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PLATFORM-BASED DESIGN OF A FAMILY OF SHIPS CONSIDERING BOTH PERFORMANCE AND SAVINGS

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ABSTRACT

This paper presents a multiobjective ship family design optimization methodology that accounts for mission effectiveness, cost, and commonality savings. A ship synthesis model is adapted to predict design performance, and cost and savings models are developed to evaluate design alternatives. An evolutionary algorithm is utilized to search the design space for feasible designs of multiple ship variants. The methodology is applied to the U.S. Coast Guard Deepwater High and Medium Endurance Fleets that are currently being constructed and developed, respectively, to enable interpretation of results relative to a real family design problem. Results demonstrate that commonality across ship designs does not necessarily yield fleet-wide savings: platform-based family design decisions must be made while accounting appropriately for performance-cost-savings tradeoffs.

Keywords: Product families, product platforms, commonality, performance, cost, savings, naval ship design, multiobjective optimization, evolutionary algorithms

1 INTRODUCTION

Naval ship design has been performed traditionally on a ship class by ship class basis. Ships are generally designed to maximize their mission performance without considering the design of other ships in their fleet. Common hull blocks, main engines, engine rooms, ship service generators, sensors, and weapons could be used in different ship classes to decrease costs associated with design, development, construction, and operation, and thus offer part of the solution for an affordable future fleet. Despite the presence of commonality within a fleet of ships, the shipbuilding industry has yet to accept platform techniques as a standard of practice. The strategic design question is which elements should be included in the platform (the set of common subsystems) to maximize savings without excessive degradation of the performance of the variants in the family, as the use of commonality in design often comes with compromises in mission effectiveness of individual designs.

Several methods for platform-based design of product families have been reported in the literature; a recent survey paper does an excellent job in classifying them [1], and a book based on invited contributions presents most of the popular methodologies [2]. We discuss here a relatively small sample due to paper length limits. Gonzalez-Zugasti, Otto, and Baker used a general optimization problem which balances the advantages of sharing components with the constraints of individual product variants to form an interactive, team-based negotiation model for designing a product family based on a common platform [3]. Designs are optimized for performance subject to cost constraints, and the optimization is performed on the variants on a “one at a time” basis rather than optimizing them concurrently. Simpson, Maier, and Mistree focus on scale-based product families that are derived based on both functional and manufacturing considerations [4]. Their methodology has been extended several times. For example, Nayak, Chen, and Simpson developed robust design concepts to formulate a variation-based platform design methodology [5]. They consider performance and production considerations, but do not explicitly mention cost savings considerations. Fujita and Yoshida proposed a simultaneous optimization method for module combination and module attributes of multiple products [6]. Their method optimizes the combinatorial pattern of commonality and similarity, similarities on scaled-based variety, and continuous module attributes. Considerations are made for performance, cost, and profit of the design variants based on a fixed modular architecture. Fellini et al. developed a methodology for selecting the product platform by using information from the optimization of individual product variants and maximizing it subject to performance loss bounds under the tacit assumption that more commonality is better [7-8].

In ship design, Brown and Salcedo presented a design optimization methodology based on life cycle cost and mission effectiveness [9]. They explore the many variations that are possible in a given ship design, and, by using various combinations of combat systems, engine selections, hull form parameters, manning, endurance, and mobility, they explore the design space efficiently for non-dominated designs using life cycle costs and a measure of mission effectiveness. A multiobjective genetic algorithm is used to search the design space. Zalek, Parsons, and Papalambros use a multiobjective evolutionary algorithm to search the design space for optimized monohull forms with respect to calm water powering and seakeeping [10]. Neither paper considers the design of a family of ship variants, but rather gives the methodology for the optimal design of one ship class. In 1992, the U.S. Navy began an initiative titled "Affordability through Commonality" [11, 12]. The goal of this initiative was to lower costs of fleet ownership through the use of increased commonality. The Navy defined commonality as using modularity, equipment standardization and process simplification. The use of commonality would ultimately lower all life cycle costs associated with design, construction and operation of the Navy's ships. Though the Navy was committed to using this new fleet ownership strategy, it does not appear they had a formal methodology developed to help them make cost effective commonality decisions.

This paper presents a methodology that extends the traditional approach to making commonality decisions by accounting explicitly for the cost savings associated with the use of commonality in designs. A multiobjective design optimization problem is formulated and solved for maximizing both family savings and individual performance of each variant in a family (or fleet) of ships.

2 PROBLEM DESCRIPTION AND MODELS USED

In the marine design problem considered here, we adopt a multiobjective optimization approach [13] with explicit consideration of the savings related to commonality decisions. Without loss of generality, we include only two variants in the vessel design family and we seek designs that:

- maximize the fleet-wide savings resulting from the use of a common platform
- maximize the performance of variant one for mission one relative to average ship cost
- maximize the performance of variant two for mission two relative to average ship cost

subject to design feasibility constraints. The Pareto set is obtained using a multiobjective evolutionary algorithm [14-16]. These algorithms have been developed in recent years and have been applied to a number of marine design problems [9-10, 17-20]. The quantification and display of the Pareto front provides designers with useful information necessary to make rational platform design decisions by accounting for savings that will result from using a common platform and the resulting loss in variant performance compared with their single mission designs without the use of a platform.

2.1 Ship synthesis model

For the purposes of this work, a ship synthesis model was needed. Since the goal of the optimization is to generate scores of ship variations with minimal input, the synthesis model had to be simple yet adequate in providing initial point design characteristics which could allow for basic cost estimates and performance evaluations.

The ship synthesis model used here was adapted from the Performance-Based Cost Model of the U.S. Coast Guard Engineering Logistic Center. The model was developed by the Naval Surface Warfare Center Carderock Division as a means to conduct comparative ship studies. It is capable of synthesizing frigate-sized, deep-water, white hull cutters using previously developed models of relevant ship types, and yields acquisition, operational, and support costs. The ship synthesis algorithms are based on a combination of SHOP 5 and ASSET algorithms. SHOP 5 is a Canadian model for monohull frigates and destroyers based on NATO frigates. ASSET (Advanced Surface Ship Evaluation Tool) is used extensively within NAVSEA and represents a mixture of first principle algorithms as well as regression analysis of historical U.S. combatant ship data, including the U.S. Coast Guard's WMEC 270 class of ships. The model provides reasonable results for deep-water cutters with displacements of 1500 Long Tons or greater. The Cost Estimating Relationships (CERs) for the basic construction costs were developed by SPAR Associates Inc. and are based on the U.S. Coast Guard's WHEC 378, WMEC 270, and WMEC 210 classes of ships. Additional CERs were adapted from the CERs that were developed for the U.S. Coast Guard's Great Lakes Icebreaking estimate.

The inputs to the program are performance-based and allow the user to examine up to 21 variations in design. The program calculates ship dimensions, powering requirements, electrical load, auxiliary systems weight estimates, outfit and furnishing weight estimates, variable loads, and habitability/personnel space volumes. This information is used to determine the weight of each ship weight breakdown structure group, lightship displacement, growth margins, ship loads, and full load displacement. A volumetric check is also performed to ensure adequate space is allotted for necessary compartment volumes. Once the ship is balanced and has adequate volume, the program calculates procurement costs for the lead ship and follow-on ships as well as operating and support costs for the life of the ships.

A few changes were made to make the ship synthesis model more suitable to the needs of this work. The model (originally programmed in Microsoft Excel) was reprogrammed in C++. Initial changes included changing some of the inputs and calculations. The adapted synthesis model was changed to require fewer inputs than the original Coast Guard model. The resulting independent variable inputs were the power plant type, midship section coefficient, block coefficient, length, maximum speed, range at cruise speed, number of helicopter hangers and the weapons system type. By limiting the number of inputs to eight, the user can control the variable design space more easily and limit the number of possible ship variants to a more manageable number. The remaining variables are made dependent on the eight input variables and follow logical ship design practice. Finally, the adapted ship synthesis model was expanded to ensure that its outputs satisfied a few standard Naval Architecture constraints. These include a more refined weight-displacement check, a basic stability check, and a more robust volume check.

2.2 Coast Guard cutter variants

This study utilizes the U.S. Coast Guard's Deepwater Fleet requirements. Specifically, the Operational Requirements of the Maritime Security Cutter Large (WMSL), formerly known as the National Security Cutter (NSC), and the Maritime Security Cutter Medium (WMSM), formerly known as the Offshore Patrol Craft (OPC), are considered for the two family variants. In reality, the first NSC was launched in September 2007, and the OPC is currently being designed. The mission requirements of these two real classes of ships were used to examine the validity of the optimization methodologies. Table 1 summarizes the design characteristics of the two ships.

Table 2 shows the design independent variable ranges that were set to approximately +/- 10% of the actual/anticipated ship design characteristics. The two power plant types represent either (1) a combined four diesel engine (two cruise-two sprint) plant (CODAD) or (2) a combined two diesel cruise engine and one sprint gas turbine plant (CODOG). The three weapons system types represent either (1) a 46 mm gun, (2) a 57 mm gun, or (3) a 57 mm gun and a Phalanx Close-In Weapon System (CIWS).

2.3 Performance over average cost model

The performance or mission effectiveness of the two different ship designs (i=1,2) is related to four specific missions (j=1,2,3,4): national defense, drug interdiction, living marine resources protection, and alien migration interdiction/general defense operations. The ability of each ship i to successfully accomplish each mission j is assumed to depend upon four performance characteristics x_k: maximum speed, endurance range, number of helicopter hangars, and the weapons suite carried. The contribution of each of these performance characteristics k to the success in each mission j is characterized by a fuzzy membership function or utility $0 \leq U_{ijk}(x_k) \leq 1$. The overall mission effectiveness or performance per average ship cost is then obtained by minimum correlation inference as follows:

$$\left[\frac{Performance}{Cost}\right]_i = \sum_{j=1}^{4} \frac{MP_{ij} \min\left[U_{ijk}(x_k)\right]}{Cost_i}$$

where the MP_{ij} are the percent of time that vessel i is engaged in mission j and $Cost_i$ is the average acquisition cost of vessel i.

Table 1. Design characteristics for the considered ship family (fleet) with two variants

Characteristics	Actual NSC	Anticipated OPC
Number of cutters in the fleet	8	25
Length	418'	Estimate 350'
Max beam	54'	Estimate 51'
Navigational draft	21'	Estimate 21'
Displacement	4300 LT	Estimate 3000 LT
Sprint speed	29 kts	26.5 kts
Sprint speed range	2,600 nm	1,550 nm
Sprint speed endurance	3.91 days (94 hrs)	2.5 days (60 hrs)
Economical speed	8 kts	9 kts
Economical speed range	12,000 nm	9,000 nm
Endurance	60 days	45 days
Propulsion plant	2 Diesel engines, 1 gas turbine	4 Main diesel engines
Bow thruster	Yes	Yes
Gun for weapon system	57mm gun	57mm gun
Gunfire control	Mk-160/Mk 46/SPQ-9B	Mk-160/Mk 46/SPQ-9B
Operating days away from homeport	230	230
Mission days per year	200-220	200-220
Berthing capacity limit	148	106
Number of helicopters hangars	2	2

Table 2. Independent variable ranges

Independent variables	Range
Power plant type	1 or 2
Midship coefficient	0.75-0.99
Block coefficient	0.45-0.85
Length	270'-470'
Max speed	18-31 knots
Range at cruising speed	8000-14000 nm
Number of helicopter hangars	1 or 2
Weapons system type	1, 2, or 3

2.4 Fleet savings

By using common engines and/or weapon systems, savings can be found in a variety of ways. Some examples of where savings can be realized is in crew training, spare parts, generation of manuals, and in engineering integration of components. If a fleet of ships all have these common components, training of crew members can be simplified. If a crew member were to transfer from one class of ship to another, he/she would not have to be retrained on the engine or weapon system resulting in a savings of time and money. Instead of having to conduct training on multiple engines or weapon systems for crew members within a fleet of ships, only one school would be necessary for each. Savings could be realized in training facilities and staff. Depending on the location of the home ports of the ships within the fleet, commonality can lead to a significant savings in spare parts. If ships of two classes are located near each other, the need for two sets of spare parts is eliminated. This results in a savings in purchasing the spare parts as well as storing the spare parts. Shore based maintenance may also be a source of commonality savings in that they will only have to service one type of engine or weapon system. When an engine or weapon system is installed on a ship there is a nonrecurring cost associated with that installation. If commonality is used in a fleet of ships, the cost of this installation will only occur once and can be spread out over the entire fleet of ships. If no commonality is used, the cost may occur for each class of ships and be spread out over smaller numbers of ships. In addition to engineering design, administrative savings can also be realized. Engine manufacturers generate owner's manuals for each ship. The cost of this can be reduced if only one type is needed.

If a fleet of ships is able to use the same superstructure or midship section design, savings can be found in the construction learning curve as well as the design of those areas of the ships. As shipyards construct sections of a ship, there are lessons learned that helps them become more efficient in their work. This efficiency will save them time and money in the construction process. The more common pieces they construct, the more they will learn and significant savings can be made through this form of commonality. The fleet savings that was calculated in this case study was based on either the savings as a result of bulk purchasing or the savings associated with a construction learning curve. The savings model was limited to these two types of savings. The following sections explain how the savings for each commonality was calculated.

In calculating the fleet savings for the use of a common weapon system, the cost of the common fleet of ships was compared to the cost of a fleet of ships that were designed with no commonality. After the baseline (no commonality) Pareto front was established, the optimization was run with reduced search ranges that focused on each of the endpoints of the baseline curve. In doing so, it ensured that the ships designed were those best suited for their specific missions. This resulted in baseline ships for both the National Security Cutter (NSC) and the Offshore Patrol Craft (OPC). Commonality was considered for the weapons system, ship service generators, cruise engines, superstructure, and the midship section region of the ship hull.

2.4.1 Weapon system savings

As mentioned above, the savings associated with the purchase of weapon systems was limited to the bulk purchase for the entire fleet. A cost schedule was created based on the number of units purchased and the savings was the difference between the ships with no commonality and those with common weapons. The assumed amount of savings for using common weapon system on all 33 ships was 10% for types 1 or 2 and 20% for type 3. The fleet savings associated with using common weapon systems 1 and 2 are given by the sum of the NSC Fleet Savings and the OPC Fleet Savings

$$\#Ship_i * \begin{bmatrix} wg700Cost^0_{Ship_i} * (1.0031 - 0.0031 * \#Ship_i) - \\ wg700Cost^i_{Ship_i} * (1.0031 - 0.0031 * \#ships) \end{bmatrix}$$

,where *wg700Cost* is the material cost of one weapon system, *#Ship$_1$* is the number of NSCs (8), *#Ship$_2$* is the number of OPCs (25), and *#ships* is the total number of ships being built (33). The superscript 0 represents the NSC and OPC that were designed without commonality, and the superscript *i* represents the current ship being considered. The fleet savings associated with using common weapon system 3 was calculated similarly.

2.4.2 Ship service generator savings

The savings associated with the use of common ship service generators were computed in the same way as for the weapon systems. Because the number of generators is not constant for all ships, the savings had to include number of generators purchased. The assumed savings associated with using a common generator on all 33 ships (132 generators) is 10%. The fleet savings associated with using a common generator are calculated as the sum of the resulting NSC savings and the OPC savings

$$\#Ship_i * \#Gens_{Ship_i} * \begin{bmatrix} \dfrac{wg300Cost^0_{Ship_i}}{\#Gens^0_{Ship_i}} * (1.0008 - 0.0008 * \#Ship_i * \#Gens^0_{Ship_i}) - \\ \dfrac{wg300Cost^i_{Ship_i}}{\#Gens^i_{Ship_i}} * (1.0008 - 0.0008 * (\#Ship_i * \#Gens^i_{Ship_i} + \#Ship_j * \#Gens^i_{Ship_j})) \end{bmatrix}$$

where *wg300Cost* is the material cost of ship service generators for one ship.

2.4.3 Cruise engine savings

Again, a cost schedule was created for the savings associated with the use of common cruise engines. All ships have two cruise engines. The cost savings associated with using common engines for all 33 ships (66 engines) was 15%. The fleet savings associated with using common cruise engines are calculated as the sum of the resulting NSC savings and OPC savings

$$2 * \#Ship_i * \begin{bmatrix} 0.6 * wg200Cost^0_{Ship_i} * HPRatio^0_{Ship_i} * (1.0023 - 0.0023 * 2 * \#Ship_i) - \\ 0.6 * wg200Cost^i_{Ship_i} * HPRatio^i_{Ship_i} * (1.0023 - 0.0023 * 2 * \#ships) \end{bmatrix}$$

where 0.6 is the fraction for the engines in the total propulsion system, *wg200Cost* is the material cost of the propulsion system, and *HPRatio* is the fraction of total ship power provided by the cruise engines.

2.4.4 Superstructure and midship section savings

The savings used for common superstructures and the midship sections were limited to construction labor costs. By applying a learning curve to the labor cost of construction, savings can be calculated by summing the savings for the NSC and the OPC. For a common superstructure, the savings was calculated using

$$\frac{\#Ship_i}{\#ships} * \left[\begin{array}{l} ((wg100Cost^0_{Ship_i} * SSRatio^0_{Ship_i} * (\sum_{i=1}^{8} Learn)) + (wg100Cost^0_{Ship_j} * SSRatio^0_{Ship_j} * (\sum_{i=1}^{25} Learn))) - \\ (\frac{\#Ship_i * (wg100Cost^0_{Ship_i} * SSRatio^0_{Ship_i} + \#Ship_j * wg100Cost^0_{Ship_j} * SSRatio^0_{Ship_j}}{\#ships} * (\sum_{i=1}^{33} Learn)) \end{array} \right]$$

where *wg100Cost* is the material cost of a ship hull and superstructure, S*SRatio* is the ratio of superstructure weight to ship weight, and *Learn* is the learning curve rate. The midship section savings were calculated the same way with one exception. Instead of using at term parallel to *SSRatio*, a constant ratio of 0.2 was used to model the extent of the common midship section block(s).

Another form of savings may also occur. In some instances, a pair of optimized designs may have a common component despite not having designated it as common. This can occur with the weapon systems, ship service generators and cruise engines, but is very unlikely with the superstructures and midship sections. When such an occurrence exists, the savings value for that component is calculated as described in the equations above. The total fleet savings that results from the use of commonality in design are calculated by summing up each of the savings components described above.

3 PLATFORM-BASED FAMILY DESIGN

3.1 Considered commonality alternatives

As presented in Section 2.4, we considered five subsystems as commonality candidates in this study: weapon systems, ship service generators, cruise engines, superstructure, and midship section. There were three options available for the first two and two each for the other three, resulting into a total of 432 possible combinations (including the "no-commonality" option for each). From these 432 combinations, 144 proved to be infeasible due to mutual incompatibility leaving 288 combinations to be examined.

For the three possible weapon system types, the difference from one weapon system to another is limited to its weight and cost. The weight of the weapon system obviously has some impact on the designs but this effect is small in this example.

The ship service generators are a little more complex regarding their impact on the overall ship design. Since the choice of ship service generators is not an independent variable, but rather a dependent variable, its implementation is different from that of the weapon systems. If no generator is designated as common, the ship synthesis selects a generator to be used in each design and the number of generators used in each design is four. However, if the generators are designated as common, the ship synthesis selects the number of generators required to meet electrical load requirements of the ships. The effect of the generators also goes beyond just weight considerations. In addition to accounting for the weight of the generators, the synthesis must also allocate space for the generators in the design.

The cruise engines showed another aspect of the use of commonality in the optimization process. The choice of cruise engines limited the number of possible designs that could meet the cruise speed requirement. Similar to the ship service generators, the choice of cruise engines is a dependent variable and cannot simply be designated without further consideration. The ship synthesis was permitted to run as if no cruise engine commonality were chosen. Once it had a ship designed, it checked to see if the engine used was the desired common engine. If it were, the design was kept. If not, the design was discarded. This process allowed for the iterative ship design process to take place while ensuring that the cruise engines satisfied the cruise speed requirements. During the iterative process, the synthesis model changes engines as needed to ensure the correct engine is being used for each design. If the common cruise engine is forced into the design, the iterative process is disrupted and the synthesis model may not work as expected. While less efficient, this process proved more reliable in its ability to create valid ship designs.

The superstructure is primarily a function of the number of helicopter hangars on the ship which also influences the beam of the ship. These characteristics along with the volume of the superstructure make up a commonality component. By using the superstructure as a common component both independent variables and dependent variables are being designated. The number of helicopter hangars is an independent variable while the beam and volume of the superstructure are dependent variables. In the synthesis, the beam and the volume were first calculated in the iterative model. The synthesis model would perform calculations for beam and volume as if no commonality was being used. Once calculated, the values were overwritten to the necessary values for the designated commonality and the process was continued.

The size of the midship section was also largely dependent on the number of helicopter hangars on the ships. Other characteristics of the midship section included the midship coefficient, depth of the hull, and the beam of the ship. This commonality component consists of both independent (number of hangars and midship coefficient) and dependent variables (depth and beam). Similar to above, the depth and beam of the ship were determined in the iterative process and then changed when necessary to satisfy the commonality requirement.

3.2 Evolutionary Algorithm

The optimization was conducted using a multiobjective evolutionary algorithm adapted from the one used in Zalek et al. [10]. The following settings were used: archive size = 50, population size = 150, number of offspring per generation = 100, maximum number of generations = 200. Due to paper length limitations, we do not provide more information about the optimization algorithm and process here. The interested reader can find a detailed description in references [21, 22].

3.3 Results

The scope of this paper is to present the methodology that accounts for fleet savings due to commonality and to discuss the obtained results. Figure 1 depicts the design endpoints for each of the 288 feasible Pareto optimal pairs corresponding to a commonality option. The results are grouped in three sections. The uppermost section consists of 128 NSC designs. The middle section consists of 160 NSC designs. The remaining section near the bottom makes up the 288 OPC designs. The reason that the NSC designs are split into two sections is due to the nature of the commonality that is being forced into the designs. The 160 NSC designs in the middle of the plot have certain defining characteristics: 144 of those designs have a small superstructure, a small midship section, or both designated as common. The remaining 16 designs have no commonality designated for the superstructure or the midship section but have the smaller cruise engine designated as common. These three characteristics are all indicative of smaller vessels. All 160 designs have only one hangar, which is a requirement for the small superstructure and midship section commonalities. To meet the cruise speed requirement, the use of the smaller common cruise engine supports only smaller vessels. Because of the way the fuzzy utility functions have been set in this example, the single hangar introduces the significant drop in the NSC performance/cost. Also as a result, all NSC designs with one hangar have reduced ranges near 9000 nm. The weapons systems and generators selected for these designs do not influence this tendency toward the middle of the graph.

It is often presumed that commonality is always good although it is expected that by using common components there will be a loss in performance. It is assumed that this loss in performance is outweighed by the cost savings associated with using common components. These cost savings are the driving force behind the use of commonality in design. One can observe in Figure 1, however, that negative fleet savings actually occurred in 129 of the 288 combinations. The negative fleet savings are a result of penalties from overdesigning the OPC. The OPC that was designed without any commonality had the least expensive weapon system, generator and cruise engine used in the solutions. These less capable components enabled the OPC to meet its mission performance requirements. If more expensive options for each of these components are forced into the design through commonality, the OPC will still meet its performance requirements but at a more expensive cost. Even though bulk savings will occur, the cost of the more expensive components will be more expensive overall. The result is that if the more expensive weapon systems, generators or cruise engines are made common, the OPC will have a negative savings that may overwhelm the savings realized from the NSC.

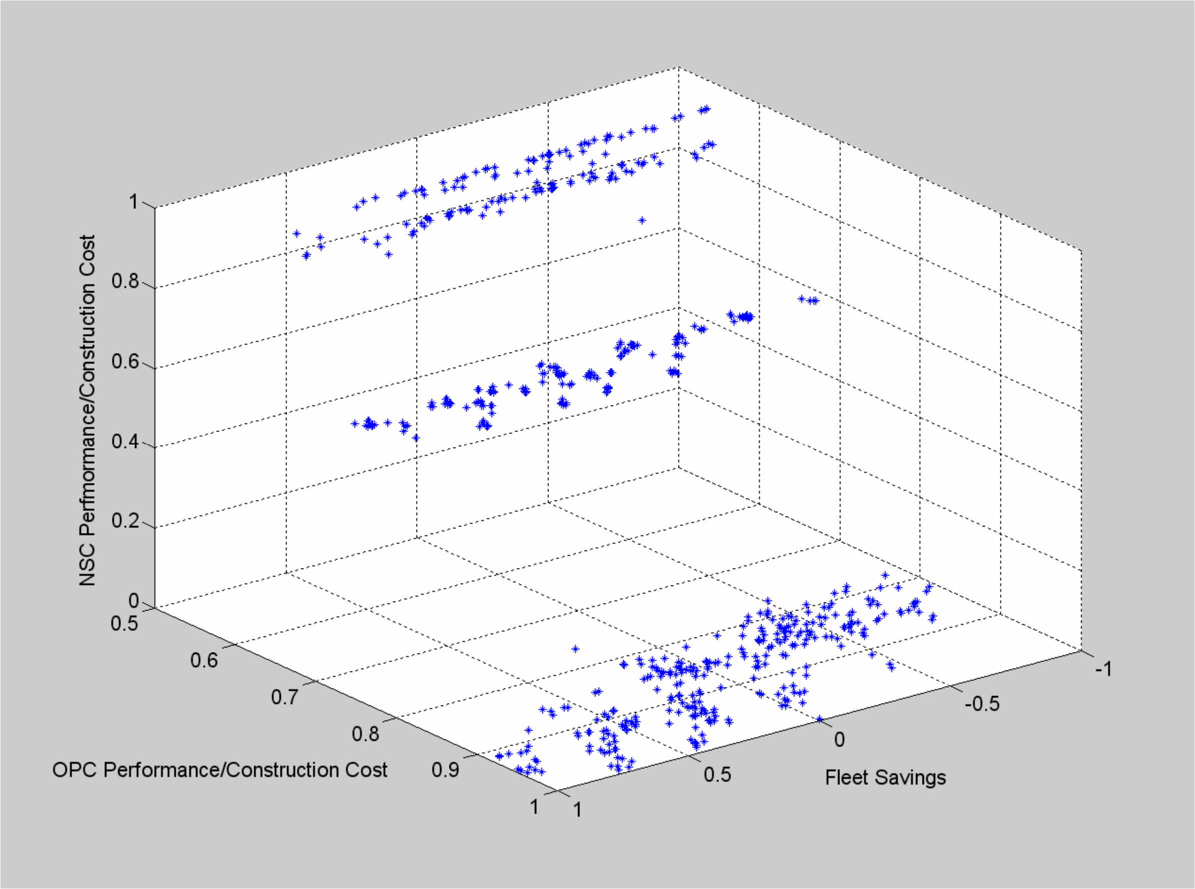

Figure 1. Solution set prior to dominance sorting

The components with the greatest potential for large commonality savings are the ship service generators, cruise engines, and superstructure. These large savings are possible when the smallest generators and cruise engines are designated as common. The cruise engines and generators can also have large negative savings values. Using the largest generator or cruise engine as common will result in the greatest negative savings values. A common superstructure, which always results in a positive savings, has the largest savings when the smaller option is used. The midship section and weapon systems have a much smaller impact on savings, either positive or negative. Again, the smaller options tend to result in positive savings and larger options tend to result in negative savings due to OPC over design. Because of the relative costs of each of the components that are considered for commonality among the designs, some are more influential to savings than others. Table 3 lists the relative importance of each component in its potential to create savings.

Table 3. Relative influence of components on savings

Positive Savings		**Negative Savings**	
Component	**Relative Importance**	**Component**	**Relative Importance**
Generators	1.000	Generators	1.000
Cruise engines	0.806	Cruise engines	0.934
Superstructure	0.512	Midship section	0.230
Midship section	0.120	Weapon system	0.031
Weapon system	0.014	Superstructure	0.000

A final dominance sorting was performed to obtain the designs on the final Pareto set. Figure 2 shows the baseline ships and the twelve pairs of ships determined to be distinctly different from a naval architectural viewpoint.

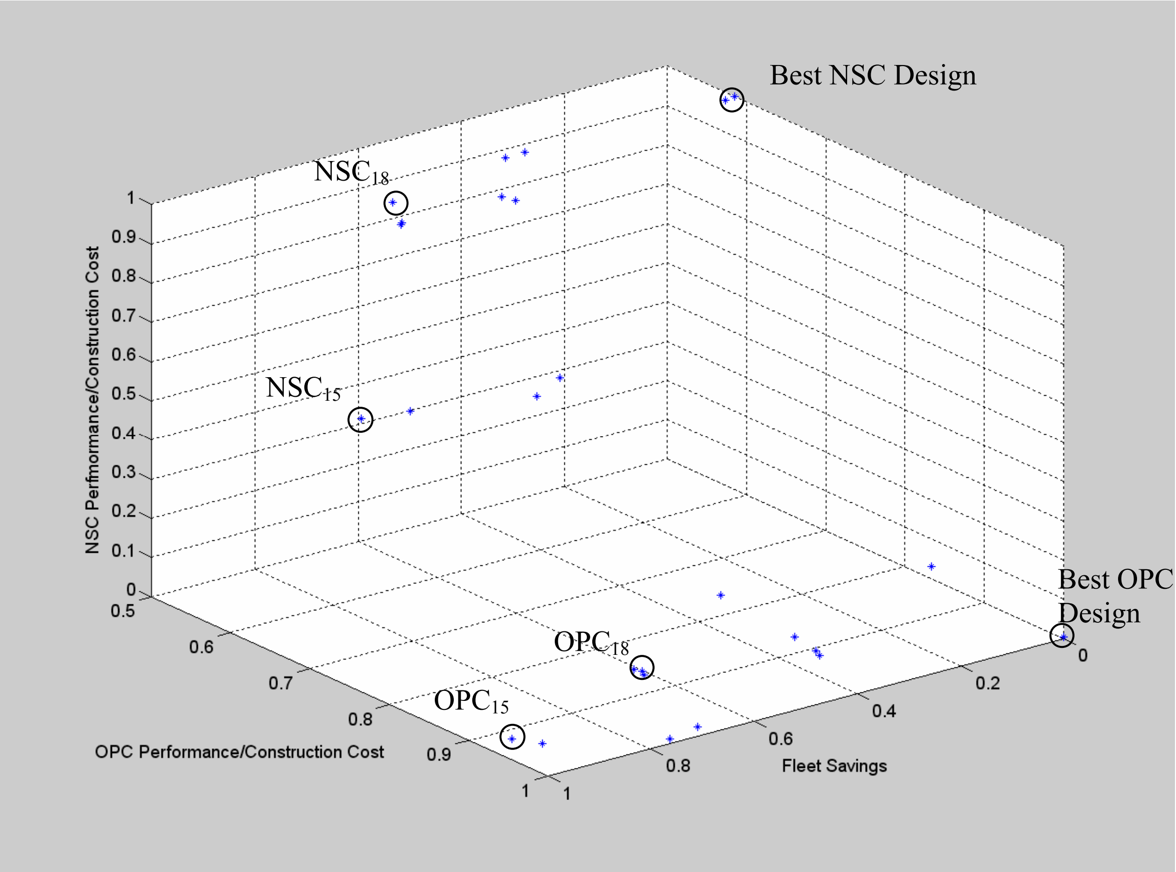

Figure 2.Final Pareto set

Table 4. Pareto Front Commonality Strings with Corresponding OPC and NSC Ship Numbers

CW	CG	CC	CS	CM	OPC Ship	NSC Ship
1	1	1	N	N	14	3
1	1	N	N	N	7	7
2	1	N	N	N	9	9
3	1	N	N	N	12	12
1	1	1	N	Small	16	2
3	1	2	N	Large	10	10
3	1	N	N	Large	11	11
1	1	1	Small	N	13	17
1	1	1	Small	Small	15	15
1	1	N	Large	N	6	6
2	1	N	Large	N	8	8
N	1	N	Large	N	18	18

Table 4 shows the commonality strings and the corresponding OPC and NSC solutions that comprise the final Pareto set. In some instances, ships that were not originally paired together have been matched with another ship. In these cases, one or more components were not designated as common. Through the course of the optimization, certain components may have naturally become common. One example of this occurring is seen in Table 4. OPC ship 14 and NSC ship 3 have been paired together. During the optimization run, OPC ship 14 only had ship service generators and cruise engines designated as common. However, the synthesis designated weapon system 1 as being the best choice for this particular ship. NSC ship 3 had weapon system one designated as common along with generators and cruise engines. Since OPC ship 14 was determined to be a better design that OPC ship

3, it was used in its place. As a result, these two ships have the same components common and can be paired together.

The results in Table 4 show some interesting trends. First, each pair of ships remaining on the final discrete Pareto front has the small generator designated as common. Generally speaking, the use of the small generators has little to no impact on performance. It may add weight, and therefore cost, to NSC ships that need more than four generators to meet the electrical load requirements, however, the performance will not suffer and the net fleet savings will benefit greatly from this choice.

There is no clear best choice for a common weapon system. Half of the solutions on the final Pareto front have weapon system 1, which allows for good savings with some loss in performance for the NSC. Weapon system 2 has a slight positive affect on savings and a loss of performance for the NSC. Weapon system 2 does not benefit the OPC's performance while increasing its cost. Weapon system 3 has a negative fleet savings while completely satisfying the requirements of the NSC. Again, the OPC suffers with the use of weapon system 3 because of increased cost with no performance gain.

Seven of the twelve pairs do not designate common cruise engines. Even though the ships will not benefit from the cost savings, this can be good. Each ship is able to optimize its performance when able to use the engine that is best suited for its requirements. One third of the designs have the small cruise engines as common. This maximizes cruise engine savings. However, the performance of the NSC tends to suffer from the use of the small cruise engines. The small cruise engines only support a smaller ship in order to meet the cruise speed requirements. By forcing the NSC to be smaller, its performance declines. Its range has to be smaller and it can only have one helicopter hangar. The OPC is not affected in this manner. The use of the larger cruise engines is seen in one pair of designs on the final Pareto front. In most cases, negative fleet savings occur when the large cruise engines are used. The performances tend to stay the same, but the OPC may have excess horsepower at cruise speed which will negatively affect its performance over cost.

The study has shown that common superstructures never result in a negative fleet savings. However, only five of the twelve solutions realize a savings from the use of a common superstructure. Generally speaking, the smaller common superstructure does not hinder the performance or cost of the OPC. The NSC is again limited in size and this will cause a decline in performance. The larger superstructure adds unnecessary costs to the OPC without a comparable increase in performance.

Common midship section hull blocks have little effect on savings, but can influence performance and cost. Similar to the superstructure, the small midship section hinders the performance of the NSC. The larger midship section benefits the NSC while at the same time adding cost and possibly hurting the performance of the OPC.

Analysis of the results illustrates how finely balanced the three objectives can be. What tends to benefit the fleet savings the most generally hurts the performance of the NSC. At the same time, what maximizes the NSC performance tends to not produce large savings by increasing the cost of the OPC. In order to maximize all three objective functions, a multi-objective balance in common components must be made.

Table 5. Design Characteristics for Selected Ships on the Final Pareto Front

Point	L ft	B ft	V_{max} kts	Range nm	Wep Sys	# of Helo Hangars	Cruise Eng	Dies Gen	OPC Perf	NSC Perf	Fleet Savings $mil
OPC_{18}	353	54	22.0	9158	1	2	8	0	100.0	0.314	45.5
NSC_{18}	399	54	27.9	12074	3	2	9	3	100.0	97.0	45.5
OPC_{15}	300	40	22.2	9046	1	1	7	0	89.7	2.946	75.0
NSC_{15}	303	40	25.5	9019	1	1	7	0	89.7	47.6	75.0

Perhaps the most attractive pair of designs from this study are the two designs indicated as OPC_{18} and NSC_{18} on Figure 2. This pair of designs is OPC ship 18 and NSC ship 18 in Table 4. This pair of designs has the smaller ship service diesel generators and the large superstructure in common. This pair has the highest fleet savings from commonality possible before the NSC designs take the large loss in performance/cost and, thus, this might be the most likely choice for a design team. This commonality achieves 60.7% of the maximum fleet savings considered, but the performance of the NSC is only compromised to 97.0% of its maximum and the OPC performance remains at 100% of its maximum. The characteristics of OPC ship 18 and NSC ship 18 are shown in Table 5 along with OPC ship 15 and NSC ship 15, which had the highest net fleet savings on the Pareto front. It is worth noting that because of the strong similarity of OPC ship 15 and NSC ship 15 consideration should really be made to build a single ship to perform both ship missions. A single ship design would achieve even more fleet savings.

4 CONCLUSIONS

The methodology presented in this paper is a valuable tool in making commonality decisions. It provides a systematic procedure for the use of commonality in design while taking into consideration performance loss, cost, and savings. In most platform-based family design methods, the basic assumption is that commonality hinders the performance of a variant. This loss in performance is accepted because of the savings associated with using common parts. This research showed that positive savings are not always realized. If poor commonality decisions are made, the fleet of products could both cost more and perform worse.

The mission performance model used in this study relied on the use of fuzzy utility values. Performance was determined using the four design characteristics for each mission area and applying the corresponding fuzzy utility value to each. A designer could easily modify this model to include more design characteristics or more mission areas. The fuzzy utilities could be replaced with another tool for awarding value to a given design characteristic. In short, the mission performance could easily be expanded or modified to meet the needs of a given designer.

Commonality decisions were limited here to five components. These components were selected to illustrate that commonality could be integrated into the design in different ways to show the versatility of the optimization model. In this research there were a finite number of commonality options from which to choose. As a result, an exhaustive search was used to determine which commonality choices were the best. If more commonality choices are available, another evolutionary algorithm could be used to search for good commonality combinations.

Bulk purchasing and construction learning curves were used to determine the savings associated with the use of commonality. The savings model was kept relatively simple. Other forms of savings could be realized as well. These could include training of personnel, technical design costs, administrative savings, facility costs and spare parts. The type of savings and the number of different factors to consider varies with each product being designed. A designer may choose to make the savings model more elaborate when information of these other forms of savings is available or it may be kept relatively simple as seen in this research.

Using the systematic methodology described in this research will enable a designer to present a much more complete analysis of the impact of commonality decisions in design. Designers can expand the optimization model in many ways to adapt it to their particular needs.

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