Optimum Risk Tanker (ORT)

A Systematic Approach to a TAPS Tanker Design

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Abstract

This paper proposes a total-system design methodology that includes three important components necessary for a systematic approach to ship 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*
- *An effective format to describe the design space and to present non-dominated concepts for rational selection by the customer*

The methodology is described in the context of an Optimal Risk Tanker design project conducted by senior undergraduate design students at Virginia Tech. A Pareto-Genetic Algorithm (PGA) 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. The oil outflow model is based on the International Maritime Organization (IMO) "Interim Guidelines for the Approval of Alternative Methods of Design and Construction of Oil Tankers" [1]. The optimization considers hull form characteristics, producibility, cargo block subdivision and double hull dimensions, propulsion and power redundancy, manning and automation, structural design margins, and trade route and port characteristics. The emphasis of this paper is on process. Four sets of results are generated and examined based on different metrics for oil outflow risk. Future applications of this methodology will consider tanker crashworthiness in collision and grounding as part of the work of SNAME Ad Hoc Panel #6, sponsored by SNAME and the Ship Structure Committee (SSC).

Presentation

Introduction

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.

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 [2].

The Oil Pollution Act of 1990 (OPA 90) includes a number of important changes effecting oil tanker design and operation. Possibly the most significant of these changes in terms its effect on the industry is the redefinition of oil spill liability. Liability is a legal concept, not an engineering one, but in order to demonstrate that every reasonable precaution has been taken to prevent and minimize oil spills, tanker owners are specifying extensive and costly tanker design enhancements targeted at minimizing tanker risk, or more specifically, minimizing potential liability. In the absence of a formal and legal definition of risk, this may be the best defensive approach for responsible tanker owners and operators, but ultimately, a formal definition of risk is essential to responsible decisions and the cost-effective protection of the environment.

This paper provides a systematic design methodology to address these problems in the context of an Optimal Risk Tanker design. 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 [3]. Objective attributes in the tanker application are cost and oil outflow risk.

Cost and risk are dissimilar attributes, and require different units of measure. They cannot rationally be combined into a single objective attribute. They must be presented individually, but simultaneously in a manageable format for tradeoff and decision-making. A non-dominated frontier is used for this presentation.

Ultimately, a ship design is defined by specifying millions of design parameters, in thousands of drawings, and with libraries full of technical specifications and information. Even in its simplest concept form, the definition of a balanced ship design requires many design parameters. The functional relationship of these design parameters cannot be described in a closed-form set of equations.

A total-system approach to ship design makes an already complex problem more complex. The goal of a total system approach is to optimize the life cycle cost-risk-effectiveness of the total ship system. This system includes the ship and everything outside the ship that either affects it or is affected by it. It usually requires an iterative and interactive process that depends on an effective concurrent engineering organization to produce a true total-system result.

The hierarchy of systems and subsystems included in a total-ship-system is rightly called a "supersystem" [4]. At the bottom of this hierarchy are the detailed components and characteristics that define the ship. Many lower-level system decisions can be made at their own level or one higher. Others must be determined at the total ship level. Some compromise between global and local optimization is essential to keep the problem manageable. The number of design parameters at any level must be kept to the minimum necessary to capture important interdependence. The highest level of optimization should consider only those variables that have a major impact on ship balance. Frequently components, systems and ship characteristics can be grouped into synergistic packages or suites. This reduces the number of variables that must be managed early in the design process.

The primary objective of the concept exploration process (as defined here) is to identify non-dominated and feasible concepts for selection by decision-makers based on the objective attributes of cost and risk. This is accomplished at the highest possible hierarchy level and with the fewest possible design parameters necessary to capture important system behavior and interdependence. Ideally, there should be no bias or preference for particular design parameters. Design parameters are only intermediate parameters. Cost and risk are the relevant objective attributes. This is often a difficult concept for customers and designers to accept.

A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists that is better in one objective attribute and at least as good in all others. Figure 1 illustrates this concept for a simple two-objective (cost-effectiveness) problem. The heavy curve represents non-dominated solutions or the Pareto-optimal frontier. The preferred design should always be one of these non-dominated solutions. Its selection depends on the decision-maker's preference for cost and effectiveness. This preference may be affected by the shape of the frontier and cannot be rationally determined a priori. This methodology specifies the baseline concept design parameters, and in the process completes the definition of cost-effective customer requirements. The baseline concept design is a necessary intermediate product in the process of determining cost and risk, and defining cost-effective requirements.

The concept exploration process may be followed by the more traditional design spiral approach or may continue in a multi-disciplinary optimization. In subsequent design iterations detail is added to the design within the boundaries of the baseline concept design definition.

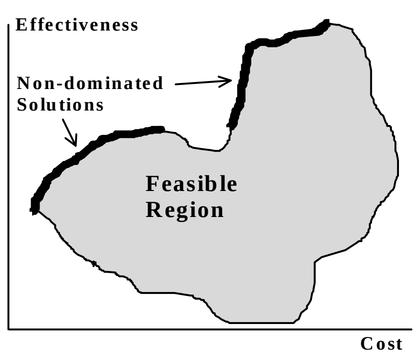

Figure 1 - Two-Objective Attribute Space

TAPS Trade Tanker Case Study

The notional circular of requirements (COR) developed for this study specifies an oil tanker. The tanker is required to transport crude oil between the Trans-Alaskan Pipeline System (TAPS) in Port Valdez, Alaska and the West Coast of the United States. This is a Jones Act Ship, and must be built in a U.S. shipyard.

Table 1 provides a summary of the general requirements for this design. Specific requirements are developed as part of the concept exploration process considering the trade-off between cost and oil outflow risk developed in the system optimization.

Table 1 - ORT General Requirements

Requirement	
Dead Weight Tonnage	125,000 MT plus 15,000 MT margin for future growth
Minimum Sustained Speed	15 knots At 90% MCR
Endurance Range	12000 nautical miles at 15 knots
Nominal Cargo Density	0.8674 MT/m^3
Delivery (Base)Year	2000
Service Life	30 years
Discount Rate	7%
Shipbuilder Profit Margin	8%
Cargo Segregation	Minimum 4x2 with 2% slop tanks
Cargo Pump (off-load) Capacity	50000 bbls/hr at 150 psig
Maximum loading rate	110,000 bbls/hr
Maximum Full Load Draft	24 m at 125000 dwt
Maximum In-Ballast Height Above Water	50 meters

The ORT must comply with applicable IMO regulations, the U.S. Code of Federal Regulations (COFR), various port regulations, and American Bureau of Shipping (ABS) Class rules as specified in the COR.

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 [5,6]. Mean oil outflow and the probability of zero outflows in side and bottom damage are calculated using a simplified oil outflow calculation methodology [7,8]. This calculation is based primarily on ship principal characteristics and subdivision.

Three measures of oil outflow risk are constructed using these parameters [8]:

- Mean lifetime oil outflow

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

- Lifetime probability of spill

$$P_{spill} = P_{grounding}(1 - P_{0bot}) + P_{collision}(1 - P_{0side}) \quad (2)$$

- Environmental Index

$$E = .5\frac{P_{SpillBest}}{P_{Spill}} + .5\frac{O_{MBest}}{O_M} \quad (3)$$

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)
P_{0bot} = Probability of zero outflow in grounding
P_{0side} = Probability of zero outflow in collision
$P_{SpillBest}$ = Minimum P_{Spill}, all designs = 5.9 x 10^{-6}
O_{Mbest} = Minimum O_M, all designs = .04 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.

Probability of Grounding and Collision

Probabilistic risk assessment (PRA) methods are used to develop the grounding and collision models [9]. PRA is a method to identify and quantify hazards and solutions with the greatest risk-reducing potential. The models include Performance Shaping Factors (PSFs) and Management and Organizational factors (MOFs). Figure 2 illustrates the process used to build the grounding model, and assess the impact of PSFs and MOFs. For this study, it is assumed that owner/operator management is fully effective and compliant with the International Safety Management (ISM) Code.

Tanker groundings are either powered groundings or drift groundings, defined as follows [10]:

- Powered grounding - An event in which grounding occurs because the tanker proceeds down an unsafe track, even though it is able to follow a safe track, due to errors related to planning or piloting failure.
- Drift grounding - An event in which grounding occurs because the tanker follows an unsafe track because it is unable to follow a safe track due to equipment failure, anchor failure, assistance failure, or adverse environmental conditions.

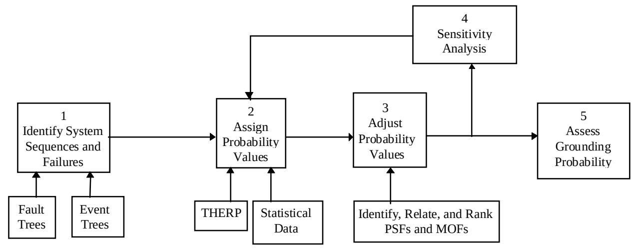

Figure 2 - PRA Process

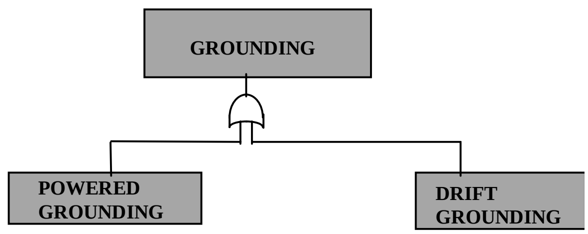

Figure 3 - Grounding Model

The top portion of the fault tree developed for grounding is shown in Figure 3. The simple Boolean expression for the probability of grounding, resulting from this structure of the fault tree, is:

$$P_{Grounding} = P_{PoweredGrounding} + P_{DriftGrounding} \quad (4)$$

The powered grounding portion of the grounding fault tree is shown in Figure 4. The fundamental failures involved in a powered grounding are failures in passage planning and in piloting. Human error probabilities (HEPs) are derived from extensive testing in the nuclear power industry [8], and event trees are used at various levels of the fault tree to calculate fault probabilities.

The result of piloting error depends on the characteristics of the waterway and the relative timing of the error along the track. For this study, waterway, ship, and ship track characteristics were chosen based on a TAPS trade tanker operating between

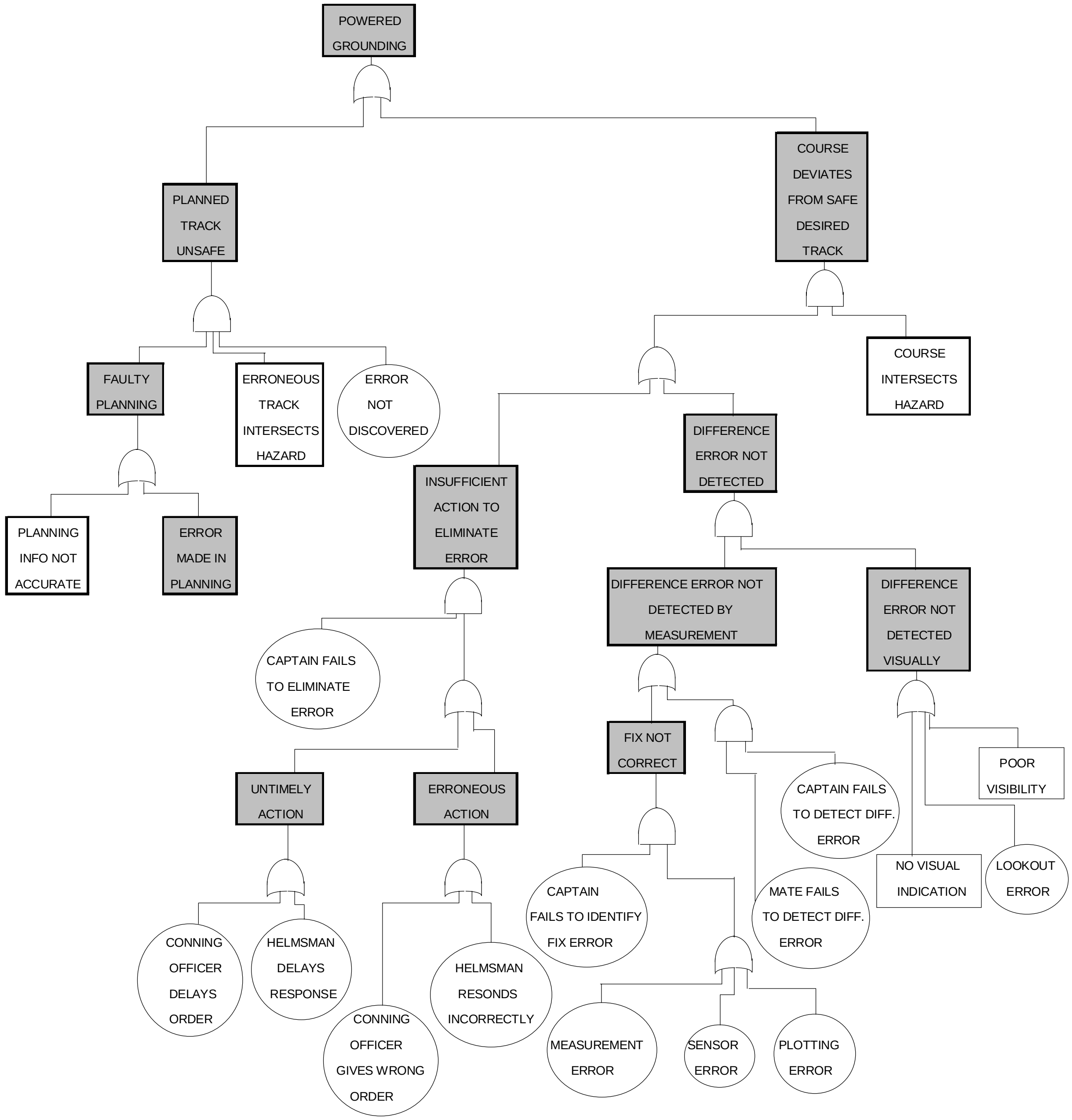

Figure 4 - Powered Grounding Fault Tree

Port Valdez, Alaska and Cherry Point, Washington. The probability that the ship deviates from the planned track is calculated assuming a Poisson process and considers straight channel tracks and turns.

Drift grounding is an event in which the tanker is unable to follow the planned, safe route. For drift grounding, all of the following types of failures and conditions must occur simultaneously:

- Loss of steerage way
- Unsafe winds/currents
- Assistance failure
- Anchor failure

An analysis methodology similar to that used with the planning and piloting processes is followed for calculating the probability of drift grounding. Standard HEPs, machinery reliability data and actual grounding accident data are used to estimate drift

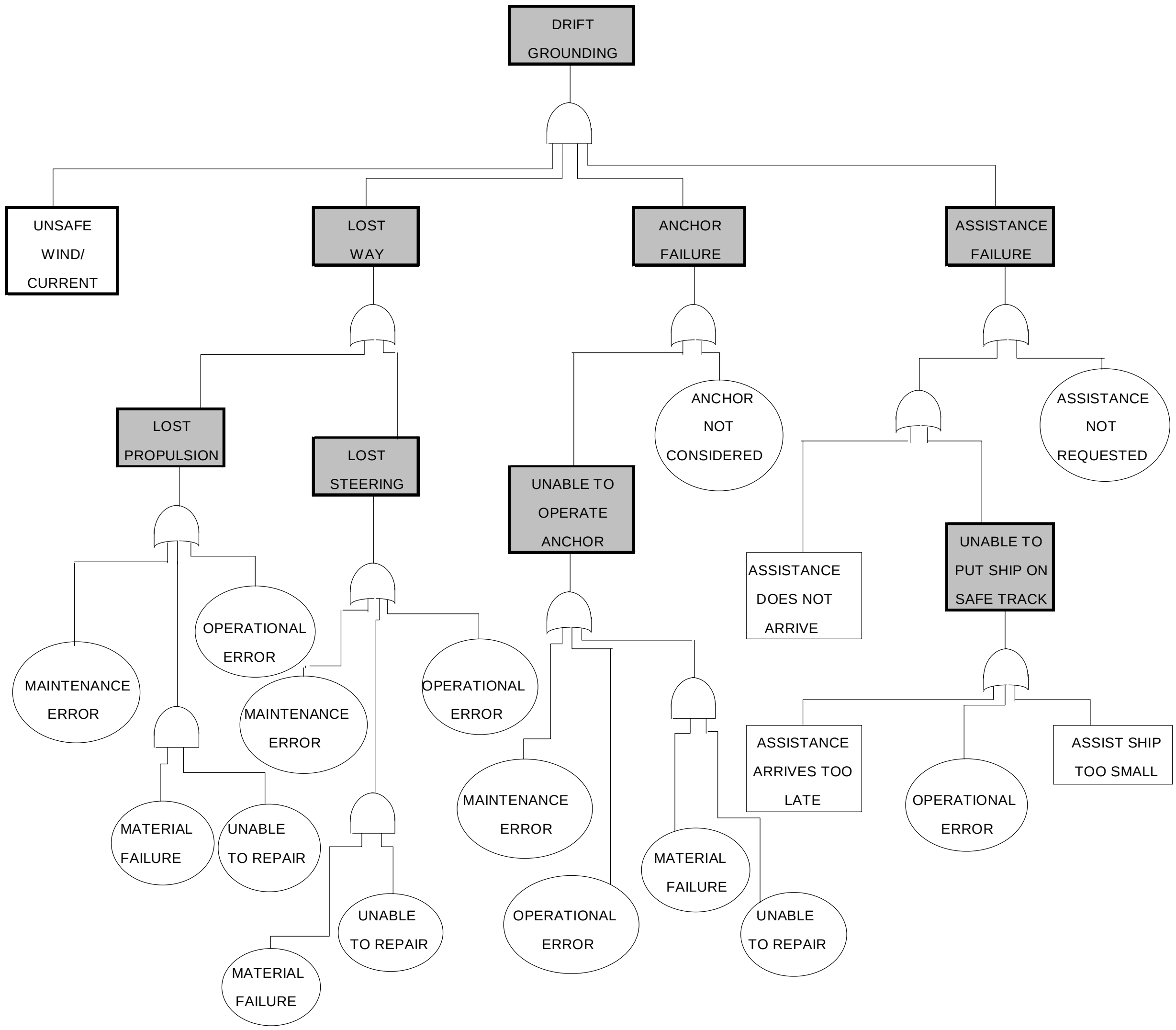

Figure 5 - Drift Grounding Fault Tree

grounding fault probabilities. The probability of drift grounding is:

$$P_{DriftGrounding} = P_{Unsafewindorcurrent} \cdot P_{LostWay} \cdot P_{AnchorFailure} \cdot P_{AssistanceFailure} \qquad (5)$$

The probability of collision is calculated using a similar methodology.

Oil Outflow

There are four main steps in the IMO Guidelines simplified oil-outflow methodology [1,7]:

Step 1: Assemble Damage Cases - Application of the IMO damage extent pdfs to the ship's subdivision provides the probability of occurrence for a series of damage cases. The IMO Guidelines provide pdfs describing the location, extent and penetration of side and bottom damage. The locations and extents are normalized by the ship length for longitudinal location and extent, by ship breadth for transverse location and extent, and by ship depth for vertical location and extent. Figure 6 illustrates the IMO probability density function for the longitudinal extent of damage in grounding. The histogram represents statistical data collected by the classification societies and the linear plot represents IMO's piece-wise linear fit of the data. The other pdfs are constructed in a similar manner.

The *SIMPLIFIED* methodology applies the same probability density functions and many of the assumptions contained in the conceptual approach described in the IMO Guidelines. The primary difference is in the assessment of damage cases. Rather than determining each unique damage case and its associated probability, in the *SIMPLIFIED* approach the probability of damaging each cargo tank is calculated. This is the probability that a tank is breached, either alone or in combination with other tanks. The total probability that at least one tank is breached is also calculated. These probabilities are calculated separately for side and bottom damage.

For application of the *SIMPLIFIED* method, the pdfs are converted into tables that indicate the probability that the damage is bounded on one side by a given longitudinal, vertical or transverse plane. To determine the probability of damage for a region in three-dimensional space the appropriate probabilities in each dimension are multiplied together. To simplify the calculation process, the extreme boundaries of the compartment are used.

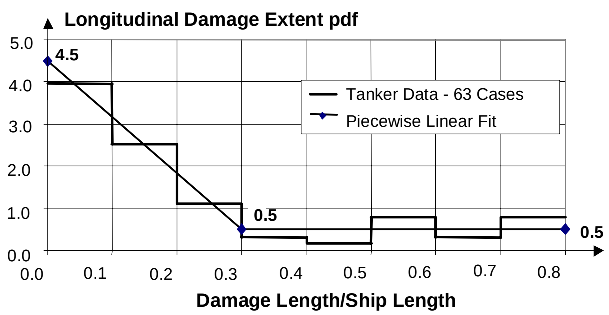

Figure 6 - Damage probability density function (pdf)

Step 2: Calculate Oil Outflow - Consistent with the IMO Guidelines, 100% outflow for all cargo tanks sustaining side damage is assumed. 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 bottom 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 is computed by treating the cargo block as a single tank. If P_{CB} is the probability of breaching the cargo block, then the probability of zero outflow P_O (i.e. the probability of breaching the outer hull but not spilling any oil) is: $P_O = 1 - P_{CB}$.

Total Ownership Cost

Total ownership cost (TOC) components considered in this study are shown in Figure 7. 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 for each SWBS group using weight-based equations adapted from an early ASSET cost model [11]. The base year is assumed to be 2000. Equation costs are inflated to the base year using a 5% average annual inflation rate from 1981 data.

Producibility is also considered in the TOC. Producibility factors are based on hull form characteristics, machinery room volume, and deck height.

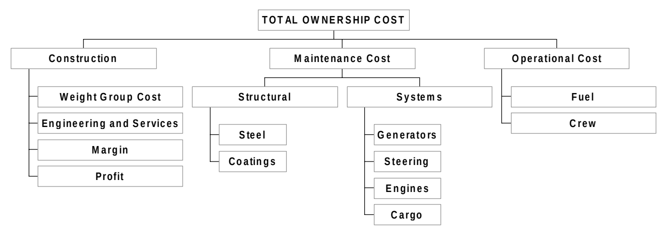

Figure 7 – Cost Components

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 8 provides a flowchart of this process.

The ship synthesis model used in this research is based on a model originally developed at MIT, and later modified for use with a genetic algorithm (GA) [12]. This model was adapted at Virginia Tech to the oil tanker design application.

The objective attributes calculated by the synthesis model are total ownership cost and oil outflow risk. These attributes are only calculated for balanced ships. Specific attributes that are balanced in the model include:

- Displacement and weight
- Deckhouse area

- Cargo block volume
- Electric power

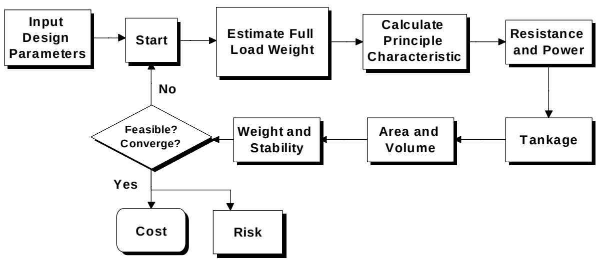

Figure 8. Ship Synthesis Model Process

Feasibility requires that other specified attributes of the design be within prescribed limits. Table 2 lists concept exploration feasibility requirements for the ORT.

Table 2 – ORT Feasibility Requirements

Description	Metric	Maximum	Minimum
Sustained Speed	knots	NA	15
Draft	m	loadline and navigational	NA
Machinery box dimensions and volume	m, m^3	NA	calculated
Deckhouse length	m	calculated	NA
GM/B Ballast	ND	0.25	0.08
GM/B Loaded	ND	0.25	0.08
Ballast Capacity	MT	NA	.33*DWT
Damage Stability	degrees	30 degree heel angle	NA

In the Genetic Algorithm application using this synthesis model, input design parameters are specified in a design matrix. Design parameters with ranges and resolution are listed in Table 3.

The first four design parameters are hull form coefficients. The synthesis model balances weight and buoyancy in an iterative process by varying total ship displacement, and applying these coefficients to calculate ship principal characteristics.

Double bottom height, double side width and cargo block transverse subdivision are critical design parameters effecting oil outflow in side and bottom damage. An N_{CARGO} x 2 centerline-bulkhead cargo tank configuration is assumed.

The crew size is based on three factors: the number of shafts, the volumetric size of the tanker, and the manning factor. A regression-based equation is used to calculate a conservative baseline manning with minimum automation. The baseline manning is multiplied by the manning factor to estimate reduced manning levels with increased automation. A manning factor of 0.5 describes a minimum crew of specialists to monitor a highly automated ship. A manning factor of 1.0 describes the standard number of personnel for a less automated ship. Command and control weight (SWBS 400), construction cost, maintenance cost and the probability of accidents are all increased with increased automation. Decreased manning reduces operational cost and total ship accommodation requirements. Deckhouse area, volume and height are calculated as a function of crew size, average deck height and bridge visibility requirements.

Table 3 - 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

The structural margin factor adjusts structural scantlings and weight relative to minimum ABS requirements. The Option 1 stern type is more producible with less curvature and lower propulsion coefficient (PC). Option 2 is less producible, but has a higher PC. Average deck height effects producibility, and relates volume and area in the deckhouse.

All propulsion system options use direct-drive diesels with power take-off (low cost/low risk). All have fixed-pitch propellers. Preliminary ship resistance calculations indicate that the total propulsion engine brake horsepower should be in the 25000-35000 bhp range. Six Man B&W engines were selected for trade-off based on the number of shafts, power, fuel consumption, size, and weight. The six propulsion options are:

- 1 shaft, 1 engine
  - S70MC-C (6 cylinders) – 25320 bhp
  - S70MC (8 cylinders) – 30560 bhp
  - L80MC (7 cylinders) – 34580 bhp
- 2 shafts, 2 engines
  - S50MC-C (6 cylinders) – 12870 bhp
  - S50MC-C (7 cylinders) – 15015 bhp
  - S50MC-C (8 cylinders) – 17160 bhp

Characteristics for each of these engines (brake horsepower, specific fuel oil consumption, weight and size) are incorporated in the synthesis model for trade-off and selection in the optimization. These characteristics determine the ship speed, size of the machinery box, fuel consumption and the cost of the propulsion plant.

Two options are considered for electrical redundancy. Option 1 provides sufficient capacity to support the maximum functional load with margins for two power conditions:

- In-port – Cargo Operations
- Underway - Winter Cruise

Option 2 doubles the Option 1 capacity. Propulsion and power redundancy reduces the probability of drift grounding and collision. The inport condition is used to size PTO generators. The underway condition is used to size ship service and emergency generators. Regression-based equations calculate electric load requirements for propulsion, steering, lighting, control systems, firemain, auxiliaries, services, and HVAC. Electric power for cargo systems is based on specified pump capacities and equipment including cargo pumps, ballast pumps, crude oil washing and stripping pumps.

Once input parameters are processed and principal characteristics are estimated, hull resistance and required shaft horsepower at endurance speed are calculated. The propulsion margin factor (PMF) used for exploratory design is ten percent. Bare hull resistance is calculated using the Holtrop method. Frictional resistance is calculated using the 1957 ITTC curve. The wave making, or residuary, drag calculations include the effect of a bulbous bow. Wind resistance is calculated as a function of deckhouse and hull frontal area. A propulsive coefficient (PC) of 0.7 is applied to calculate shaft horsepower for the producible stern, and a PC of 0.75 is applied for the high curvature stern.

Tankage volume and liquid weights are calculated as a function of crew size, shaft horsepower and electric power at endurance speed. Cargo block and ballast tank volume and dimensions are calculated as a function of dead weight tonnage, double side width and double bottom height.

Total hull structural weight is estimated as a function of midship scantlings that are based on ABS rules. Other single digit SWBS group weights are estimated using regression-based equations. A ten percent weight margin factor (WMF) is applied.

Vertical centers of gravity are estimated for all lightship weights, loads and cargo using regression-based equations and hull principal characteristics. Metacentric height (GM) is calculated for the full load and ballast conditions. GM/B ratios are used to assess intact stability. A rough order assessment of damage stability is made considering free surface flooding of two adjacent pairs of cargo and ballast tanks on one side of the ship.

Design Optimization

A Genetic Algorithm (GA) is a probabilistic optimization methodology based on the principle of *the survival of the fittest* [13]. 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 [14]. Dominance may be assessed using a number of objective attributes. In this application, dominance is based on minimizing cost and risk. The product of this optimization is a non-dominated frontier as illustrated in Figure 1.

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.

Genetic algorithms are able 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.

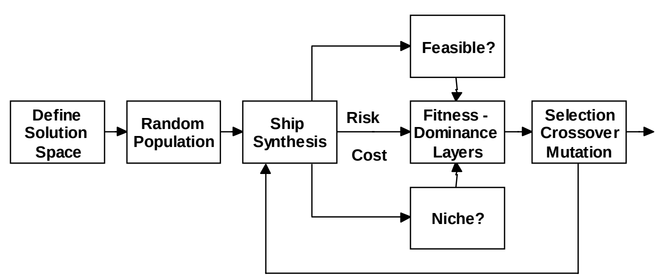

Figure 9 – PGA Optimization Process

Figure 9 illustrates the Pareto-Genetic Algorithm (PGA) used in this application. An initial population of 200 designs is created by random selection of design variables within the design space specified in Table 3. 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 [15]. 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.

Results

Four PGA optimizations were 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 of these searches are presented in Figures 10 through 13. Each data point in these figures 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.

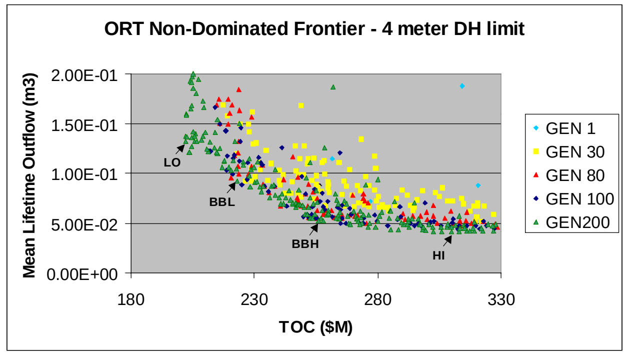

Figure 10 – Risk vs. Cost Frontier

Table 4 – Mean Outflow/TOC Selected Designs

	HI	BBH	BBL	LO
DP1 - Cbt	2.4	2.8	2.6	2.9
DP2 - Clb	6.9	5.7	5.2	5
DP3 - Cb	0.81	0.805	0.735	0.745
DP4 - CD10	1.2	1.3	1.4	1.6
DP5 - hdb [m]	3.6	4	3.2	4
DP6 - wds [m]	3.7	4	4	3.8
DP7 - manfac	0.7	0.55	0.65	0.75
DP8 - smf	1.5	1.4	1.3	1
DP9 - HDK [m]	4	3.9	4	4
DP10 - Ncargo	8	8	8	7
DP11 - Psystype	6	2	2	1
DP13 - Nstern	1	2	1	2
DP12 - Nkw	2	1	1	1
LBP [m]	309	281	255	253
Beam [m]	45	49	49	51
Draft [m]	19	18	19	17
D10 [m]	24	23	27	27
Cp	0.814	0.809	0.739	0.749
Cx	0.995	0.995	0.995	0.995
Np	2	1	1	1
Lightweight [MT]	79033	60175	38278	30189
Full load displacement	219354	200496	178599	170510
FL Vertical CG [m]	13	13	15	15
W1 [MT]	68884	51620	30991	23535
W2 [MT]	1348	1162	1162	988
W3 [MT]	260	157	157	157
W4 [MT]	8	10	9	7
W5 [MT]	2738	2633	2558	2540
W6 [MT]	1320	1186	1234	1251
W7 Cargo [MT]	137039	137533	137716	137919
Sustained speed [knt]	15.4	15.5	16.0	15.5
Lead Ship BCC [$M]	196	159.5	132.1	114.9
TOC [$M]	310	256	223.2	202.2
Manning	25	19	20	21
Om/C	0.0047	0.0052	0.0074	0.0099
RISK [m3]	0.0411	0.0526	0.0927	0.132
Pspill	7.00E-06	8.98E-06	1.15E-05	1.03E-05

In the first optimization, cost and mean lifetime oil outflow, Equation (1), are the objective attributes. The results and non-dominated frontier from the optimization are shown in Figure 10. Although non-dominated, none of these ships can be identified as "the best". Design selection depends on the customer's preference for cost and risk. High (HI) and low (LO) end ships and "knee in the curve" (BBH and BBL) ships are chosen to represent the range of selections in each frontier. Data for these ships is provided in Table 4.

In all of these designs, the double hull dimensions approach 4 meters, limited only by damage stability. This reduces the probability of outflow given grounding or collision. The cargo block subdivision approaches 8. This reduces outflow, given outflow. Only the HI ship has two shafts. Redundancy only reduces the probability of drift grounding and collision, which is typically lower than the probability of powered grounding and collision, and must occur at the time the ship is vulnerable to failure. The manning level for all ships is low (high automation). This sharply reduces operating costs with a small increase in the probability of grounding and collision.

In the second optimization, cost and lifetime probability of spill, Equation (2), are the objective attributes. The objective in this optimization is to avoid a spill altogether, rather than reduce the outflow given a spill. The results and non-dominated frontier from this optimization are shown in Figure 11. In all of these designs, the double hull dimensions approach 4 meters, and all ships have two shafts except the LO ship. In these designs, cargo block subdivision above four is cost-effective only to improve damage stability problems caused by the large double hull dimensions. Manning is higher in these designs than in the first optimization. With this risk metric, the higher operational cost is worth the reduction in the probability of an accident.

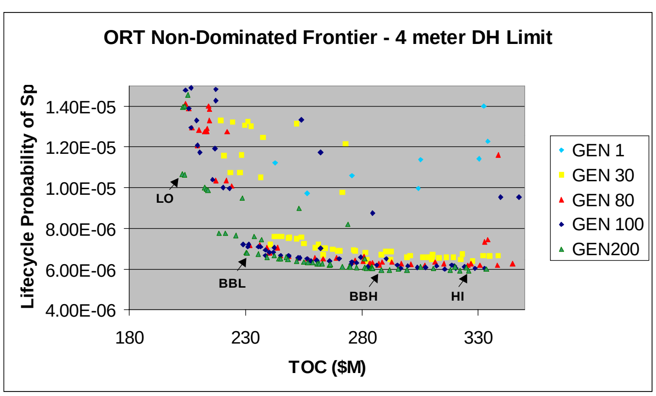

Figure 11 – Spill Probability vs. Cost Frontier

Table 5 – P_{SPILL}/TOC (4 meter) Selected Designs

	HI	BBH	BBL	LO
DP1 - Cbt	3.50	3.50	3.50	2.75
DP2 - Clb	7.00	6.70	5.50	5.05
DP3 - Cb	0.855	0.885	0.86	0.705
DP4 - CD10	1.92	1.83	2.01	1.52
DP5 - hdb [m]	4	4	4	3.8
DP6 - wds [m]	3.9	4	3.9	4
DP7 - manfac	0.95	0.85	0.7	0.75
DP8 - smf	1.1	1	1	1
DP9 - HDK [m]	4	4	4	4
DP10 - Ncargo	7	5	6	8
DP11 - Psystype	6	6	6	1
DP13 - Nstern	2	2	2	2
DP12 - Nkw	2	2	1	1
LBP [m]	356	329	277	255
Beam [m]	51	49	50	51
Draft [m]	15	14	14	18
D10 [m]	28	26	29	28
Cp	0.859	0.889	0.864	0.709
Cx	0.995	0.995	0.995	0.995
Np	2	2	2	1
Lightweight [MT]	90321	65373	37395	30777
Full load displacement	230642	205694	177716	171098
FL Vertical CG [m]	15	14	16	16
W1 [MT]	78977	55825	29692	24060
W2 [MT]	1348	1348	1348	988
W3 [MT]	279	260	169	157
W4 [MT]	6	7	8	7
W5 [MT]	3176	2861	2758	2570
W6 [MT]	1423	1372	1303	1251
W7 Cargo [MT]	136828	136831	137258	138033
Sustained speed [knt]	15.09	15.03	15.68	15.86
Lead Ship BCC [$M]	201.4	169.5	128.5	116.2
TOC [$M]	325.9	288.4	230.6	203.7
Manning	31	28	24	21
Om/C	0.0127	0.0119	0.0142	0.0089
RISK [m3]	0.1408	0.1285	0.1613	0.118
Pspill	5.91E-06	5.98E-06	6.81E-06	1.07E-05

Although the ship model includes a simplified damage stability analysis, the four-meter double hull could cause damage stability problems. In order to examine the effect of limiting the double hull dimensions, the third optimization uses the same objective attributes as the second, but the double side width and double bottom height are limited to 3 meters. Results from this optimization are shown in Figure 12 and Table 6. All ships on the frontier except the single LO ship have 2 shafts and the 3 meter limiting value for double side width and double bottom height.

In the final optimization, cost and a combined metric, an Environmental Index, Equation (3), are the objective attributes. This index is similar to the metric used in the IMO Guidelines [1], except that it is non-dimensionalized using the best values of mean lifetime oil outflow and lifetime probability of spill calculated in the previous optimizations, vice values for IMO reference double hull tankers. This insures that the index is between zero and one with a value of one representing the optimum. Results are shown in Figure 13 and Table 7.

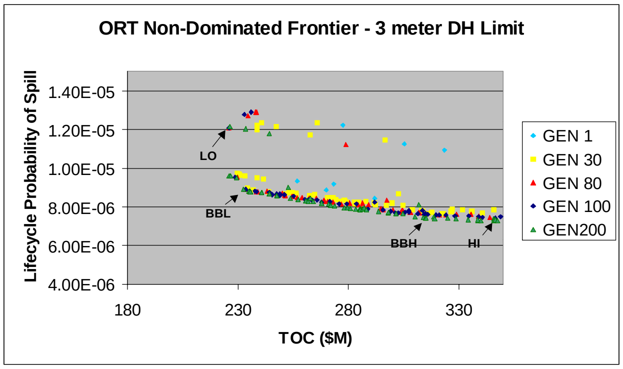

Figure 12 – Spill Probability vs. Cost Frontier (w/3 meter double hull limit)

Table 6 – P_{SPILL}/TOC (3 meter) Selected Designs

	HI	BBH	BBL	LO
DP1 - Cbt	3.65	3.65	3.10	3.10
DP2 - Clb	6.85	6.85	5.55	5.55
DP3 - Cb	0.845	0.845	0.785	0.785
DP4 - CD10	2.15	2.24	1.79	1.79
DP5 - hdb [m]	3	3	3	3
DP6 - wds [m]	3	3	3	3
DP7 - manfac	0.95	0.9	0.65	0.65
DP8 - smf	1.1	1	1	1
DP9 - HDK [m]	4	4	4	4
DP10 - Ncargo	8	7	5	5
DP11 - Psystype	6	6	5	3
DP13 - Nstern	2	2	2	2
DP12 - Nkw	2	2	1	1
LBP [m]	354	346	275	275
Beam [m]	52	50	50	50
Draft [m]	14	14	16	16
D10 [m]	30	31	29	29
Cp	0.849	0.849	0.789	0.789
Cx	0.995	0.995	0.995	0.995
Np	2	2	2	1
Lightweight [MT]	84410	68527	35130	34988
Full load displacement	224731	208848	175451	175309
FL Vertical CG [m]	16	16	15	15
W1 [MT]	73263	58428	27890	27841
W2 [MT]	1348	1348	1178	1165
W3 [MT]	279	279	169	160
W4 [MT]	6	6	9	9
W5 [MT]	3313	3199	2610	2599
W6 [MT]	1423	1389	1286	1234
W7 Cargo [MT]	136912	137053	137674	137681
Sustained speed [knt]	15.2	15.5	16.0	16.7
Lead Ship BCC [$M]	223.2	199.4	137.3	136.7
TOC [$M]	347.7	315.4	232.5	226.4
Manning	31	29	23	20
Om/C	0.0193	0.0207	0.0183	0.0183
RISK [m3]	0.2181	0.2346	0.2005	0.2737
Pspill	7.27E-06	7.41E-06	8.90E-06	1.22E-05

This combined index results in a compromise between the design attributes seen in the earlier optimizations. All the ships on the frontier are two-shaft designs. The double bottom height and double side width again take their maximum value of 3 meters. All the designs except for the LO ship have 8 transverse cargo block divisions. All have low manning.

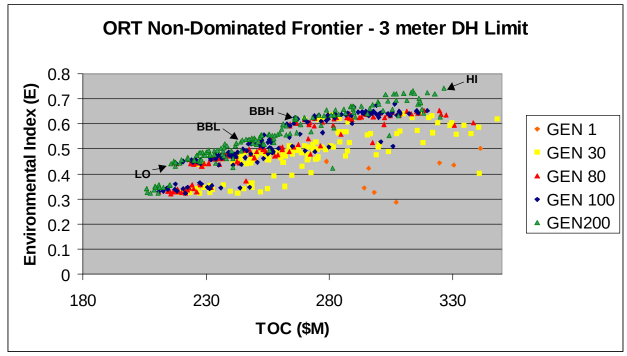

Figure 13 – Environmental Index vs. Cost Frontier (w/3 meter double hull limit)

Table 7 – E Index/TOC (3 m) Selected Designs

	HI	BBH	BBL	LO
DP1 - Cbt	2.35	2.35	2.55	2.75
DP2 - Clb	6.95	6.95	5.60	5.00
DP3 - Cb	0.845	0.755	0.785	0.740
DP4 - CD10	1.25	1.34	1.43	1.52
DP5 - hdb [m]	3	3	3	3
DP6 - wds [m]	3	3	3	3
DP7 - manfac	0.65	0.75	0.65	0.75
DP8 - smf	1.5	1	1.2	1
DP9 - HDK [m]	4	4	4	4
DP10 - Ncargo	8	8	8	6
DP11 - Psystype	6	4	5	4
DP13 - Nstern	1	2	1	2
DP12 - Nkw	2	1	1	1
LBP [m]	304	302	260	248
Beam [m]	44	43	46	50
Draft [m]	19	18	18	18
D10 [m]	23	25	26	27
Cp	0.849	0.759	0.789	0.744
Cx	0.995	0.995	0.995	0.995
Np	2	2	2	2
Lightweight [MT]	74165	47582	36997	27476
Full load displacement	214486	187903	177318	167797
FL Vertical CG [m]	13	13	14	15
W1 [MT]	64338	39705	29686	20947
W2 [MT]	1348	1016	1178	1016
W3 [MT]	260	169	169	169
W4 [MT]	9	7	9	7
W5 [MT]	2710	2671	2576	2478
W6 [MT]	1303	1320	1286	1303
W7 Cargo [MT]	136892	137721	137465	137869
Sustained speed [knt]	15.1	15.3	15.5	15.7
Lead Ship BCC [$M]	206.1	162.6	142.5	124.6
TOC [$M]	326.4	266.3	244.5	216.8
Manning	24	25	23	24
Om/C	0.0058	0.0073	0.0093	0.0137
RISK [m3]	0.0518	0.0686	0.0923	0.1395
Pspill	8.28E-06	8.82E-06	9.25E-06	9.66E-06
E Index	0.7426	0.626	0.5357	0.4489

Conclusions

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. Figures 11 through 13 appear to provide simple and somewhat intuitive results, but they are not simple, and their implications are significant. Without this kind of information, we cannot make responsible decisions. This paper presents an effective methodology for making responsible cost-effective ship design decisions.

These results are very sensitive to the definition of risk and to the models for oil outflow and probability of accidents, but some design parameters show particular leverage for achieving cost-effective risk reduction. When risk is defined as mean lifetime oil outflow, the most critical design parameters are:

- Cargo block subdivision
- Double hull dimensions within the limits of damage stability

When risk is defined as the lifetime probability of spill, the most critical design parameters are:

- Machinery plant redundancy
- Double hull dimensions within limits of damage stability
- Manning and quality of automation

The "best" values for these parameters depend on the customer's preference for cost and risk. All designs presented in this paper exceed current regulatory requirements.

The quantitative definition of risk raises some interesting questions:

- Should we minimize mean outflow or maximize the probability of zero outflow?
- Is mean outflow a valid consequence metric?
- How do we relate risk and liability?

These are not new questions [7,8]. The current IMO index is a compromise based on these questions.

Many tankers being built today do not even fall on the chart with the non-dominated frontiers. Should increased subdivision and double hull dimensions be considered before machinery plant redundancy and larger crew size? Only a formal and legal definition of risk can answer this question. For now, the public must depend on the efforts of responsible owners and operators to make these decisions for them.

This paper has only considered double hull designs, but its performance-based approach is very applicable to other alternatives. In fact, a systematic approach is more essential as more alternatives are considered. This will be a topic for future work.

The current IMO oil outflow methodology [1] does not consider the effect of crashworthiness and structural design on damage extents. This is a very important element of the design problem. SNAME Ad Hoc Panel #6 and others are working on tools to address this problem. These tools will be included in the framework of this design methodology in future analyses.

The methodology described in this paper 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.

References

[1] "Interim Guidelines for Approval of Alternative Methods of Design and Construction of Oil Tankers under Regulation 13F(5) of Annex I of MARPOL 73/78", Resolution MEPC.66 (37), Adopted September 14, 1995.
[2] Brown, A. and Amrozowicz, M., "Tanker Environmental Risk - Putting the Pieces Together", SNAME/SNAJ International Conference on Designs and Methodologies for Collision and Grounding Protection of Ships, August 1996.
[3] Brown, A., Thomas, M., "Reengineering the Naval Ship Concept Design Process", From Research to Reality in Ship Systems Engineering Symposium, ASNE, September, 1998.
[4] Hockberger, W.A., "Total System Ship Design in a Supersystem Framework", *Naval Engineers Journal*, 1996.
[5] Amrozowicz, M., Brown, A., Golay, M., "A Probabilistic Analysis of Tanker Grounding", 7th International Offshore and Polar Engineering Conference, Honolulu, Hawaii, May, 1997.
[6] Brown, A., Haugene, B., "Assessing the Impact of Management and Organizational Factors on the Risk of Tanker Grounding", 8th International Offshore and Polar Engineering Conference, May 1998.
[7] Sirkar, Ameer, Brown, Goss, Michel, Nicastro, and Willis, "A Framework for Assessing the Environmental Performance of Tankers in Accidental Groundings and Collisions", presented at the SNAME Annual Meeting, October 1997.

[8] Rawson, Crake and Brown, "Assessing the Impact of Structural Design on the Environmental Performance of Tankers in Accidental Grounding and Collision, SNAME Annual Meeting, November, 1998.

[9] Swain A.D., Guttmann H.E., (1983), Handbook of Human Reliability Analysis with Emphasis on nuclear Power Plant Applications, NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington, D.C.

[10] “Oil Spills from Tankers in Collisions and Grounding. DAMAGE STATISTICS", DNV Report No. 93-0518.

[11] DTMB, *ASSET/MONOSC User Manual*, Version 3.3, DTMB, Carderock Division, Naval Surface Warfare Center, 1990.

[12] Shahak, S., “Naval Ship Concept Design: an Evolutionary Approach”, Master of Science Thesis, MIT Department of Ocean Engineering, 1998.

[13] Goldberg, D.E., “*Genetic Algorithms in Search, Optimization and Machine Learning”*, Addison-Wesley Publishing Company, Inc., 1989.

[14] Thomas, Mark, “A Pareto Frontier for Full Stern Submarines via Genetic Algorithm”, PhD Thesis, MIT Department of Ocean Engineering, 1998.

[15] Baker, J.E., “Reducing Bias and Inefficiency in the Selection Algorithm”, pp. 14-21, *Proceedings of the Second International Conference on Genetic Algorithms*, Hillsdale, NJ, 1987.

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discussion