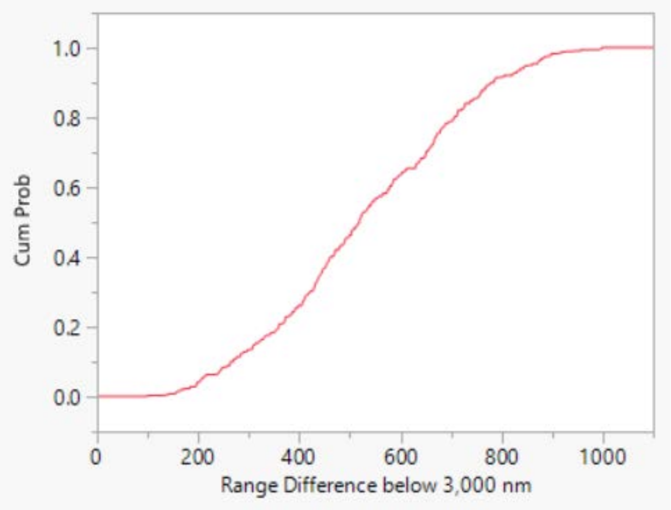

Figure 3. CDF of Range Distribution

This design space exploration around the baseline shows that even if the ship's current outfitting was optimized, the ship would be unable to meet the threshold requirements set forth by ONR. Therefore, in order to meet the requirements, a shift to new technologies outfitted to the ship is needed.

D. *Technology Identification*

Since the baseline design is unable to meet the full set of design requirement thresholds, technologies that have the potential to increase the performance metrics in question should be identified. One key metric for identifying new technologies is to examine the Technology Readiness Level (TRL) of a technology in question. TRL is a NASA-developed tool that quantifies how far along a certain technology is in its life cycle. [5]. It is based upon a 1 to 9 scale, shown in Figure 4. Technologies with a lower TRL are still in the conceptual development phase, a middle range TRL indicates that the technology has been taken to the prototype stage, and a high TRL indicates that the technology is ready for operational use.

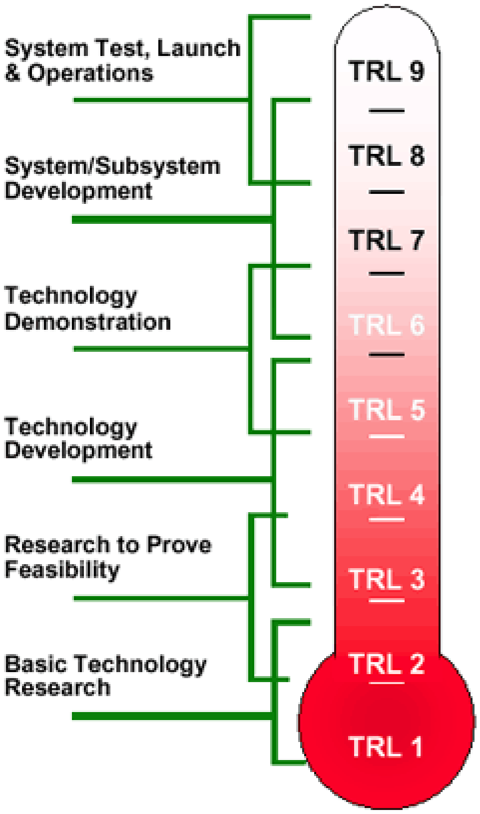

Figure 4. Technology Readiness Level Graphs [6]

TRL correlates with the level of uncertainty concerning the impacts of a certain technology. For example, researchers could identify a theoretical technology that could have a possible 25% impact on a certain criterion; however, as the theoretical technology is developed into a production technology, its true benefits could only be 12%. This illustrates the need for varying levels of uncertainty at each TRL. Even at a high TRL (8-9), a small amount of uncertainty will need to be accounted for in studies since the technologies have yet to be integrated onto a production ship. A strength of the TIES method is that it allows designers to explore technologies at all TRLs; for lower-TRL technologies, the uncertainty surrounding their performance will just need to be increased appropriately.

The work done by Chalfant et al. identified three possible technologies that have the potential to reduce the weight of the installed systems, thus increasing the range of the ship: 1. High speed generators (TRL ≈ 9), 2. Advanced Material power equipment (TRL ≈ 4), and 3. an alternative zonal topology based upon the MVDC architecture created by the U.S. Navy (TRL ≈ 8) [4][7]. These technologies and their impacts will be detailed below.

1. High Speed Generators [4]

High speed generators are currently one of the technologies being evaluated by the Navy for use on its surface combatants. When utilized in conjunction with a DC distribution system, the need for synchronization between the generators is eliminated, which allows for a significant reduction in weight as well as simplifying integration of machines with different operation speeds and frequencies. However, there is a tradeoff when using this technology: an increase in generator losses. Initial calculations estimated a total weight savings of approximately 207.7 metric tons in SWBS 311 – Power Generation and 2.5 metric tons in SWBS 321 - Cabling.

2. Advanced Material Power Equipment [4]

Advanced Material Power Equipment incorporates advanced wide-bandgap power conversion technologies. These technologies are currently being investigated by the Navy and other entities, as they offer several advantages such as increased distribution voltages, reduced transmission losses, higher operational temperatures, and reduced size & weight. The cascading effects of this allow for reduced cable weight and reduced cooling requirements. Initial calculations based upon regression from existing units in use in other application areas estimated a total weight savings of approximately 3.7 metric tons in SWBS 235, 20.6 metric tons in SWBS 311, 19.5 metric tons in SWBS 321, 92 metric tons in SWBS 324, and 5 metric tons in SWBS 514.

3. MVDC Alternate Topology [4]

Though this is being listed as a technology, it is technically an early-stage design choice; however, for the purpose of this case study, it is being classified as a technology by incorporating the weight saving benefits. This alternate topology is based on the proposed MVDC zonal architecture developed by the U.S. Navy, shown in Figure 5. The alternative topology is estimated to provide a weight savings of 36.6 metric tons in SWBS 311 and 9.8 metric tons in SWBS 324 at the expense of a weight increase of 37.8 metric tons in SWBS 321. It should be noted that this study is only exploring the impacts in terms of weight savings and not any potential survivability or other considerations.

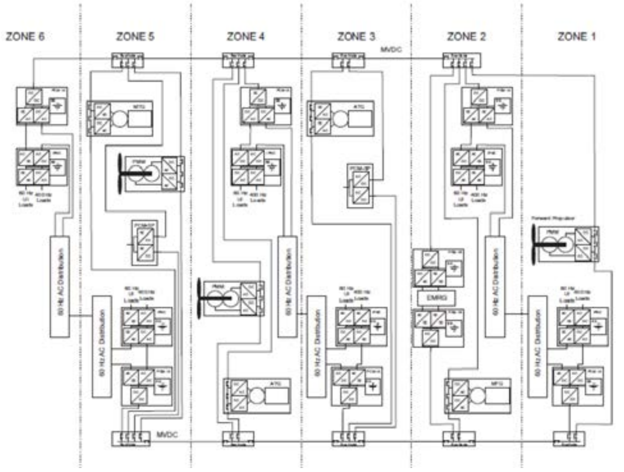

Figure 5. Notional MVDC Alternate Topology [6]

Table 4 summarizes all the weight savings identified in this section below; all numbers are listed in metric tons.

Table 4. Summarized Technology Weight Savings

	SWBS					
Technology	235	311	321	324	514	532
Advanced Materials	-3.7	-20.6	-19.5	-92	-5	0
Alternate Topology	0	-36.6	37.8	-9.8	0	-2.5
High-Speed Generators	0	-207.7	-2.6	0	0	0

E. *Technology Evaluation*

With the technologies identified and their initial benefits estimated, the next step in the TIES process is to evaluate each technology along with evaluating each possible technology combination. To do this, a technology compatibility matrix (TCM) is needed. A TCM is a symmetric matrix that lists the possible technologies across the left-hand side and the top. A 1 is inserted into the corresponding row and column of two compatible technologies and a 0 is inserted for two incompatible technologies.

There is also a possibility that two technologies are only partially compatible. This means that they can both be placed on the system, but the impact of both of them in combination is not simply the sum of their individual impacts, i.e. the impacts of two technologies are not purely additive. For cases like this, the TCM can be adapted to use a number between 0 and 1 to indicate the extent of the compatibility. However, for the purpose of this initial case study, the authors opted to simplify the analysis by inserting a 0 for any partially compatible technology combinations, such as the advanced power materials and the alternate topology. More thoroughly accounting for partial incompatibilities can be an area of future work.

The resulting TCM for this case study is shown in Table 5.

Table 5. Technology Compatibility Matrix

	Advanced Materials	**Alternate Topology**	**High-Speed Generators**
Advanced Materials	1	-	-
Alternate Topology	0	1	-
High-Speed Generators	1	1	1

Thus, it can be seen that there are five possible technology combinations for this initial case study: three for the base cases where just one technology is applied, a combination of advanced power materials & high-speed generators, and a combination of alternate topology & high-speed generators. Each of these five technology combinations required a new model in ASSET to be created. This was done by copying the baseline model and inserting the values identified in Table 4 into the payload & adjustments table. Recall that it is assumed in this study that the impacts of the technologies were simply additive, since the aim is to simply demonstrate the capabilities of the TIES method. In practice, this is often not the case, since these are complex systems, and integrating even one technology has cascading effects through the entire system. To capture these cascading effects, a more detailed design space exploration is needed, where components of the system are modeled at a higher fidelity level, which is why future studies will also bring in S3D.

With the models for each combination created, the next step is to evaluate the impacts of the technologies on the FOMs. To do this, RSDE was utilized with the design space being +/10% the values listed in Table 4. This was done to account for the uncertainties in the technologies' benefits, since they have yet to be utilized on a surface combatant. Even though the TRLs for each of the identified technologies were at different levels, the level of uncertainty in their impacts was assumed to be the same to demonstrate the TIES method. As with the baseline, each of the five new models was run through RSDE using an appropriately sized Latin Hypercube corresponding to the number of design parameters. The results were then loaded into JMP to conduct the statistical analysis.

In order to evaluate the performance of each technology combination, technology k-factors were used. K-factors normalize the design variables (the SWBS values listed in Table 4) to all designers to see which technology combinations have the greatest impact on the FOMs. As stated earlier, the only FOM that was studied in this paper was the design endurance range. Further details will be provided in the future

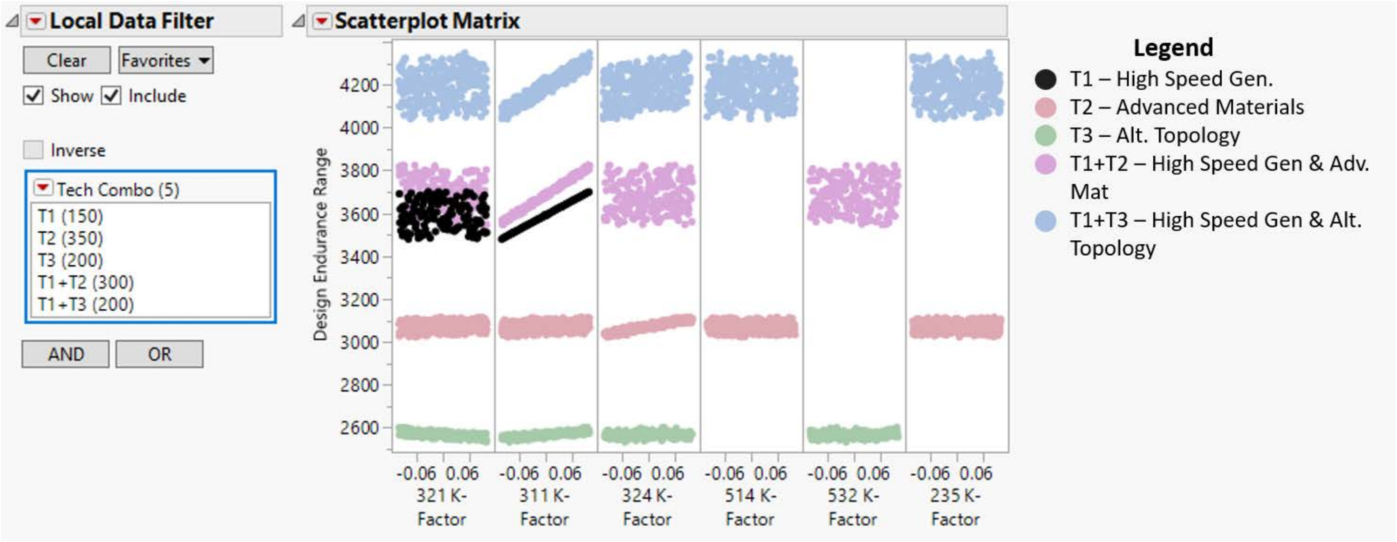

Figure 6. Scatterplot matrix of Tech Combinations evaluations

work section about expanding the design space to allow for more FOMs to be studied.

The results of the k-factor technology evaluation are shown in Figure 6. From this figure, it can be seen that all technology combinations aside from the alternate topology allow the ship to reach the range threshold of 3,000 nm. However, this study did not explore the other potential benefits that could be realized from this alternate topology due to the constraints of the simulation tools. As a result, the best combination from this study is the combination of high-speed generators and advanced power equipment materials. On average, this combination increased the range of the ship by about 1,800 nm over the baseline. This is a significant improvement over the baseline, and even in the worst case of the estimated technology combination benefits, they still enable the ship to obtain a 4,000 nm endurance range. One item to note is that the weight saving benefits from the high-speed generator are an order of magnitude higher than the other technologies, which accounts for the fact that it appears in all of the top technology combinations.

Since there was only one FOM considered, the technology combination that should be selected is the combination of high-speed generators and advanced material power equipment. However, when there are multiple FOMs and multiple technology combinations, there is a need for a robust selection method that allows for designers to understand the tradeoffs between different technology combinations. This process, while not done for this particular case study, will be detailed in the following section.

F. Technology Selection

In the design of complex systems, there are competing FOMs in a design and multiple technology combinations that can each satisfy the various FOMs to different degrees. As result, designers need a robust method that allows for them to make these multi-attribute decisions, i.e. which technology combination to select for the design. Multi-Attribute Decision Making (MADM) is a set of techniques that determine the best alternative, the best technology combination in this case, based upon a multi-attribute utility function that is closest to a hypothetical ideal solution.

The MADM techniques that the authors of this paper utilize in other works is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [8]. TOPSIS is a seven-step process and is detailed below [8][9]:

Step 1. Develop an n by m evaluation matrix, E, consisting of n alternatives and m criteria where x_{kj} is the evaluated criterion for that alternative.

	Criterion 1	Criterion 2	…	Criterion m
Alternative 1	x_{11}	x_{12}	…	x_{1m}
Alternative 2	x_{21}	x_{22}	…	x_{2m}
⋮	⋮	⋮	⋮	⋮
Alternative n	x_{n1}	x_{n2}	…	x_{nm}

$$E = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \ddots & x_{2m} \\ \vdots & \ddots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix}$$

Step 2. Normalize each entry of the evaluation matrix using the following equation:

$$\hat{x}_{kj} = \frac{x_{kj}}{\sqrt{\sum_{k=1}^{n} x_{kj}^2}}, k = 1,2, \dots, n; \;\; j = 1,2, \dots, m$$

Step 3. Determine a set of weights, w_j, such that their sum is equal to one and then create a diagonal matrix W such that each weight is assigned to its corresponding criteria number, i.e. w_1 is in the first column, w_2 is in the second, and so on.

$$W = \begin{bmatrix} w_1 & 0 & \cdots & 0 \\ 0 & w_2 & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & w_m \end{bmatrix}$$

Then create the weighted evaluation matrix, A, by multiplying E with W.

$$A = E * W = \begin{bmatrix} w_1 * \hat{x}_{11} & w_2 * \hat{x}_{12} & \cdots & w_m * \hat{x}_{1m} \\ w_1 * \hat{x}_{21} & w_2 * \hat{x}_{22} & \ddots & w_m * \hat{x}_{2m} \\ \vdots & \ddots & \ddots & \vdots \\ w_1 * \hat{x}_{n1} & w_2 * \hat{x}_{n2} & \cdots & w_m * \hat{x}_{nm} \end{bmatrix}$$

Step 4. Determine the best ideal alternative, A_b, and the worst ideal alternative, A_w, which are the maximum and minimum values for each column of the weighted evaluation matrix.

$$A_b = [\max(w_1 * \hat{x}_{11}, w_1 * \hat{x}_{21}, \ldots, w_1 * \hat{x}_{n1}), \ldots, \max(w_m * \hat{x}_{1m}, w_m * \hat{x}_{2m}, w_m * \hat{x}_{nm})]$$

$$A_w = [\min(w_1 * \hat{x}_{11}, w_1 * \hat{x}_{21}, \ldots, w_1 * \hat{x}_{n1}), \ldots, \min(w_m * \hat{x}_{1m}, w_m * \hat{x}_{2m}, w_m * \hat{x}_{nm})]$$

Step 5. Determine the Euclidian distance between the best, d_{kb}, and worst, d_{kw}, solution for each alternative.

Step 6. Calculate the similarity to the worst solution using the following formula:

$$s_{kw} = d_{kw} / (d_{kw} + d_{kb})$$

Step 7. Rank the alternatives in descending order by their similarity to the worst solution. Since the better solutions will have larger distances from the worst solution and smaller distances from the best solution, their s_{iw} values will be larger. Thus, the first item in the descending order ranked list will be the best solution that accounts for the relative weighting of the criteria.

It is considered best practice to repeat the TOPSIS process several times using a variety of weight vectors to remove any biases from the weights and then plot all results on a radar plot to count the number of times a design appears in the top rankings. This allows the designer to determine if there is a small subset of design alternatives that outperform the rest. By doing this, designers could perform a more detailed analysis on that much smaller subset in order to select their final design.

IV. Conclusion And Future Work

This case study demonstrated how the TIES method could be applied to the design of a U.S. Navy electric surface combatant. It showed how to identify a baseline and then perform a design space exploration around the baseline to determine its possible performance capabilities. The next step was to determine if the baseline was able to achieve the requirements detailed in the problem definition using probabilistic methods. If it was unable to meet any of the requirements, the next step was to identify possible technologies. Once the technologies have been identified, a design space exploration is done again to determine the performance of the technology-infused baseline. The last step was to use a MADM process to select which technologies should be used for the design. This is a very robust methodology that can be applied to any design process.

As shown by Figure 6, although the 3,000 nm minimum threshold range could be met, no possible technology combination explored in this study was able to reach the goal range of 6,000 nm, so future work is needed to identify and evaluate technologies that will enable a 10 kton ship to get closer to achieving all of ONR’s goals. The main driver behind this inability to meet the range requirement stems from the issue of meeting the power generation requirements while also having sufficient fuel load. Therefore, future research thrusts should explore technologies that can increase the power density of the ship, the efficiency of the power generation systems, or the efficiency of the propulsive system. Increasing any of those factors could allow for an increase in fuel load, which in turn leads to a probable increase in the ship’s range.

In addition to that, there needs to be continued effort on working with the evaluation tools to allow for many different hullforms to be created and evaluated in a more automated process. An immediate effort is to expand the modeling and simulation environment to include not only ASSET and RSDE but also the Smart Ship System Design (S3D) tool, which has been undergoing extensive development and upgrades to support this type of broad trade space exploration for the latest electric ship technologies [11][12]. There is also ongoing effort in using templates to aid in design space exploration [10]. These types of upgrades will allow designers to explore more design alternatives and technologies in the early stages of the design cycle, which should ultimately result in a more effective surface combatant.

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