DESIGN ASPECTS OF SURVIVABILITY OF SURFACE NAVAL AND MERCHANT SHIPS

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Abstract. The paper addresses various design aspects of survivability for surface naval and merchant ships through a common probabilistic methodology. In the essence, the suggested methodology is based on earlier work of Kurt Wendel introduced in the early sixties on a probabilistic approach to the damage stability of surface ships. This method was adopted by SOLAS 1974 in the regulatory framework of IMO through Res. A.265 (VIII) as an alternative to the deterministic SOLAS criteria for passenger ships and finally by SOLAS 1992 for the evaluation of stability of new cargo ships. The method is currently under review by relevant working groups of IMO for application to all types of merchant ships in the framework of harmonization of all existing stability rules. On the other side, the method found recently access into the design process of modern naval ships. The declining defence budgets world-wide and the reduced manning requirements bound the size and thus the payload of modern naval ships, required in addition to operate in an increased dangerous warfare environment. Thus, one way to efficiently proceed is the introduction of a new naval ship design philosophy, namely the introduction of rather small naval ships of *enhanced survivability*. Most designer decisions, associated with survivability, as compartmentation and arrangements, are taken at the preliminary design stage and are very difficult and costly to change, if at all, in latter stages. Therefore, a proper guidance in the preliminary design stage would greatly help to design the next generation surface combatants, as it is expected from the design of merchant ships, to comply with future more stringent survivability and safety requirements. The paper addresses the fundamental aspects of survivability and introduces this relatively new probabilistic approach for assessing the damage stability and survivability properties of both naval and merchant ships.

Keywords. Survivability, damage stability, probabilistic stability method, A.265-IMO, vulnerability, lethality, susceptibility, modelling, simulation, simulation based acquisition (SBA).

1. INTRODUCTION

Introduction

One might wonder what is common between the design of a naval surface combatant and a Ro-Ro passenger ship. The answer is simultaneously easy and complex: they both *have to* survive in case of damage, for obvious reasons, however under quite different constraints, external damage threats and environmental conditions. For surface combatants, although the probability of damage is very high and it should be a significant factor in their design, there was never before a systematic examination and assessment of their survivability. On the other hand, many tragic events occurred recently in passenger shipping, turning the attention of the public to the inherent safety of Ro-Ro Passenger Ferries. The public outcry stressed the need for enhancing the inherent survivability of this type of ships in case of damage by efficient design measures. In the following, a consideration of possible common methodologies for the survivability analysis of these two totally different ship types is attempted.

The Naval Ship Dimension

Modern naval warfare is characterised by highly sophisticated weapon systems. Surface combatants have to counter a great number of air, surface and underwater weapons guided with various sensors: radar, infrared, electroptic, or laser-guided. In order to accomplish their mission they have to carry a large arsenal and a complicate suit of advanced (but nevertheless sensitive) electronics. All these have increased their acquisition and operational cost and have reduced the size of the fleets operated by various Navies. On the other hand the need for a high payload to displacement ratio has driven the designers to a reduction of the shell plate thickness for keeping the structural weight as low as possible. It was a change in the philosophy of designing naval ships: a shift *from enhanced armour to sensor capability*. The so made naval ship designs were more vulnerable as could be proven in the *Falkland Islands* Conflict, in the *USS Stark* (FFG-31) incident and during the *Gulf War* Naval Operations. It becomes obvious that an effective solution to this problem is the adoption of a rather a new design philosophy, namely *Design for Enhanced Survivability*.

Nature makes its creatures adaptive to their environment for survival. In the same way, ships should be designed with an inherent ability to survive in the threat environment they have to operate. For naval ships survivability is the capability to continue to carry out their missions in the combat lethal environment. This is obviously first of all a function of their ability to prevent the enemy from detecting, classifying, targeting, attacking or hitting them. The *inability* to "intercept" any of the above threats is a measure of their *susceptibility*. In case the later proves to be insufficient for eliminating the threat to the ship and an enemy hit succeeds, then the ship's survival depends on the extend of degradation as result of the damage it suffers. The degree of impairment characterises the ship's *vulnerability*. The product of *susceptibility* and *vulnerability* defines the *killability* of the combatant. Mathematically this can be expressed by the following global formula:

$$\textit{Killability} = \textit{Susceptibility} \times \textit{Vulnerability}$$

or in terms of the respective probabilities

$$P_K = P_H \times P_{K/H} \qquad (1)$$

Thus the probability of survival S is expressed by:

$$S = 1 - P_K \qquad (2)$$

It is obvious that *in order to maximise the naval ship's survivability we have to minimise its susceptibility and vulnerability*.

The susceptibility of a naval combatant is dependent on its *signature* characteristics. Signature reduction measures will decrease the chance of being detected and classified. These measures include the minimisation of the radar cross section, infrared and noise, magnetic and electro-optical signature.

The vulnerability reduction measures must be addressed in the early design phase in order to maximise the results. These measures include arrangements, redundancy, protection, and equipment hardening as well as damage containment.

If we restrict our analysis only to conventional (high explosive) anti-surface weapons then there are two main damage effects that threat the survival of a combatant: **flooding** and **fire**. Though both are equally essential we will limit our survivability analysis herein only to the first one. The reason is first of all that the second aspect (fire) can be effectively performed only at advanced stages of design. Besides for any ship we have to counter a fire onboard, it is assumed that it is staying afloat and upright. Mathematically this means that we consider flooding and fire as *independent* events:

$$P_K[\text{Hit} \cap (\text{Flooding} \cup \text{Fire})] = P_K[(\text{Hit} \cap \text{Flooding}) \cup (\text{Hit} \cap \text{Fire})] =$$
$$= P_K[\text{Hit} \cap \text{Flooding}] + P_K[\text{Hit} \cap \text{Fire}] - P_K[\text{Hit} \cap \text{Flooding}] \times P_K[\text{Hit} \cap \text{Fire}]$$

which also means that in the following we will be assuming that the probability of loss after a hit due to fire, given the progressive flooding due to the same hit, is zero, i.e. $P_K[(\text{Hit} \cap \text{Fire}) \mid (\text{Hit} \cap \text{Flooding})]=0$. Therefore for the rest of this paper we will be referring to the survivability of naval ships by meaning just *flooding survivability* and by calculating the $P_K[\text{Hit} \cap \text{Flooding}]$.

The Passenger Ship Dimension

Since the early seventies (SOLAS 1974) the International Maritime Organisation (IMO) has adopted probabilistic methodologies for the assessment of survivability of passenger ships. We refer to the regulation A.265 (VIII) of IMO setting an equivalent to the deterministic stability criteria, namely part B of Chapter II of the International Convention for the Safety Of Life At Sea, 1960 (SOLAS 60). The vast number of the required calculations for a full probabilistic assessment of a ship under consideration, was, in those days of limited computer hard- and software, a serious drawback that led to only limited applications to actual ships. This was one serious reason for the further development of the deterministic criteria (SOLAS 90, 92 & 95), whereas the results of the probabilistic approach (or a simplified version thereof) was only used as an indicator for the implementation of new regulatory schemes to existing ships (phase-in procedure). However, it is a taken decision of IMO to formulate[1] and approve a "harmonised" new probabilistic stability framework for all types of ships, possibly by the SOLAS conference in the year 2000.

According to IMO Res. A.265, and following the fundamental concept of K. Wendel [1], there are the following probabilities of events in the framework of damage stability:

1. The probability that a ship compartment or group of compartments *may be flooded (damaged)*, **p**.
2. The probability of *survival after flooding* the ship compartment or group of compartments under consideration, **s**.

The total probability of survival is expressed by the attained subdivision index **A** which is given by the sum of the products of $\mathbf{p}_i$, and $\mathbf{s}_i$ for each compartment and compartment group, **i**, along the ship's length:

$$\mathbf{A} = \sum_i \mathbf{p}_i \cdot \mathbf{s}_i \qquad (3)$$

The regulations require that this attained subdivision index should be greater than a required subdivision index **R**, which is determined as a function of the number of passengers the ship is carrying and the extent of life-saving equipment onboard. This value is a measure for the acceptable risk of the ship for not surviving a random damage and it is obvious that this value increases with the number of passengers onboard the ship. The factors in the formula determining **R** are so selected to correspond to the mean values of the attained subdivision indexes of a sample of existing ships with *acceptable* stability characteristics. This is, of course, a point for lengthy discussions, because the safety standards of passenger ships have significantly changed over the years, therefore the basis for the evaluation of **R** must be updated to account for these changes.

In order to determine how we can increase the survivability of the RoRo passenger ships we have to specify the "threats" (or better the "risks") they have to counter. Similar to naval vessels, passenger ships face mainly two major threats: Flooding and Fire. It is obvious, that for A.265 the survivability is virtually identical to the vulnerability in case of flooding. The regulation does not take into consideration either the *vulnerability* in case of fire or the *susceptibility* of the ship. However, it is formally not difficult and probably advisable to incorporate *susceptibility* to the survivability of Ro-Ro passenger ships, as it has been suggested for naval ships. This concept is more or less adopted in the formulation of the "Safety Assessment", or "Formal Safety Assessment (FSA)"[2]. In this way we can

[1] See, SLF39, SLF 40, SLF 41, forthcoming SLF 42

formulate a unified scheme model (methodology) for assessing the survivability of both naval surface combatants, passenger Ro-Ro ships and any other type of ship. The main difference to naval ships is in the formulation of the anticipated risks, namely in case of passenger ships, and of merchant ships in general, we should be considering flooding due to one of the following impact events [2]:

1. Ship to ship (collision)
2. Ship to berth/breakwater (contact)
3. Ship to bottom (grounding/stranding).
4. Explosion
5. Terrorist act
6. Material Failure
7. Human Error

The probability of a passenger ship loss in case of flooding or fire is calculated by the formula:

$$P_L[\text{ Flooding} \cup \text{Fire}] = P_L[\text{Flooding}] + P_L[\text{Fire}] - P_L[\text{Flooding}] \times P_L[\text{Fire}]$$

As has been noted above, we should herein discuss only the probability of loss in case of flooding, namely P_L[Flooding].

2. OUTLINE OF POSSIBLE SHIP DAMAGE CONSEQUENCES

It is obvious that between the intact condition and the total loss of a ship there are many intermediate stages. Though these stages can be defined in various ways a very common characteristic is the one relating them to a *functional hierarchy* [3].

According to this in case of a **naval ship** we may have, in descending order, one of the following damage extents:

- **Total Kill** when the ship is considered lost entirely because of sinking (foundering) or completely damaged by fire (or other phenomenon).
- **Mobility Kill** if immobilisation or loss of controllability of the ship occurs.
- **Mission Area Kill** if a mission area (e.g. AAW capability) is considered lost for the ship.
- **Primary or Combat System Kill** in case of one or more vital systems of the ship, such as a propulsion engine or a CIWS, are damaged.
- **Hull, Machinery or Electrical (HM&E) Support System Kill** if one or more components supporting a primary/combat system of the ship are damaged (e.g. the cooling water system).

Apparently a *combat system kill* can lead to a *mission area kill* or a *mobility kill* or even a *total kill*. Likewise a *mission area kill* may decrease to a *combat system kill* after the crew makes necessary repairs. Our primary target is herein to confine damage extent to the lowest possible level.

Accordingly, in case of a **Ro-Ro passenger ship** we may have:

- **Loss of stability** (Intact or damage ship capsizing)
- **Loss of floatability** (progressive flooding, foundering)
- **Loss of power**
- **Loss of mobility** (controllability)

Loss of stability and of floatability, though they might have the same outcome, namely the foundering of the ship, they might be addressed separately, because of the different time scales available for evacuation of the ship. With the loss of power and controllability we consider herein the outcome of damage of the ship's main machinery and vital equipment compartments, and not of an isolated failure incident of the ship's equipment.

3. FUNDAMENTALS OF NAVAL SHIP DESIGN

Compared to a merchant ship, the design of a naval ship is a very complicate task. There is a vast number of requirements -many of them contradicting- and additionally a large number of constraints. Our effort to develop ships of enhanced survivability imposes further constraints to the naval ship design. This means penalties associated with cost, weight and impact on other features. It is generally recognised that during a naval ship development program, though the expenditure at the early design stage amounts only 6% of the total cost, related decisions concern 80% of the final realisation cost and should be taken with great care [4]. Thus it is important in the early stages of design to have a methodology to assess the survivability of the proposed vessel, to identify shortcomings and to explore feasible improvements. Furthermore, it seems that simulation methods and the development of virtual demonstrators will be indispensable approaches to ship design for the 21st century [5]. Within such approaches, the *Survivability Performance Analysis* is an indispensable design tool, to be briefly addressed in the following.

In order to properly assess the survivability of a naval ship we have first to identify the major threats it has to counter. Considering only conventional weapons, which are the most widely used, we can focus on the consideration of a threat posed by a radar guided missile. The same type of analysis can obviously be modelled for other type of weapons, sensors and threats in general.

4. SURVIVABILITY PERFORMANCE ANALYSIS FOR NAVAL SHIPS

This analysis is based on the modelling of the event sequence from the enemy's arrival to ship's operational area up to the moment at which a hit might strike the vessel. Thus we have the detection, classification, target acquisition and launch of an enemy attack. The ship's response is to jam, attempt to deceive, or to destroy the enemy's incoming weapons.

The probability of ship's detection is a function of the threat's sensor, its range and the ship's signature. A first estimation of the RCS of a surface combatant can be taken from the formula [6]:

$$\sigma = 52 \cdot \sqrt{f} \cdot \sqrt[3]{Disp^2} \qquad (4)$$

where: = ship's RCS in m^2
f = incident radar frequency in MHz
Disp = ship's displacement in tons.

The range at which the ship will be detected from the enemy's radar is given by the equation [7]:

$$R_{\max} = \left[\frac{P_T G^2 \lambda^2 \sigma}{(4\pi)^3 P_{\min}} \right]^{1/4} \qquad (5)$$

where:
R_{max} = maximum detection range
P_T = transmitter's power
G = antenna gain
= radar's operating wavelength
= ship's Radar Cross Section (RCS)
P_{min} = minimum detectable received signal from the enemy's sensor

Obviously the lower the RCS of the ship, the closer the enemy has to come for detecting it. An optimization of the RCS is nowadays possible by application of STEALTH technology.

P_{min} depends on the enemy radar characteristics and also on the environmental conditions. By the later we mean temperature, sea condition as well as jamming. Increase of any of these parameters results to an increase of P_{min} and eventually decrease of the R_{max}.

Following the vessel's detection it is up to the enemy to decide on the tackle of the target he has picked up. In case he does, classification, targeting and the release of missiles will follow.

Assuming that the missile is radar-guided, its course to the target will also depend on ship's RCS. The path, it will follow, depends very much on its accuracy. This property for weapons engaging surface combatants can be expressed by their Linear Error Probability (LEP). Knowing (or assuming) missiles' LEP we may assume that the missile's position relatively to ship's profile follows a normal distribution with standard deviation σ, related to the LEP by the formula [8]:

$$LEP = 0.6745\sigma. \qquad (6)$$

At this phase the ship will try (if it has not started at a previous stage, assuming it knows that it is under attack) jamming the missile's radar. Because of its higher power, the ship's jamming device will block the missile's radar until it reaches a certain distance from its target. This distance depends on the power ratio between the radar and the jamming device. At the moment the missile regains a lock on the ship it depends on its aerodynamic characteristics (i.e. maximum turning acceleration and speed) whether it will allow it to turn to the vessel's direction. If not, it will miss the target vessel. To be successful, the missile's minimum turning radius has to be less than its distance from the ship at that moment, namely [6]:

$$\text{Missile Radius} = \frac{V_m^2}{N \cdot g} \le R_{regain} \qquad (7)$$

Where:

V_m missile's velocity.

N maximum turning acceleration of missile in [g].

g gravitational acceleration.

The range at which the missile will regain a clear picture of the ship's location is given by the formula [6]:

$$R_{regain} = \sqrt{\frac{P_M}{P_J} \cdot \frac{\sigma}{4\pi}} \qquad (8)$$

where P_M/P_J power ratio between the missile seeker and the jammer.

Thus the effectiveness of jamming can be expressed by the integral of the normal distribution from the ship's either end to a distance R_{max}—R_{regain} towards the centre of the ship.

The next step in the above ship-missile struggle includes the use of decoys. Their performance depends also on their RCS. If it is higher than that the ship it will allow the "throw off" the threat. If it is the same, there is a 50% probability that the missile will follow the decoy.

In case of the ship's arsenal includes a "close in" weapon system (CIWS) it will try to destroy the incoming missile. Its probability of success is usually known from trial experiments and it can be incorporated into the model. If there are also missiles that can be used against the incoming threat, their contribution must be also included.

The above can be estimated relatively easily by computer. The problem is that in order to assess the survivability of a ship design we have to estimate the ship's vulnerability and in particular her single hit kill probability. Therefore we have to calculate:

- the probability of "hit of a particular point of the ship".
- the probable "damages extent given a hit at that point".
- the probability of "ship's survival given the hit point and extent".

5. VULNERABILITY - ADVANCED PROBABILISTIC DAMAGE STABILITY (APDS) FOR NAVAL SHIPS

The impact of a hit can be at any point of the ship's length. The target point of the missile guidance system depends on its type, sensor type and guidance system characteristics. For instance, an *Exocet* missile will aim at the ship's waterline, while a *Harpoon* missile will try to enter the ship higher at the ship's superstructure. Likewise, the longitudinal point of impact will depend on the shape that the signature of the ship presents to the particular threat sensor. An IR (infrared) missile will target at the ship's machinery that is an intense hit source. On the other hand a radar-guided missile will probably aim at the ship's radar image centre. For simplicity and generality, we may assume that the impact location is described by a normal probability distribution with its centre at the ship's centre and a linear error probability (LEP) equal to $0.5 \cdot L_{WL}$.

The damage extent can be taken from a Log-Normal Damage Function. This is given by the function [8]:

$$d(r) = 1 - \int_0^r \frac{1}{\sqrt{2\pi}\beta r} \exp\left[-\frac{\ln^2(r/a)}{2\beta^2}\right] \cdot dr \qquad (9)$$

where:

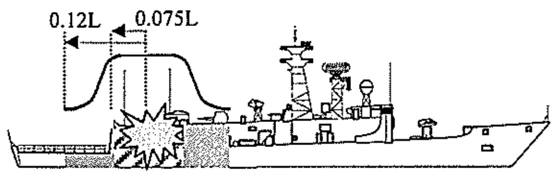
$= (R_{SK} R_{SS})^{0.5}$

$= \frac{1}{2\sqrt{2} z_{SS}} \ln(\frac{R_{SS}}{R_{SK}})$

R_{SK} "dead-sure kill radius"

R_{SS} "dead-sure surviving radius"

which correspond to 98% and 2% probabilities of damage respectively. Their values can be derived from empirical data for the threat missiles considered. Herein we will assume a R_{SK} diameter equal to the U.S. Navy standards namely 15%L_{BP} [9]. The "sure-save" diameter will be taken as 0.24·L as in the A.265 IMO-SOLAS regulations for merchant ships. This results in a ratio of R_{SK}/R_{SS} equal to 0.625. The variation of the log-normal damage function is shown in the following figure.



Having defined the first two probabilities namely hit at a particular point and damage extent given the impact point, we are left to define the probability that the ship will survive given the damage location and extent.

A rational methodology for this evaluation can be based on the survival criteria of the U.S. Navy [9], considering that the latter:

- are based on extensive World War II damage reports, though many changes occurred in naval warfare.
- have been proved quite reliable, because they refer to a large number of events during almost 40 years of use. Even though several ships of the U.S. Navy suffered serious combat damages, none of them was lost due to the lack of stability or floatability.
- include dynamic effects though in a "quasi-static" way.

The philosophy for transforming these deterministic criteria into a set of rational probabilistic approach criteria will be based on A.265 IMO-SOLAS regulations for merchant ships.

It is well established that in all relevant criteria there is an underlying assumption that the sea conditions at the time of damage are "moderate". This constraint could be lifted if we knew (or we could assume) a specific operational sea spectrum for the ship design in question. Thus, we could calculate the probability that waves will not exceed the wave height considered as basis for the current deterministic U.S. Navy criteria, namely a sign. wave height of 8 feet. This wave height was the relevant one for the determination of $_{roll}$, namely the roll amplitude due to wave action. It was also the underlying assumption behind the guidelines for establishing the watertight features/closures to prevent progressive flooding. Thus, any attempt to change the wave amplitude must take into account changes in both $_{roll}$ as well as the margin line. Another important environmental parameter is the wind speed. Given the small probability of exceeding the values given by the U.S. Navy standards (namely, about 33 knots for a 3500 tons frigate), this value could be left unchanged.

We can propose, as a first step, the following guidance for the formulation of **survival criteria** to be applied in the frame of a probabilistic approach to the survivability of **naval ships**:

S = 1 ($_{roll}$) =25 deg.
Wind speed : acc. to USN-DDS-079-1
Min Freeboard $\geq$ 3in + 0.5×(H_S(0.95)-8 ft)
$A_1 \geq 1.4\ A_2$

S = P(H_S<8 ft) if the ship meets the current (deterministic) damaged stability criteria of the U.S. Navy.

S = 0 ($_{roll}$) =5 deg.
Wind speed $\leq$ 11 knots
$A_1 \leq 1.05\ A_2$
Margin line immerses.

For intermediate stages, interpolant values could be used.

It is obvious, that some systematic experimental and theoretical work is needed in order to specify in a more rigorous way the calculation of the ***S*** value for naval ships. In any case, the calculation of the probability distributions of wave exceedence in the area of operation are necessary. For instance, the $P(H_S<8\text{ ft})=0.60$ holds for the North Atlantic, but $P(H_S<8\text{ft})=0.90$ for the Mediterranean Sea. Thus, a combatant, meeting the U.S. Navy criteria, should have, according to the criteria formulated above, a 60% probability of survival for any 2-compartment damage in the North Atlantic and a 90% probability of survival in the Mediterranean Sea [10,11].

The above procedure for assessing the damage stability component of the vulnerability could form an important element of a new *Advanced Probabilistic Damage Stability* method for naval ships. It makes possible the assessment of damage cases, where multiple hits of non-adjacent compartments can occur. This increases the flexibility of the designer. It makes also the damage stability of the vessel a property of the design and not just a requirement that has to be met later on.

6. THE RO-RO SHIP DESIGN PROCEDURE

The existing probabilistic method A.265 is a rational but complicate and non transparent procedure for assessing the probability of survival of a ship. On the other hand, the ship specific survivability characteristics should be reflected in a clear way in its survivability index for possible design optimization. By use of modern hardware and software computing tools, an optimization appears today feasible, as it will be outlined in the following.

As far as the possible risks for passenger ships are concerned, it has been noted at the stage of definition of the various possible damage cases for Ro-Ro vessels that multiple stages of damage prior to the total loss of ship can be considered. The probability of loss of controllability, or of power (black out) should be actually also considered. Piping transferring cold water for cooling vital machinery or power transfer lines passing through the damaged compartment should be identified. The probability of their damage has to be considered and properly included in the calculations. Additionally, the time required to evacuate the ship must also be taken into account. This would encourage ship designers to consider arrangements and efficient equipment for the safe evacuation of passengers and crew, beyond the least requirements set by the regulations. Recent work by D. Vassalos [12] stresses the need for assessing the available evacuation time in case of damage and prior to capsizing or foundering. Existing regulations specify the maximum time available for evacuation but no special care is given to consider the ship damage conditions that might affect this time. Large heel or trim may increase the evacuation time significantly especially for children, elderly or persons with mobility problems. Thus damage cases with large heel or significant trim have to receive reduced weights even though the stability requirements are met.

The consideration of the particular significance of the various ship spaces can be incorporated in the regulations by assigning them so-called *"vitality"* coefficients as it has been already done with the variation of space permeability. Thus spaces with vital machinery or equipment will receive more weight in the survivability analysis. This will account for the fact that even though the ship stays afloat, in case of damage, the associated risks are greater compared to the same post-damage condition after damage of non-vital spaces. The Attained Subdivision Coefficient formula should be therefore modified as following:

$$\mathbf{A} = \sum_{i} \mathbf{p}_i \cdot \mathbf{s}_i \cdot \mathbf{w}_i \qquad (10)$$

where w_i is a properly defined <u>vitality coefficient</u> for compartment i. The vitality coefficients ($w_i \leq 1.0$) of the various compartments should be in descending order to their significance. As defined above, vitality of course depends on the existence of redundant equipment. Also, if for a damage case involving multiple compartments, both the primary and the emergency equipment are contained in the damage extent, the vitality coefficient has also to be reduced. The above procedure calls for the introduction of innovative machinery and equipment arrangement concepts (multiple machinery spaces, redundancy of equipment, etc.) as, e.g., has been indicated in recently published work by M. Kanerva [13].

Specific values cannot be proposed in this paper because more work has to be done in this area. It should involve both damage statistics and actual machinery arrangements of existing ships.

The above revision of the Attained Subdivision Coefficient formula calling for special consideration of vital spaces can be incorporated in a more general Ro-Ro ship design optimization scheme, as outlined in the attached chart. The procedure considers the optimization with respect to the Local Subdivision Index, as proposed earlier by P. Sen and M. Gerigk [14] and properly modified, as given above to account for the vitality of spaces.

7. CONCLUSIONS

The paper addressed the survivability of naval and merchant ships (here: Ro-Ro passenger ships) through a common ("harmonized") probabilistic procedure. Possible risks for naval and passenger ships have been outlined. Special attention has been paid to the formulation of survival criteria for naval ships. At present, at the authors' knowledge, all known damage stability criteria for naval ships are deterministic. They all assume a specific extent of damage and require that the ship achieves certain values of metacentric height, or maximum righting levels (GZ), at certain heel angles. The only probabilistic method known to the authors at this stage is that of the German Navy, but only for those ships which do not satisfy the set deterministic criteria. Therefore the authors suggest, herein, specific survival criteria for naval ships, to be included into a formal probabilistic assessment of survival of naval ships. Finally, following general design concepts of naval ships, a modification of the formula of the Attained Subdivision Index of passenger ships has been proposed accounting for the vitality of specific ship compartments, securing the powering, electric supply and controllability of the ship after damage.

The increased importance of modelling and simulation methods in modern ship design requires the development of more rational concepts. Though the above methodology is, at this stage, not complete, it is suggested as a first step to a new design direction. It is of course obvious that much work is still needed to test and to fully verify the proposed procedures. A framework for discussion of the suggested design procedures for Ro-Ro passenger ships is the Thematic Network SAFER-EURORO [15] supported by DG XII of the European Commission. Their financial support is herein acknowledged.

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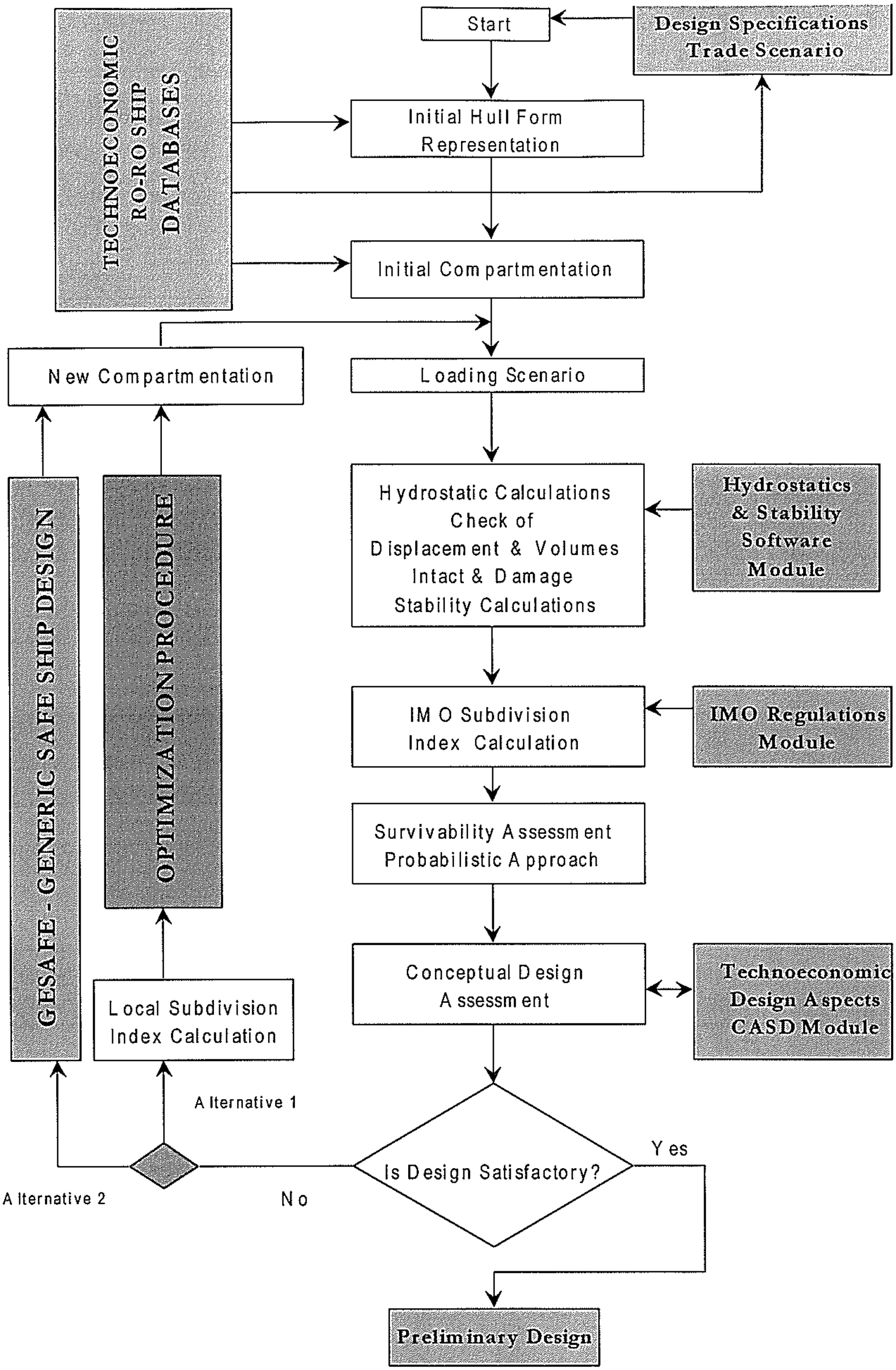

SAFER-EURORO: COMPUTER-AIDED SAFE FERRY DESIGN PROCEDURE