Rapid Generation and Optimisation of Ship Compartment Configuration based on Life Cycle Cost and Operational Effectiveness

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***Abstract* - Decisions made in the early stages of ship design can have profound effects on the cost of the ship throughout its life. For example, poor compartment configuration or hull selection can result in hydrodynamic inefficiency and significantly increased energy consumption and fuel costs. Space limitations, inadequate or non-existent removal routes and other accessibility problems may result in expensive equipment overhaul and replacement procedures, invasive removal methods, longer maintenance availabilities and increased maintenance costs. This highlights the need for a better understanding of Life Cycle Cost (LCC) implications early in the ship design process and development of better tools to aid early stage design decision making. This paper explores a methodology that combines existing and proven techniques to rapidly generate and objectively compare valid ship compartment configurations in consideration of the effects on LCC. The proposed methodology utilises life cycle costing techniques and a genetic algorithm within a Multi Criteria Decision Analysis (MCDA) framework. The objective of this paper is to demonstrate the methodology rather than provide a specific or defined solution.**

***Keywords* -Naval ship design, compartment configuration, cost estimation, multi-criteria decision analysis, genetic algorithm**

I. INTRODUCTION

A. Background

It has been well established that the majority of ship Life Cycle Cost (LCC) is incurred during the in-service period. Among other factors, this is strongly linked to the design of the ship and the decisions made during the early design phase. In particular, compartment configuration can have a significant effect on fuel and maintenance costs which are two of the main operating cost constituents for a military ship. It should make sense, then, to objectify these key LCC components in the early stages of design.

Figure 1 shows the common analogy of the 'life cycle cost iceberg' which demonstrates the tendency to focus on the acquisition cost without giving heed to the much larger in-service costs.

Traditional design methods and decision analysis techniques focus mainly on the trade-off between operational effectiveness and acquisition cost rather than LCC. In recent research by a NATO Task Group [8], the need to make LCC the denominator in solutions analysis is stressed, thus providing a trade-off between capability or operational effectiveness and LCC.

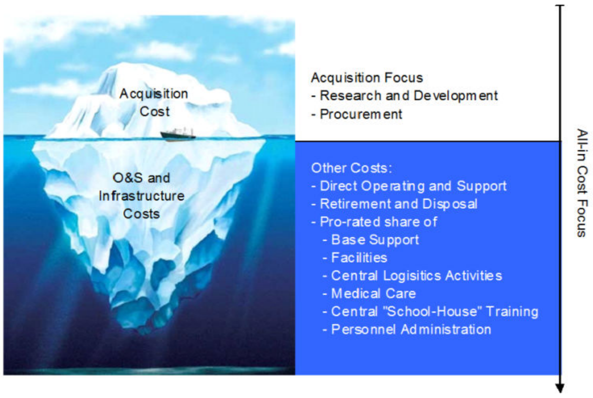

Figure 1 - The Life Cycle Cost Iceberg [8]

Keane [2] highlights some key problems with the traditional "Outside-In" design approach (see section II, subsection A) which lead to significant increases in LCC. Poor compartment configuration or hull selection can result in hydrodynamic inefficiency, which significantly increases energy consumption and fuel costs. Associated space limitations, inadequate or non-existent removal routes and other accessibility problems may result in expensive equipment overhaul and replacement procedures, invasive removal methods, longer maintenance availabilities and increased maintenance costs.

It has been observed that ships with greater density have higher ownership and production costs and Keane [2] goes on to suggest that "the ship designer needs to have the early stage design tools to convince decision-makers that bigger is better, not necessarily more costly". This indicates the need for smarter compartment arrangement and allocation of sufficient free space for fitment and maintenance of equipment and suitably efficient hull forms designed to accommodate such space requirements. The overarching theory is that although larger ships generally require more steel to make and more power to propel, this does not always imply increased cost. A small increase in the ship's size for the sake of allowing a more efficient hull shape may in fact reduce the required power; and improved accessibility for maintenance work within the ship can lead to significant reduction in maintenance costs. Thus, the savings generated from hydrodynamic efficiency gains and cheaper maintenance over a 25-30 year service life can more than offset the increases in other costs associated with a larger ship.

Research on the effects of producibility on cost [3] suggests simplification of the hull design and allocation of additional deck height and space [4] can reduce design and construction costs. It has also been noted that more construction work is being undertaken on-shore (as ships are constructed into units and blocks prior to final assembly) and hence the impact of higher density is diminishing [7]. However the same cannot be said for ongoing through life maintenance costs where, in most cases, work must be undertaken within a fully assembled ship. The allocation of additional space increases the efficiency of outfitting and consequently reduces the density of the ship. The associated reduction in cost is consistent with Cost Estimating Relationships (CER) that show a positive correlation between density and production cost. Such design measures will have a proportionate effect on through life maintenance costs, though this is substantially more difficult to quantify.

In order to investigate the effect of compartment configuration on LCC, a common list of compartments must be configured in many different, feasible combinations with varying surplus space and deck height whilst estimating and analysing the resultant LCC. This enables comparison of the different alternatives in order to identify the features or aspects of the compartment configuration that impact the LCC greatest.

Traditionally, the task of compartment arrangement is performed by a ship designer who employs a manually executed, iterative approach. Due to the labour involved, the number of different configurations that can be considered is limited. If this process is automated, a large number of different potential compartment configurations can be evaluated, covering many more possibilities than a manual approach and potentially discovering a superior solution to the manually designed configuration.

There have been many attempts at automating compartment arrangement in the ship design process (van Oers [10] provides a review of the recent work in this area). The task is generally formulated as an optimisation problem, where a computational algorithm searches the space of possible solutions and, given a set of design objectives, attempts to find a good solution. In the case of ship design, these objectives are usually performance or effectiveness and value for money.

The methodology proposed in this paper attempts to design this measure of utility and adapt a computational algorithm to this task in order to facilitate the optimisation of concept designs. Initially, the optimisation objectives will include some basic design goals such as optimal length to breadth ratio.

Further development of this method could incorporate other critical design objectives including minimisation of LCC and maximisation of operational effectiveness. The versatility of this methodology would also allow different combinations of equipment and capability levels to be arranged and evaluated. When integrated into a Multi-Criteria Decision Analysis framework, this could provide a valuable tool for early design trade offs between LCC and operational effectiveness for different combinations of candidate equipment, systems and capability levels.

An outline of the structure of this paper is as follows. The remainder of Section I details the issues that this work aims to address. Section II reviews some of the techniques currently used in early stage ship design that can be utilised in dealing with these issues. Some previous approaches that have combined different techniques to assist with early stage ship design optimisation are summarised in Section III. Section IV details the methodology proposed by the authors, while Section V demonstrates the application of this methodology to a simplified design problem.

B. *Importance Of The Early Stages Of Design*

It has been well documented that the LCC of a ship, and indeed many other commercial and defence platforms, is decided well before the money is expended. Like many of these relationships, this is difficult to quantify, however the governing principles are well known and understood. The key decisions made in the early stages of design cannot be changed in the later stages of development when requirements change and or new information becomes available that reveals inherent design flaws and shortcomings. This is best represented by Figure 2.

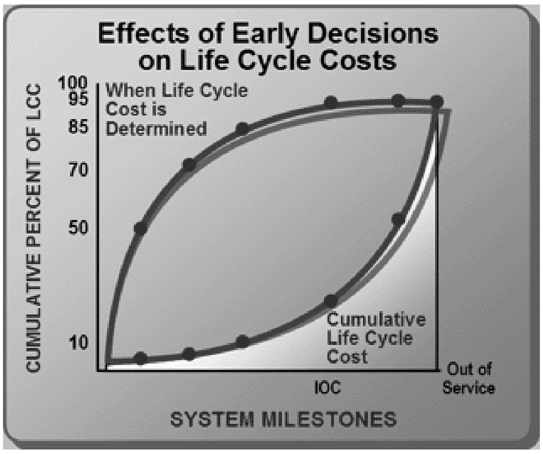

Figure 2 - Time Related Cost Impacts [5]

Taking this into consideration, there are two ways in which LCC can be minimised during early stage design:

- Improve early stage design techniques and tools to facilitate better decision making [1] [2]; and/or
- Design in a manner that maintains flexibility throughout the development of the design such that changes can be made in later stages without adverse program schedule or budget effects [5].

This paper is primarily focused on the first point, by providing an early stage design methodology and subsequently a tool that can allow key design decisions to be made in full cognisance of the LCC effects.

C. *Acquisition Cost Versus Life Cycle Cost*

The breakdown of costs for a defence platform program, specifically for a military vessel, is well illustrated by the Navy Center for Cost Analysis (NCCA) as shown in Figure 3.

The acquisition cost includes design, development, construction and commissioning costs. As this is perceived by many to be the cost of buying something, acquisition cost normally becomes the focus of the decision making process. The bulk of the acquisition cost is made up of material and construction costs, illustrated in Figure 3 as “Sailaway Cost”. This is seen as something tangible and quantifiable, and the impact of early design decisions is more easily measured when just considering acquisition cost. Consequently, this becomes one of the main objectives during early stage design, despite the fact that the acquisition cost typically makes up only 30-35% of the total LCC.

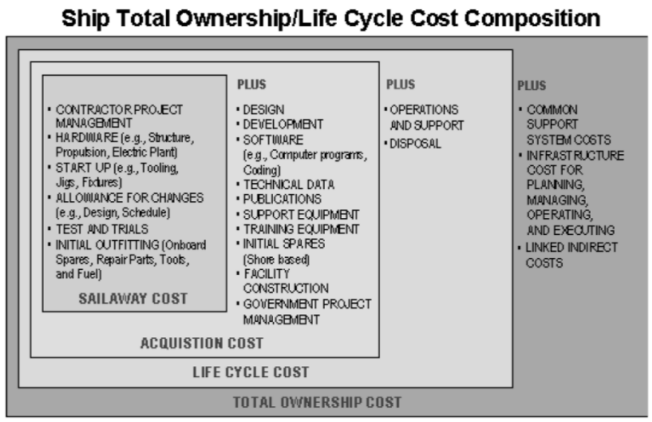

Figure 3 - Ship Cost Composition [5]

LCC is inclusive of acquisition and disposal cost, but is primarily made up of operation and sustainment (O&S) costs. An example is illustrated in the NAVSEA Cost Estimating Handbook [6] as shown in Figure 4.

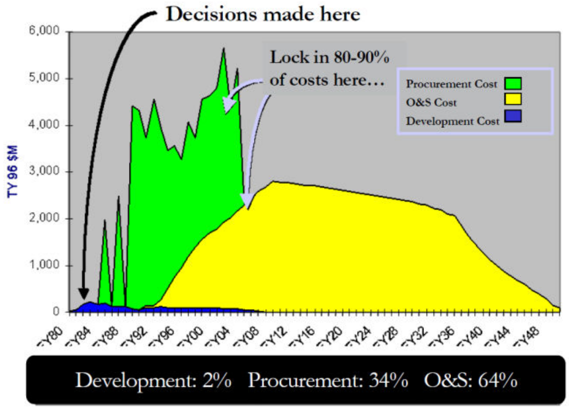

Figure 4 - Life Cycle Cost Breakdown

Given that O&S costs typically make up 65-70% of the LCC and that the majority of LCC is effectively “locked-in” during early stage design, the implications of early stage design decisions hold greater consequence than just in the acquisition cost.

Further investigation into the aspects of ship design that drive LCC are likely to provide valuable input to the initial design phases. It could serve to answer questions such as: How will the arrangement of compartments affect maintenance costs? Will the allocation of additional space and removal routes provide an overall saving despite additional fuel and construction costs? How much space should be allocated and where?

It should be noted that the views expressed in this paper are those of the authors and are not necessarily the official view of the BMT Group or any other organization. The intent of this paper is to foster dialogue to gain a better understanding of the LCC drivers of Naval ships and propose a methodology that might facilitate investigation in this area.

II. EXISTING TECHNIQUES

A. Inside-Out Design

Conventionally, ship design follows an ‘outside-in’ approach, where the compartments to be included are arranged after a hull form has been determined. This approach can lead to various issues (as noted by Keane [2]) due to the possible compartment arrangements being restricted by the hull form. Satisfying adjacency requirements, location preferences and maintenance/repair access considerations may not be simultaneously achievable within the given hull, but this may not be apparent until the later stages of the design process, when it is difficult to change the hull form.

The alternative approach involves arranging the compartments first, then ‘wrapping’ a hull form around them, so that the issues mentioned above can be avoided. This approach prioritises the arrangement of the ship’s systems to best achieve the required operational effectiveness, treating the hull as a means of supporting the ship’s systems, as opposed to a primary, defining aspect of the design [1]. The method proposed in this paper is based on this idea.

B. Compartment Configuration Methodologies

The task of arranging the necessary compartments within a ship design can be approached in numerous ways. Traditionally, it has been the role of human designers to decide where each compartment should be positioned, based partly on experience and an intuitive understanding of how best to meet the requirements and objectives of the design. Due to the amount of work involved in designing a feasible arrangement using this approach, the number of different possible arrangements that can be considered is limited. With the advance of computer technology, Computer-Aided Design tools have vastly improved the efficiency with which this design work can be performed, but this level of dependence on a human designer still imposes some limitations. The process is labour intensive and slow, making it infeasible to consider a significant fraction of the vast multitude of different configuration alternatives. A human designer’s approach relies partly on intuition, meaning important design decisions are often made on a somewhat subjective basis. If the arrangement problem can be represented in a way that is solvable by a completely automated process, based on quantitative measures of the merit of an arrangement, these problems can be mitigated, potentially allowing superior arrangements to be produced.

The approaches taken in the use of computers in ship design and compartment configuration range from providing varying degrees of computer assistance to a human designer, to completely automating the compartment arrangement task. (A comprehensive review of much of the recent work in this area is given by van Oers [10].) While it is difficult for a computer to deal with certain aspects of the design problem that humans deal with intuitively, an automated approach has numerous advantages. The combinatorial nature of the arrangement problem means that computers are particularly suited to this task when large numbers of compartments must be arranged.

To illustrate, consider the following. The number of possible arrangements of a given set of compartments grows very rapidly with the number of compartments, making it difficult to consider all alternatives explicitly for even modest numbers of compartments. In the simplest case, where n different objects are to be arranged in a linear sequence, the number of possible arrangements is given by $n!$ (For example, a set of only 10 compartments has approximately 3.6×10^{6} possible arrangements, while a set of 20 has over 2.4×10^{18} permutations). For large numbers of compartments, even the most powerful computers cannot generate all possible arrangements in a reasonable period of time. A search algorithm must then be used to find good configurations without having to exhaustively compare all possible configurations. Subsection C (below) describes one such algorithm often used for this application.

The problem of compartment arrangement is essentially a particular example of the layout problem (alternately referred to as the packing, packaging, configuration, container stuffing, pallet loading or spatial arrangement problem throughout the literature [12]). This problem has been extensively studied, and a multitude of approaches exist for producing solutions.

Layout problems are generally classified as NP-complete or NP-hard (non-deterministic polynomial, referring to the time taken to solve the problem as a function of the problem's size), depending on the particular formulation of the problem, so finding the global optimum within a reasonable time is not computationally tractable [9][11][12][16][21]. The search space is often multi-modal [12], meaning that simple gradient-based search methods usually 'get stuck' at local inferior maxima. In order to proceed, a computational algorithm that can operate on a discontinuous, multi-modal search space and can explore large areas of this space (without considering all solutions exhaustively) is necessary. Genetic algorithms (described in the following section) meet these requirements and are often used for this type of problem [9][11][13].

The compartment configuration problem may be regarded as a variation of the bin-packing problem (a particular type of layout problem), which consists of packing a number of objects within one or more larger spaces. It has been studied extensively and there exist numerous heuristics and rules to generate solutions, in one, two and three dimensions [14][21][22]. This approach is particularly useful when the optimal use of available space is a high priority.

C. *Genetic Algorithms*

Genetic algorithms are a class of evolutionary search algorithms loosely based on biological processes. A brief explanation of their operation is given in this section.

Within a genetic algorithm, each solution to the problem is represented as a string of numbers (or other characters) known as a genome (or chromosome). Each genome uniquely encodes a single solution (and vice versa). As in most optimisation problems, an objective function is defined, which the algorithm will attempt to maximise. This function is evaluated for each genome, yielding a 'fitness' score which represents how desirable the solution it represents is.

In a typical genetic algorithm, an initial 'population' of different genomes is varied by selectively applying various operators to them. The selection operation is based on the fitness scores, where the genomes with the best fitness are selected to form part of the next 'generation' (i.e. the population at the next iteration of the algorithm).

The usual operators used are the 'mutation' and 'crossover' operators, named after the genetic processes on which they are loosely based. The mutation operator causes a random change to some part of a genome, while the crossover operation exchanges one or more sections of two parent genome strings to produce one or more child genomes. Crossover is designed to combine good solutions in order to potentially generate better ones, gradually increasing the fitness of the population, while mutation introduces random variation into the population, forcing the algorithm to search a greater range of the solution space and helping to avoid convergence at inferior maxima.

D. *Multi-Criteria Decision Analysis*

Multi-Criteria Decision Analysis (MCDA) is a systematic framework for decision making, providing a rational, objective means of comparing the available choices and their consequences in order to rank them from most to least preferred.

The basic steps involved in an MCDA are as follows. Initially, the various options or choices must be identified, and the criteria for assessing these options must be defined. Each option must then be evaluated according to each of the criteria and given a score for each. These scores are then weighted according to their relative importance to the decision. Finally, the sum of these scores for each option is calculated, forming an overall score for the option. The options are then ranked according to this score, thereby placing them in order of preference.

III. INTEGRATED TECHNIQUES

A. *Consideration of Cost in Automated Ship Design*

While there are many tools for the automatic arrangement of ship compartments, few of these take cost into consideration. Those that do account for cost usually do so in an indirect manner (for example, by minimising the size of the ship to minimise material and fuel costs). There are some examples of explicit cost modelling in automated ship design optimisation (see, for example, [17] and [18]), but these cases do not treat ship designs at the level of detail where compartment layout is considered explicitly, thereby failing to account for the influence that compartment arrangement has on the cost of a ship.

B. *Comparison of Design Options*

In the early stages of ship design, it is often necessary to compare multiple different platform design options in a manner which quantitatively accounts for a range of important objectives for the ship and indicates how well the proposed options meet these objectives. Various techniques have been used to perform this function; examples include MCDA [19][20] and creating an Overall Measure of Effectiveness (OMOE) [17].

The method proposed in this paper (detailed in the following section) is an attempt to build on these approaches, combining cost modelling and a decision making framework with an automated compartment arrangement technique.

IV. PROPOSED METHODOLOGY

A. LCC Oriented MCDA Utilising a Genetic Algorithm

The methodology explored here combines established techniques from different disciplines, resulting in a tool capable of exploring many possible ship concept designs at the early stages of development and facilitating selection of the best design in terms of cost and effectiveness. The various elements of the tool are explained in this section.

The core function of the tool is the generation of feasible configurations from a given set of compartments. This task is performed by a bin packing algorithm augmented with a genetic algorithm to search the space of potential solutions. Both of these components are implemented in C++ and the genetic algorithm uses the GAlib library of genetic algorithm components written by Wall [23]. A rendered model of a compartment configuration produced by the arrangement algorithm in its present form is shown in Figure 5. The functionality of these two components is explained in the following paragraphs.

Given an ordered list of compartments and a set of spaces representing decks on the ship, the packing algorithm fits these compartments into available space on the decks one at a time, using the Extreme Point rule formulated by Crainic et al. [14]. The primary objective of the packing algorithm at this stage is to fit all of the compartments into the available space while minimising unused space. The algorithm is repeated, varying the scale of the ship each time, until the configuration that fits all of the compartments into the smallest hull possible is found. How well this can be achieved depends on the order in which the compartments are packed. Various ordering schemes exist in order to achieve this objective, such as ordering the compartments in decreasing order of volume or base area. In this case, the order of the compartments is varied by the genetic algorithm to search the range of possible configurations.

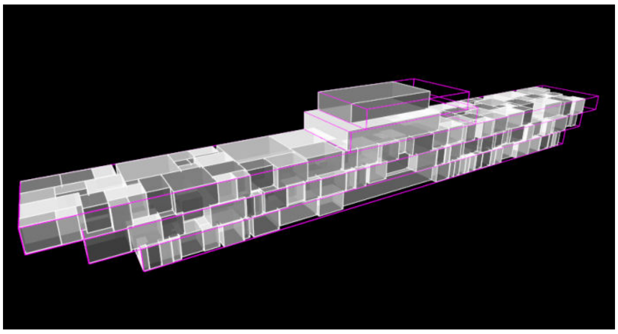

Figure 5 - Example Output of the Arrangement Algorithm

The genetic algorithm creates different orderings of the compartments (representing different configurations) through the mutation and crossover operators. Each of these orderings is converted into a configuration using the bin packing algorithm. The resultant configuration is then evaluated according to the objective function, which awards a score to the arrangement based on how well it meets the design requirements and objectives. This score is used by the genetic algorithm to judge the relative 'fitness' of the particular configuration, and to guide it towards configurations that yield higher fitness scores. A schematic showing the basic function of the genetic algorithm used here is shown in Figure 6.

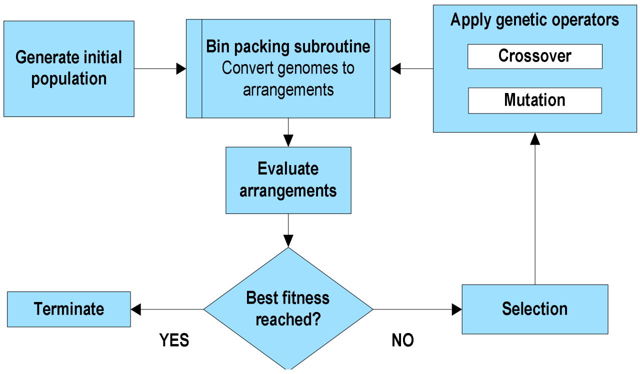

Figure 6 - Genetic Algorithm Schematic

The compartment arrangement technique proposed here can be incorporated into an MCDA in order to compare different platform design options (in this case, different combinations of equipment, corresponding to different selections of compartments). For each option considered in the MCDA, the arrangement algorithm can determine a feasible arrangement that meets the design objectives, facilitating rapid evaluation of the different options considered.

The arrangement algorithm can be modified to optimise different aspects of an arrangement. Ultimately, it will be developed to optimise cost and effectiveness as part of an MCDA. A schematic of this proposed framework is shown in Figure 7. The arrangement algorithm will also take into account preferred absolute and relative locations of the compartments, using fuzzy preferences (which allow for compromise between conflicting allocation objectives [1],[11]). In the following analysis, the primary objective of the algorithm is to find the most compact configuration of the given set of compartments.

Combining the above technique with a cost model permits the MCDA to quickly compare and rank different platform design options based on their estimated cost and effectiveness.

B. Integration of Life Cycle Costing

To facilitate the investigation and trade-off of compartment space allocation and LCC, the cost element structure must be configured in a way that captures the effects of ship density on producibility and accounts for the variation of acquisition and in-service support costs with ship size.

This calls for the separation of labour and material costs for both the construction and maintenance of the ship. In doing so, an Outfit Productivity Factor (OPF) which varies with the density of the ship, as proposed by Deschamps and Greenwell [7], can be applied to the labour costs. This accounts for the increase in productivity as ship density decreases due to increased working space for outfitters, maintainers and tradesmen.

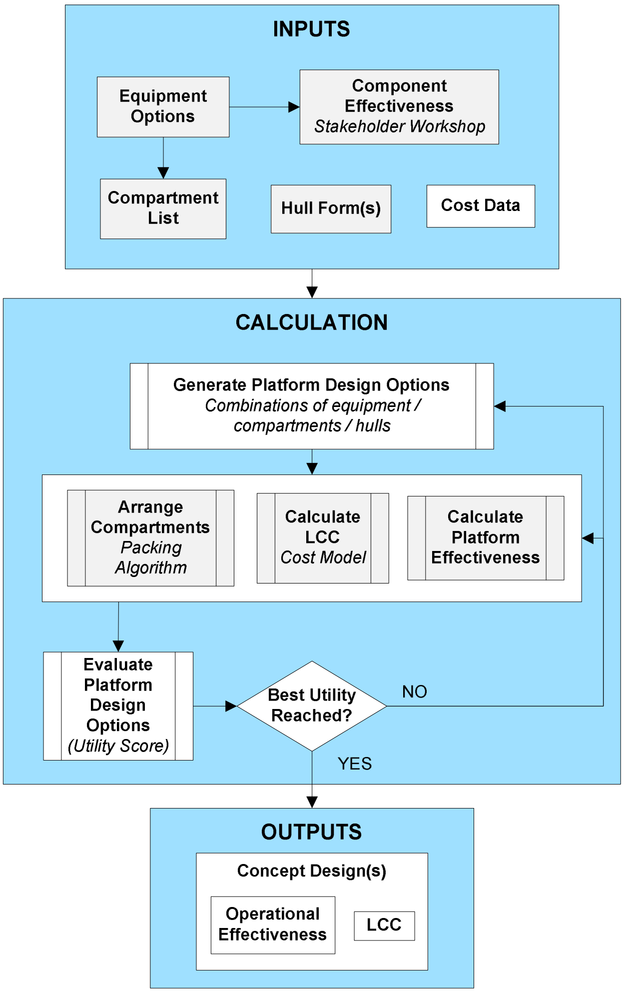

Figure 7 - MCDA Framework utilising Genetic Algorithm for Compartment Arrangement

It also requires the segregation of costs attributed to individual elements of the Ship Work Breakdown Structure (SWBS). The popular and widely used SWBS based on that specified in MIL-HDBK-881 [15] has been adopted in this case with the 100 group containing all hull structural elements and groups 200-700 comprising all other physical systems and elements of the ship. As compartment space allocation and size is increased, the cost of SWBS 100 will increase as a proportionately larger hull is required to enclose the larger compartments. With the exception of the propulsion system and perhaps some other auxiliary systems, the cost of SWBS 200-700 will remain unchanged, as it is only the space within compartments that is increasing. It is assumed here that this holds true for relatively small changes in compartment space allocation.

The required cost model dynamics were achieved with use of extensive parametric analysis on SWBS weights and development of Cost Estimating Relationships (CER) for appropriately segregated LCC elements.

Modelling the cost in this way allows for the variation of ship density whilst maintaining the same capability baseline, as well as the application of producibility effects to only the applicable cost elements. With the integration of the cost model into the objective function of the genetic algorithm, the compartment space allocation and arrangement can be optimised for minimised cost.

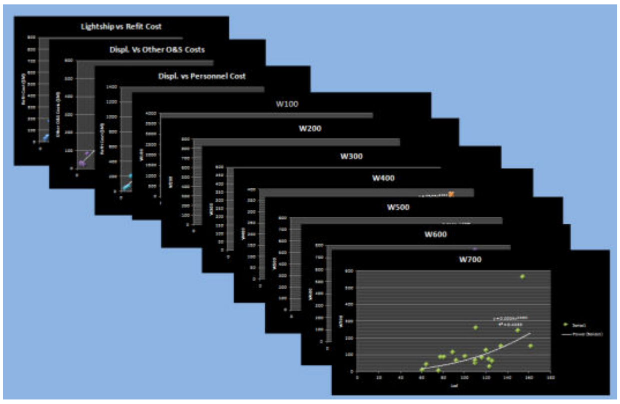

Figure 8 - CER and SWBS Parametric Analysis

C. *Integration of Operational Effectiveness*

A similar methodology can be used to integrate operational effectiveness into the trade-off space. This is most applicable when considering multiple system and equipment options, which are combined in different ways to provide a range of platform design options.

Each candidate system will have a specified compartment space requirement and associated cost which can be input into the cost model and compartment arrangement components of the early stage design tool. Furthermore, each platform design option can be assessed for operational effectiveness against set capability requirements and evaluation criteria. Weighting of criteria and scoring of options as part of an MCDA approach is normally conducted by the relevant stakeholders, including military personnel with specific in-theatre experience, strategic advisors, designers and engineers. The individual system and equipment capability scores are then tallied to quantify the operational effectiveness of the various possible platform design options.

Operational effectiveness scores can be included in the objective function of the genetic algorithm, so that solutions with better operational effectiveness are favoured. The different elements of the objective function, representing different, competing objectives, can be weighted according to their relative importance for the desired design. The algorithm can thus be tailored to find, for example, solutions with minimum LCC, maximum operational effectiveness, or a balance between objectives to optimise value for money.

V. SIMPLIFIED SHIP DESIGN PROBLEM

A. *Problem Description*

To demonstrate the methodologies discussed in this paper, a generic military ship design has been selected for early stage design analysis and optimisation. The ship design resembles what might be classed as a large frigate or destroyer and the compartment listing has been generated based on the typical capability requirements of such a vessel. Compartments have been sized in-line with previous ship designs and are considered to be of ‘standard’ size for modern-day military ships.

The objective of this exercise is to first find a suitable compartment configuration using a bespoke early stage ship design tool developed using the techniques discussed in this paper. The resultant design will be costed utilising the life cycle costing method described above. Lastly, the space allocation for each compartment will be varied and the resultant designs costed to explore the effect of additional space allocation on LCC. By varying compartment space for the same baseline design whilst holding all other parameters constant, the cost impact of additional space can be investigated and traded with the overall LCC.

B. *Method*

Since the genetic algorithm compartment arrangement component of the proposed method was still under development at the time of writing, a bespoke development in Computed Aided Design (CAD) package Rhinoceros was used in its place. A BMT-developed plug-in utilised the Rhinoceros nesting add-on RhinoNEST to achieve a feasible configuration for the ship from a supplied list of compartments. While RhinoNEST contains an efficient arrangement algorithm for space utilisation, the genetic algorithm will ultimately be used in later developments since it is a more flexible, powerful tool (enabling the optimisation of multiple objectives simultaneously, e.g. preferred compartment locations, cost minimisation, sea-keeping, etc.).

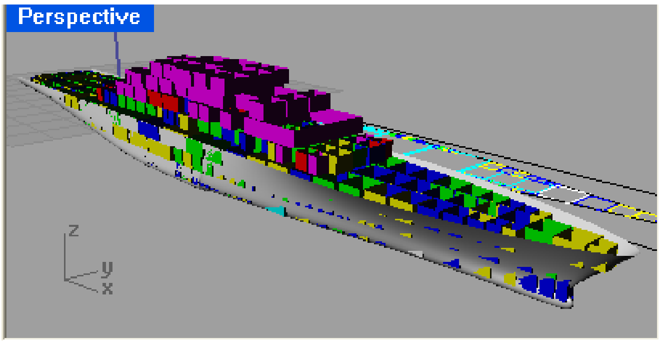

Figure 9 - Automated Compartment Arrangement

The resultant design parameters were exported to the LCC model and the LCC calculated. The baseline compartment dimensions were varied in size by 5% increments to form compartment listings at -10% to +20% of the original baseline compartment sizes. The compartment arrangement algorithm was used to generate new solutions for each evolution and the LCC was evaluated.

C. *Results*

The results of the Simplified Ship Design Problem analysis are summarised in Figure 10.

D. *Discussion*

As space was added to compartments, construction and through-life maintenance costs decreased due to a decrease in density and the associated increase in producibility. This contributed to an overall decrease in acquisition and refit costs. Conversely, the resulting increase in ship size led to higher fuel and other upkeep costs which increased markedly when more than 10% extra compartment space was added. The personnel cost remained constant, as the capability of the platform and manpower required for operation remained the same.

The results show a minimum LCC at +5% space and only a slight increase in cost for the +10% solution when compared to the baseline. Overall, the analysis shows that up to 10% more space can be added to the ship with little consequence to LCC. It also shows that whilst making the ship smaller may seem like a suitable way to reduce cost, the increase in density and consequent penalties to producibility and maintainability result in significantly increased construction and maintenance costs. It should be noted that LCC is quite sensitive to space allocation. Whilst this seems obvious, it also highlights the importance of striking the right balance between reduction of ship size and space allocation to provide efficient work spaces.

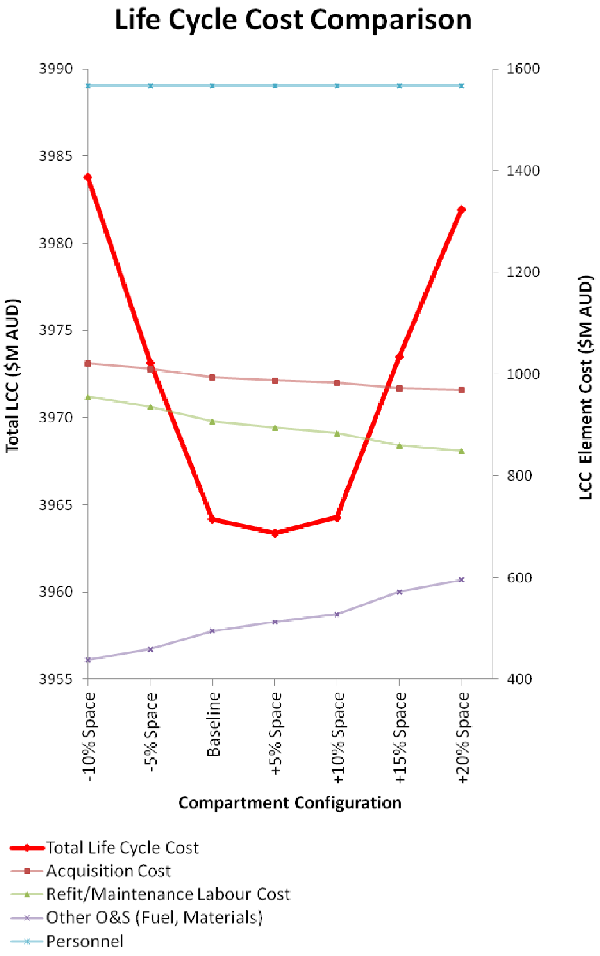

Figure 10 - LCC versus Compartment Space

Despite the simplified nature of this design problem, it raises some interesting points. In the context of a real world design problem, if this type of analysis was conducted at the early design stage, it could support the development of a slightly larger ship that traditional methods would have quickly discounted. The resultant design could incorporate additional working space and removal routes to assist with efficient completion of outfitting, refitting, overhaul and other major maintenance tasks.

Even if there are no significant cost savings in having a slightly larger ship, the design would serve to reduce the risk of costly maintenance schedule delays and unforseen complications with a commensurate increase in vessel availability and decrease in budget blowouts. This could also lead to other valuable benefits which can't be captured in the modelling process.

VI. CONCLUSIONS

Traditional design methods and decision analysis techniques focus mainly on acquisition costs with little consideration for LCC. It is well understood that the life cycle cost of ships is decided in the early stages of design and that total LCC far outweighs acquisition costs. Therefore, reducing LCC requires the right tools to affect the decision making process and influence ship design before LCC is set. One area of particular interest is the trade-off between compartment space allocation and LCC with respect to ship producibility and through-life maintainability.

This paper has explored a number of early stage design tools and techniques, namely, Multi-Criteria Decision Analysis, Genetic Algorithms and Life Cycle Costing analysis. These are all useful tools in their own right, but it is the integration of these implements that can provide holistic and valuable input to early stage design decisions with significant effect.

A methodology was proposed that combines the generation of ship compartment configurations using a genetic algorithm with life cycle costing within an MCDA framework. The key concept of the methodology is to incorporate feasible ship designs, LCC and operational effectiveness into the objective function of the genetic algorithm. This facilitates the optimisation of early stage designs with respect to the users' key objectives, whether they are cost, capability or overall value for money.

A bespoke tool was created for demonstrative purposes and applied to a simplified ship design problem. The aim of the exercise was to investigate the effect of increasing compartment space on LCC. The analysis suggested that up to 10% extra compartment space could be incorporated into the design with little consequence to LCC. This lends strength to the idea that additional costs associated with building and running a larger ship can be largely offset by savings generated by improved maintainability and producibility. Access to such tools and information during the early stage design could lead to slightly larger ships designed to facilitate efficient and less complicated maintenance regimes resulting in increased vessel availability and reduced cost overruns.

Overall, the ideas discussed and the outcomes deduced in this paper certainly support further development of improved design tools and a better understanding of life cycle cost implications early in the design process.

VII. FURTHER WORK

There is great scope for further development in this area. With more work, the level of sophistication with which the compartment arrangement algorithm is able to produce concept designs could be vastly improved. Similarly, further data collection, analysis and validation could serve to improve the way in which cost dynamics are captured in early stage design trade-off studies.

ACKNOWLEDGMENT

BMT Design & Technology wishes to acknowledge Matthew Wall at the Massachusetts Institute of Technology [23] whose GAlib genetic algorithm package was used for this work.

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