Combatant Design and Fleet Mix Assessment and Optimisation using BAEFASIP

Courts, M, Brett, C

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Dstl
Defence and Security Analysis
Portsdown West
Portsdown Hill Road
Fareham
PO17 6AD

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[Release Statement]

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Authorisation		
Role	**Name**	**Date**
Project Manager		
Technical Reviewer		
Author		

Executive summary

The paper describes two models developed at Dstl using the BAEFASIP high level general system modelling and optimisation software developed by BAE Systems. The program can evaluate multiple system properties through interlinked data layers representing different system aspects, e.g. equipment, functions, capabilities and operations. Models in BAEFASIP can incorporate both complex engineering interactions and high level requirements in appropriate data levels. Specialised algorithms perform multi criteria Pareto front optimisations on element options while accounting for constraints and rules defining allowable interactions between element types.

The first model synthesises and assesses surface combatant configurations from options for platform and combat system elements against a set of engineering constraints and rules. Pareto front optimisation is performed by trading off the system cost against its ability to deliver a range of capabilities required to conduct a set of operations.

The second is a capability based fleet optimisation model. Candidate ship types provide capabilities that are matched to sets of concurrent operational requirements expressed as demands for numbers of units with particular capabilities, critical levels of capability and off board systems. Multi- criteria optimisation of the allocation of ships to operations is performed maximising overall benefit, operation concurrency and minimising both acquisition and through life cost drivers.

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1 Introduction

With the increasing cost of technology and declining, or at best static, defence budgets it is now more important than ever to carefully balance aspiration and requirements against cost. This means that it is necessary to understand:

- **All costs:-** implying that full solutions must be generated and analysed.
- **Benefit:-** implying that potential solutions must be analysed against a wide range of operational requirements.
- **Best Value for Money:-** implying that the widest possible range of feasible options must be searched for those that are the most cost effective for any given budget level.

In order to do this quickly new tools and processes have had to be developed.

At the earliest stages of a project when the key trade off decisions are made three broad classes of activity are required (Courts, Brittain, Lamble, & Osborne, 2012):

1. **Concept synthesis:-** to generate viable solutions quickly to the point that reasonable cost estimates can be made
2. **Operational analysis:-** to assess the military value of the solutions
3. **Multi criteria decision analysis:-** to make sense of the large amount of data generated by 1 and 2.

In order to understand the resultant trade space a simple 2D cost-effectiveness trade space can be used **Figure 1**, adapted from (Courts, Brittain, Lamble, & Osborne, 2012) .

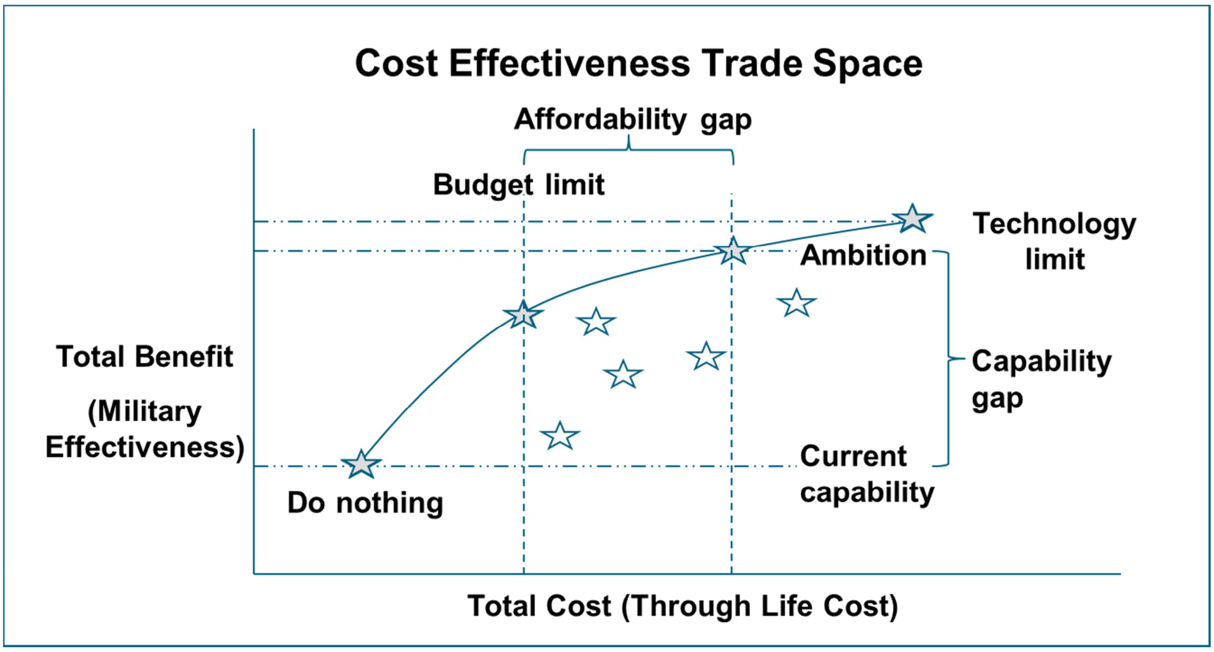

Figure 1 2D Cost Effectiveness Trade Space

This shows the optimum Pareto Front of best value for money solutions. Understanding how the solutions vary along this front helps in trading off cost and capability when budgets are insufficient to meet initial aspirations.

2 Functional Analysis

One general high level method that has shown itself to be particularly useful in the early concept stages of a project is System Functional Analysis (Courts, Brown, Tucker, Maxwell, Andrew, & Searle, 2004). This is based on evaluation of the relationships between system properties through multiple interconnected data structure layers, each representing a different aspect of a system. For example a three layer model of a complex military system such as a warship could be arranged as follows:

- **Capabilities/Operations:-** requirements and measures of effectiveness
- **Functions:-** breakdown of system implementation
- **Equipment:-**system components and measures of performance

Additional layers can be added as required, perhaps to separate capabilities and operations, such as scenarios, as a means of combining operations, or sub-assemblies, breaking down complex equipment items.

The properties associated with the data elements at the lowest equipment levels are typically measures of cost and performance against functions. As the properties pass up through the layers they are likely to change into measures of effectiveness or some other measure of general benefit. The lower levels thus represent an engineering based view of the system while the upper layers contain the requirements and user preferences. The intermediate layers essentially link these two views

The resulting structure is shown in **Figure 2**.

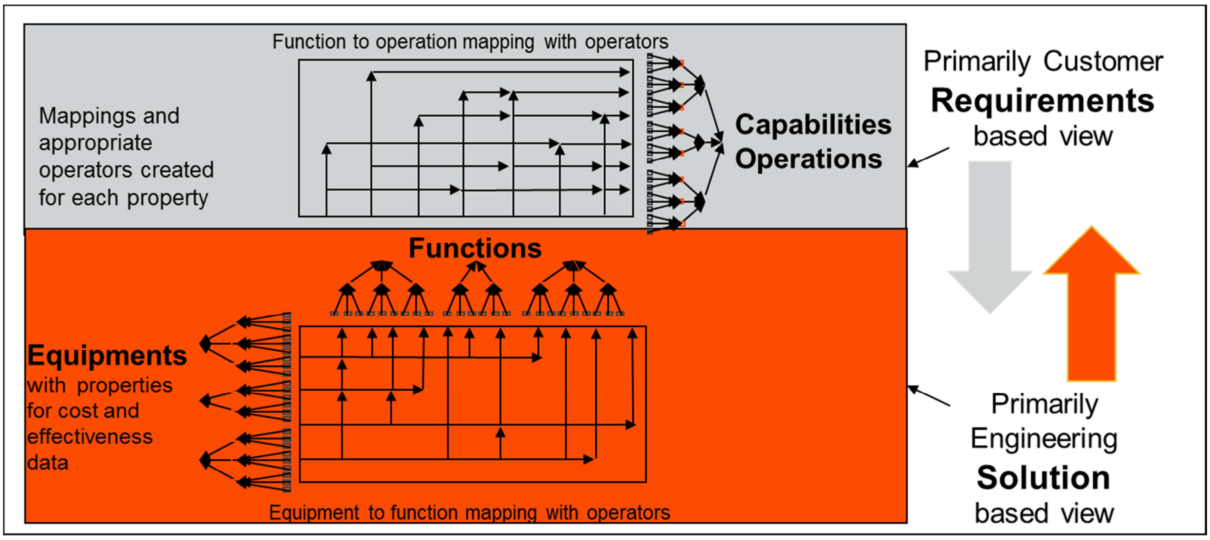

Figure 2 High Level System Breakdown Using Functional Analysis

If a means of switching alternative data elements in each layer on or off is available then different system configurations can be compared with each other against a fixed requirement. Alternatively the system configurations can be compared against different requirement sets. It is also desirable to be able to vary property and link values within the model as these may themselves represent key system variables.

It is possible to use search algorithms to seek out solutions that maximise properties quantifying user benefit and minimise those representing cost. Such system solutions are said to lie on the Pareto Front representing the best value for money. However in a realistic system model that takes account of real world practicalities, such as sub system interdependencies and other engineering constraints, the trade space is likely to be non-linear and quite possibly discontinuous. These characteristics, combined with the exponential explosion in possible solutions that arises if multiple choices are available for many data element options, make optimisation extremely difficult for many traditional algorithms. Fortunately genetic algorithms (Deb, Pratap, Agarwal, & Meyarivan, 2002) have proved themselves to be very robust and useful in such cases and, provided that they are made adaptable to suit the characteristics of the particular system model under consideration and are augmented by mechanisms to ensure that option choice interdependencies are accounted for, they can be very successful in finding cost effective solutions in complex trade spaces representing real world systems.

The functional analysis system modelling, assessment and optimisation method described has been implemented by BAE Systems - Maritime Naval Ships in a general purpose modelling shell known as BAEFASIP, an abbreviation for BAE Functional Analysis of System Implementation Parameters. This software offers a range of facilities, designed to address the complexities described, as follows:

- Calculates multiple properties of system through model data tree structure layers and links
- Allows variety of relationships between properties of different data tree elements and layers, reflecting engineering dependency, redundancy etc.
- Generates new properties from existing
- Allows selection of subsets of any data tree items for evaluation and sensitivity analyses
- Allows choices of data items to be set up within data tree structures
- Allows Pareto front multi variable optimisation to optimise selection of choice options and selected model property and link values in complex trade spaces
- Allows constraints to be imposed on solutions
- Allows rules to be applied to choice combinations and property/link values, reflecting real world practicalities and engineering constraints
- Can find optimum solutions that are robust to variations in property values
- Configurable by the user to deal with a wide range of model structures

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As the software has evolved system models have been developed by both BAE Systems and DSTL for a range of applications:

- T26 Capability Decision Point option analysis (Courts, Brittain, Lamble, & Osborne, 2012)
- Alternative combatant fleet mix optimisation
- Surface combatant configuration optimisation
- General purpose fleet mix optimisation
- Balance of Investment to mitigate risk (Ludford, 2016)

3 Combatant Design Model

This model developed jointly by DSTL and BAE Systems performs cost effectiveness assessment of alternative surface combatant configurations by allowing the selection of platforms and sets of combat system equipment units from predefined lists of options. These options have costs assigned as appropriate and are scored as to how well they implement a range of functions that the system must fulfil. The functions are in turn scored to reflect their value in providing a range of military capabilities, which in turn contribute to the performance of a set of military operations. The operation scores are combined to produce overall figures of merit to reflect both how many operations can be supported and how well the operations are performed by the different system options defined at the equipment level. The framework is thus constructed using four interconnected data layers:

- **Operations:-** defined by Defence Policy
- **Capabilities:-** high level definitions familiar to user requirements setters
- **Functions:-** broken down into sub functions where appropriate
- **Equipment:-** divided into alternative platforms and combat system elements

Each layer has an effectiveness value property linked to, and calculated from, the layer below it. The link values between the layers act as relative weight factors for the lower level effectiveness values as they are combined into values at the upper layer. In addition the lowest equipment level has a cost parameter together with additional constraint properties used to label the equipment as being of a particular equipment type such as weapon module, command system console, boat etc. Each platform can only carry a certain number of each equipment type and so the type properties can be used as a check on the limit to the number of different equipment items that can be fitted in particular areas of any given platform.

The system model has been implemented in both an Excel spreadsheet and in the BAEFASIP tool. The Excel implementation provides verification that the model has been correctly implemented in BAEFASIP. The latter implementation can automatically synthesise potential design solutions optimised for cost and effectiveness from equipment and platform choice options. Engineering practicality of the synthesised systems is achieved by the specification of constraint properties and rules on which equipment and platform options can be selected with which other options e.g. Land attack missiles require sufficient VLS cells to be available and some missile types require a tracker radar to be fitted in addition to the search radar used for target detection.

In summary the model considers

- Alternative **Equipment** units inherent ability to perform **Functions**
- Alternative **Equipment** platform performance levels contribution to **Functions**
- **Equipment** unit demands on platform and platform capacities for demands
- Rules on which **Equipment** unit can be fitted to which **Equipment** platform
- Consideration of **Equipment** platform constraints when selecting multiple **Equipment** units

- **Function** contributions to **Capabilities**
- Critical levels of **Function** benefit scores required for particular **Capabilities**
- **Capability** contributions to **Operations**
- Critical levels of **Capability** benefit scores required for particular **Operations**
- Critical **Equipment** units required for particular **Operations**
- Costs of **Equipment** units and platforms

The Pareto front optimisation results from the model can be displayed in several ways examples of plots of different information about the optimum front in **Figure 3** and **Figure 4** while optimum system configurations are displayed in **Figure 5** and **Figure 6.**

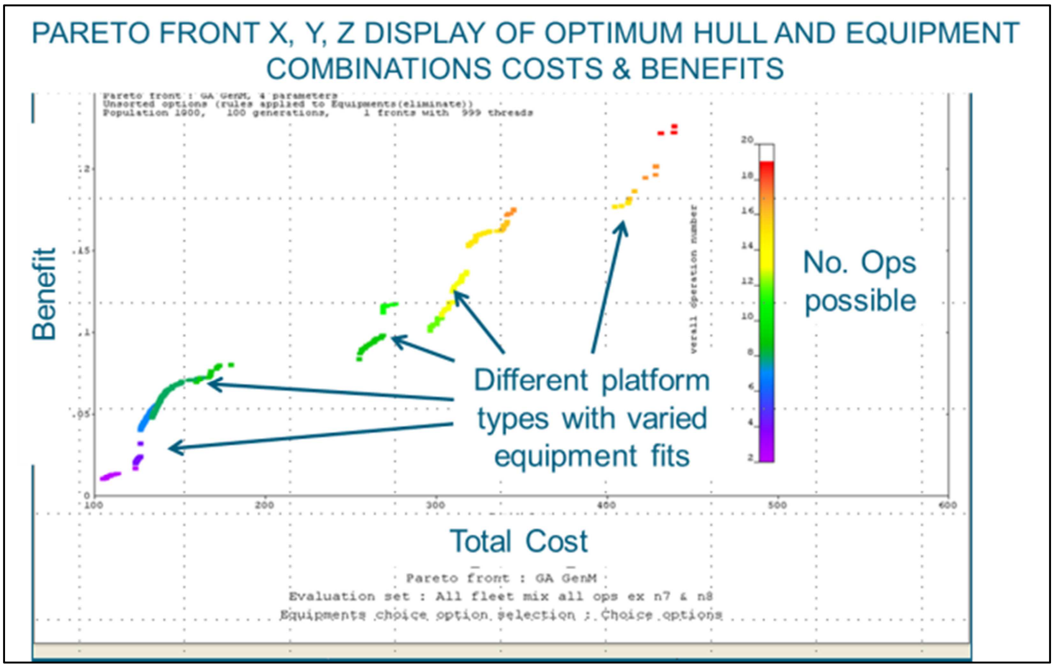

Figure 3 Combatant Optimum Cost Effectiveness Front – X,Y,Z Display of Optimisation Parameters

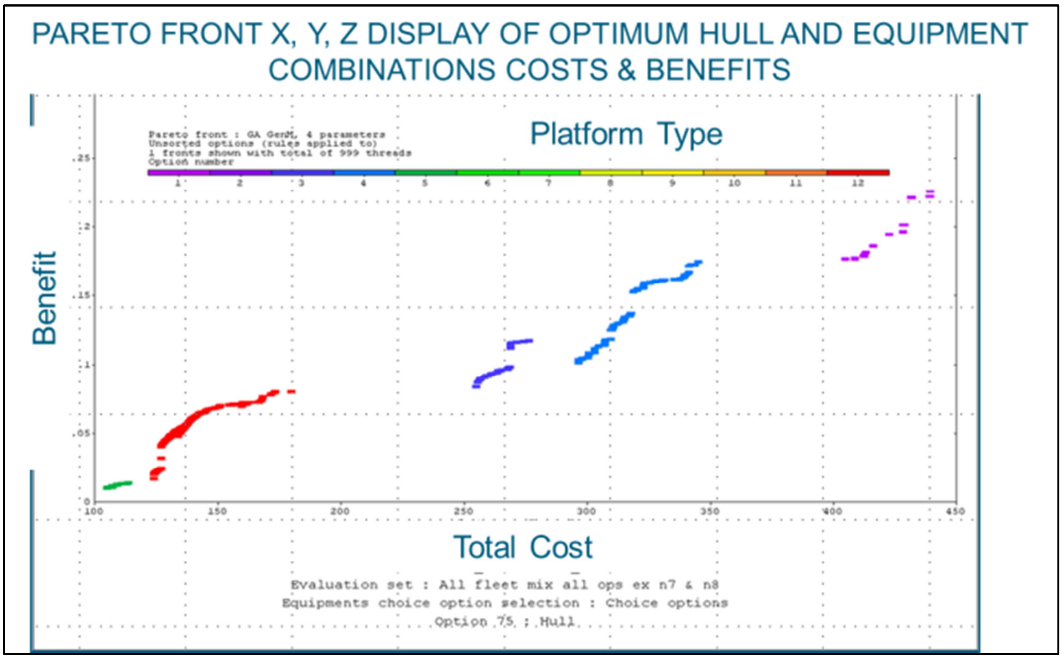

Figure 4 Combatant Optimum Cost Effectiveness Front - Platform Options

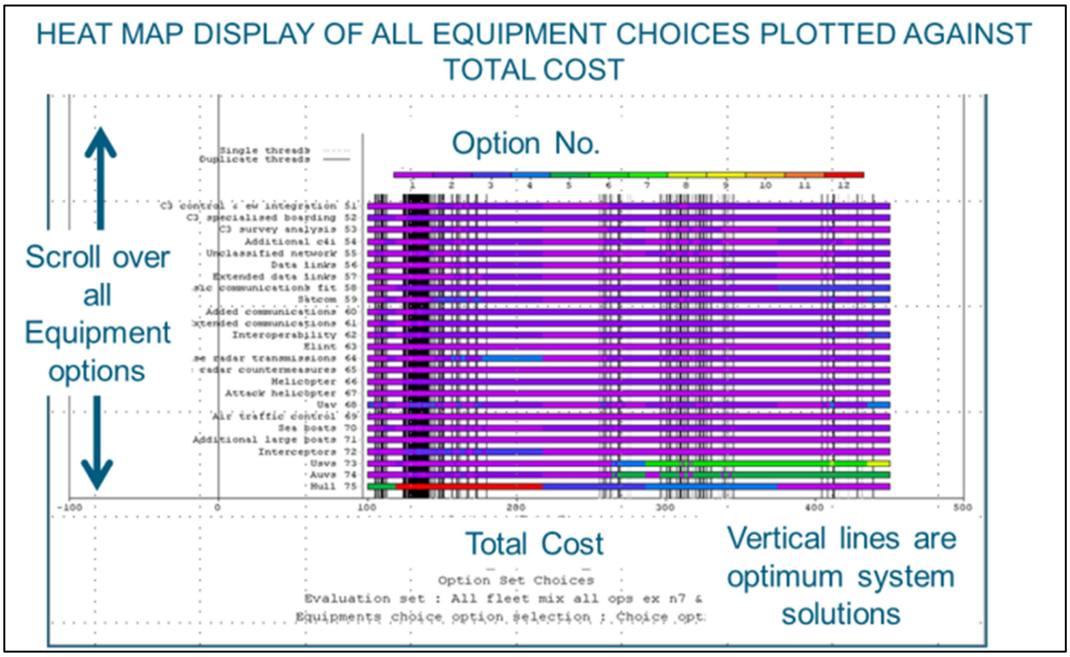

Figure 5 Combatant Optimum System Configurations - Heat Map Display of Options Against Cost

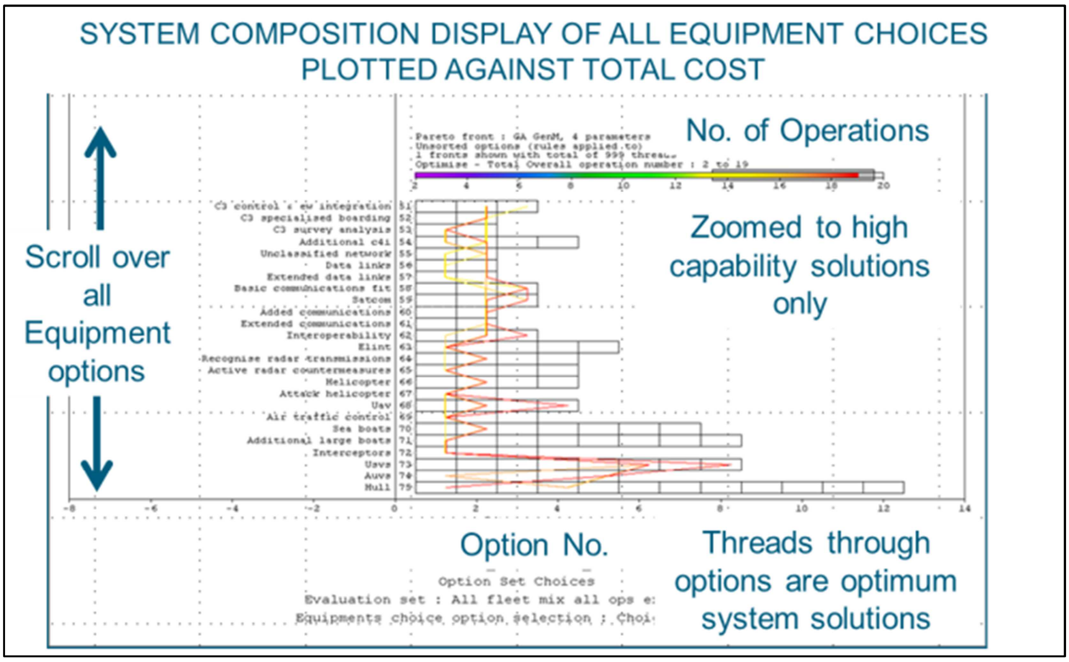

Figure 6 Combatant Optimum System Configurations - Zoomed Option Display

4 Fleet Mix Models

An early version of the software was used to implement a fleet mix optimisation model to be used to investigate alternative combatant concept designs intended to supplement the current in service and planned ship types. The model consisted of three layers:

- **Operation Concurrencies:-** Sets of concurrent operations defined by Defence Policy
- **Operations:-** with capabilities required by them specified as properties
- **Ship types:-** choices within each ship type defining the total number of that type available

The model was constructed using the properties passed through the layers to define the required numbers of units with each of 30 general and critical capabilities to be made available for each operation. The required capabilities could be provided by variable numbers of each ship type, each of which had a different mix of capabilities. At the fleet level the total number of ships required was given by the taking the numbers required by the worst operation concurrency case for each ship type. The limitation of this approach is that individual ships are not allocated to operations, only the total numbers of ships, and capability units available are checked. This has the potential to slightly underestimate the numbers of ships required as capabilities may not be where required. This limitation meant that further studies had to be conducted in order to confirm the validity of the results obtained. These later studies confirmed the general conclusions from this initial FASIP fleet mix model.

Subsequently software developments have allowed the development of a more comprehensive model that deals with ship allocation accurately and so the capability requirements can be met exactly. The new model is again constructed in three layers but is able to consider more factors than previously. As well as operation requirements for numbers of units with capabilities and critical capabilities, numbers of required off board systems can be specified. This requirement is checked against the numbers of such systems available on ships allocated to that operation. In addition rules on how ships may or may not be deployed together can be specified, e.g. support ships or shore based support facilities etc. At the fleet level the need for bases or repair facilities can be tied to overall numbers of ships.

A 5 parameter multi criteria optimisation was performed on the following parameters:

• Total costs (acquisition costs)	**Minimise**
• Total benefits	**Maximise**
• No. of concurrencies	**Maximise**
• Total manning (Through life cost driver)	**Minimise**
• Number of classes (Through life cost driver)	**Minimise**

In summary the latest model offers the following facilities:

- **Ship** inherent capabilities & capacity for deploying facilities e.g. USVs etc.
- Numbers of **Ships** with capabilities required by **Operations**
- Numbers of **Ships** with capabilities above critical level required by **Operations**
- Numbers of **Ship** deployed facilities required by **Operations**
- Critical total capability benefit scores for particular **Operations**
- Rules tying one type of **Ship** to others required within an **Operation** (i.e. support ship per no. of other ships etc.)
- **Operations** required by each **Concurrency**
- Critical **Operation** benefit scores for particular **Concurrencies**
- Relative importance of **Concurrencies**
- Force generation factors for different **Ship** types
- Manning and associated generation factors for each **Ship** type
- Costs, both Unit Production Cost (UPC) and Non-Recurring Expenditure (NRE)
- Limits of numbers of a **Ship** type across fleet (e.g. T45 and T26)

Additional items required to support fleet depending on numbers of **Ships** required (e.g. dockyards, etc.) & their costs/manning

Example outputs from the latest model are shown in the attached figures. **Figure 7, Figure 8** and **Figure 9** shows X, Y Z plots of cost, benefit and one other optimisation parameter. It can be seen that there are correlations between the parameters. Alternative displays of the numbers of each ship type allocated to each operation are shown in **Figure 10** and **Figure 11**.

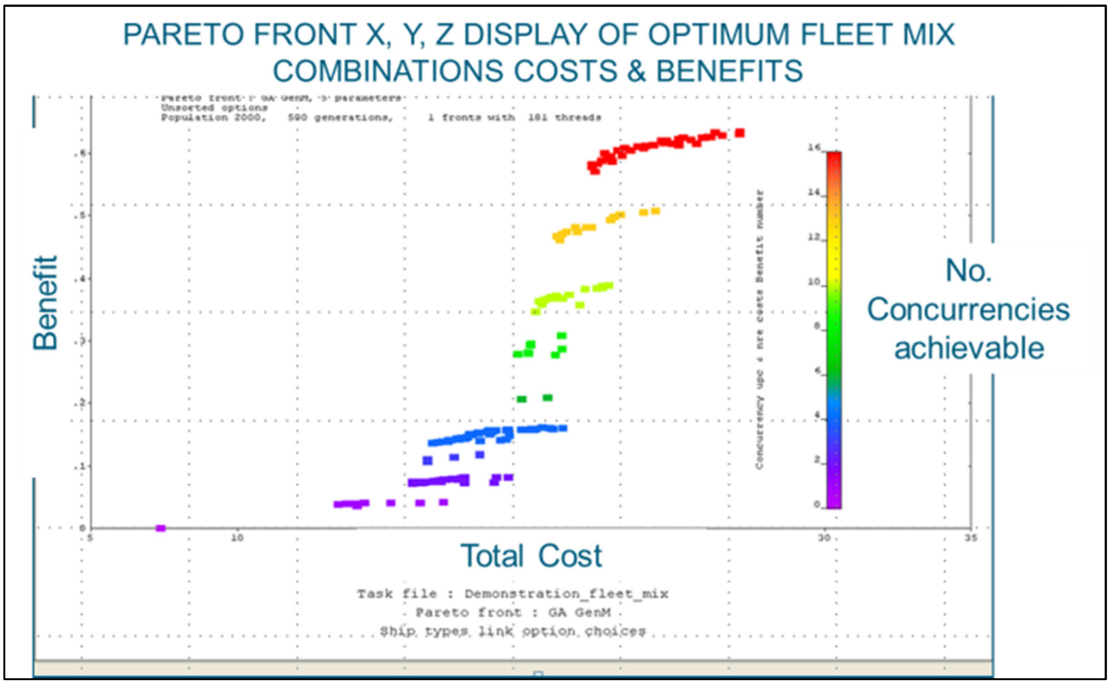

Figure 7 Optimum Fleet Mix - Optimum Front X, Y, Z Plot Cost, Benefit, No. Concurrencies

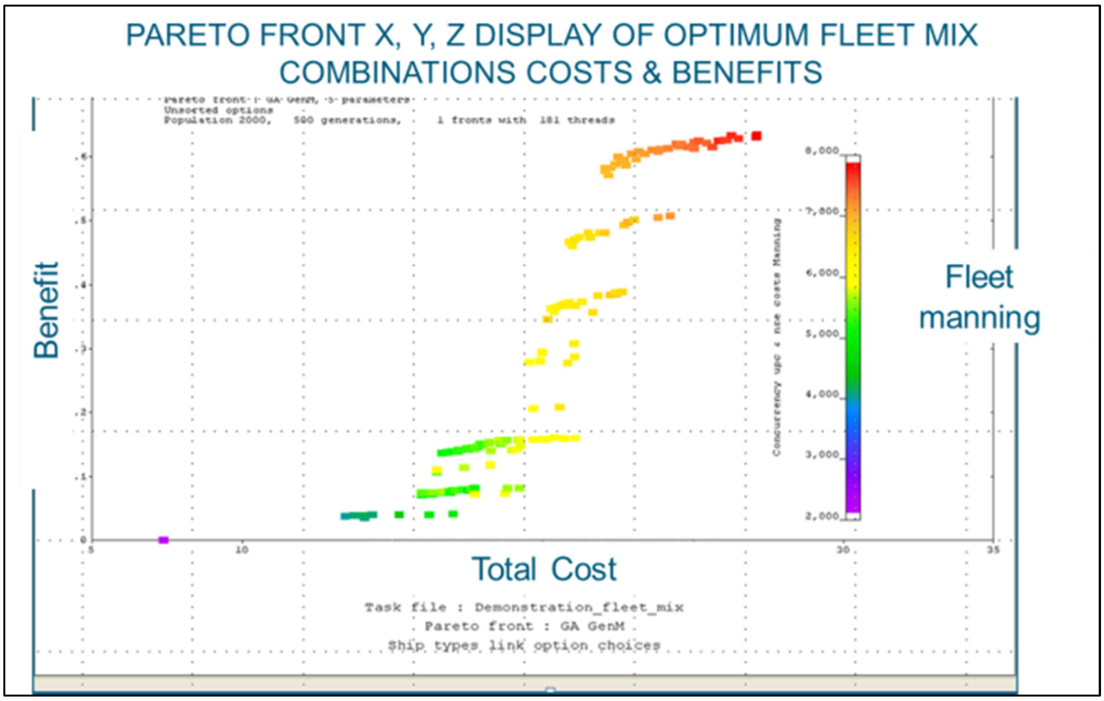

Figure 8 Optimum Fleet Mix - Optimum Front X, Y, Z Plot Cost, Benefit, Fleet Manning

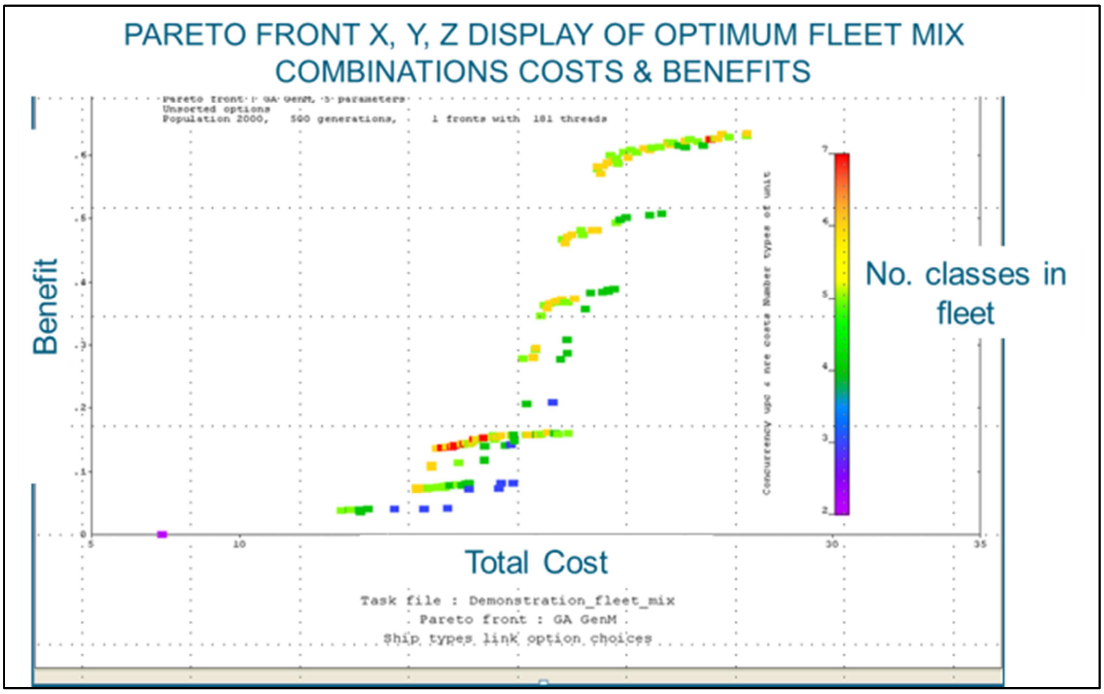

Figure 9 Optimum Fleet Mix - Optimum Front X, Y, Z Plot Cost, Benefit, No. Classes

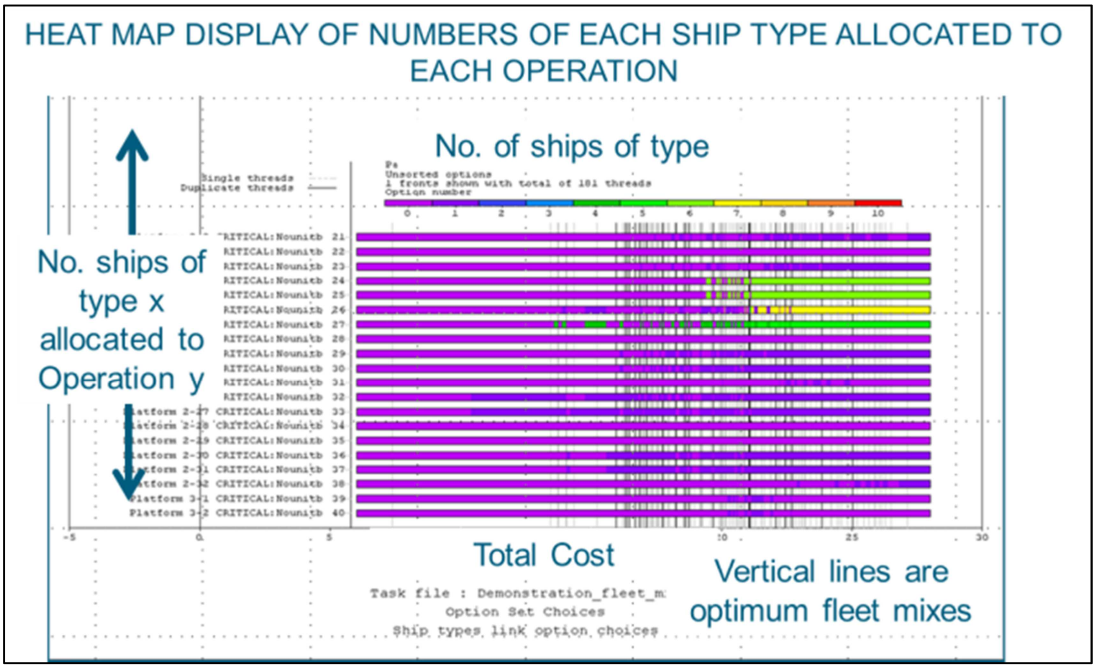

Figure 10 Optimum Fleet Mixes :- Heat Map Option Display

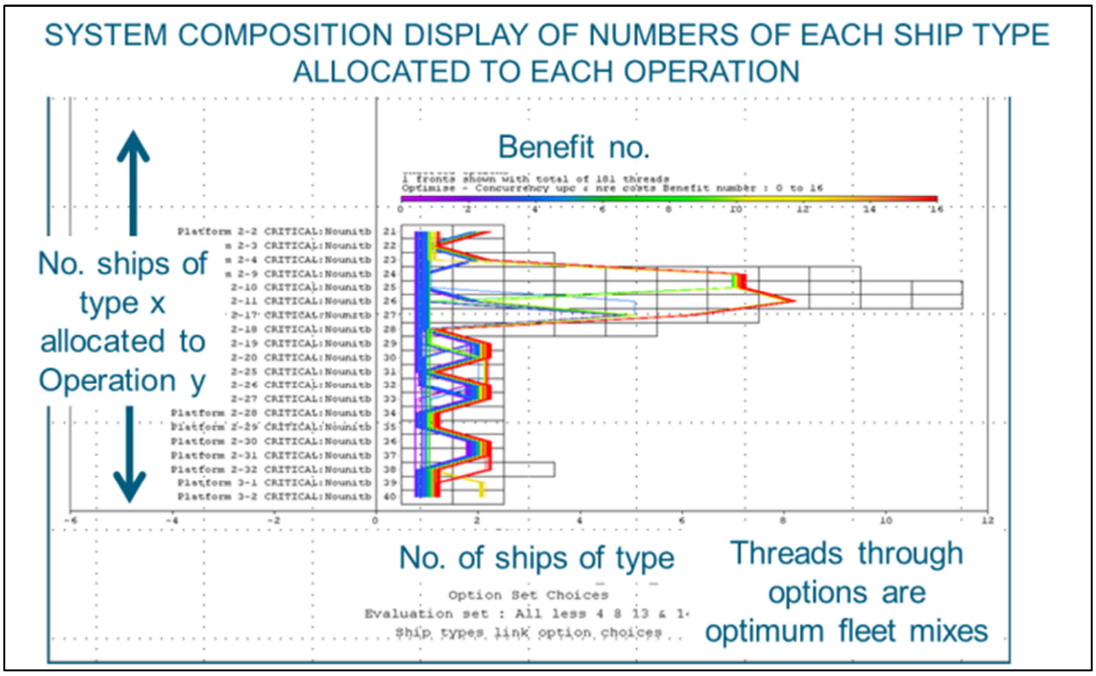

Figure 11 Optimum Fleet Mixes: Option Display

The data can also be output to Excel and an example of a plot found to be useful in discussions with stakeholders is shown in **Figure 12.** This shows how the optimum numbers of each ship type available for deployment (y-axis) at any one time vary as the available budget is increased (x-axis). Only the fleets that are capable of delivering all concurrency cases are shown.

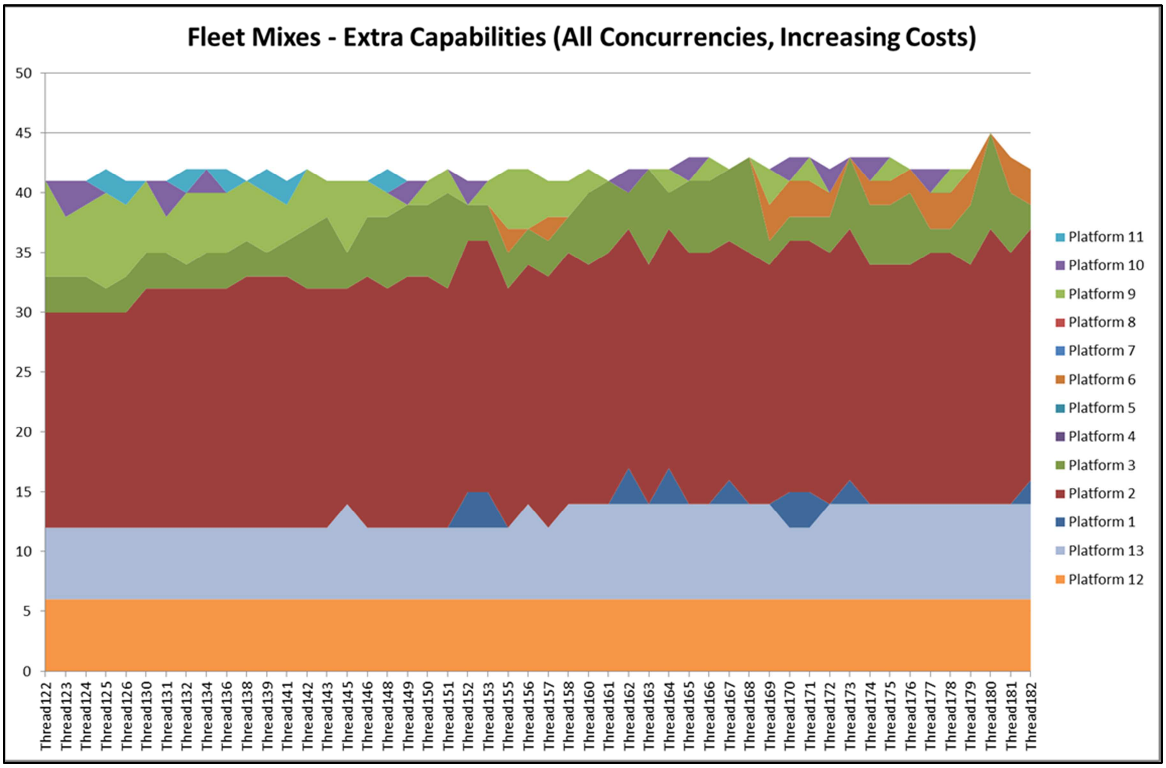

Figure 12 Optimum Fleet Mixes at Increasing Cost Points

5 Utilisation of Models in Decision Process

Both of the models have been developed to support decision making in the Maritime domain. They have been constructed to provide direction to the research programme and future Force Development studies.

The Combatant Design model has been set up to pull through operational considerations into platform design. Force Structure analysis has been used to identify scenarios that need to be delivered from platforms and then recent historical data and tactics and operating processes determine the operational activities within the scenarios.

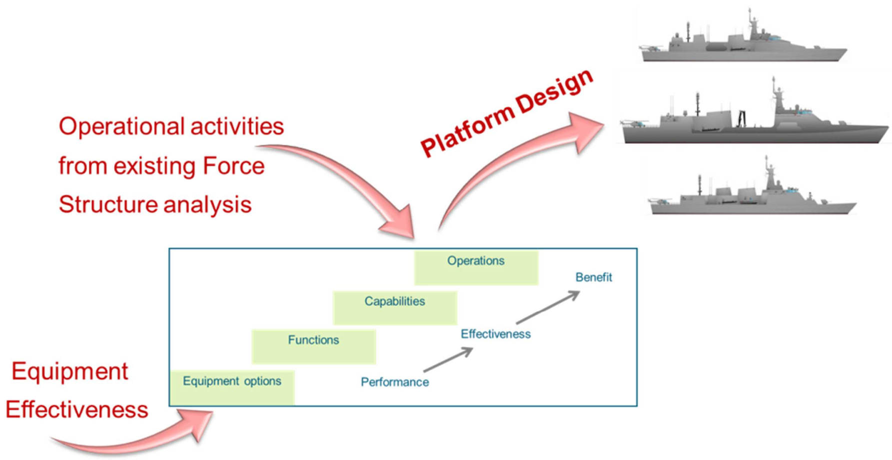

Figure 13 Utilisation of Combatant Design model

Low level assessments are used to determine the effectiveness of equipment for each function and capability. This means that platforms can be designed with features tailored towards specific operations or mix of operations. This tool can also be used to assess the benefit of new equipment or new technologies against an operational backdrop.

The Fleet Mix model has been set up to allow consideration of a broad range of platforms within Force Development analysis for the Royal Navy. Platform designs can be pulled through form the Combatant Design Model and assessed against the same types of operations and activities.

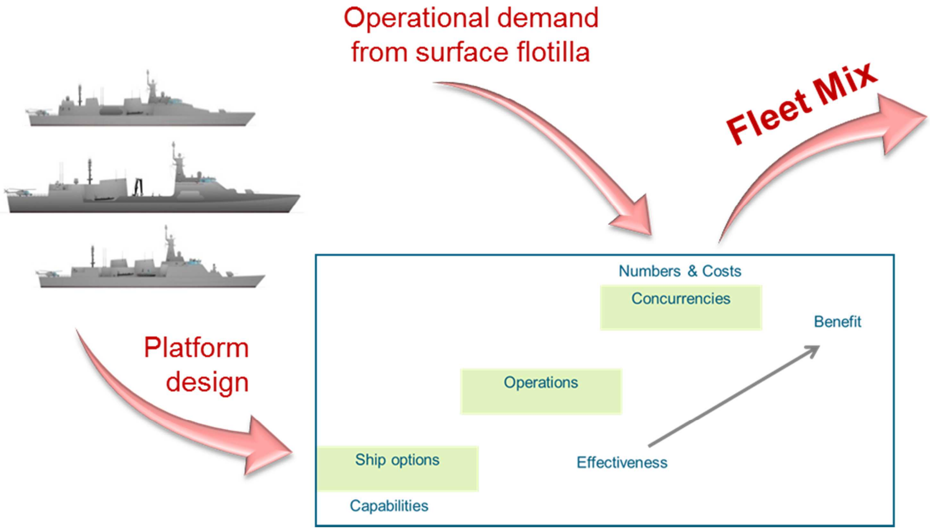

Figure 14 Utilisation of Fleet Mix model

An earlier version of this model was developed during 2015 and used to support RN preparations for SDSR15. A number of fleet mixes were developed and assessed against appropriate concurrency sets. The platforms assessed were drawn from platform designs developed within the research community and real world RN platforms. This helped gain an understanding of the robustness of the existing fleet and areas where alternative platform designs or additional systems provide benefit.

6 Conclusions

The functional analysis approach has proved successful in modelling the Top Down customer view of high level operational requirements and combining it with the Bottom Up engineering synthesis view of how practical systems are actually constructed and integrated using discrete units, either developed or off the shelf, with their inevitable constraints and limitations.

At the lower levels realistic equipment, sub system and system costs can be calculated and measures of performance of equipment against functions defined with a reasonable degree of accuracy.

At the upper levels subjective judgement becomes more important and stakeholder preferences play an important role. The techniques of value theory can be used in the models to describe these views.

The upper and lower levels are linked using insights gained from user experience and the results of operational analysis studies. Together these can be used to define the links and relative importance of different functions and capabilities to particular operations.

The trade space covering all possible systems, when choices are available for some elements, can be narrowed down to the Pareto Front of Best Value at a range of cost points by using genetic algorithm based optimisers. These optimisers are made much more valuable by the incorporation of algorithms to ensure that generated solutions are compliant with real world constraints and limitations on how alternative sub system elements interact with each other.

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Disclaimer

The views expressed in this paper are those of the authors and do not necessarily represent those of DSTL.

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