

OIL TANKER DESIGN METHODOLOGY CONSIDERING PROBABILISTIC ACCIDENT DAMAGE

A.J. Brown

*Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0203, USA
Email: brown@aoe.vt.edu*

This paper proposes a total-system design methodology that includes four important components necessary for a systematic approach to oil tanker concept design. These are:

- An efficient and effective search of design space for optimal or non-dominated designs
- Well-defined and quantitative measures of objective attributes, cost and risk
- An effective format to describe the design space and to present non-dominated concepts for rational selection by the customer
- A probabilistic method for predicting damage in tanker accidents and improving tanker crashworthiness

A Multi-Objective Genetic Optimization (MOGO) is used to search design parameter space and identify non-dominated design concepts based on total ownership cost and oil outflow risk. A simplified ship synthesis model balances the designs and assesses their feasibility. A cost model estimates total ownership cost which is defined to include construction cost, and discounted operational and maintenance costs. A risk model calculates the probability of grounding and collision and the resulting oil outflow in bottom and side damage. Damage is predicted using simplified damage models in a Monte Carlo simulation. The optimization considers hull form characteristics, producibility, cargo block subdivision and double hull dimensions, structural design characteristics, propulsion and power redundancy, manning and automation, and trade route and port characteristics. The emphasis of this paper is on process. Some preliminary results are presented.

Keywords: ship design, optimization, tanker accidents, genetic algorithms

1. INTRODUCTION AND MOTIVATION

The traditional approach to ship design is largely an “ad hoc” process. Selection of design concepts for assessment is guided primarily by experience, design lanes, rules-of-thumb, preference and imagination. Objective attributes are not adequately synthesized or defined to support effective decisions and optimization. The design space is very large, non-linear, discontinuous, and bounded by a variety of constraints and thresholds. These problems make a structured search of design space difficult. Without a structured search, there is no rational way to measure the optimality of selected concepts relative to the millions of other concepts that have not been considered or assessed. Responsible decisions cannot be made without this information and perspective.

This paper provides a systematic design methodology to address these problems. The approach presented in the paper was developed originally for application to naval ships, but its application to the cost-effective optimization of tanker risk is a natural extension [1]. Objective attributes in the tanker application are cost and oil outflow risk. Mean oil outflow is used as the metric for outflow risk. Damage in collision and grounding is calculated using models developed under the Society of Naval Architects and Marine Engineers (SNAME) Ad Hoc Panel on Structural Design and Response in Collision and Grounding [2].

The tools necessary to quantify tanker risk and to effectively make investment and regulatory decisions relative to tanker safety are limited. In the absence of a complete quantitative understanding of tanker risk we see a number of knee-jerk reactions to public outcries over tanker safety. The complexity of the tanker/waterway system forces industry, government and academia to focus on manageable pieces of the total problem or, when a total system perspective is necessary, to take a top-down statistical approach. No one method of analysis, regulation, or piece of the system tells the whole story [3].

The serious consequences of ship grounding and collision necessitate the development of regulations and requirements for the subdivision and structural design of ships to reduce damage and environmental pollution, and improve safety. The International Maritime Organization (IMO) is responsible for regulating the design of oil tankers and other ships to provide for ship safety and environmental protection. Their ongoing transition to probabilistic performance-based standards requires the ability to predict the environmental performance and safety of specific ship designs. This is a difficult problem requiring the application of fundamental engineering principles and risk analysis.

IMO first introduced probabilistic standards in damage stability regulations for passenger ships [4] and later for cargo ships [5]. IMO's first attempt to apply a probabilistic methodology to tankers was in response to the US Oil Pollution Act of 1990 (OPA 90). In OPA 90 the US required that all oil tankers entering US waters must have double hulls. IMO responded to this unilateral action by requiring double hulls or their equivalent. Equivalency is determined based on probabilistic oil outflow calculations [6].

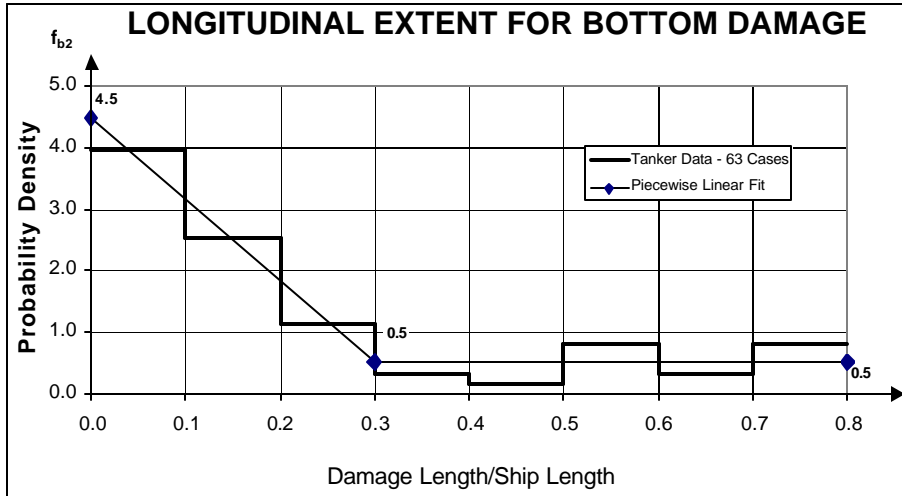


Figure 1. Bottom damage pdf [6,7]

These regulations use probability density functions (pdfs) to describe the location, extent and penetration of side and bottom damage. These pdfs are derived from limited historical damage statistics [7], and applied identically to all ships without consideration of their structural design. Figure 1 is the IMO probability density function used to define the longitudinal extent of bottom damage from grounding in oil outflow calculations. The histograms represent the statistical data collected by the classification societies and the linear plot represents IMO's piece-wise linear fit of the data. Other IMO pdfs are constructed in a similar manner.

A major shortcoming in IMO's current oil outflow and damage stability calculation methodologies is that they do not consider the effect of structural design or crashworthiness on damage extent [6,7]. The primary reason for this exclusion is that no definitive theory or data exists to define this relationship. Other deficiencies include:

- Damage pdfs consider only damage significant enough to breach the outer hull. This penalizes structures able to resist rupture.
- Damage extents are treated as independent random variables when they are actually dependent variables, and ideally should be described using joint pdfs.
- Damage pdfs are normalized with respect to ship length, breadth and depth when damage may depend to a large extent on local structural features and scantlings vice global ship dimensions.

It is logical and essential that crashworthiness is considered in oil outflow and damage stability calculations. Analytical methods to estimate damage must be applied in a probabilistic framework to predict possible accident damage and oil outflow over the life of a specific ship with a specific structural design.

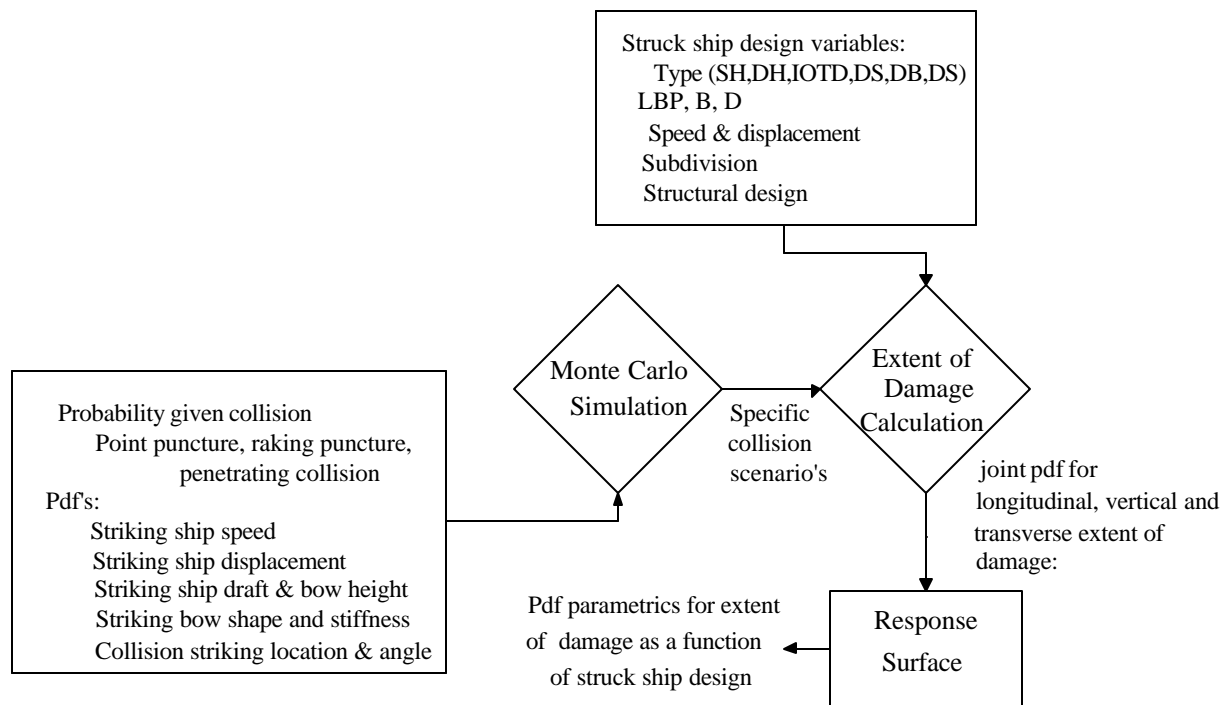


Figure 2. Process to predict probabilistic damage [1]

2. PROBABILISTIC FRAMEWORK

Figure 2 illustrates the process proposed to predict the probabilistic extent of damage in collision as a function of ship structural design [3]. A similar process is proposed for grounding. This process is part of the oil outflow risk model used in the multi-objective design optimization.

The process begins with a set of probabilities and probability density functions (pdfs) defining possible grounding or collision scenarios. Using these pdfs, a specific scenario is selected in a Monte Carlo simulation, and combined with a specific ship structural design to predict damage. This process is repeated for thousands of scenarios and a range of structural designs until sufficient data is generated to define damage and ultimately oil outflow distributions.

2.1 Oil Outflow Risk Model

The risk model used in this study considers oil outflow resulting from grounding and collision accidents. The probabilities of grounding and collision over the lifetime of the ship are calculated based on ship principal characteristics, ship manning and automation, ship management factors, and waterway characteristics [8,9]. Mean oil outflow and the probability of zero outflow in side and bottom damage are calculated using a simplified oil outflow calculation methodology [10,11] modified to include the calculation of damage extent shown in Figure 2 using models developed at Virginia Tech and MIT [12,13,14,15].

Mean lifetime oil outflow is calculated as follows:

$$O_M = P_{grounding} O_{Mbottom} + P_{collision} O_{Mside} \quad (1)$$

where:

$P_{grounding}$ = Lifetime (30 yr.) probability of grounding

$P_{collision}$ = Lifetime (30 yr.) probability of collision

$O_{Mbottom}$ = Mean oil outflow from grounding (m^3)

O_{Mside} = Mean oil outflow from collision (m^3)

These parameters are not conditional on the occurrence of an accident as in present IMO regulations. They are absolute quantities that consider the probability of grounding or collision for the specific ship on a specific route. As a result, they are sensitive to design parameters such as machinery redundancy, manning and ship maneuverability.

2.2 Probability of Grounding and Collision

Probabilistic risk assessment (PRA) methods are used to develop the grounding and collision models [8,9]. The models use fault trees including Performance Shaping Factors (PSFs) and Management and Organizational factors (MOFs). Tanker groundings are either powered groundings or drift groundings. The powered grounding portion of the grounding fault tree is shown in Figure 3. The probability of collision is calculated using a similar methodology.

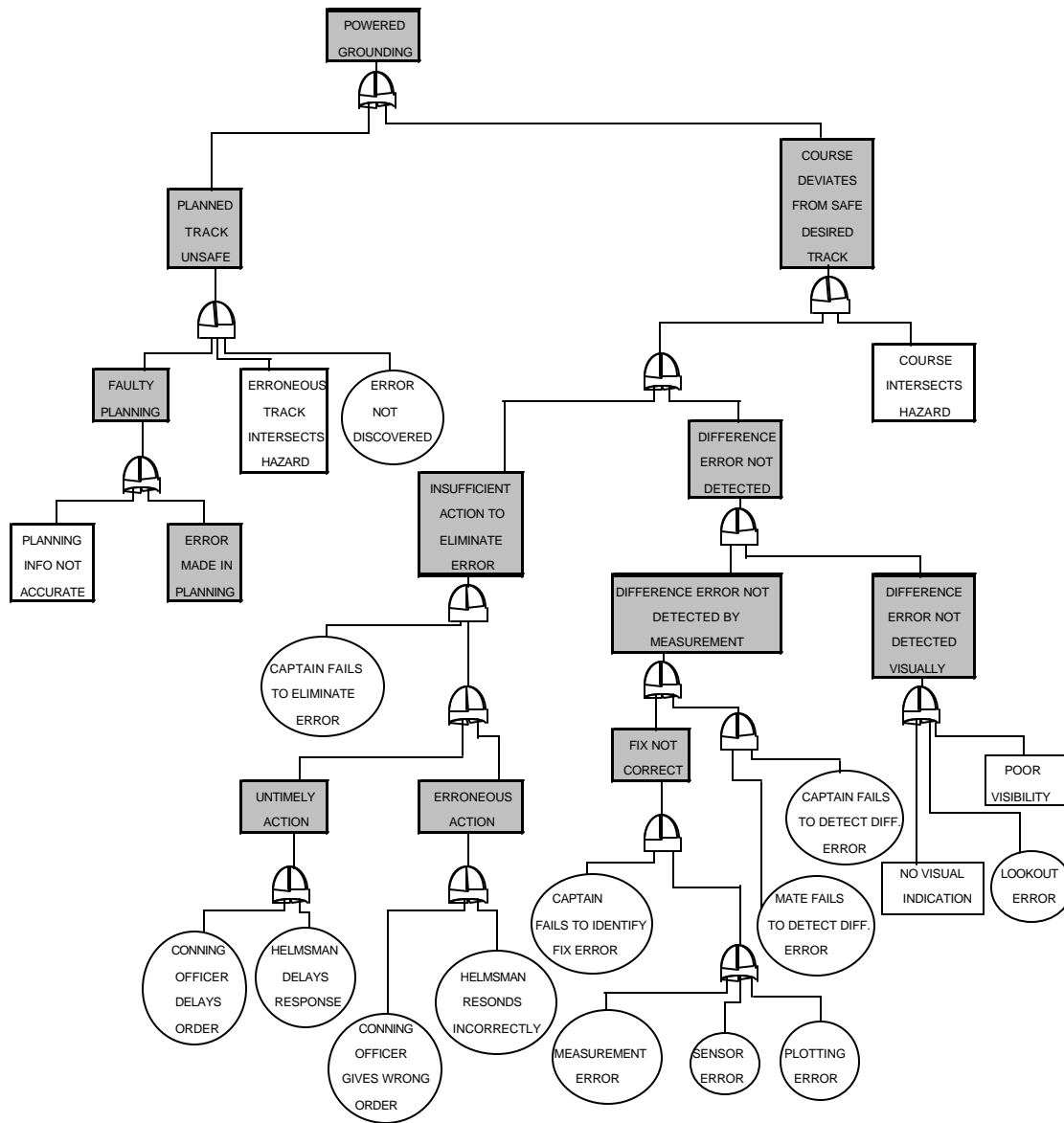


Figure 3. Powered grounding fault tree

2.3 Oil Outflow

There are four main steps in the simplified oil-outflow methodology [11]:

Step 1: Assemble Damage Cases – Use the Monte Carlo simulation methodology and damage models shown in Figure 2.

Step 2: Calculate Oil Outflow - Consistent with the IMO Guidelines [6], 100% outflow is assumed for all cargo tanks sustaining side damage. Outflow from bottom damage is calculated for tidal ranges of zero and 2.5 meters based on hydrostatic pressure differentials. The flooded volume of double bot-

tom ballast tanks or voids located below ruptured cargo tanks retain up to 50% of the outflow oil by volume.

Step 3: Calculate Oil Outflow Parameters - Mean outflow is calculated by summing the products of the probability of damaging each cargo tank and the oil outflow associated with each tank. Mean outflow is calculated separately for side and bottom damage. The probability of zero outflow P_0 (i.e. the probability of breaching the outer hull but not spilling any oil) is:

$P_0 = 1 - P_{CB}$, where P_{CB} is the probability of breaching any tank in the cargo block.

3. TOTAL OWNERSHIP COST

Total ownership cost (TOC) components considered in this study are shown in Figure 4. Only cost components that depend on the model's design parameters (DPs) are included in the TOC. Other life cycle costs, not included in the TOC, are assumed to be second order or approximately constant for all designs. Annual life cycle costs are discounted to the base year, using an annual discount rate of 7%. Construction costs are estimated using weight-based equations adapted from a naval ship cost model [16].

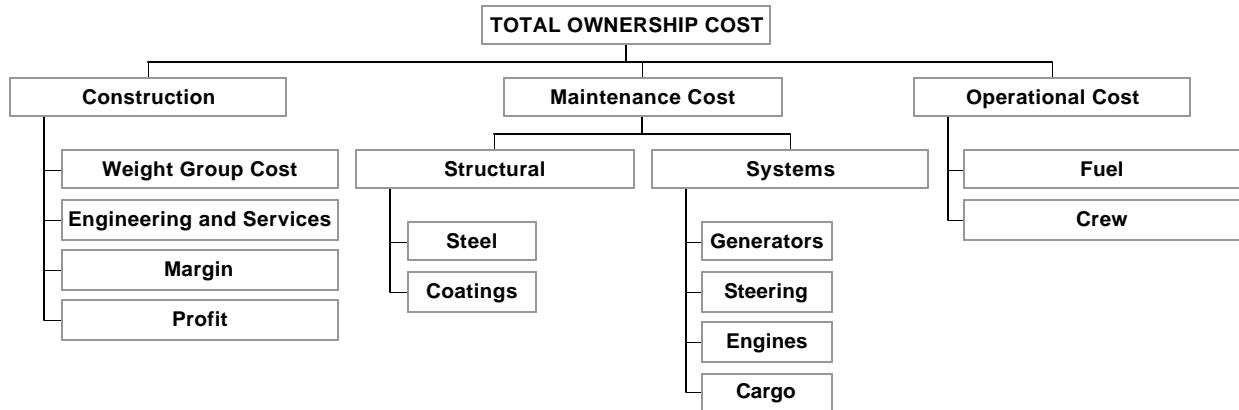


Figure 4. Cost components

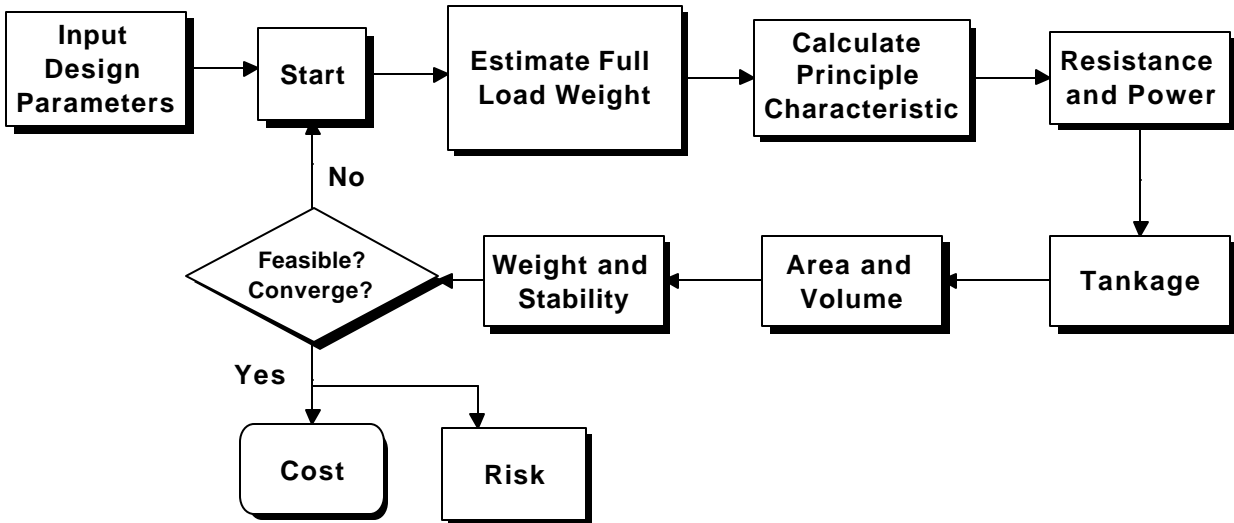


Figure 5. Ship synthesis model

4. SHIP DESIGN SYNTHESIS MODEL

Selected ships are balanced and assessed for feasibility using a ship synthesis model. The model balances the ship in terms of weight, displacement, volume, area and power for a given set of design parameters. It assesses the feasibility of the balanced design, and calculates total ownership cost and oil-outflow risk using the models described above. Figure 5 provides a flowchart of this process.

In the Genetic Algorithm application using this model, input design parameters are specified in a design matrix. Design parameters with ranges and resolution are listed in Table 1.

5. DESIGN OPTIMIZATION

A Genetic Algorithm (GA) is a probabilistic optimization methodology based on the principle of *the survival of the fittest* [17,18]. The goal of a GA is to use its evolutionary process to gradually evolve a population of individuals, ship designs in our case, in the direction of improved fitness. Fitness may be defined using a simple objective function, or a more complex combination of objectives and criteria. In a Pareto-Genetic Algorithm (PGA), Pareto dominance is used to assess fitness [19]. Dominance may be assessed using a number of objective attributes. In this application, dominance is based on minimizing cost and risk. The result of this optimization is a non-dominated (Pareto) frontier.

Genetic Algorithms (GAs) are ideally suited to optimizing discontinuous and disjointed functions, and to optimization where no closed-form function exists. The robustness of a particular GA depends on its exploration and efficiency qualities. Exploration refers to its ability to master the design space and consistently identify the global optima. Efficiency refers to the effort required to identify the global optima. Robustness implies an effective balance between these qualities. Genetic algorithms are very robust relative to other methods.

Table 1. Design Parameter Range and Resolution

Design Parameter	Description
1 - Beam to Draft ratio (C_{BT})	2.0-4.0; 40 increments
2 - Length to Beam ratio (C_{LB})	5.0-7.0; 40 increments
3 - Block Coefficient (C_B)	0.7-0.9; 40 increments
4 - Depth to Draft Ratio (C_D)	1.2-2.0; 40 increments
5 - Double Bottom Height (hdb)	2.0-4.0 meters; 20 increments
6 - Double Side Width (wds)	2.0-4.0 meters; 20 increments
7 - Manning Factor (Manfac)	0.5-1.0; 10 increments
8 - Structural Margin Factor (SMF)	1.0-1.5; 5 increments
9 - Average Deck Height (HDK)	3.0-4.0 meters; 10 increments
10 - Cargo Block Transverse Subdivision (N_{CARGO})	4-8; 4 increments
11 - Propulsion System Options (N_{PSYS})	1-6; 6 options
12 - Electric Power Redundancy Factor (N_{KW})	1,2; 2 options
13 - Stern Design Options (N_{STERN})	1,2; 2 options; 1 – producible, 2- high curvature

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Genetic algorithms are particularly well-suited to generate a Pareto-optimal frontier because they improve the fitness of a population of concepts simultaneously. By penalizing fitness for niching or bunching-up, the population of designs can be forced to spread out over non-dominated values of the objective attributes, and ultimately define the Pareto-optimal frontier.

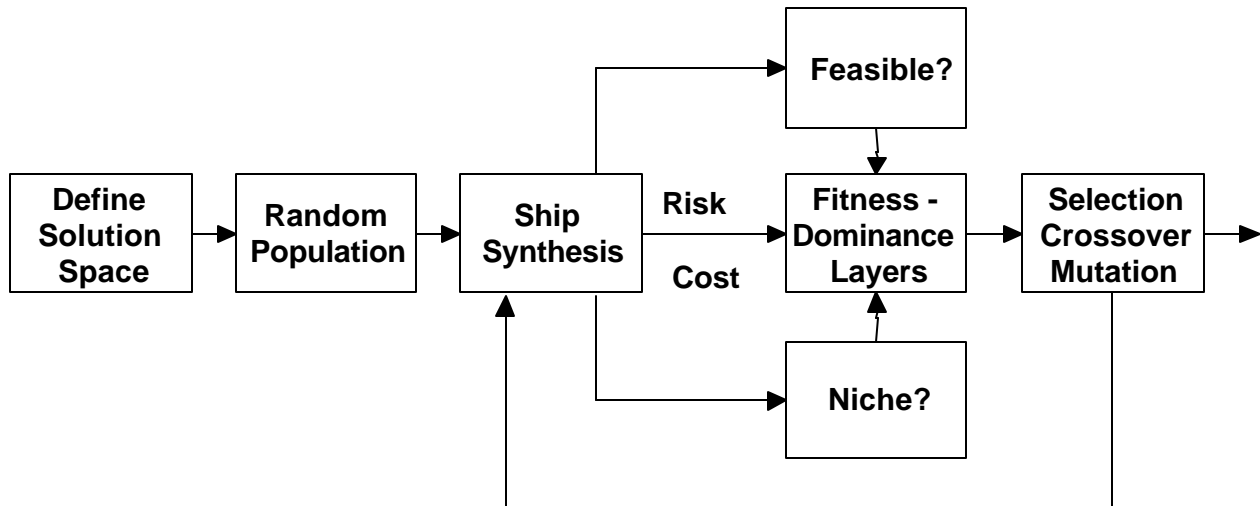


Figure 6. PGA Optimization Process

Figure 6 illustrates the Pareto-Genetic Algorithm (PGA) used in our multi-objective genetic optimization (MOGO). An initial population of 200 designs is created by random selection of design variables within the design space specified in Table 1. A chromosome or design vector with 13 design parameters represents each design. The ships defined by these chromosomes are balanced, and evaluated

using the ship synthesis model. This produces a cost and risk value for each design. Next, designs are sorted into layers of Pareto-dominance. Each layer contains designs that are dominant to subsequent layers. A geometrically decreasing probability of selection is assigned to each design based on its layer. Designs are penalized for infeasibility and for niching.

Once selection probabilities are calculated, the selection operator is applied. A roulette wheel is constructed with 200 segments each representing a design. The area of each segment is equal to the design selection probability. Baker's selection method is used [20]. This method "spins" 200 (population size) equally space markers once (vice spinning one marker 200 times) to select 200 designs (some multiple times) for survival and reproduction.

Once a surviving population is selected, 25 percent of these are chosen in pairs at random for crossover. A cut is made at a random location in the chromosomes of each pair. Design parameters below the cut are swapped between the parents producing new variants or offspring. A small percentage of individual design parameters (genes) in the selected variants are chosen randomly to mutate. In mutation, the value of a single design parameter is replaced with a new value chosen at random. After these operations are completed, new designs in the new population are sent to the ship synthesis model the process cycles until convergence. Each cycle defines a new generation.

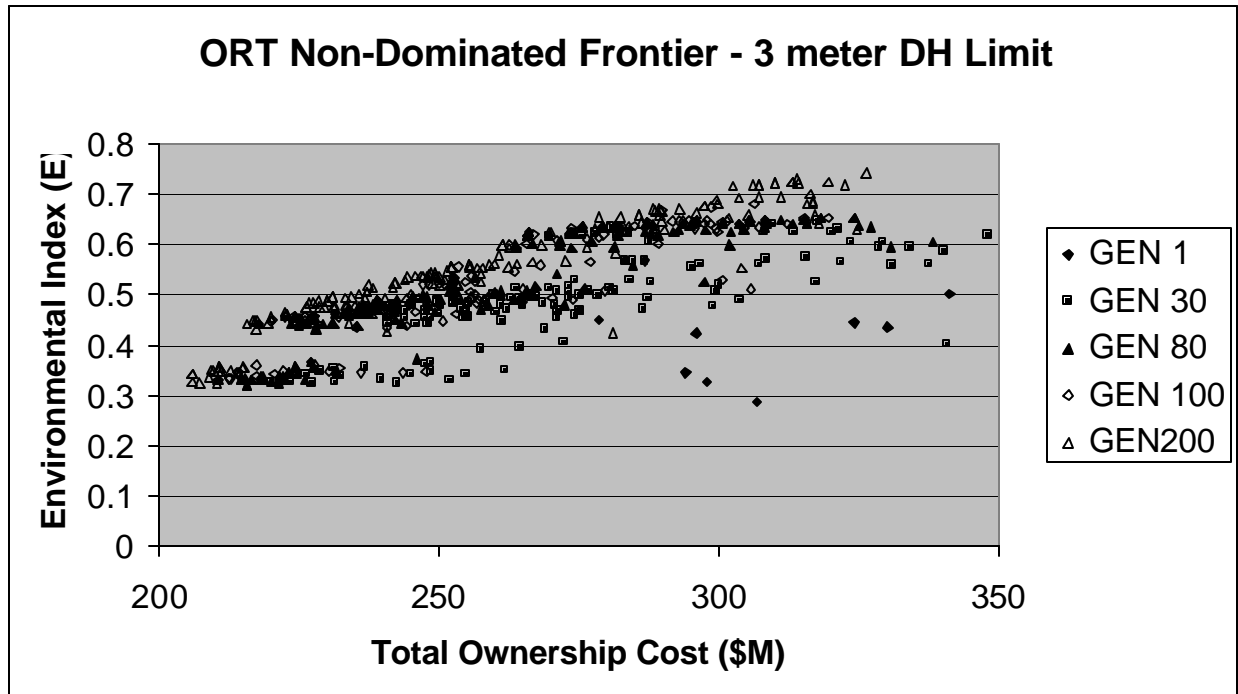


Figure 7. Risk vs. cost non-dominated (Pareto) frontier

6. RESULTS

A preliminary MOGO was completed for the design space specified in Table 1. Each optimization was run for 200 generations, taking 15 minutes on a 400 MHz PC. Results are shown in Figure 7. Each data point in this figure represents objective attribute values for a specific ship design. Results are shown for generations 1, 30, 80, 100 and 200 in each optimization. Generation 1 is a random selection of design parameters. Convergence to a non-dominated frontier can be seen in the evolution from Generation 1 to Generation 100 and finally to Generation 200. Generation 200 results approximate the non-dominated frontier. All of the designs shown are feasible. Duplicates are not shown. The customer can use this presentation to select preferred options on the non-dominated frontier based on his preference for cost and risk and looking for “knees in the curve”.

7. CONCLUSIONS AND FUTURE WORK

It is estimated that more than 80 percent of a ship’s ownership cost is locked-in during concept design. For a class of ships, this means hundreds of millions of dollars. An “ad hoc” process for making these critical design decisions is not adequate, and does not provide the most cost-effective protection of our environment. This paper presents an effective methodology for making responsible cost-effective ship design decisions.

The current IMO oil outflow methodology [6] does not consider the effect of crashworthiness and structural design on damage extents. This is a very important element of the design problem that is rationally considered in the proposed methodology. The proposed methodology

does not replace imagination and experience. It provides a practical tool to manage a complex total-system problem that cannot be managed by experience and intuition alone. It represents responsible change in how we assess the cost-effective performance of our ship designs.

Future work and papers will focus on the relationship between structural design variables and oil outflow risk using sensitivity analysis. The sensitivity of results to the probabilistic scenario description and other assumptions will also be explored. Response surfaces generated in this analysis may also be used in simplified regulatory calculations.

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