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EVALUATION OF DESIGN PARAMETERS ON THE BASIS OF SURVIVABILITY OF SURFACE COMBATANT SHIPS

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EVALUATION OF DESIGN PARAMETERS ON THE BASIS OF SURVIVABILITY OF SURFACE COMBATANT SHIPS

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ABSTRACT

The reason the author selected this subject is her interest in warships and their unique design aspects. Since 1970s and 1980s survivability has become one of the prime aspects of warship design due to the expensive and time-consuming nature of naval ships. Objective of the thesis is to provide an overall understanding of survivability of combatants and its effect on the design process as a whole. Previous studies mostly focused on the vulnerability aspect of survivability using probabilistic approaches whereas, in this paper all components of survivability in warships has been examined in three phases using system analysis. Total survivability approach has been utilized assuming the ship is operating in areas with multiple threats. 'Measures of Effectiveness' theory have been addressed and a theoretical approach has been made, to implement the theory in warship design process from survivability point of view. System breakdown analysis will help to better judge the design to be made and whether it meets the given RFI and survivability design criteria efficiently.

ÖZET

Yazarın bu konuyu seçmesinin nedeni, savaş gemilerine ve onların kendine has dizayn özelliklerine duyduğu ilgidir. Donanma gemilerinin inşasının çok fazla zaman ve kaynak gerektiren doğasından dolayı, 1970 ve 1980'lerden itibaren hayatta kalınabilirlik (beka) birincil dizayn hususlarından biri haline gelmiştir. Bu tezin hedefi, savaş gemilerinin beka kabiliyetinin etraflıca anlaşılmasını sağlamak ve onun dizaynın tümüne olan etkisini göstermektir. Hayatta kalınabilirliğin, olasılıksal yaklaşım ile daha çok hassasiyet yönüne odaklanan geçmiş çalışmaların aksine, bu çalışmada hayatta kalınabilirlik bütün yönleri ile üç etapta sistem analizi kullanılarak incelenmiştir. Geminin birden çok tehdite maruz kalacağı bölgelerde görev alacağı göz önüne alınarak bütünsel hayatta kalınabilirlik yaklaşımı kullanılmıştır. "Etkinlik Ölçüsü" teorisine değinilmiş ve teoriyi savaş gemisi dizayn sürecine beka bakış açısıyla yerleştirmek için teorik bir yaklaşım uygulanmıştır. Sistem analizi, yapılacak olan dizaynı daha iyi değerlendirmek ve bilgi isteme dökümanı ile hayatta kalınabilirlik kriterlerine uygunluğunu ölçmeye yardımcı olacaktır.

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LIST OF ABBREVIATIONS

AAW	Anti Aircraft Warfare
ACP	Active Cathodic Protection
AE	Alternating Electric
AHP	Analytical Hierarchy Process
AIREX	Airborne Explosion
AM	Alternating Magnetic
AR&M	Optimum Availability
ASG	Active Shaft Grounding
ASuW	Anti Submarine Warfare
ASW	Anti Surface Warfare
C2	Command and Control
CSC	Combat System Capability
DCHQ	Damage Control Head Quarters
Disp	Ship Displacement
DP	Design Parameter
IR	Infra Red
LCC	Life Cycle Cost
LEP	Linear Error Probability
MAUT	Multi-Attribute Utility Theory
MAV	Multi-Attribute Value
MOE	Measure of Effectiveness
MOFE	Measure of Force Effectiveness
MOM	Measures of Merit
MOP	Measure of Performance
MORS	Military Operations Research Society
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
OMOE	Overall Measure of Effectiveness
OSE	Overall Survivability Effectiveness
RAM	Radar Absorbent Material
RAMS	Reliability Availability Maintainability and Survivability
RCS	Radar Cross Section
RD/RF	Radio Direction and Range Finding
S9	Survivability Attributes
SE	Static Electric
Sfc	Specific fuel consumption
UNDEX	Underwater explosion

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LIST OF SYMBOLS

A_O	Mission availability
B	Beam
B/D	Beam to depth ratio
B/T	Beam to draft ratio
Cb	Block coefficient
ci	Set of controlled variables.
Cm	Midship coefficient
Cp	Prismatic coefficient
Cvp	Vertical prismatic coefficient
Cwa	Waterplane area coefficient
C_{WAVE}	Wave Coefficient
D	Depth
E	A measure of the performance of the organization
F	Freeboard
f	Relationship between variables
Fn	Froude Number
GM	Metacentric height
K	Gyration Diameter
L/B	Length to beam ratio
L/D	Length to depth ratio
L/T	Length to draft ratio
LBP	Length between perpendiculars
LOA	Length Overall
LWL	Length Waterline
MAM	Mission attainment measure
η	Efficiency
P	Power (Effective, Installed)
P_C	Probability of control
P_E	Probability of engagement
P_{WK}	Probability of weapon kill
$R_{FRICTION}$	Friction Drag
R_M	Mission reliability,
Rn	Reynolds Number
R_{SK}	Dead-sure kill radius,
R_{SS}	Dead-sure surviving radius
R_{TOTAL}	Total Resistance
$R_{VISCOUS}$	Viscous Drag
R_{WAVE}	Wave Drag
S	Survivability as a probability of ship loss

t time
T Roll period
T Draft
ui Set of uncontrolled variables.
Va Speed of advance of the propeller
Vmax Maximum Speed
Vp Phase velocity
W Wake fraction coefficient
WSA Wetted Surface Area
θ Heeling angle
∇ Volume
Δ Displacement

Probability Calculations

F(TSL) Probability of keel emerge
F(VTH) Probability of exceeding the threshold velocity
PA Probability of active threat
PC Probability of control
PDCT Probability of detection, classification and targeting
PE Probability of engagement
PH Probability of ship getting a hit.
PK Probability of killability
PK/H Probability of vulnerability
PLFD Probability of successful weapon launch, fly out and impact
PS Probability of survivability
PWK Probability of weapon kill
S Survivability as a probability of ship loss

Radar Calculations

Ap Projected object surface
B Radar operating bandwidth.
Bn Radar receiver bandwidth
D Target visibility distance
D_{Direct} Directivity, ratio of the maximum intensity of the radiator to the intensity of an isotropic source
dh Radar horizon distance,
dt Distance from the point of tangency to the target
f Radar frequency
F Noise figure
G Antenna gain factor
g Gravitational acceleration
hr Radar antenna height;

ht	Target height,
K	Boltmann's constant
L	Radar losses
N	Noise factor
$N_{missile}$	Maximum turning acceleration of missile
P	Radar Peak Power
Pj	Power ratio of jammer
Pm	Power ratio of missile
Pmin	Minimum detectable received signal from sensor
Pt	Transmitters power
R	Distance from radar to target
$R_{Reflect}$	Reflectivity, re-radiated fraction of intercepted power
R_0	Mean radius of the Earth.
Rmax	Maximum range of radar detection
T	Temperature
Ts	Total effective system noise temperature
Vm	Missile velocity
λ	Radar operating wavelength
σ	Radar cross section

Seakeeping Calculations

V_{TH}	Vertical threshold velocity
A	Vertical distance between centre of gravity of the ship to its drifting centre
A_{WA}	Waterplane area aft of amidship
A_{WF}	Waterplane area forward of amidship
c/L,	Cut-up ratio
C_{VPA}	Vertical prismatic coefficient aft of amidships
C_{VPF}	Vertical prismatic coefficient forward of amidships
C_{WA}	Waterplane coefficient aft of amidships
C_{WF}	Waterplane coefficient fore of amidships
D_F	Freeboard height
D_{PROP}	Propeller diameter
F	Volume of displacement fore of amidship
$F_{(TSL)}$	Probability of keel emerge
$F_{(VTH)}$	Probability of exceeding the threshold velocity
IL	High Speed Turning
$m_{0,M}$	Zero order spectral moment of relative vertical motion response
$m_{0,V}$	Zero order spectral moment of relative vertical velocity response
$m_{2,M}$	Second order spectral moment of relative vertical motion response.
PE	Propeller emergence

R	Turning radius
‘R’	Bales’ Seakeeping Rank Estimator
SI	Slamming Index
v	Speed
WI	Wetness Index
Z_{PROP}	Distance from the propeller axis to the calm water sea surface
∇A	Volume of displacement aft of amidship
∇F	Volume of displacement fore of amidship

Infra-Red Calculations

a	Absorption coefficient
c	Speed of light
E	Total Energy Emitted
H	Plank’s Constant
r	Distance of travel of the signal
s	Scattering coefficient
T_{TRANS}	Transmittance
T	Thermodynamic Temperature
$W_0\lambda$	Spectral radiant emittance
ε	Emissivity
σ	Stefan Boltzmann Coefficient

1. INTRODUCTION

A warship is a naval vessel equipped with weapons and is designed to take part in warfare at the sea unlike commercial vessels. Several types of warships exist; NATO classifies them into numerous different groups which are aircraft carriers, surface combatants, submarines, patrol combatants, amphibious warfare, combat logistics, mine warfare, coastal defence, mobile logistics, support ships and service type craft.

In this paper, the focus will be on surface combatants, which according to NATO are "large, heavily armed surface ships which are designed primarily to engage enemy forces on high seas, including various types of corvettes, destroyers, patrol vessels and frigates."

Surface combatants are designed according to their assigned missions, which can be either one of the given ASuW (Anti-Submarine Warfare), AAW (Anti-Aircraft Warfare), ASW (Surface Warfare) missions or they can be multi-functional combatants. These vessels are expensive and time consuming to build, therefore they aren't easy to replace as it takes years to design and build. To be deemed suitable as a successful design, a surface combatant's operability during missions and how effective they outlast their assigned mission play significant roles. The first question comes to mind before building is "What can be done to maximise life time of the vessel?" and this is where 'survivability' comes into play. The main question to be answered becomes "What can be done to maximise survivability with minimum loss of vital design points?" and "Which optimization is better for enhanced survivability?"

Survivability of a warship depends on a high number of parameters and therefore is often surrounded by uncertainties. Thus it is vital to assess and decide what kind of components and systems should be prioritized in order to enhance the ship's survivability in early design phase as it will get harder and time consuming to change or enhance survivability after commencing construction of the vessel. In order to observe and execute survivability effectively 'Measure of Effectiveness' system analysis is a method to choose for pursuing mission effective design to be built. Breaking down survivability as a system with hierarchical ranking order using a methodology derived from Systems Engineering consists of choosing 'Measures of Merit' through asking and answering right questions to achieve the desired goal and deciding upon the constraints, aiming the system will succeed for measuring effectiveness.

Analysing the behaviour of the combatant to its environment in which the vessel is intended to operate in and to balance all survivability measures implemented on hull during design in any possible foreseen version of the scenario is the way to achieve the OMOE of "Overall Survival Effectiveness-OSE". In this paper survivability will consist of mobility, which will cover all navigation capabilities and behaviour of the hull to the effects of its environment through covering all naval architecture principles of an operational vessel, and time phases of survivability during a mission, which are; susceptibility and detectability, vulnerability and recoverability as well as combat system capability of a combatant.

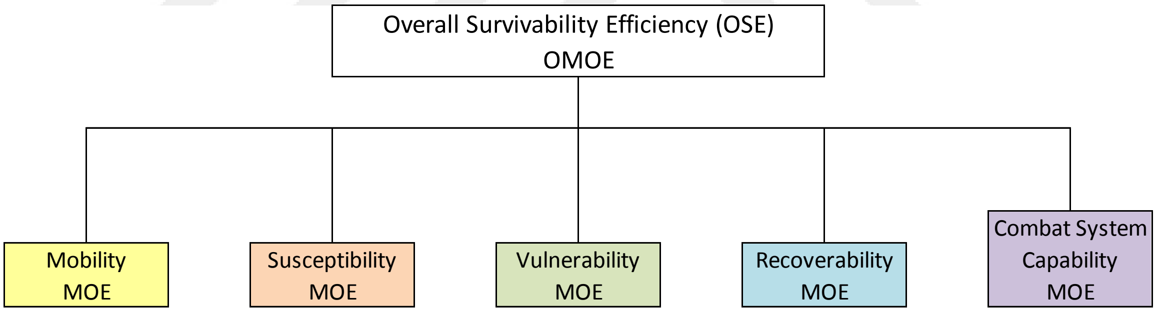


Figure 1.1 - Overall Survivability Efficiency (OSE)

The results can be cross checked with the criteria and/or rules of classes or previous already-been-built designs worldwide. A comparison can be made if the design is looking efficient enough to be successful. It is safe to say, according to research done in writing this thesis; survivability emerges as the utmost important factor in warship design during and after 1980's. Cost will be excluded from this analysis for the sake of maximum achievable survivability efficiency calculation, even though it is known that for a complete design trade-off analysis it cannot be excluded as it is one of the main shapers of the whole ship-super-system.

1.1. “What Is A Combatant?” - Ship as a System

Surface combatants are a particular subset of warships as they are made to operate in an environment that is lethal, compared to other types of ships and primarily intended for naval warfare against threats. Protection against these threats defines the mission or missions of the warship. Threats can be expected from everywhere, even invisible threats exist in CBR (Chemical, biological, radiological) warfare and/or Information Warfare. Other main missions can be; ASuW (Anti-Submarine Warfare), AAW (Anti-Aircraft Warfare), ASW (Surface Warfare). The increasing operational needs of navies to provide flexibility within increased multi-mission capability performance requirements lead to giving the order of precedence to survivability of a warship as the time for planning and constructing a warship takes years and the ship cannot be replaced quickly. The requirements of the navies include vessels to go faster, to carry more payloads, to eliminate/kill more targets, to be more survivable and be better than any other ship and outperform the enemy. Designer’s goal is to provide the maximum possible survivability within an inevitably restricted feasibility. Mentioned ‘Survivability’ is the balance between expected threats, susceptibility and vulnerability reduction, damage control and recoverability which will be discussed and explained further in this paper. In this paper, cost will not be taken into consideration for it may vary and is effective on warship design.

1.2. Warship Design Process

It is well known that the choices and decisions made within the liminal design stages can have the most noteworthy impact on the whole life costs of a ship. Ship design is a complex activity that requires an interdisciplinary approach, with the end goal of creating a valuable and optimum design solution. The design work is generally considered a sequential process, increasing the detail by each step, until a single design that satisfies all constraints, balancing all considerations. An approach to start the design phase is to choose the prime aspects affecting the survivability of a combatant ship.

Warship design is acknowledged to be a highly complex process and the reason is that warships must balance a number of factors in order to operate without any kind of loss which are; weights, arrangements, missions, powering, propulsion, life cycle, cost, crew and survivability. During the design period, the “design spiral” (Figure 1.2) conveys both the interactive and the iterative nature of the whole ship design. A change in any one parameter will influence numerous components and, in turn, require changes to other parameters; it is essentially impossible to alter one measurement or parameter without noteworthy impacts upon numerous dependent variables.

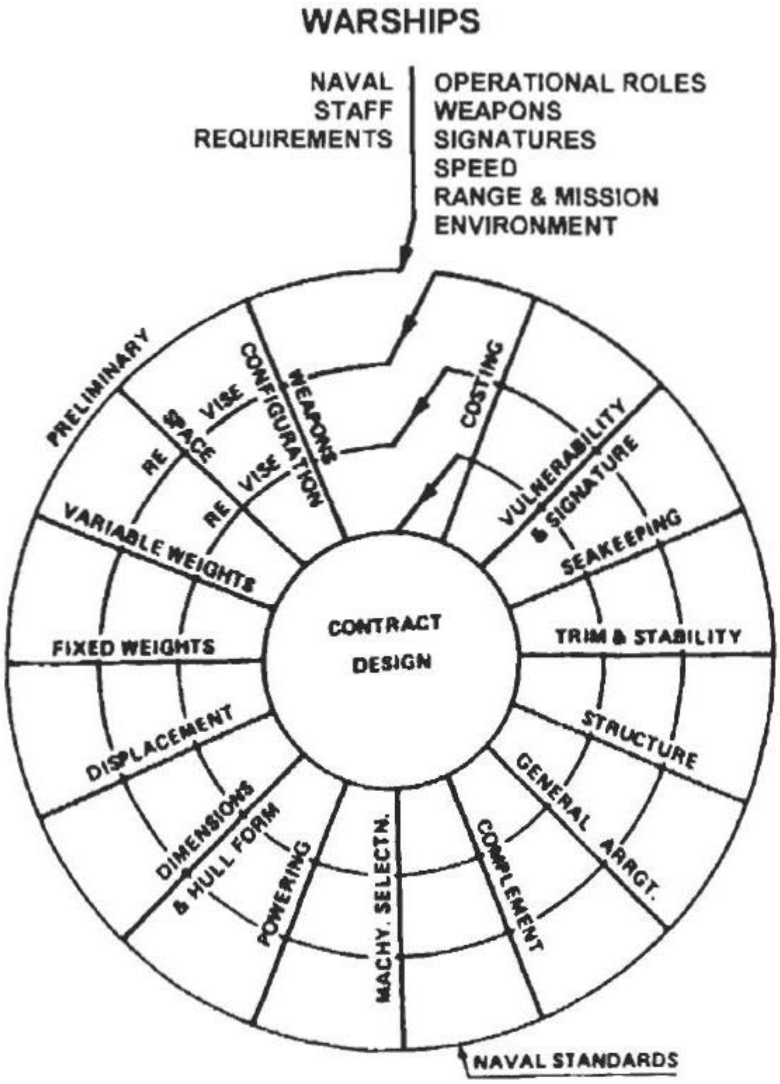


Figure 1.2 - Warship Design Spiral [33]

The design process starts with naval staff requirements which are defined by operational roles, weapons on board, signature boundaries, desired achievable speed limits, range and mission capabilities and environmental conditions that will be effective on the vessel throughout her life-cycle.

Where on the other hand, the traditional approach to warship design starts with determination of the payload, with payload confirmed, the classification and the missions of the warship vaguely come into the open. Afterwards total internal volume needed to house the payload and standard interior elements of the warship is calculated; therefore first shot at displacement of the vessel can be obtained. Machinery is selected and implemented according to the requirements from the respective Navy. The complement of the ship is shaped in accordance with the required specifications and man power to operate the vessel at full potential. The remainder of the process can be followed by assigning auxiliary power and services in accordance with the early decisions. Total volume of tanks aboard is specified considering the required range, endurance, capabilities of the vessel. All of the aforementioned processes dictate the overall displacement and internal volume of the warship and the design process ends with balancing displacement and volume. Meanwhile, it is utmost important to calculate mobility abilities such as seakeeping, manoeuvrability, stability to match with the physical survivability of the vessel.

In Rawson and Tupper’s design spiral [34], Generation of the need for ship is represented at the centre of the spiral from military or economic argument.

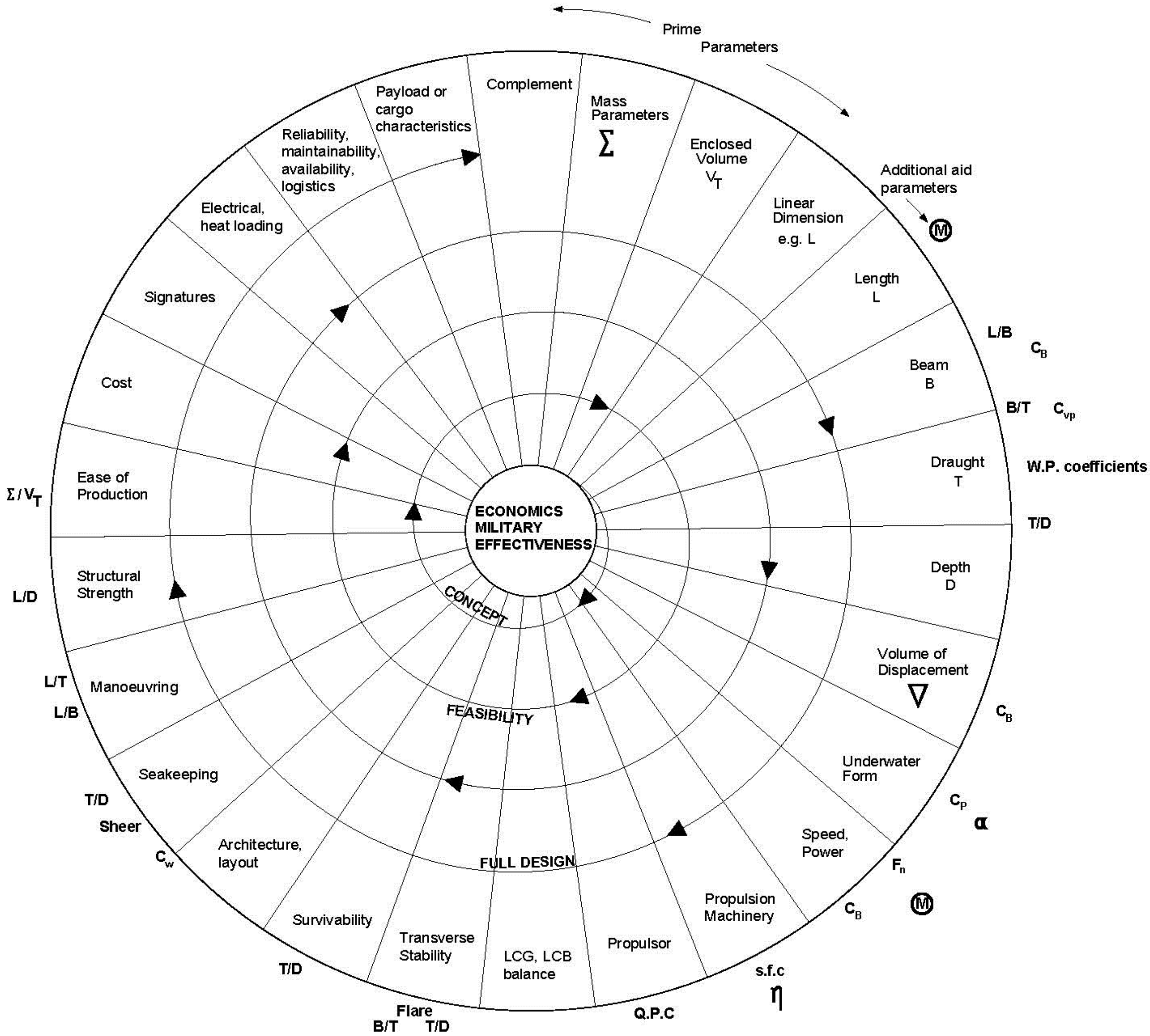


Figure 1.3 - Warship Design Spiral [34]

There are many different ways of representing this convergent process, one of them being hierarchical ranking system analysis, where a parameter change can affect multiple measures at once. Design spiral and system break-down both are useful to calculate the effects of varying one specific parameter on the parameters and performances represented in other sectors of the spiral or system, just to find out how much of an influence it has. A small change in any design parameter may affect strength, survivability, seakeeping, stability, cost and propulsion.

2. TERMINOLOGY – INTRODUCTION TO SYSTEMS

To be able to perform an overall system analysis, definitions and execution areas in the past must be known and absorbed. The first question to be answered should be what a system means. A system is a combined en masse of people, products and processes that provide a capability to satisfy a stated need or objective. As an engineer point of view, engineering a system suggests the rational order of actions and decisions which ultımately converts an operational necessity into a narrative of system performance parameters as well as a preferred system configuration. The systems viewpoint refers to considering the entire characteristics of a system as one, within its surroundings; environment. Hence, system's engagement with its very own surroundings in which it operates and with the other systems with which it co-operates is crucial for an engineer to take into account.

The term 'super-system' has derived from this broaden scope as it contains all the outer components which has an impact on the ship and/or gets impacted by.

To examine and acquire, the functional engagement of the structured system and its qualities along with their effect on total system behaviour and/or performance, a simpler interpretation of the system is used which is regarded as a hierarchy.

The specific terms used in the effectiveness analysis process coined by Green and Johnson in hierarchical order in their 2002 paper. [31]

These terms are;

1) Dimensional Parameters (DPs) which are the proportions or characteristics of the physical entities whose values determine system behaviour and the structure under consideration even when at rest [31, 32, 35, 36].
2) Measure of Performance (MOPs) which are related to inherent parameters (physical and structural) but measure attributes of system behaviour [31]. MOPs are generally non-probabilistic measure of performances thus MOPs are the "consequence" of specific configurations of physical elements [31, 32, 35, 36].

3) Measure of Effectiveness (MOEs) are a measure of how the system performs its functions within an operational environment [31].
4) Measure of Force Effectiveness (MOFEs) are a measure of how the system and the force of which it is a part, perform its missions. Also is referred to as measures of system effectiveness (MOSEs) or overall measures of effectiveness (OMOE) [31, 32, 35, 36].
5) Measure of Merits (MOMs) are a general term for all measures that characterize a system under analysis MOMs collectively may refer to MOPs, MOEs and MOFEs [31, 32, 35, 36].

After defining and putting the effectiveness measures in order, it is essential to do necessary repetitions to make sure they are the accurate ones that achieve the system performance which is an acceptable degree of user anticipation. Trade off decisions are structured based on the aforementioned norms and applied to run the possible system solutions.

Effectiveness measures extract through the foundation. They rely on the predefined mission and scheme as well as appoint the choices. Effectiveness measures should not be confused with system parameters. Green's example is that, while it is known that raising the search rate of a sensor enhances the detection likelihood and in this instance it is defined as a parameter; sensor search rate alone is considered to be an MOP [35].

Effectiveness measures are expected to be measureable and testable since they amount to quantity. A critical matter to highlight here is the issue of sensitivity. Effectiveness measures both have to indicate a shift in the parameter set and possess a reference within to observe the change valuation. When MOPs, MOEs and MOSEs are articulated as a prospect, this enables to decide whether the parametric change provides a meaningful statistical data.

Effectiveness measures should be taken as an autonomous section under evaluation during the analysis process. Otherwise stated, MOP's should be autonomous however can be amassed with MOE's.

The relationship between parameters and effectiveness measures leading performance prediction process has been schematically described by Leite and Mensh [37], seen in Figure 2.1 below. Dimensional parameters forming the system along with scenario requirements and environmental conditions which the system is affected by has been elected as inputs into the system model and the sought after effectiveness measures (MOM's) are the outcomes.

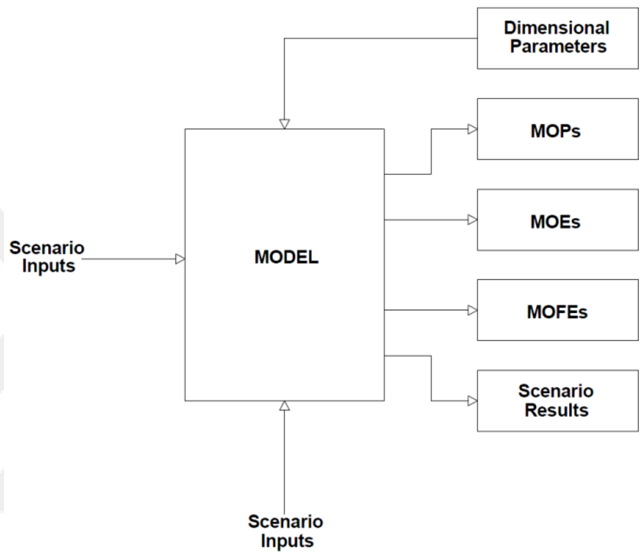


Figure 2.1 - Modelling System Performance [37]

To conclude the effectiveness measures as the set of parameters and their hierarchical structure within the scope of the system of systems that induces the performance of the system; the system bounding process should be taken as the origin. Effectiveness measures appear under the hierarchical schema of MOPs which are regarded as the sets of parameters, MOEs constructed of the aggregation of MOPs, and the MOSEs constructed of the MOEs.

3. PREVIOUS STUDIES ON SYSTEM ANALYSIS IN NAVAL ENGINEERING

Green's paper 'Towards a Theory of Measures of Effectiveness' [31] emphasizes the theory to be able to understand OMOE. The paper explains the theory through MORS (Military Operations Research Society) workshops of the 80's and 90's. The workshops have provided a solid foundation for developing a needed mathematical approach to measure of merits focusing on the process. The outcome of a process is "an expected value based upon system parameters for a given environment." They laid a foundation for a more theoretical approach to "measure of effectiveness" in their Command and Control workshop. Their approach consisted of two parts which are; theory and analytic framework, respectively.

Their theory started with a set of standard terminology and ideas about the concept of Command and Control, which will be called C2 from now on. The specific terms used in the effectiveness analysis process were written in terms of C2 in the table below;

Table 3.1 - MORS definitions

Name of the Term	Definition
C2	"The exercise of authority and direction by a properly designated commander over assigned forces in the accomplishment of his mission." This definition was extracted directly from the Joint Chiefs of Staff Publication 1 (JCS Pub 1).
C2 System	System has three components, physical entities, structure, and a C2 process.
C2 Process	"The C2 process reflects the functions carried out by the C2 system."
Boundaries	"The boundary of a C2 system is a function of the system under analysis and defines the system being studied from the environment."
Dimensional Parameters	"Properties or characteristics in the physical entities whose values determine system behavior and the structure under consideration even when at rest."
Measures of Performance (MOP)	"Measuring attributes of the system behavior through dimensional parameters."
Measures of Effectiveness (MOE)	"Measure of how the C2 system performs its functions within an operational environment."
Measures of Force Effectiveness (MOFE)	"A measure of how the C2 system, and the force of which it is a part, performs its missions."
Measures of Merit (MOM)	"MoMs subsume all the measures that characterize a C2 system. The context in which MoMs are measured affects the way in which they are defined. Depending upon the analytic perspective, a MoM could be a MOP or a MOE. It depends upon the question being answered in the analysis."

MORS's developed theory builds on three points which are;

- The importance of system bounding,
- The hierarchical relationship between measures and,
- The focus on process and resulting interactions with the environment.

Rudwick [38] notes that to evaluate system effectiveness the system must be placed in its operational environment and operated in accordance with the specified environmental conditions established in the analysis.

As mentioned earlier, he states that by this definition, system effectiveness is always measured in a probabilistic fashion. Ackoff defines this idea mathematically [39].

$$E = f(c_i, u_i) \quad (3.1)$$

Where:

E = A measure of the performance of the object, organism, or organization involved.

c_i = the set of controlled variables.

u_i = the set of uncontrolled variables.

f = the relationship between the preceding variables.

Referring back to the MORS definitions c_i and u_i represent the parameter set of the system and the environment respectively. Ackoff [40] further specifies that A_i ($1 \leq i \leq m$) represents different actions available to a system in a specific environment (a change in the parameter set will change the behaviour). P_i is the probability that the system will select these courses of action in that environment. Then (1.2):

$$\sum_{i=1}^{m} Pi = 1.0$$

If E_{ij} represents the probability that a course of action A_i will produce an outcome O_j then the efficiency of the system in producing the outcome O_j is (3.3);

$$Po = \sum_{i=1}^{m} Pi\ Eij$$

As noted earlier systems will instantiate their behaviours either continuously or discretely or in a combination. As an example radar can search (continuous) and detect (discrete) at the same time. Processes can also occur sequentially or parallel or in combinations thereof. The processes of systems can be calculated through;

1) Serial Processes

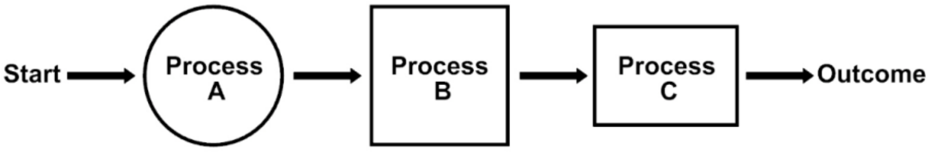


Figure 3.1 - Serial Processes [31]

The product of the individual outcomes of A, B, and C gives the overall outcome of these processes.

$$P_T = P_A P_B P_C \quad (3.4)$$

Parallel Processes

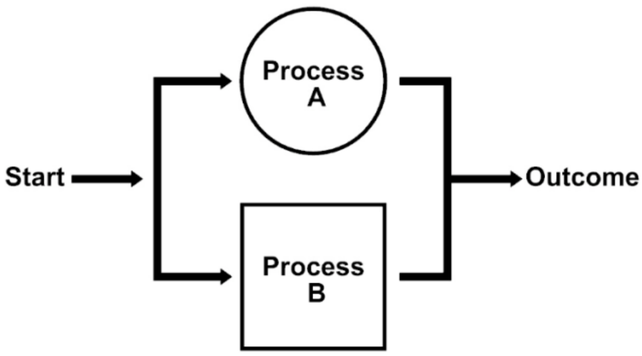


Figure 3.2 - Parallel Processes [31]

For a parallel network the overall outcome is given by;

$$P_T = P_A + P_B - P_A P_B \quad (3.5)$$

2) Series of Parallel Processes

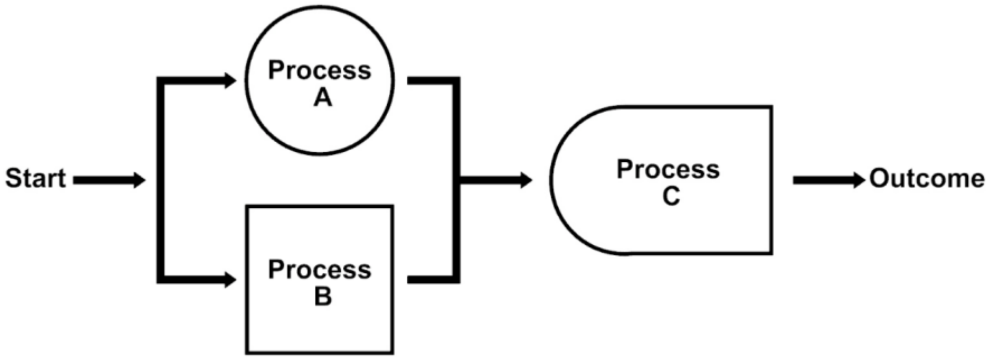


Figure 3.3 - Series - Parallel Processes

For a series-parallel network the overall outcome is given by;

$$P_T = P_C \, (P_A + P_B - P_A P_B) \quad (3.6)$$

Evaluation of more complex processes can be accomplished by applying the mathematics of reliability theory to the network of processes.

After comprehending the main theory beneath effectiveness measures, defence guidance, mission requirements, threat, war game outcome and experience within the scope of professional opinion to incorporate various views is used to calculate an Overall "Measure of Effectiveness" index which consist the methodology that is cited by Brown's paper [36].

Mission effectiveness is stated in particular schemes by MOEs. For instance, MOEs can be the length of the conflict, territory lost or gained, damage and targets destroyed while Measures of Performance (MOPs) can be sustained speed, endurance and signatures. Physical portrayal of the ship system is through the Design parameters (DPs). MOPs are defined by DPs and MOE's by MOPs. Additionally, cost and risk forecast are estimated via DPs. Applying professional approaches precisely in order to accommodate these various views and analyse the worth or utility of ship MOPs placed in an OMOE function, can be considered as a substitute modelling and simulation.

Brown's "super-system" breakdown of a ship consists of four domains, which are; mission, functional, physical and process domains. The "Super-system" concept was first mentioned by W.A Hockberger in 1996 [41], he defined it as "the hierarchy of systems and sub-systems included in a total-ship-system".

As seen below in Figure 3.4, mission domain compromises of customer needs and requirements, the effectiveness is also covered in this domain. Functional domain determines top level functional requirements of operability. Physical domain consists of physical design parameters defining the vessel itself. This domain is utmost important as the optimization and balance of these parameters generate the effective hull design for buoyancy and effective ship systems integrated on board. Measures of Performance (MOP)'s are created according to these parameters and "ultimately determine mission effectiveness." Process domain consists of "process variables" which are related to critical design parameters. In order to establish a feasible build process with a maximum level of producibility, the process in question should be cultivated in each and every phase of design hierarchy.

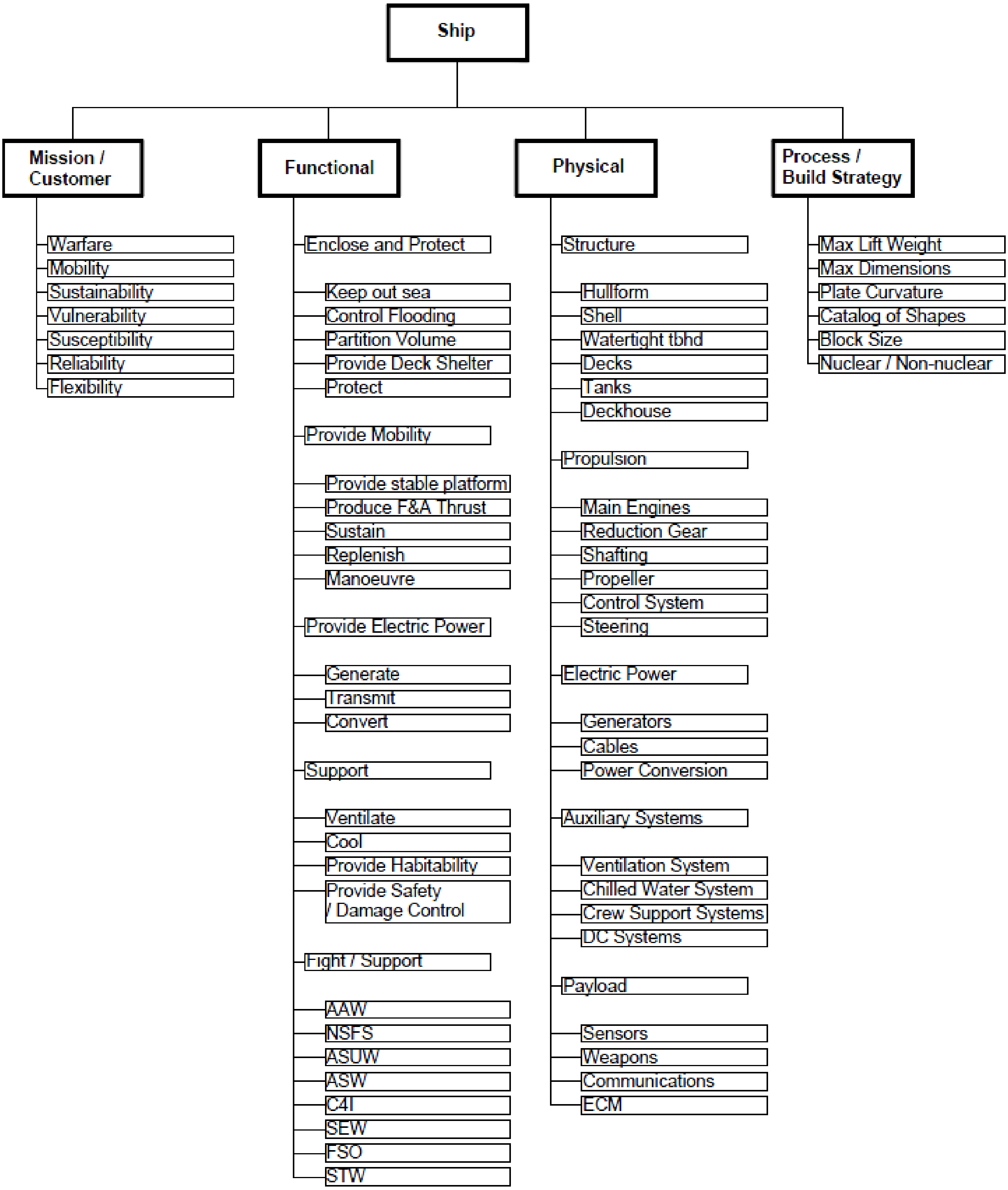


Figure 3.4 - Notional Top Level Design Hierarchy [36]

Designer and engineers are expected to define a working model which evaluates the mission effectiveness' mutual understanding by the operators and policy makers, followed by outlining its relationship in terms of functionality to ship MOPs to be able to start building the "overall measure of effectiveness" function.

Concluding the complete mission effectiveness requires various data to be combined [36],

1- Defense policy and goals
2- Threat
3- Existing force structure
4- Mission need
5- Mission scenarios
6- Modeling and simulation or war gaming results
7- Expert opinion

However, aforementioned may as well be taken as a multi-attribute decision issue. There are two main techniques used commonly in order to address these issues: Multi-Attribute Utility Theory, MAUT, [42] and the Analytical Hierarchy Process, AHP [43]. While there is an effort to find the mutual ground and combine the most beneficial aspects of these methods these days in Multi-Attribute Value, MAV, [44] functions, previously the fronts, which supported either one, had been quite detracting to one another. In Brown's research, this recent approach is used to conclude an OMOE. The crucial attributes, which influence the decision and/or system behaviour, are the initial steps to construct an AHP hierarchy.

The complexity of conclusion made may fluctuate based on the details of the attributes in question. Putting these attributes in order and preparing a reasonably classified or analysed hierarchy structure should follow. The bottom of the hierarchy level is consisted of system options and substitutes.

Both sustainable and individual effectiveness/performance attributes proven to be important and applied to examine the possible ship alternatives in an infinite matter should fall under the OMOE function. In order to achieve a favourable AHP/MAVT integration to this problem is only possible through a highly well-built and methodical approach as noted below by Brown [36];

1. Identify, define and bound decision attributes

Identify critical mission scenarios. Identify MOE(s) for each mission scenario. Establish goals and thresholds for all MOEs. Identify ship MOPs critical to mission scenario MOE assessment and consistent with the current design hierarchy level.
Set goals and thresholds for these MOPs.

2. Build OMOE/MOP hierarchy.

Organize MOEs and MOPs into a hierarchy as shown in Figure 36, with specific ship MOPs at the lowest level. Association with the performance of a discrete system may define some MOPs. Others are continuous performance variables such as sustained speed.

3. Determine MOP value and hierarchy weighting factors. Use expert opinion and pair-wise comparison to determine MOP value and the quantitative relationship between the OMOE and MOPs.

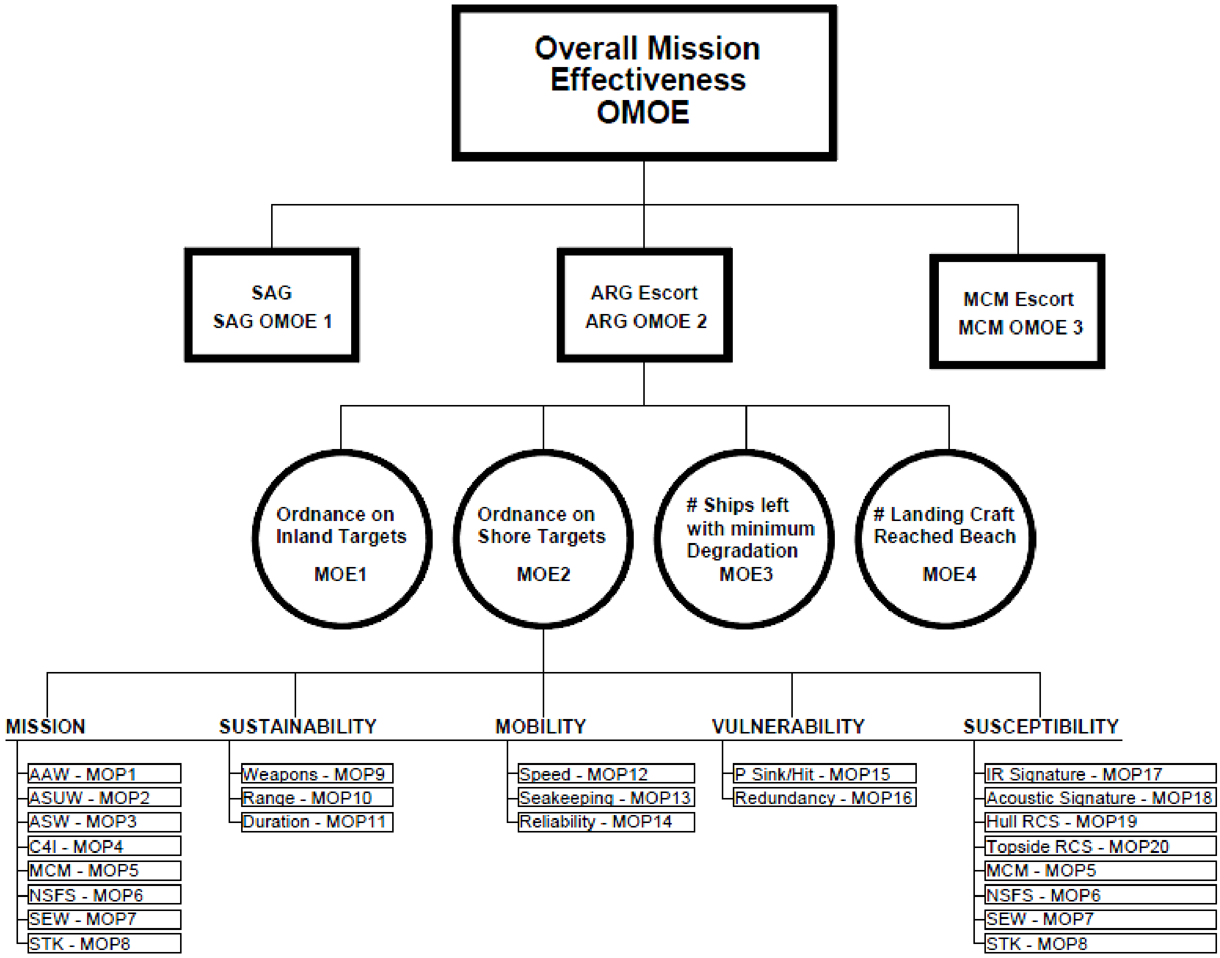


Figure 3.5 - Notional Top Level OMOE Hierarchy [36]

Brown's research refers to the ship synthesis model which was found by Reed [45]. Reed's model has been improved and updated at MIT for over two decades by a long series of naval officer students and faculty, and specifically for use with a genetic algorithm (GA) by Shakak [46].

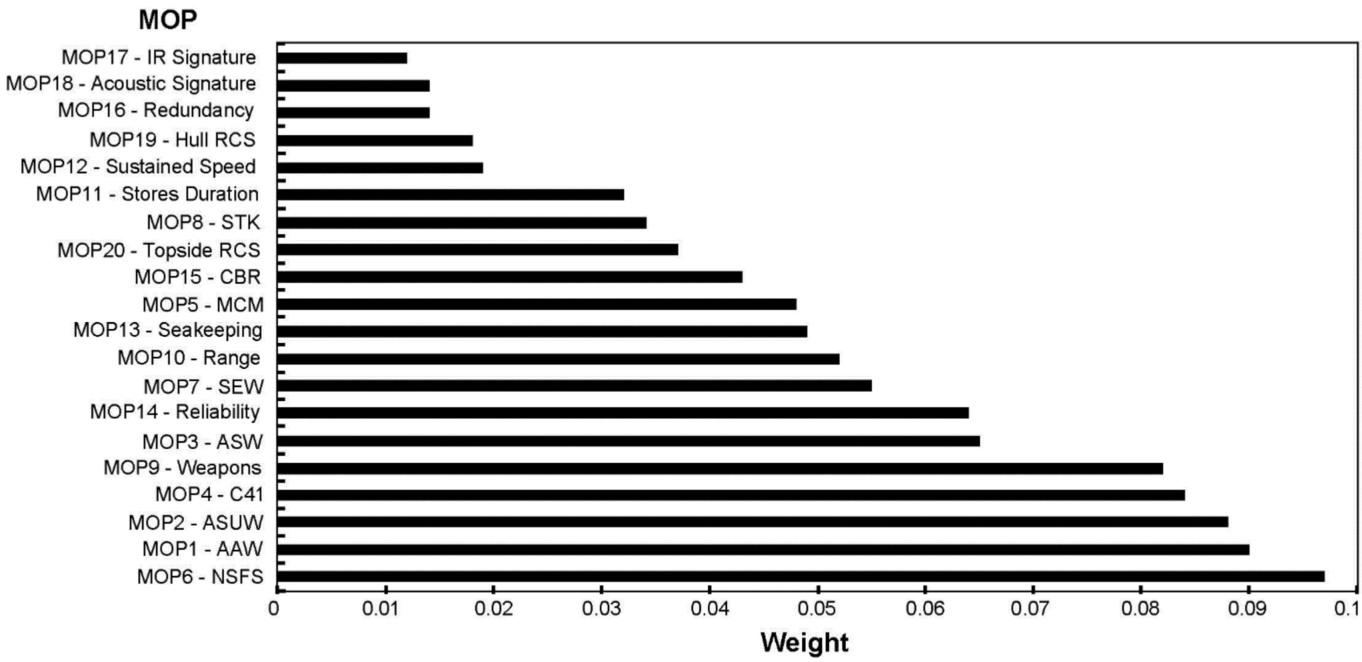


Figure 3.6 - Measure of Performance (MOP) Weights [36]

A ship design matrix (chromosome) is the table where input design parameters (genes) are stated based on the GA application of this synthesis model. (Figure 3.7). Design parameter descriptions are listed in Figure 3.8. Specific payload systems with weight, area and power requirements are associated with each payload description. The ship is balanced and resulting MOPs, OMOE and Life Cycle Cost (LCC) are calculated.

C_p 0.61	C_x 0.82	$C_{\Delta L}$ 80	C_{BT} 2.9	C_{D10} 11.1
C_{RD} 0.2	Cmanning 0.5	AAW 1	ASUW 2	ASW 1
C4I 1	MCM 4	NSFS 1	SEW 1	Weapons 1
Range 3	Stores 2	Shafts 2	CPS 1	ICR/GT 1

Figure 3.7 - Design Parameter Chromosome [36]

Design Parameter	Description
1 - Prismatic Coefficient (Cp)	0.5-0.7; 20 increments
2 - Maximum Section Coefficient (Cx)	0.7-0.9; 20 increments
3 - Displacement to Length Ratio ($C_{\Delta L}$)	60.0-90.0; 15increments
4 - Beam to Draft Ratio (C_{BT})	2.8-3.7; 9 increments
5 - Length to Depth Ratio (C_{D10})	10.0-15.0; 10 increments
6 - Raised Deck Ratio (C_{RD})	0.0-0.4; 4 increments
7 - Manning Factor ($C_{Manning}$)	0.5-1.0; 5 increments
8 - AAW Payload	1 - Theater TBMD 2 - Area TBMD 3 - Area Defense 4 - Limited Area Defense 5 - Self Defense
9 - ASUW Payload	1 - Long Range 2 - Medium Range 3 - Short Range 4 - Self Defense
10 - ASW Payload	1 - Area Domonance 2 - Adverse ASW Environment 3 - Good ASW Environment 4 - Torpedo Defense
11 - C4I Payload	1 - Advanced 2 - Current
12 - MCM Payload	1 - Limited Clearance 2 - Mine Recon 3 - Mine Avoidance 4 - Limited Mine Advoidance
13 - NSFS Payload	1 - Advanced (VGAS, NATACMS, ATWCS) 2 - Full 3 - Medium 4 - Minimum
14 - SEW Payload	1 - Advanced 2 - Current
15 - Weapons Capacity (VLS)	1 - 128 cells 2 - 64 cells 3 - 32 cells
16 – Range or fuel capacity	1 - 10000 nm 2 - 7000 nm 3 - 5000 nm 4 - 4000 nm
17 - Stores Duration	1 - 60 days 2 - 45 days
18 - Shafts	1 or 2
19 - CPS	0 (none) or 1 (full)
20 - ICR or GT	0 (ICR) or 1 (LM2500)

Figure 3.8 - Design Parameter Descriptions [36]

In order to achieve balance, physical and functional constraints should be fulfilled so the ship can stay afloat.

Brown stated the ship as a “super-system” whereas Green states warships are basically weapon systems according to his “Modelling the Ship as a Weapon System” paper [47]. However, warship design system integrations differ within a broad spectrum which may cause disengagement to a degree between weapon system performance and key ship design factors.

In order to define the ship design process, a closer look at the performance deterioration rather than the performance improvements to an acceptable certain level should be considered. “Battle force concept” consists of various elements of systems and warships should be considered as a weapon system that contributes to it. Both the sensor and combat system performance necessities should be equally taken into consideration when the ship is treated as a weapon system. This issue is more of a weapon design concern compared to a naval architecture one; therefore this thesis will focus on naval architecture point of view rather than a weapon system. If the weapon system and its attributes started with the revision of the spiral model, solutions can be constructed for performance, speed and endurance as the elements of combat capability design and equipment. Their relationships can be taken as the elements of system design.

Previous studies shed a light on methodology of this thesis.

4. WARSHIP AS A SYSTEM

While doing a system analysis on warship survivability, why not put warship into a system breakdown where the ultimate goal is to build a warship that can achieve maximum functional and operational efficiency? The ship has to be able to navigate throughout the seas, without being seen or getting hit, while eliminating enemies and providing safety for friendly sources, crew aboard and environment it's operating in.

According to Brown's studies, a ship analysis needs to be approached in the context of a super-system while Green suggests it should rather be taken as a weapon system. Bearing in mind the "Super-system" concept by W.A Hockberger in 1996 [41], breakdown of the warship can be seen below in the figure. The warship super-system is aggregate of all the components that form it.

As "warship" becomes an equation that consists of navigation, powering, payload, habitability, survivability and control systems; lacking of any factor in the function will lead the user to the point where the system cannot be completed. The system breakdown helps to pay attention to all vital components of a warship to operate in its full potential. Similar to design spiral method, a change of parameter in any of the sub-systems may result in a reconsideration and recalculation of any other sub-system. The reason the process being iterative is that all sub-systems must be compatible for main system to be efficiently successful. This paper will focus on warship survivability; one of the sub-systems of overall "super-system" warship and will be further explained.

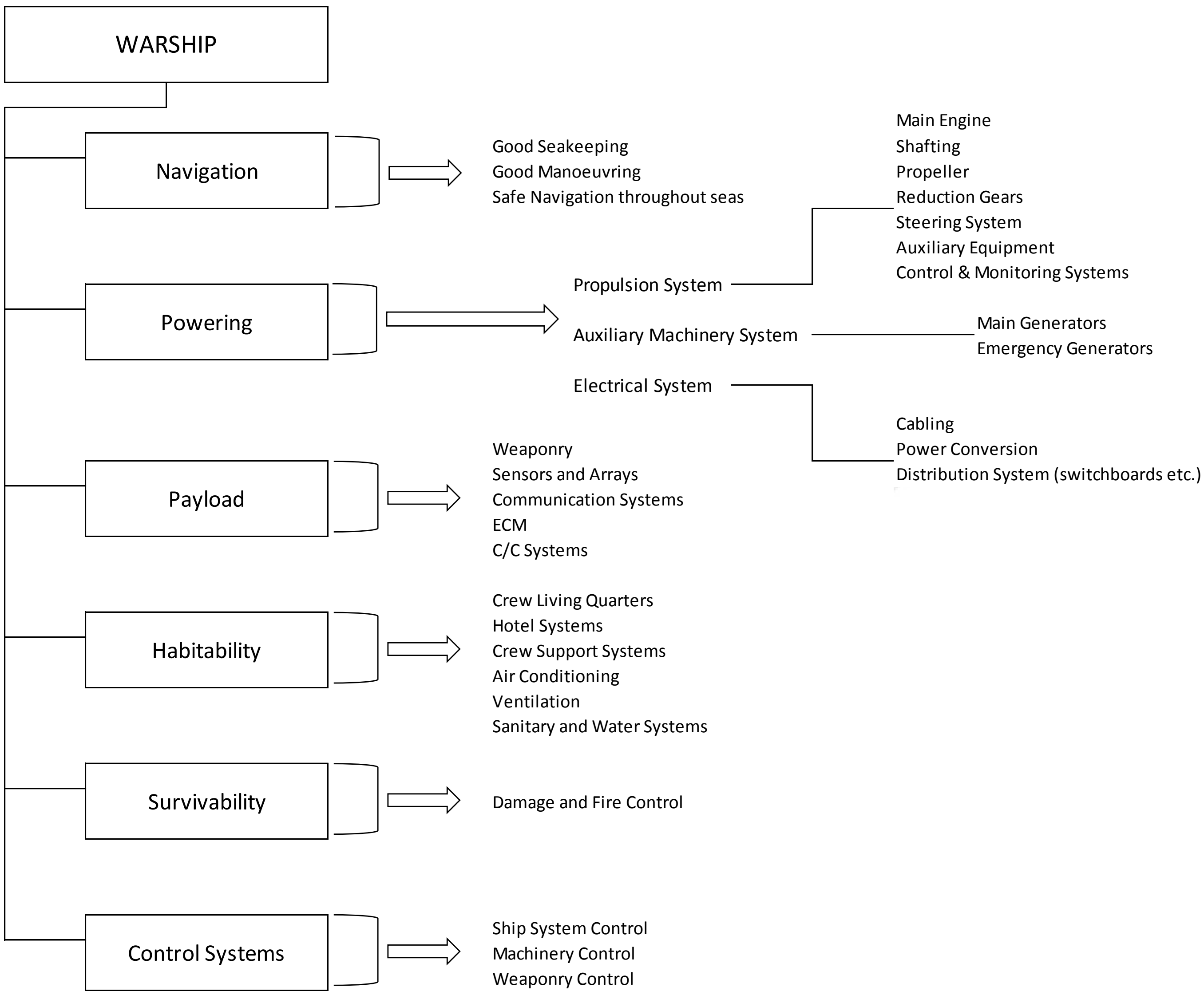


Figure 4.1 - Warship Super-System

4.1. What Is Survivability?

Survivability is defined as the competence of a system, its subsystem, equipment, process or procedure to last as long as possible while a disruption is received regardless of it being natural or artificial.

The military understanding of survivability is considered as the strength of the ship in order to continue a mission even after damage. When survivability is in question, there are four attributes in the system which engineers put their efforts on; detectability, susceptibility, vulnerability and recoverability.

- Detectability - the ability of being lack of aurally and visually detected by any radar (by an observer).
- Susceptibility - the ability of preventing the hit (by a weapon).
- Vulnerability - the ability to withstand the impact.
- Recoverability - lasting effects of a hit, damage control, and firefighting, capability restoration, or (in extremis) escape and evacuation.

Warships are ever changing thanks to the never ending improvements of technology. They must adapt to the environment and take counter measurements for any war scenario, any type of latest technology weapon systems they might face to be able to eliminate the threat.

When a naval ship in a modern combat environment is exposed to a threatening weapon and attacked, the combat system and hull structure may suffer critical damage. As mentioned before, the ability of a warship to withstand such threats encountered in a battle environment is defined as the survivability of the ship [4].

Survivability is a vital design process as the main aim of a warship is to complete its assigned missions. With enhanced survivability the chance of mission success of a warship is greater and safety of the crew is higher. Main aim of the design of a warship should always be being better than the enemy. Therefore the ship must be able to see and reach further, be faster, re-act faster, manoeuvre faster, respond quicker and be sufficiently protected while achieving the goals mentioned.

Warship design parameters for enhanced survivability related to hull design process are speed, size of the warship (dimensions), engine and propulsion power and number of shafts they are aligned with.

Factors that influence ships configuration for protection and survivability are; measures to escape or delay detection, such as importance of speed, reducing ships own signatures, armouring vital spaces, separating functions and providing for redundancy, hardening against underwater shock and air blast, compartmentation and reserve buoyancy, damage stability parameters, fire zone bulkheads and choice of materials of construction.

Erbil Serter listed these nine attributes which he called "S9" as the most important design objectives [48]. He also mentioned the respective parameters these design objectives relate to.

Table 4.1 - "S9" Design Attributes

Speed – Cb, Fn, Mass	Stealth – Architecture
Stability – B/T, T/D	Self-Defence – Payload
Strength – L/D	Strike – Payload
Sea Keeping – T/D, C*	SLEP Potential – Architecture, Structural
Survivability (form-wise) - T/D	

The most fundamental method for improving survivability of a warship is to design the ship such that its susceptibility becomes close to zero. The susceptibility of the warship refers to the probability of the ship being attacked by threatening weapons after being identified by and enemy's detection technology and equipment [5]. However, because it is difficult to attain zero susceptibility in reality, the realistic approach to improving the susceptibility involves considering various situations that may arise on being attacked [4].

The order in which a ship is considered lost is called "Kill Chain". The different phases of survivability in regards to kill chain are;

KILL CHAIN

1) Detection - SUSCEPTIBILITY
2) Identification/Localization - SUSCEPTIBILITY
3) Engagement - SUSCEPTIBILITY
4) Primary Damage – VULNERABILITY
5) Secondary Damage – RECOVERABILITY

In the end, the 'survivability' design process is an iterative one and is repeated for each significant design change. In this paper, cost is not taken into account in favour of maximizing survivability options but in reality it is one of the main parameters that effect survivability based combatant ship design process as the budget is limited. *"If the hull size and principal dimensions are constrained or reduced to minimise costs, this has an impact on the operability and survivability of a vessel."* [6]

5. ANALYSIS for OSE

In the time of war, the overall assessment of measures after ship's detection, meaning the invisibility advantage and full stealth power of the vessel has been compromised, divides into three distinct phases defined by two unambiguous events, weapon launch and weapon impact [7], and how they affect ship and personnel aboard.

Below are these three assessment phases and their respective survivability aspects which they pertain to;

PHASE I – Cover and Deception (Pertaining to susceptibility)

PHASE II – Weapon Destruction and Evasion (Pertaining to susceptibility)

PHASE III – Damage Tolerant Design / Damage Control and Repair (Pertaining to vulnerability and recoverability)

In this paper, survivability of a warship will be explained with an imaginary scenario divided into four aspects seen below with respect to these three assessment phases mentioned above, coined by F.B. Fassnacht [7].

1) To not be seen or heard, to be undetectable by all means, to use full potential of stealth advantage. This is where signature control is important.
2) In case of detection by the enemy, not being identified or classified – camouflage. This timeframe is when the signature reduction techniques gain importance.
3) After being detected and identified, avoiding threats, trying not to be hit. Combat system capability, hard and softkill terms come into play.
4) In case all above mentioned preventions fail and the warship is hit, enduring the damage and surviving the battle. Being less vulnerable as possible.

- Bearing in mind that navigation and mobility is vital during any phase of warship survivability.

This thesis serves the purpose of contributing survivability concept and its attributes to a "Measure of Effectiveness" system analysis. Thus, all stages of survivability and the potential scenarios that may occur during a battle is compiled as the system - with its related components. Based on the outcome, Overall Survivability Effectiveness System Analysis is to be derived in further detail, and will cover all the necessary aspects.

5.1.Measure Of Effectiveness Theory And Application

Effectiveness is a condition that indicates how well a specified goal or a requirement has been fulfilled. Measures are always intended to communicate information which will allow a rank ordering of the conflicting goals and desires facing an organization decision maker.

Decision makers use the information obtained from measures to rank the goals and requirements of the organization. Measures of Effectiveness (MOE) show how well a component serves its purpose. MOEs can be calculated with relation to almost everything, e.g cost, weight, placement. This is called the Measures of Effectiveness Theory as it has been explained before in the thesis.

In warship design, measures of effectiveness can be used to decide which system, equipment and/or weaponry etc. will be used within such constraints as sizes of areas needed for systems installation, ease of operability, cost, personnel, hull form design and design objectives to meet the expectations and requirements of the associated Navy.

With an understanding of the importance of MOMs, through the “goal – question – metric” method a system analysis can be developed. Kowalski et al. [49] presented the framework seen below in the figure;

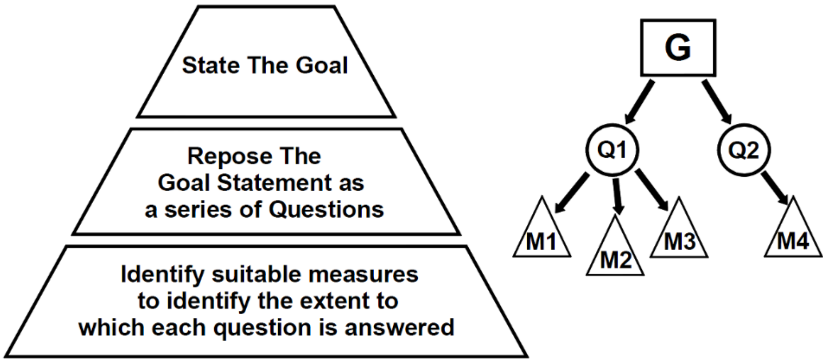


Figure 5.1 - The Goal-Question-Metric Format [49]

Steps to proceed are as follows;

1) First step is to "state the goal".

2) Second step is to repose the goal statement as a series of questions such as what is the probability of the ship avoiding detection?

3) Step three is to answer the above mentioned questions with identifying suitable measures to the extent which each question is answered.

Green's approach on the matter is [31, 35, 47];

1) "Specify the DPs and MOPs as characteristics that are measured within subsystem and system whereas MOEs and MOFEs are specified and measured external to system boundary in relation to associated forces or environments."
2) In the case where a ship is the system under analysis, Green recommends "viewing the ship as a weapons system to keep these performance goals in context with the assigned missions".

Proceeding with his approach, Green's MOMs Hierarchy is as follows; which he collectively calls mission and system solutions.

- Operational
- Avaliability
- Reliability
- Survivability
- Weapon Systems Performance

Expressing MOPs, MOEs and MOSEs as a probability allows one to determine if a parametric change is statistically significant [35]. The measure is considered ineffective if it cannot be expressed as a probability. The relationship between terms can be visually seen by the schematic Green and Johnson [35] provided.

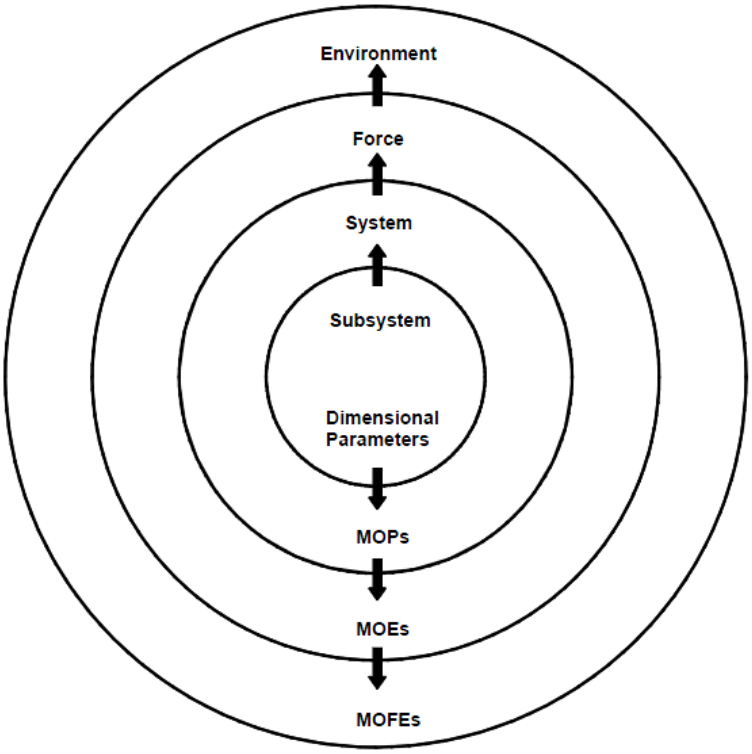


Figure 5.2 - System Boundary Levels [35]

Main idea of MOE is the ratio of sacrifice and gain, because in ship design in order to accommodate a component, another component is removed or reduced in capacity. The implementation of theory can be used to decide on which components or objectives of warship are comprised for the sake of another, and which are not.

H. Liwång, in his 2015 paper "Comparison between Different Survivability Measures on a Generic Frigate" [50] studied ship survivability by dividing it to four levels and only covering vulnerability and recoverability. This paper examines total survivability with its three phases (susceptibility, vulnerability and recoverability) assuming the ship operating in multiple threat areas. Achieving a rank for Overall Measure of Effectiveness (OMOE) based on total survivability is the aim. As in with all other systems of a ship, survivability related elements are also evaluated with MOEs and are installed according to their rank derived from these measures. The desired goal is to complete missions with maximum efficiency and minimum loss of any kind. The objective of the designer is to iterate the parameters related to potential threats and respective reduction techniques to calculate MOEs and install the systems according to the ranking obtained.

In this paper, an attempt is made on implementing survivability parameters into the 'Measure of Effectiveness Theory'. The outcome of this would be to determine the trade-offs between different survivability approaches before design phase to outfit the vessel in such a way that no major changes will be needed in short future.

Associated variables have been taken from threats and reduction techniques which will be explained later in forthcoming chapters, and are being used as the specific terms used in the effectiveness analysis process coined by Green and Johnson in their 2002 paper [31].

Associated variables will be taken according to scenario and survivability phases in regards to cover whole survivability universe within its boundaries.

Hierarchic survivability components and constraints can be lined up as follows;

<u>OSE Dimensional Parameters (DPs)</u>

In this thesis, DPs can be the main dimensions of the hull and all the fixed assets such as fixed weapons, command stations etc., hull coefficients and parameters that shape the seakeeping, stability and mobility characteristics of the combatant which are really difficult to relocate or replace after commissioning.

OSE Measure of Performance (MOPs)

This paper takes MOP's as the collective performance of all the components that combatant consists of, such as signatures, systems, combat capability of weaponry on board as well as the features a combatant must possess; such as seakeeping and stability requirements.

OSE Measure of Effectiveness (MOEs)

The first components come to mind in order to achieve survivability efficiency in regards to its assigned missions such as; ASW, SW, AAW, NBC or its navigation capability are 5 MOEs which has been selected as Mobility, Susceptibility, Vulnerability, Recoverability and Combat System Capability.

Measure of Force Effectiveness (MOFEs) also is referred to as overall measures of effectiveness (OMOE)

In this thesis, OMOE is considered as the "Overall Survivability Effectiveness – (OSE)" and is the ultimate goal to be attained.

While developing the MOEs; MOPs and DPs are the natural requirements in the design context that are known to be some of the selected and have been confined on purpose. MOEs are a combination of probabilities which are granted on certain terms and are originated from both MOPS and lower level MOES. Thus, these requirements are kept in a factor value range from a threshold to a goal value in order to be measurable. Likewise, maximized MOEs are considered as desirements. Prior to proceeding with this study, a full understanding of the terms "requirements" and "desirements" is required. "Requirement" means, the thresholds of performance which are expected to be met. "Desirement" means, the desirable value of a performance components either maximized or minimized to fulfill the requirements.

Tables below explain the aforementioned values of the system analysis;

Table 5.1 – Desirements

DESIREMENTS – MOE'S
Never losing mobility capability.
Susceptibility probability as low as possible.
Vulnerability as low as possible.
Recoverability capability as high as possible.
Combat System Capability and coverage as high as possible.

Table 5.2 – Requirements

REQUIREMENTS			
MOE	MOP/DP	THRESHOLD	GOAL
MOBILITY	• Speed • Endurance • Seakeeping • Manoeuvrability • Stability • Sustainability • Propulsion/Resistance		
SUSCEPTIBILITY	• Probability of Detection • Probability of Hit • Measure of Detected Signature		
VULNERABILITY	• Probability of withstanding impact		
RECOVERABILITY	• Probability of surviving the impact. • Probability of Operation despite the damage taken • Measure of damage and fire control • Restoration Capability • Damage Stability		

In other words, it consists of all aspects perfecting the ships operational effectiveness.

The relationships of one another can be shown using set notation;

$$MOM_{OSE} = \{ DP_{OSE}, MOP_{OSE}, MoE_{OSE}, MoFE_{OSE} \}$$

Each MOP in the OMOE is given a value weight and the below equation is used to calculate the OMOE for each design.

$$OMOE = \sum_{1}^{n} VMOE_n * MOE_n$$

OMOE function can be written as;

$$OMOE = (MOE_1 \cup MOE_2 \cup MOE_{V3} \cup MOE_4 \cup \ldots. \cup MOE_n) - (MOE_1 \cap MOE_2 \cap MOE_3 \cap MOE_4 \cap \ldots. \cap MOE_n)$$

Which becomes;

$$OMOE = MOE_1 + MOE_2 + MOE_3 + MOE_4 + \ldots. + MOE_n - (MOE_1 * MOE_2 * MOE_3 * MOE_4 * \ldots. * MOE_n)$$

5.2. A Probabilistic Approach to Three Phases Of Survivability

Another approach has been carried out by Ball and Calvano [3] in probabilistic terms to survivability of a ship. When defining survivability quantification, Ball and Calvano presented the relationship of various probability measures shown below in the figure.

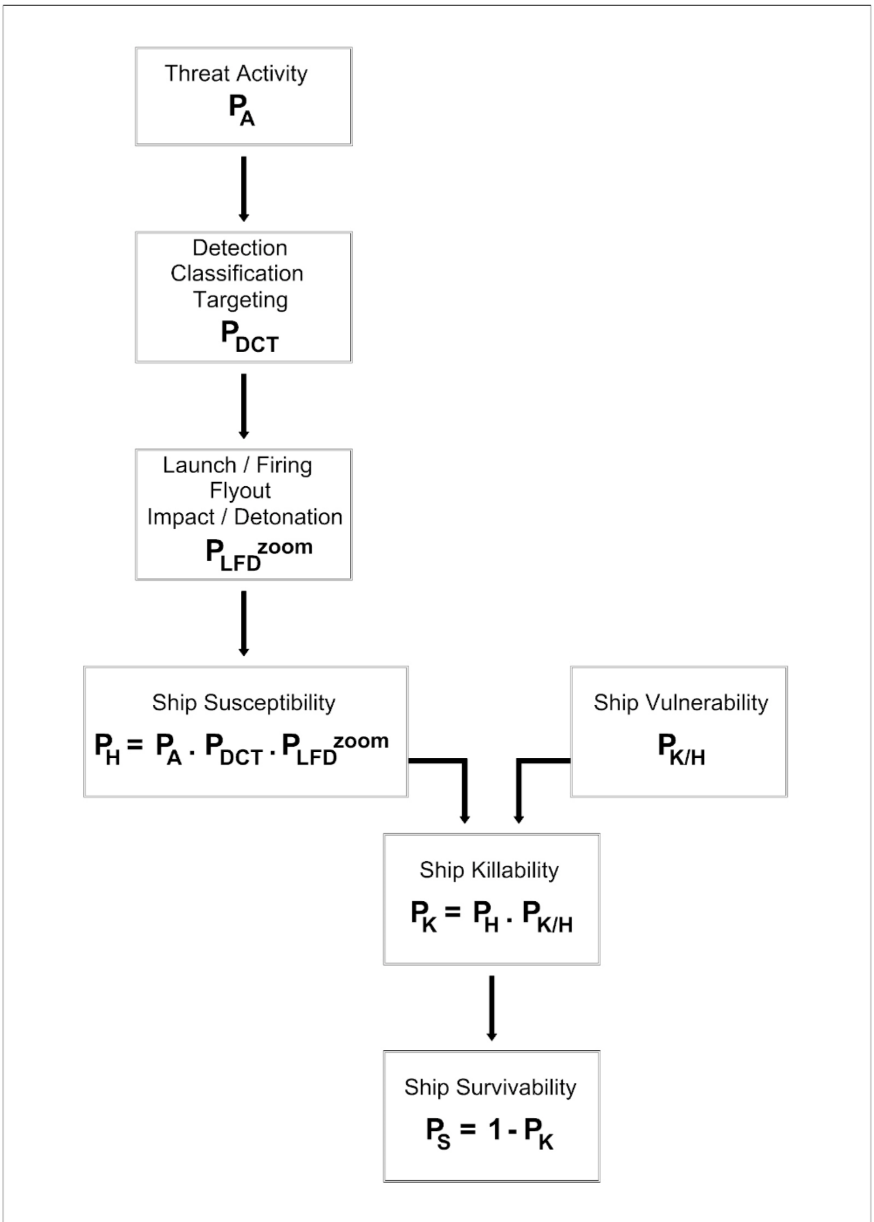


Figure 5.3 – Relationship of various measures of probability [3]

Their paper describes a conceptual structure of ship survivability definitions and concepts and deals with the need to incorporate a total ship approach to surface ship combat survivability as a part of the philosophy used to guide a ship's design.

Ball and Calvano [3] define ship combat survivability as "the capability of a surface ship to avoid and/or withstand a manmade hostile environment while performing its mission." Susceptibility is the inability of a ship to avoid the sensors, weapons and weapons effects of that man-made hostile environment. In addressing the other half of that key phrase, the inability of the ship to withstand the effects of the hostile environment is called vulnerability.

A ship's susceptibility, in a very general way, can be quantified by P_H, the probability the ship is hit by a weapon or its damage mechanisms. Susceptibility has been considered in three sequential phases: the probability the threat is active (P_A); the probability of the enemy's detection, classification and targeting of the ship (P_{DCT}); and the probability that the enemy's weapon will successfully launch, fly out and impact (P_{LFD}).

Probability of vulnerability has been called $P_{K/H}$, as it is the conditional probability of being killed after impact. Ball and Calvano stated that "features that reduce vulnerability will increase post-hit survivability."

If survivability is the ability to survive, then susceptibility is the inability to avoid and vulnerability is the inability to withstand the effects of the hostile environment. The term "killability" comes from the mathematical complement of survivability.

The equation for killability becomes;

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

$$P_K = P_H \times P_{K/H} \quad (5.1)$$

The probability of the ship to survive this hostile environment is P_S.

$$\text{Survivability} = 1 – \text{Killability}$$

$$P_S = 1 – P_K \quad (5.2)$$

With two equations combined, relationship can be stated as;

$$P_S = 1 – (P_H \times P_{K/H}) \quad (5.3)$$

Through these formulas, it is safe to say that susceptibility reduces as P_A,P_{DCT},P_{LFD} probabilities decrease, and vulnerability reduces as $P_{K/H}$ reduces. In their work, Ball and Calvano did not cover the third asset of survivability, which is recoverability but they aimed to create a coherent approach to the weighing of survivability values during design process by a clear application of these principles in order. As recoverability is a function dependent on crew and operating personnel on board in the time being of the situation, and cannot be developed, Ataseven and Yılmaz in their 2019 paper [51] stated that risk reduction method, which is a probability of recoverability can be applied in a holistic manner, therefore formulas become;

$$P_K = P_H \times P_{K/H} \times (1-P_R) \quad (5.4)$$

$$P_S = 1 – [(P_H \times P_{K/H}) \times (1-P_R)] \quad (5.5)$$

Building on the foundation laid by Ball and Calvano in their 1994 paper titled “Establishing the Fundamentals of a Surface Ship Survivability Design Discipline”, Kwang Sik Kim et al.’s paper “ Naval ship’s susceptibility assessment by the probabilistic density function”[4], the survivability of a warship is defined as the vessels capability to avoid or withstand a hostile environment. As previously mentioned in the present paper, survivability is dependent on three factors which need to be assessed separately. Those factors are vulnerability, susceptibility and recoverability.

Paper assesses ships survivability with an emphasis on susceptibility by proposing two equations, one for the probability of detection and one for the probability of hit, based on a theoretical procedure, the latter being dependent on the former. [4]

Hence the survivability of a ship (P_H) is proposed as follows:

$$P_H = P_D \times P_{Hit} \quad (5.6)$$

The equation for the probability of detection is constituted as a function of the below variables:

Table 1.3 - List of Probability of Hit Variables

Variable	Definition	Dimension
P	Radar Peak Power	Watt
R	Distance from radar to target	m
λ	Wavelength of signal	m
G	Antenna gain factor	Constant
K	Boltmann's constant	1.381 x 10-23 J/deg
N	Noise factor	Constant
T	Temperature	C^o
Bn	Radar receiver bandwidth	Hz
L	Signal echo power loss factor	Constant

The equation is then denoted as:

$$P_D = \left[1 + \frac{2(\frac{T}{N})(\frac{S}{N})}{2+\left(\frac{S}{N}\right)^2}\right] e^{-2(T/N)(2+S/N)} \qquad (5.7)$$

T/N is the threshold to noise ratio, S/N value is the signal to noise ratio which is also the minimum detection limit. S/N ratio value (dB) represents the extent of unnecessary noise in the signal.

Probability of hit takes into account the length(x) and depth(y) of the target area. This paper assumes the target area a two-dimensional surface.

The probability density function for a single hit from the enemy is denoted as follows:

$$\mathrm{PDF(x) \times PDF(y)} = \int_{-a/2}^{u/2} P(x)dx \,.\, \int_{-b/2}^{v/2} P(y)dy \quad (5.8)$$

$$P(x_1<x<x_2) = \int_{x1}^{x2} \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(x-\mu)^2}{\sigma^2}\right]dx \quad (5.9)$$

$$P(y_1<y<y_2) = \int_{y1}^{y2} \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{(x-\mu)^2}{\sigma^2}\right]dy \quad (5.10)$$

Whereas the probability density function for multiple hits from the enemy weapon is denoted as:

$$P_H(H\geq 1) = \sum_{n=1}^{n}(1 - Psingle)^{n-1}.P_{single} \quad (5.11)$$

Which is based on the expected hit value calculations obtained from the single hit equation.

This equation incorporates data such as the target area on the friendly ship, the location of the target area and the effectiveness of the hostile weapon. This research assumes that the probability distribution of hits on the target area both depth and lengthwise as normal distributions.

Papanikolaou and Boulougouris stated that “the magnitude of susceptibility of a warship encountering with threat is dependent upon the attributes of detection equipment and weapon system” [5]. Naval ships survivability emphasizing the susceptibility is assessed by the probability of detection and the probability of hit in their “Design Aspects of

Survivability of Surface Naval and Merchant Ships" paper. They addressed various design aspects of survivability for surface naval ships through a common probabilistic methodology based on the earlier work of Kurt Wendel and Ball and Calvano, covering probabilistic approach to the damage stability and survivability of ships.

Considering increased dangerous warfare environment in which warships operate, they introduced a new naval ship design philosophy, named 'enhanced survivability'. They stated that "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." The paper addresses the fundamental aspects of survivability and introduces this relatively new probabilistic approach for assessing the damage stability and survivability. They restricted their analysis to high explosive anti-surface weapons and two main damage scenarios that effect the survivability and operability of the warship which are flooding and fire.

The probability equation dependent on these two events can be written as;

$$PK\ [Hit \cap (Flooding \cup Fire)] = PK\ [(Hit \cap Flooding) \cup (Flooding \cap Fire)] = PK\ [Hit \cap Flooding] + PK\ [Hit \cap Fire] - PK\ [Hit \cap Flooding] \times PK\ [Hit \cap Fire] \quad (5.11)$$

Further assumption has been made as the probability of loss after a hit due to fire, given the progressive flooding due to the same hit is zero.

$$P_K\ [Hit \cap Fire] / P_K\ [Hit \cap Flooding] = 0 \qquad (5.12)$$

Papanikolaou and Boulougouris continued with identifying major threats a ship has to counter in order to properly assess the survivability of a naval ship. Taking in consideration only mostly used conventional weapons which are radar guided missiles and IR missiles.

The analysis is based on modeling the event sequence from enemy's arrival to ship's operational area up to the moment at which a hit might strike the vessel. Therefore, detection, classification, target acquisition requirements needed by the enemy to launch an incoming threat has been met. The friendly ship can activate its soft kill abilities to jam, deceive or destroy the incoming threat.

Assuming the incoming threat is radar-guided, a first estimation of the RCS of a surface combatant can be derived from the formula (5.13);

$$\sigma = 52 \, . \sqrt{f} . \sqrt[3]{Disp^2}$$

Where; 'σ' is ships radar cross section in m², 'f' is incident radar frequency in MHz and 'Disp' is the ship's displacement in tons as the probability of a ship's detection is a function of the threat's sensor, its range and the ship's signature.

The range at which the ship will be detected from the enemy's radar can be estimated by the equation (2);

$$R_{max} = \left[\frac{PtG^2\lambda^2\sigma}{(4\pi)^3 Pmin}\right]^{1/4}$$

Where; R_{max} is the maximum detection range, Pt is the transmitters power, G is the antenna gain, λ is the radar's operating wavelength, σ is the ship's radar cross section and P_{min} is the minimum detectable received signal from the enemy's sensor.

The path the radar-guided missile depends heavily on its accuracy of identifying the ship's RCS. This property for weapons engaging surface combatants can be expressed by their Linear Error Probability (LEP).

Gathering information on incoming missiles LEP, an assumption of the relative position of the missile to the ships profile can be made through normal distribution.

$$LEP = 0.6745\sigma \quad (5.15)$$

The moment the missile gains a lock on the ship it depends on its turning acceleration and speed. Occurrence of missile impact is only successful if the missile's minimum turning radius is lesser than its distance from the ship in case if the ship is trying to avoid the impact through its mobility capabilities, such as manoeuvring and sprint speed.

Missile radius estimation formula can be written as;

$$\frac{Vm^2}{N.g} \leq R_{regain} \quad (5.16)$$

Where Vm is the missile velocity, g is the gravitational acceleration and $N_{missile}$ is the maximum turning acceleration of missile in g.

The range at which the missile will regain a target lock in case of successfully dodging enemy's softkill abilities can be written as;

$$R_{regain} = \sqrt{\frac{Pm}{Pj} \cdot \frac{\sigma}{4\pi}} \quad (5.17)$$

Where PM/PJ is the power ratio between the missile seeker and the jammer.

Assuming weapon 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 0.5LWL. The damage extent can be taken from a Log-Normal Damage Function.

This is given by the function where “dead-sure kill radius” and “dead-sure surviving radius” comes into play for the first time;

$$d(r)=1-\int_0^r \frac{1}{\sqrt{2\pi\beta r}}\exp\left[-\frac{\ln^2(\frac{r}{\alpha})}{2\beta^2}\right].dr \quad (5.18)$$

Where;

α is equal to $(R_{SK}.R_{SS})^{0.5}$ (5.19)

β is equal to $\frac{1}{2\sqrt{2}_{Zss}}\ln\left(\frac{Rss}{Rsk}\right)$ (5.20)

R_{SK} stands for dead-sure kill radius, R_{SS} stands for dead-sure surviving radius which correspond to %98 and %2 probabilities of damage respectively. Derivations of their values are dependent on the empirical data on threat missiles. US navy standards sets the dead sure radius, R_{SK}, of a warship equal to %15 of its length between perpendiculars and A.265 IMO SOLAS Regulations sets the sure survive radius, R_{SS}, to be taken as 0.24L.

Papanikolaou and Boulougouris reviewed the common probabilistic procedure led by previous works on the subject with addition of special attention and equations to the formulation of survival criteria for warships. This led them to the knowledge of all known damage stability criteria for naval ships being deterministic.

6. OVERALL SURVIVABILITY EFFECTIVENESS SYSTEM ANALYSIS

Main components providing warships survivability can be divided into two groups, weaponry and hull. Combat system consists of additional weapons and equipment boarded on warship to improve defensive and offensive power, therefore increasing self-defence and survivability of the warship. Hull design consists of all design parameters combined that makes the ship itself. Survivability measures of hull design being the main focus of this thesis, it is helpful to emphasize the fact that combat system is not a priority which we will be taking into consideration in this particular study.

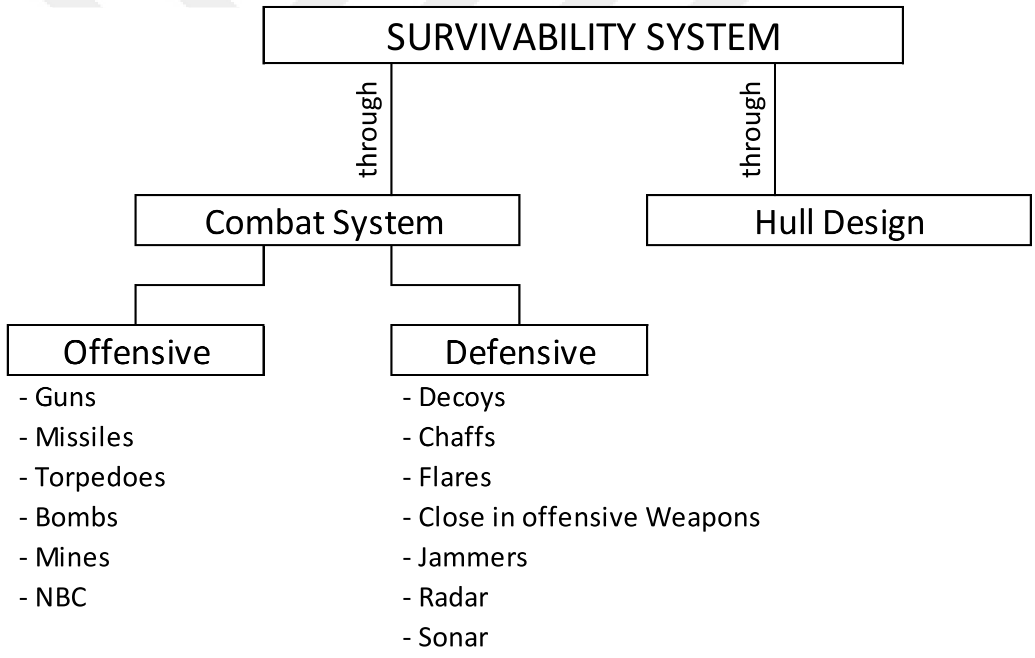


Figure 6.1 - Survivability System

Users are expected to understand the aforementioned three assessment phases and their applied respective survivability stages, thoroughly in order to conclude a system analysis that covers the whole survivability system of a warship.

Which in detail are;

1) Phase I – Cover and Deception – Susceptibility

This phase covers avoiding any sort of detection by the enemy or, if detected not appearing as a hostile target to the enemy through deception, all prior to any of the parties' weapon launch.

Although it is impossible to achieve full invisibility of a warship in modern warfare, to appear non-existent in battleground, main aim is to accomplish this scenario. Unfortunately, it cannot be achieved with the current state of the technology. So the desired result of being invisible in all aspects and to be undetectable by all means, to use full potential of stealth advantage is unobtainable. Therefore, the characteristics and performance of the equipment used for detecting enemy warships and/or threats and the possibility of being hit or detected by the enemy must be analysed and perfected to a probability close to zero. To be able to achieve this close-to-zero probability the warship must; avoid detection, being targeted or locked down by other war platforms by reducing above and below water signatures. Above signatures include radars, infrared detection, electromagnetic fields and visual detection, whereas below signatures can be acoustic/magnetic or wake signature of the warship or pressure changes underwater. In other words, the warship must prevent the enemy from establishing and maintaining a track of its own. So first phase is about avoiding detection by the enemy, or if detected, preventing the enemy from obtaining the necessary data to engage the friendly warship in a specific time-frame before the enemy weapon launch to protect the ship or task group aboard.

2) Phase II - Weapon Destruction and Evasion – Susceptibility

This phase covers the time interval before and during enemy weapon launch and weapon impact. Ships offensive and evasive capabilities emerge as important factors in this phase. The ship must act first in case of confrontation by attempting to eliminate hostile weapons or ship through hard kill capabilities. Types of weapons to be taken into account are; projectiles, torpedoes, mines, bombs and missiles that can be launched from other ships, submarines, aircrafts or land. Modern combatants also face CBR threats, meaning chemical/biological/radiological through warhead detonation effects or surrounding hazard areas which the ship may happen to pass. Another input that can improve warships hard kill capability is the gathering information on enemy's jamming and deception capabilities. Through jamming and hacking, information warfare can lead to a loss of ships command and control centre, leading to a loss of ships all offensive or defensive capabilities.

Conventional threats fall into two categories which are AIREX and UNDEX threats, though CBR threats, meaning chemical/biological/radiological, exist. AIREX threats aim for any location above waterline on a target vessel. These weapons include missiles, ballistic projectiles and bombs. Whereas UNDEX threats do majority of their damage below the waterline. The weapons include mines and torpedoes.

Phase III – Damage Tolerant Design (Vulnerability) and Damage Control & Repair (Recoverability)

This phase covers the ability of ship to withstand and survive any weapon impact and recover and salvage its essential operational systems. Impact damage on warship is caused by the effects of the warheads. Warhead effects can be blast, fragmentation, shaped charge, underwater shock, chemical/biological or radiation and/or electromagnetic pulse. In cases which the warship fails at susceptibility, the importance of vulnerability comes out. Vulnerability reduction lowers the chance of sinking or full inoperability if the ship is damaged or hit somehow. Recoverability comes into play when one or more systems of the ship is damaged due to an enemy attack and is the ability to continue operations whether by means of secondary or substitutionary units or by fixing the already damaged equipment while also containing and controlling the spread of the damage. Both the vulnerability and the recoverability of a warship are taken into consideration during the early design phase. These structural design elements both shape the vessel throughout its iterative design process and construction. The strategic placement and composition of personnel is also important in terms of mission continuity due to operability.

In case a hit is received, pre-defined damage scenarios become operative. As coined by Goddard C. H. et al. in their ‘How much stealth?’ paper [52], *“Between the intact condition and the total loss of a ship there are many intermediate stages*.” The “Kill Chain” is a functional hierarchy, in descending order, showing what damage extent stages can be;

1) Total Kill – When the ship is considered lost. (sinking, foundering or damaged by fire completely.
2) Mobility Kill – Immobilisation loss of controllability.
3) Mission Area Kill – Mission area (AAW,ASW, ASuW capability) is considered lost.
4) Primary or Combat System Kill – One or more vital systems of the ship are damaged.
5) Hull, Machinery or Electrical (HM&E) Support System Kill – One or more components supporting a primary/combat system of the ship are damaged.

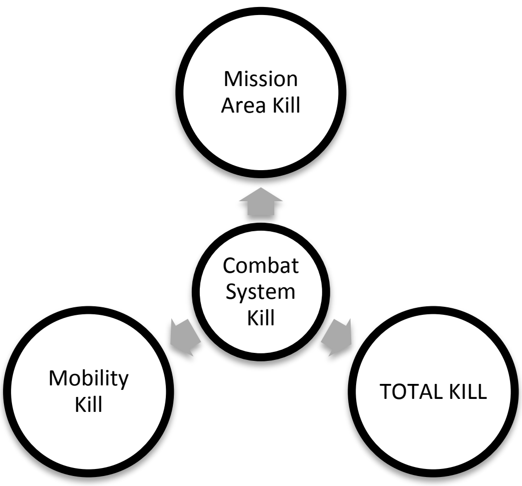


Figure 6.2 - Schematic Kill Chain

Damage scenarios can be dependent on each other, for example a combat system kill can lead to other kill scenarios.

According to The Goal Question Metric Format stated by Kowalski [49], the first step from Figure 14 is to ‘State the Goal.’ The ultimate goal of the system is to complete its mission without losing any survivability capability. Therefore the goal becomes, trying to calculate how reachable it is to attain the maximum survivability efficiency. In order to achieve the ultimate goal, second step of the figure, ‘Repose the Goal Statement as a Series of Questions’ is used.

This leads to the below essential questions:

1. What is the probability of safe operability?
2. What is the probability of detection?
3. If detected, what is the probability of not being recognized?
4. If recognized, what is the probability of not receiving a hit?
5. If hit, what is the probability of survival?

Step three, ‘identify suitable measures to identify the extent to which each question is answered.’ enables users to find answers to these questions by dividing the system into five separate branches. These branches become MOEs for the system.

First and foremost, the main priority of a combatant should be navigating throughout the seas without any inconvenience. Therefore, mobility ability is utmost important through completing missions and self-defence purposes. For safe operability, mobility is selected as the first MOE for Survivability System.

The second and third questions are covered in phase 1 as described previously, and the reason of detection and recognition is the unique signature combatant itself creates. Therefore, susceptibility of a combatant is selected as a MOE for the system.

After recognition, avoiding a hit is a matter of Combat System installed aboard since CS defines how well the combatant’s hardkill/softkill capability is. Higher skill means better avoidance.

Vulnerability and Recoverability are taken as the last MOE’s for the system, when a combatant receives a hit during mission or navigation. Any damage occurred on the combatant may directly affect the overall survivability. In order to keep the vulnerability of the ship at its lowest possible level, it has been outlined as one of the MOEs.

In the event of any inconvenience on board, and/or the combatant has been breached, the combatant has to proceed its predefined mission with limited operability. Recoverability is highly crucial to define minimum values of physical survivability measures, even if the combatant has taken irreversible damage, it is important

Therefore, the system schema below was found by taking the 'Survivability' attribute into consideration in order to achieve OMOE;

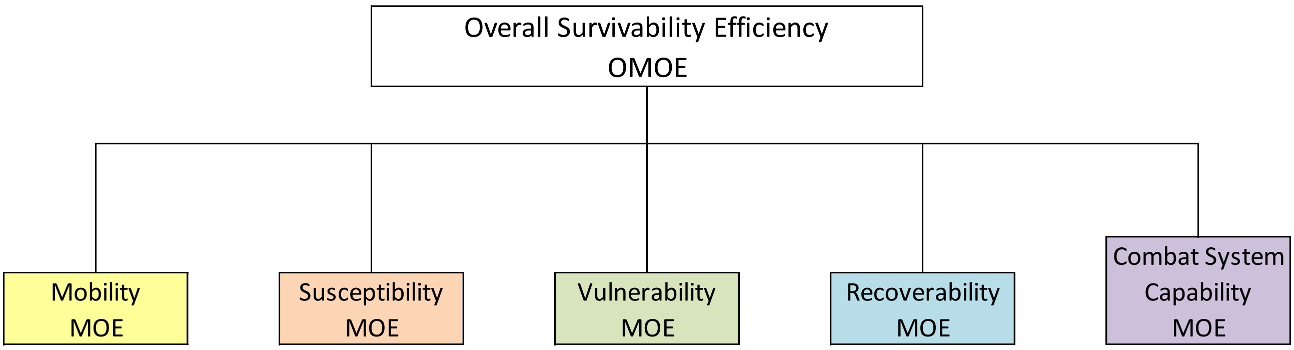


Figure 1.1 - Overall Survivability Efficiency (OSE)

6.1.Combat System Capability

The warship can be designed according to the traditional design spiral shown in Figure 1.2. Another approach to plan the design process is to look at it from combat system point of view for strike power/mission dominance (Figure 6.3).

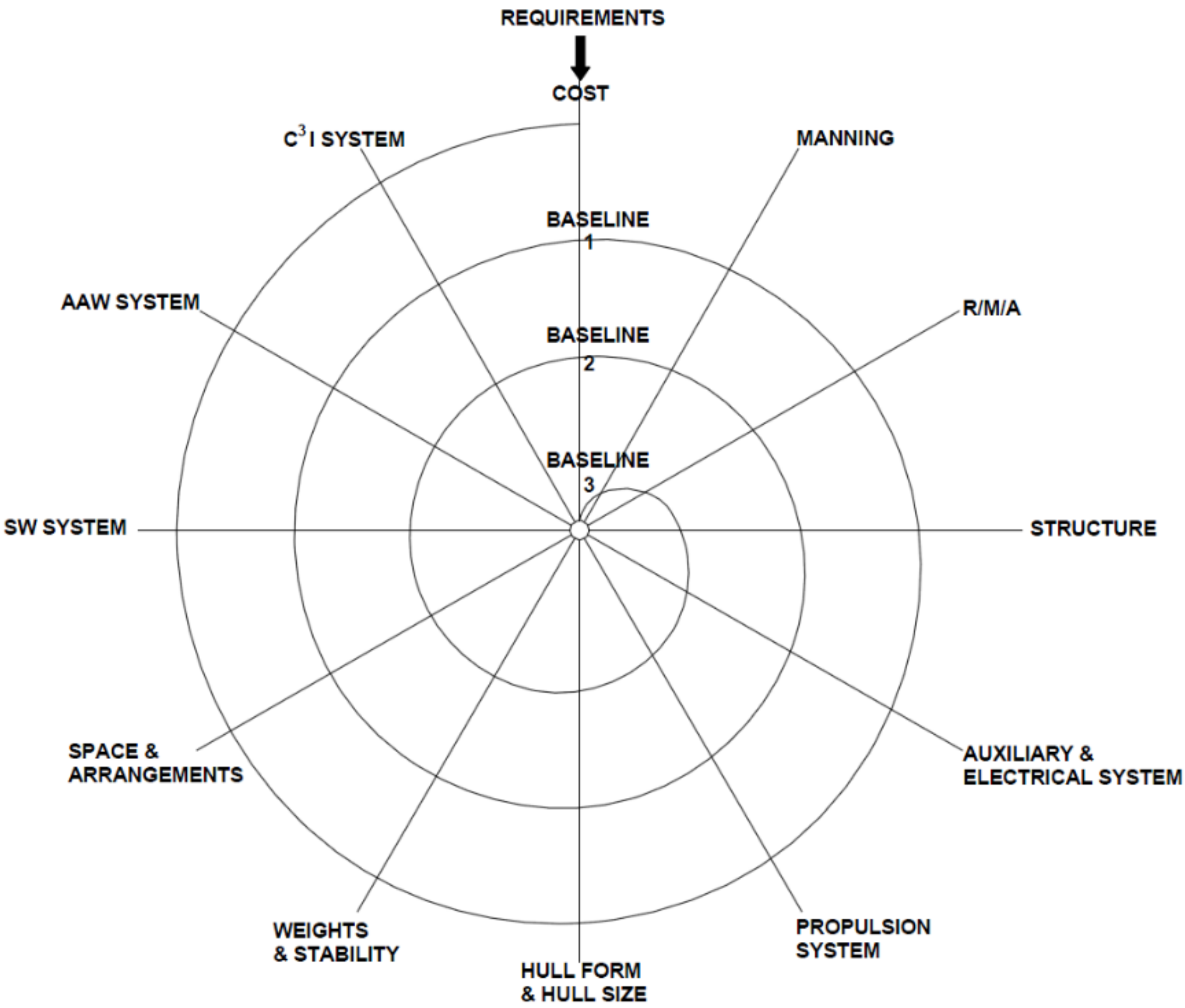


Figure 6.3 - Combat System Point of View Warship Design Spiral

Source: Prof. Dr. Nurhan Kahyaoğlu's Lecture Notes

The ability to detect, classify, track and engage threats or targets all together is called "Combat System Capability". Parameters affecting CSC, which are not necessarily related with hull design are, detection range, reaction time, weapon coverage and weapon range, links with other friendly forces and ships combat direction system.

Inputs are:

1) Detection Range – dependent on precisions of weaponry electronics.
2) Reaction Time – dependent on precisions of weaponry and capabilities of personnel.
3) Weapon coverage and range
4) Links with other friendly forces – dependent on navigation and communication electronics.
5) Ship combat direction system.

In this paper, hull design aspects and parameters are mainly focused upon. Though, it is a common fact that a "total-ship-system" analysing a warship cannot be efficiently calculated unless payload and/or armaments are not induced in the formula. In the end, it is safe to say, a warships mission success rate is positively correlated to its combat system capability.

Therefore CSC has been shown in the system as the branch below;

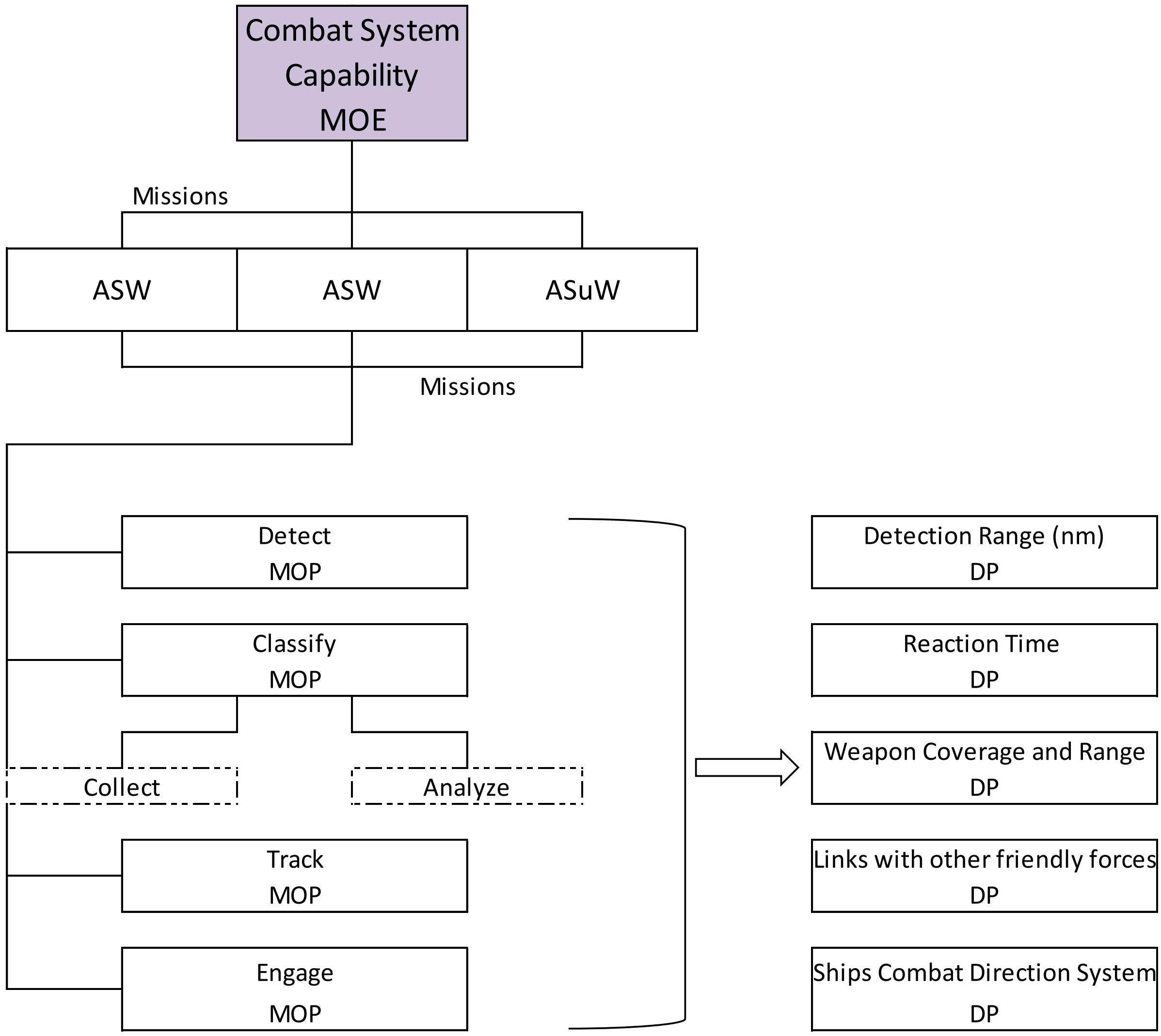


Figure 6.4 - Combat System Capability (CSC)

CSC MOE formula becoming;

$$MOE_{CSC} = (MOP_{DETECT} \cup MOP_{CLASSIFY} \cup MOP_{TRACK} \cup MOP_{ENGAGE}) - (MOP_{DETECT} \cap MOP_{CLASSIFY} \cap MOP_{TRACK} \cap MOP_{ENGAGE})$$

$$MOE_{CSC} = (MOP_{DETECT} + MOP_{CLASSIFY} + MOP_{TRACK} + MOP_{ENGAGE}) - (MOP_{DETECT} * MOP_{CLASSIFY} * MOP_{TRACK} * MOP_{ENGAGE})$$

6.1.1. Weapons Of Warfare

As CSC is mainly dependent on payload, weapons of warfare gain utmost importance. When in a stand-off with the enemy, an engagement analysis should be performed to determine, for a given scenario, whether or not any of the enemy weapons would succeed to hit or burst near an area at which the ship would suffer damage. If the warship is engaged before any chance to eliminate the enemy (hard kill), soft kill capabilities such as decoys and chaffs are used to deceive, distract and/or confuse the enemy inbound weapons. In the event where these precautions fail the warship must attempt to destroy any inbound threats using close in weapon system weaponry before impact or use evasive manoeuvres to dodge or parry the incoming attack. Understanding the concepts ‘soft kill’ and ‘hard kill’ and implementing them into the survivability design process is beneficial to enhance efficiency of survivability.

‘Soft Kill’ is the means of defence that attempt to prevent an inbound weapon from hitting the warship without directly engaging. Methods include decoys, chaffs/flares, close in offensive weapons with limited range and means of electronic warfare. These weapons are not sufficient enough to ‘total kill’ an enemy, but are very efficient in destroying ‘hard kill’ weapons which the enemy launched in order to achieve a total kill scenario on friendly combatant.

Decoys generate an artificial signature that is similar to the parent vessel or more attractive than the target. Towed decoys are common to deal with torpedoes, and airborne ‘hovering’ decoys are becoming common to deceive missile threats. Chaffs attempt to create false signature that deceives incoming weapon through their use of large metallic blooms and mimicking, spoofing or blinding the seekers of inbound threats, weapons can be prevented from targeting the ship.

This doesn’t mean that the warship cannot attempt to destroy inbound weapons at a safe distance from the warship using heavy weapons. These weapons include guns, missiles, torpedoes, bombs, naval mines. All weapons rely on high rates of fire damage and piercing strength on impact.

Missile systems are more effective at longer ranges and are better equipped to deal with terminal manoeuvres vital for avoiding and dodging incoming threats.

Weaponry system is heavily dependent on range and speed to be able to increase ship survivability by increasing the chances of not being hit. A significant problem that occurs in case of using weapons without satellite assistance at sea is that the ability to detect objects at long ranges is limited by the physical horizon vice the visibility.

Mosier stated in his 2018 publication [30]; the kill chain for anti-ship missile attack against moving maritime targets requires a detailed decomposition to identify the links in the chain of events that must be completed for attack success. The following is a representation of a theoretical anti-ship missile kill chain.

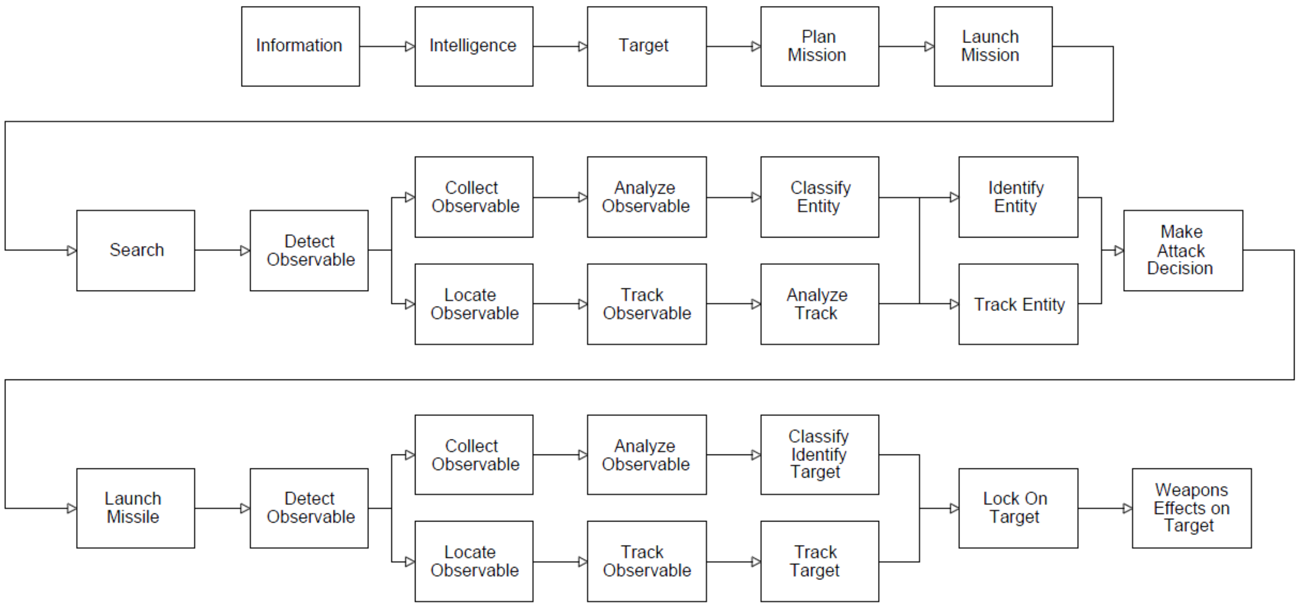
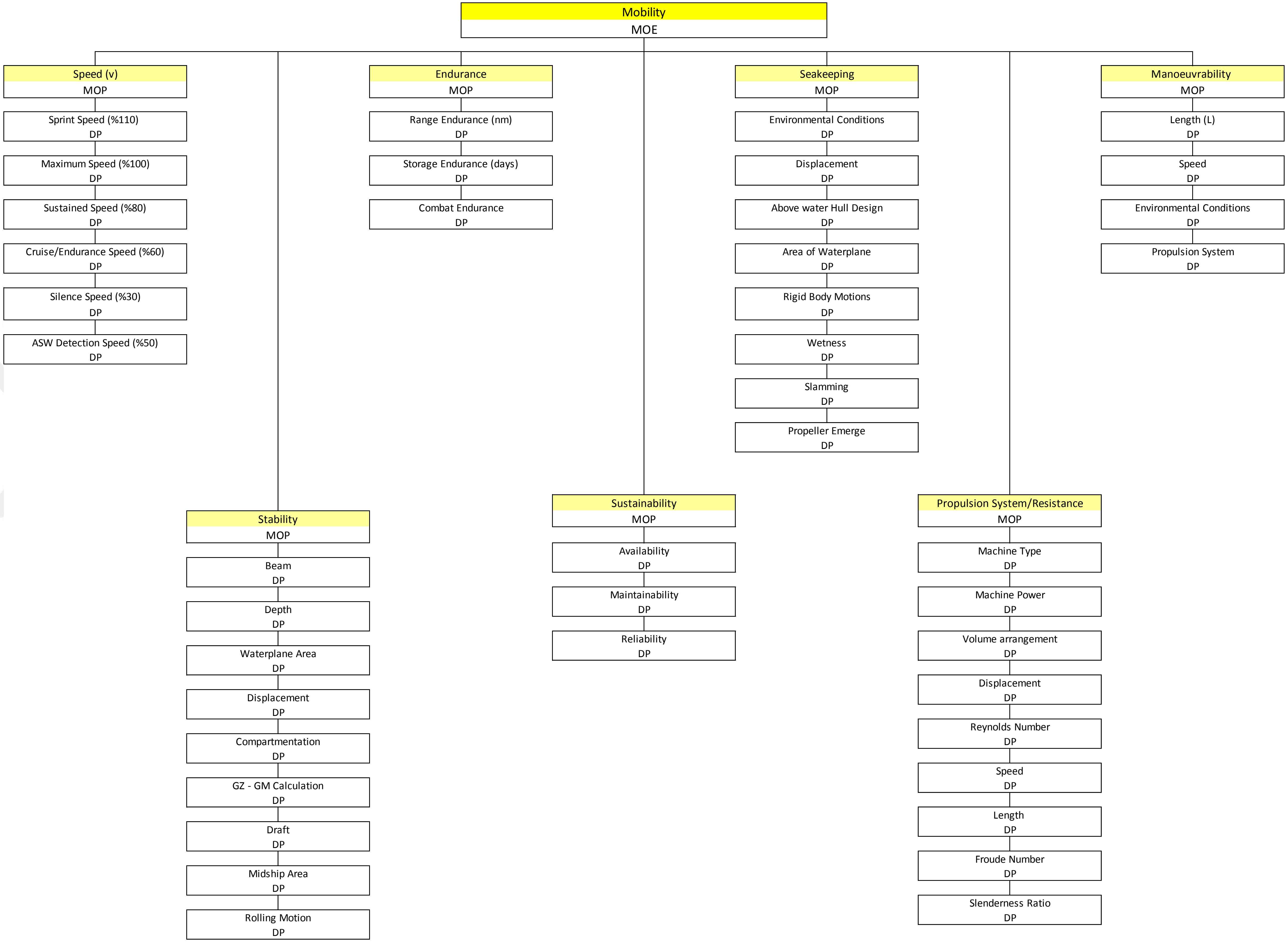


Figure 6.5 - Anti-Ship Missile Kill Chain [30]

The steps in the chain, shown in Figure 6.5, that are entitled ‘observables’ are all dependent on warships own or allied forces to offer visual, infrared, acoustic, radar, communication observations that could be exploited by the enemy to finalize the kill chain. In addition to technical observables, the operations of the force/own ship offer observables such as course, speed, and formation from which to deduce that the entities are military and that entities being screened by a formation might be the highest value. Many of the observables that can be exploited by the enemy to acquire this information can be controlled or manipulated to degrade links in the enemy’s anti-ship kill chain.

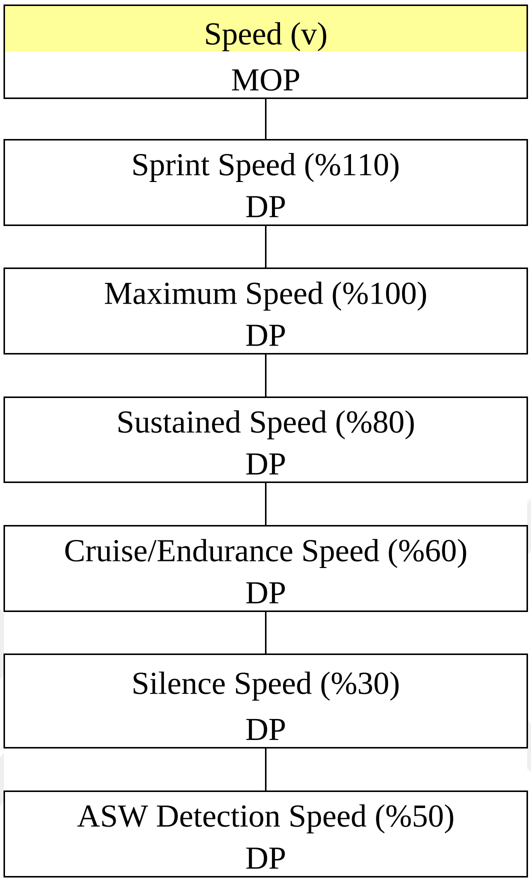
6.2. Mobility

Mobility is the ability of naval forces to move and maintain themselves in all situations over, under or upon the surface. It is utmost important as damage control and prevention and operational capability are heavily dependent on it.



$MOE_{MOBILITY}$

6.2.1. Speed



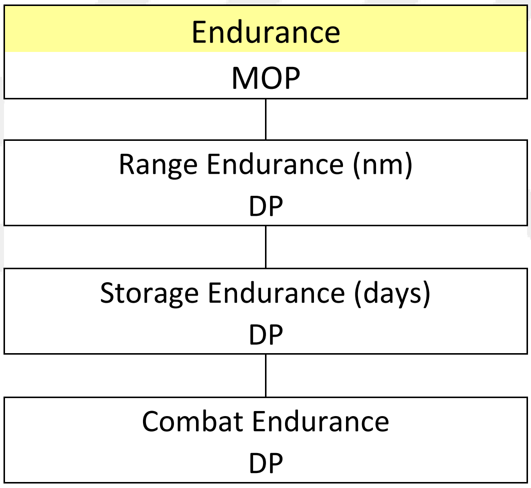
As mentioned before, speed is one of the three main parameters in survivability focused warship design. Design shouldn't be fixed around a certain "speed", but should consider multiple speed levels achievable by the selected machinery for different necessities of different missions assigned by the associated navy.

- Sprint Speed (%110) - Vital for deployment and avoiding incoming threat though it is only for a short period of time.
- Maximum Speed (%100) – Maximum speed achievable for deployment.
- Sustained Speed (%80) – Operational maximum continuous speed for deployment.
- Cruise or Endurance Speed – Optimum speed for patrolling and non-combat situations with low consumption of fuel.
- Silence Speed - The speed at which the propellers start cavitation-noise signature.

- ASW Detection Speed - For anti-submarine ships, the maximum speed at which their hull mounted sonars can be operated.

Therefore main and only parameter for MOP_{SPEED} is ‘v’ speed.

6.2.2. Endurance



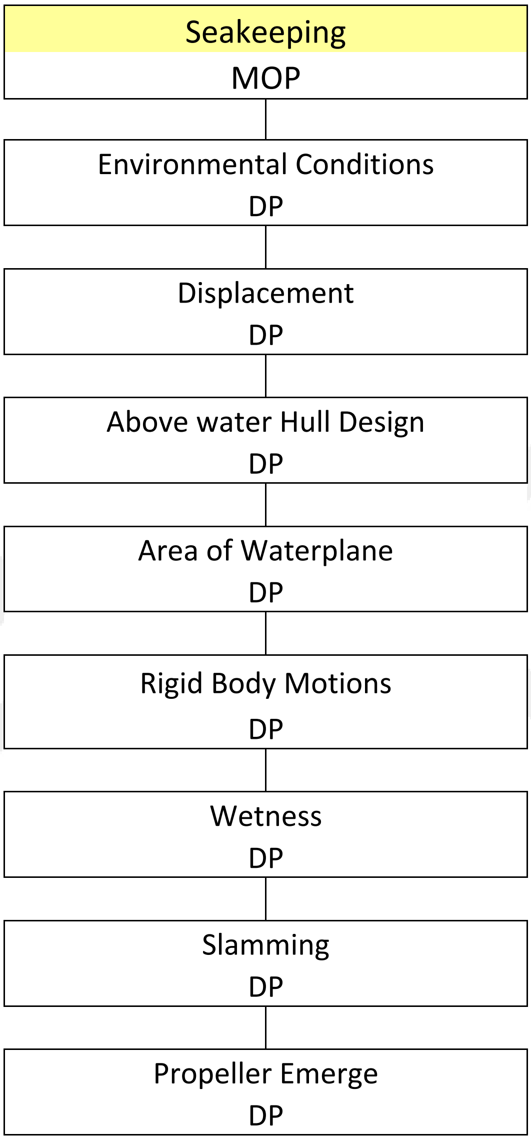
Since no warship can sustain itself forever and is dependent on reinforcement supply from outside, endurance in all of its different meanings gains importance. For example, the distance that ship can travel without being refuelled is range or fuel endurance, the amount of time the ship can remain at sea without replenishment of consumables is stores endurance and the time that the ship can engage in combat before having to rearm its weapons is combat endurance. For example, average endurance times in terms of days of for range or fuel endurance is dependent on the mission and generally 30 to 45 days, store endurance is averagely 20 to 60 days and 3 to 5 days for combat endurance where the ship can engage in combat before rearming its weaponry.

Input parameters for $MOP_{ENDURANCE}$ are type of fuel, specific fuel consumption, operational needs and volume for range endurance. Storage endurance is limited with volume provided by the design and combat endurance is proportional with payload, mission, operation and crew necessities. It is safe to say, volume is utmost important for all three kinds of endurance in function.

Range endurance formula can be seen below in equation , range endurance forms a relationship between payload and speed. The result may vary with every speed, payload weight or fuel consumption as none of them being constant.

$$\frac{\text{total fuel consumption during mission}}{\text{payload x speed}} = \text{endurance} \qquad (6.1)$$

6.2.3. Seakeeping



While defining the seaworthiness term, all the ship design features that are in direct relation to the ships competence, where it should afloat at all time and complete its assigned mission should be taken into consideration. Hence, various factors such as strength, stability and endurance and their potential of affecting from the waves should be noted. Motions, speed, power in waves, wetness and slamming are examined under seakeeping practice. Wetness and slamming may cause operational difficulties, whereas extreme motion can both interfere with the shipboard chores badly to a point that it becomes unmanageable, and impact crew performance/passenger comfort in a negative manner.

In most cases, combatant's weapon system line of sight has to be fixed in space and equipped with individual stabilizing systems. When motion amplitudes reach excessive levels, these systems require more power and may result in limited safe arcs of fire.

Factors such as high winds and waves play role in high level of resistance and the speed to be lowered for a certain power system. Reducing speed also helps with the functioning when slamming, wetness and extreme motions are concerned.

Various class societies around the world have provided rules for seakeeping characteristics. Criterias can be seen below, taken from Bureau Veritas for the Classification of Naval Ships, whereas all criterias unless stated otherwise, have been taken from BV;

Table 6.1 - Hull Criteria Limits for Monohull

Parameter	Limit	Location
Wetness Index (WI)	30/hr	Forward Perpendicular
Slamming Index (SI)	20/hr	Keel, 3/20L aft of FP
Propeller Emergence (PE)	90/hr	¼ propeller diameter

Wetness is defined as the water being carried over the forecastle when the movement of the bow and local wave surface exceeds the expected limits. It can also form as a spray of water brought to the forward part of the ship by the wind. Both of these scenarios are considered troublesome; however, it is possible to reduce the effects by freeboard increase. Upper deck equipment positioning and salt spray sensitivity are two main aspects which determine the importance of the situation. The spray is considered to be quite problematic as it causes ice accretion, particularly in cold weather. Yet; spray rails, flare angles and knuckles are known to alter such conditions at a certain level.

Wetness index is the number of occurrences of water on deck in an hour. Index is based on the variance ($m_{0,M}$) of the relative vertical motion at the bow combined with the freeboard height D_F at the same location.

$WI = N_Z \, F(D_F)$

$F(D_F) = \exp\left(-\left(\frac{DF}{\sqrt{2m0,M}}\right)^2\right)$

$N_Z = \frac{3600}{2\pi}\sqrt{\frac{m2,M}{m0,M}}$

$m_{0,M}$ = Zero order spectral moment of relative vertical motion response

$m_{2,M}$ = Second order spectral moment of relative vertical motion response.

Slamming is defined as the abundant amount of water pressure that ship's hull bears. It is best described by an unexpected change in the ship's vertical acceleration and then comes the ship grinder's tremors within its normal levels. In order to experience slamming, the ship and water should have a high relative momentum as well as shallow draught and small rise of floor.

Slamming index is the number of times in an hour a keel emerge is followed by re-entry in water that exceeds a certain threshold velocity:

$SI = N_Z \, F(V_{TH}) \, F(T_{SL})$

$N_Z = \frac{3600}{2\pi}\sqrt{\frac{m2,M}{m0,M}}$

$F(V_{TH})$ Probability of exceeding the threshold velocity:

$F(V_{TH}) = \exp\left(-\left(\frac{VTH}{\sqrt{2m0,v}}\right)^2\right)$

$F(T_{SL})$ Probability of keel emerge

$F(T_{SL}) = \exp\left(-\left(\frac{TSL}{\sqrt{2m0,M}}\right)^2\right)$

$V_{TH} = 3{,}66\sqrt{\frac{L}{158{,}5}}$ is the vertical threshold velocity and is based on the ship length.

$m_{0,M}$ = Zero order spectral moment of relative vertical motion response

$m_{2,M}$ = Second order spectral moment of relative vertical motion response.

$m_{0,V}$ = Zero order spectral moment of relative vertical velocity response

The location of the slamming assessment is to be at the keel at 3/20 L behind the fore perpendicular.

Propeller emergence is the number of times the highest quarter part of the propeller diameter (D_{PROP}) emerges from the sea surface in an hour. The index is to be based on the variance Mo.m at the propeller location combined with the distance from the propeller axis to the calm water sea surface (Z_{PROP}).

Propeller emergence occurs when the relative motion exceeds Z_{PE}.

$$Z_{PE} = Z_{PROP} - \frac{1}{4} D_{PROP}$$

The number of propeller emergences in an hour can now be determined as;

$$PE = N_Z F(Z_{PE})$$

$$F(Z_{PE}) = \exp\left(-\left(\frac{ZPE}{\sqrt{2m0,v}}\right)^2\right)$$

$$N_Z = \frac{3600}{2\pi}\sqrt{\frac{m2,M}{m0,M}}$$

$m_{0,M}$ = Zero order spectral moment of relative vertical motion response

$m_{2,M}$ = Second order spectral moment of relative vertical motion response.

Wetness and propeller emergence are to be quantified through the vertical motion relative to the free surface, and slamming is to be quantified through the relative vertical velocity.

Warship survivability is heavily dependent on the sea keeping, damage stability and mobility characteristics. Nathan K. Bales in his paper "Optimizing the Seakeeping Performance of Destroyer-Type Hulls" generated a "sea keeping factor – R", which become a parameter for evaluating and ranking ships based on their sea keeping characteristics [1]. Nowadays, Bales's method is still used to analyse sea keeping abilities in preliminary design phase, and iterating the design parameters associated with sea keeping ability till sufficient sea keeping requirements are met. Bales's work started with developing a model which relates ship hull geometry to an index of seakeeping merit. His model had been quantified for destroyer-type hulls but the method is consisting of derivative equations which can be applied on different types of warships. He selected a total of six main parameters which effect the hull geometries to be able to achieve superior sea keeping qualities. Selections were based on his previous work "The Influence of Hull Form on Seakeeping" with W.E. Cummins where they created "The Bales and Cummins Series". Series is based on the fact that a viable approximation to the vertical plain responses of a ship among waves can be obtained using a Lewis section representation of the hull.

The selected parameters are;

1) Waterplane coefficient forward of amidships, C_{WF},
2) Waterplane coefficient aft of amidships, $C_{WA,}$
3) Draft-to-length ratio, T/L, where T is draft and L is the ship length,
4) Cut-up ratio, c/L, where c is the distance from the forward perpendicular to the cut-up point,
5) Vertical prismatic coefficient forward of amidships, C_{VPF}
6) Vertical prismatic coefficient aft of amidships, C_{VPA}

It has been found that sea keeping qualities projected to improve with increasing C_{WF}, C_{WA}, c/L and C_{VPA}, whereas decrease with T/L and C_{VPF}.

The optimization methodology must be based upon the estimator, $\widehat{R}$, of sea keeping rank. After assigning and analyzing the chosen parameters and their related coefficients on 20 different destroyer-type hulls, the estimator can be obtained.

The estimator can be written as;

$$\widehat{R}= 8.422+45.104\ (2.A_{WF}/LB) + 10.078\ (2.A_{WA}/LB) - 378.465\ (T/L) + 1.273\ (c/L) - 23.501(\nabla_F/A_{WF}.T)-15{,}875(\nabla_A/A_{WA}.T) \quad (3)$$

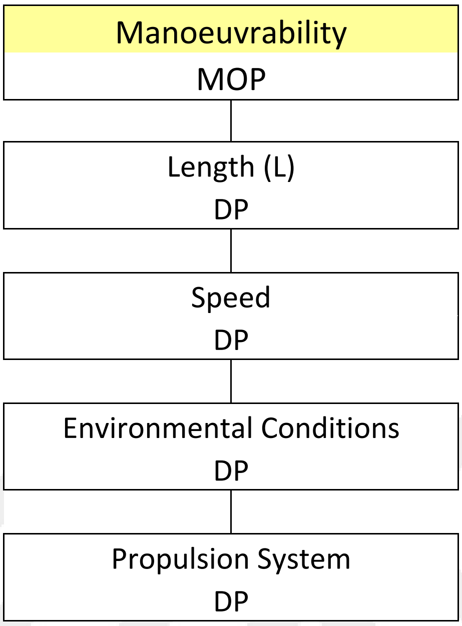
Or;

$$\widehat{R}= 8.422+45.104\ (C_{WF}) + 10.078\ (C_{WA}) - 378.465\ (T/L) + 1.273\ (c/L) - 23.501(C_{VPF})-15{,}875(C_{VPA}) \quad (6.3)$$

Where; A_{WA} and A_{WF} are water plane areas forward and aft of amidships, respectively. The estimator of sea keeping rank, $\hat{R}$, can vary between 1.0 and 10.00, for hulls with very poor or excellent sea keeping qualities, respectively [1].

Parameters effecting seakeeping performance are; L, B, T, c, A_{WA}, A_{WF}, ∇, C_{WF}, C_{WA}, C_{VPF}, C_{VPA}, F.

6.2.4. Manoeuvrability



It is mandatory for all ships to be managed smoothly while cruising horizontally since they are expected to move in a straight direction, change course and act as operational situations require. Weather conditions such as wind and wave intensity should not be an obstacle when doing so; hence, they must be both reliable and consistent. Manoeuvrability can be explained as below;

1. Easy maintenance on defined course. The utmost important determinant for a ships performance is both the directional and dynamic stability, and being a related term; "Steering" covers this subject. However, this should not be taken as ships stability.
2. If any level of heading change is either inducted or aborted, the ship is expected to have a desirable reaction to its control surfaces and rudders.

Ships should have the capability to take a 360-degree turn on a given area. During research, experienced data have been provided for the author from reliable sources in the industry.

Therefore descriptions and limitations for manoeuvrability aspects below are taken as thresholds for their associated ratio, which are;

$\frac{\text{Turning Circle Distance}}{\text{Length Waterline}}$: Vessel should be able to manoeuvre not exceeding 6.5Lwl in distance.

$\frac{\text{Initial Turning Ability}}{\text{Length Waterline}}$: Vessel should be able to turn the given test angle not exceeding 3,5 to 2 Lwl.

$\frac{\text{Crash Stopping Time}}{\text{70 seconds}}$, $\frac{\text{Crash Stopping Distance}}{\text{5 Lwl}}$: The vessel must perform crash stopping in less than 70 seconds, without exceeding 5 Lwl in distance.

$\frac{\text{Astern Speed}}{\text{8 knots}}$: Astern speed must be minimum 7 knots according to DIN standards.

Formulas for parameters are;

1) High Speed Turning

$$IL = \left(\frac{V^2}{R}\right).\left(\frac{a\cos\theta}{g}\right) \quad (6.4)$$

v = speed in m/s of the ship operating. Such a value may be assumed equal to %80 of the maximum speed when the ship starts turning.

R = Turning radius, in m (if unknown may be assumed equal to 3,3 Lbp

g = gravity acceleration

a = vertical distance in m, between centre of gravity of the ship and its drifting centre, if unknown, may be taken the half of mean draught.

θ = Heeling angle in degrees.

During manoeuvre relative ship motions may disturb intact stability condition, therefore it is better to re-check stability during high speed turning.

1) $GZ1 \leq 0.6\ Gzmax$
2) $\theta c \leq 15^{\circ}$

Additional manoeuvrability criteria found in IMO Resolution A.751 (18) and BV Pt.E, Ch 9, Sec 2 for Naval Ships with their respective test conditions can be seen below;

Table 6.2 - Maneuverability Criteria

Test	Criteria
Turning Circle Manoeuvre • Advance • Tactical diameter	 4,5 L 5,0 L
Initial turning ability	With the application of 10^{O} rudder angle to port/starboard, the ship should not have travelled more than 2,5 L by the time heading angle has changed by 10^{O} from the original heading.
$10^{O}/10^{O}$ zig-zag test	First overshoot angle should not exceed 10^{O}; Second overshoot angle should not exceed the above by more than 15^{O}
$20^{O}/20^{O}$ zig-zag test	First overshoot angle should not exceed 20^{O}
Stopping ability	The track reach in full astern (1) stopping test should not exceed 10L.
Dynamic Stability, pull-out test	After the completion of the turning circle test the rudder is returned to the midship position and kept there until a steady turning rate is achieved. This turning rate should be zero.

- Power corresponding to 85% of the maximum continuous power.
- Test Speed V = Speed of at least %90 of the ship's speed corresponding to %85 of the maximum engine output.

Conditions:

a) Wind : not to exceed Beaufort 4 (< 7 m/s)

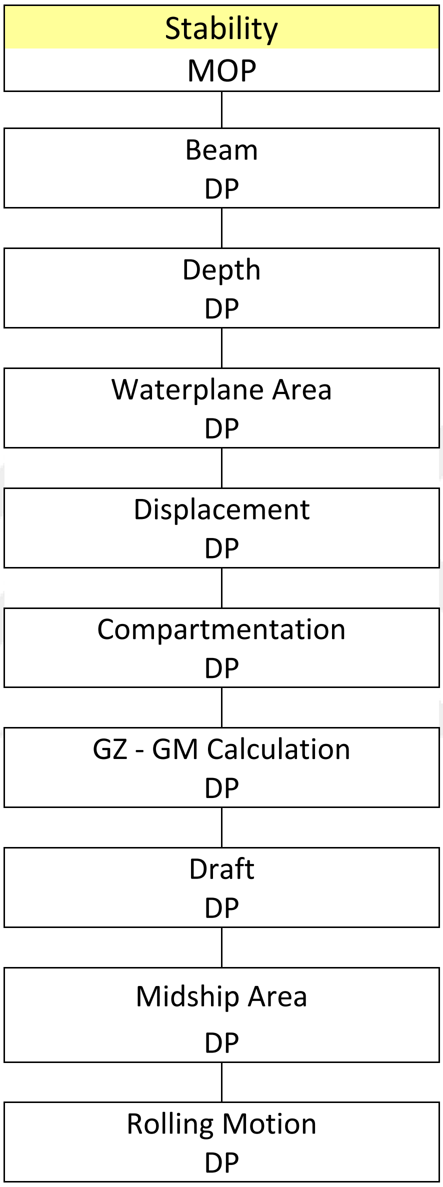
b) Wave : not to exceed sea state 3 (Hs < 1,25 m)

c) Current: Uniform only

d) Water depth should exceed four times the mean draught of the vessel.

Parameters effecting manoeuvrability are: L, v, propulsion system (P, η) and θ.

6.2.5. Stability



Stability is defined by the behaviour of the vessel at sea in any environmental conditions in any sea state. Equilibrium is always the desired outcome, which means the buoyancy force and weight must be equal and two forces must act on the same axis. This chapter will take"Intact Stability" in consideration, whereas "Damage Stability" will be explained later in the study. A good designed ship will float desirably, though too much stability may also be a problem. It can cause unpleasant motions. For a warship to have enhanced survivability, stability is utmost important, as ship will meet various conditions during a mission and these conditions vary for different scenarios and its stability standards should be set accordingly. A rigid body is the state of equilibrium when all forces acting on the vessel null each other, just as the moments of forces acting on the vessel also resultant zero.

Stability of a ship can be defined and calculated; therefore criterias were set by the Class Societies internationally.

Table 6.3 - Stability Criteria

Area under the righting arm curve (GZ) up to 30^{O} or θ_f	Not less than 0,080m rad (15 feet degree)
Area under the righting lever (GZ) up to 40^{O} or θ_f	Not less than 0,133 m rad (25 feet degrees)
Area under the righting arm curve (GZ) between 30^{O} and 40^{O}	Not less than 0,048 m rad (9 feet degrees)
Value of the maximum righting arm curve	Not less than 0,3 m (1 foot)
Heeling angle corresponding to the maximum righting arm curve (GZ_{MAX})	Not less than 30^{O}
Value of the initial metacentric height corrected for free surface effect (GM_{Corr})	Not less than 0,3 m (1 foot)
Value of capsizing angle (θ_s)	Higher than 60^{O} for ships with lightship displacement less than 5000 t. Higher than 50^{O} for ships with lightship displacement not less than 5000 t.

- Maximum value of (GZ_{MAX}) cannot be less than 30^{O} and more than 50^{O} in any case. (Requirement)
- Recommended not to exceed GM value in order to avoid high dangerous accelerations.

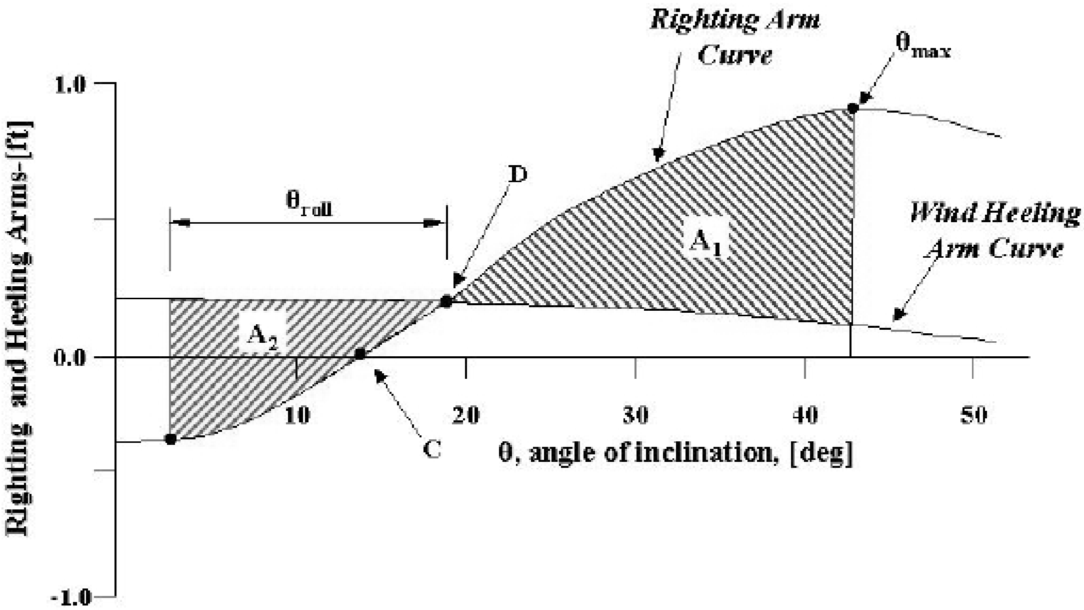


Figure 6.6 – Survival Criteria [53]

Stability requirements for wind and rolling are;

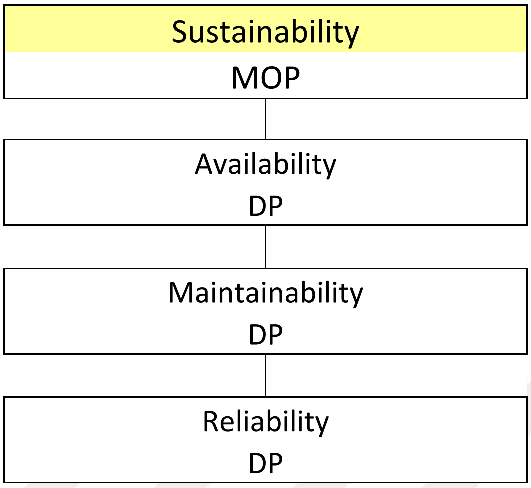
1) GZ1 ≤ 0.6 Gzmax

2) A1≥ 1,4 A2

3) $\theta c \leq 30^{O}$

Parameters effecting stability are: B, T, D, Cb, Cwp and L.

6.2.6. Sustainability



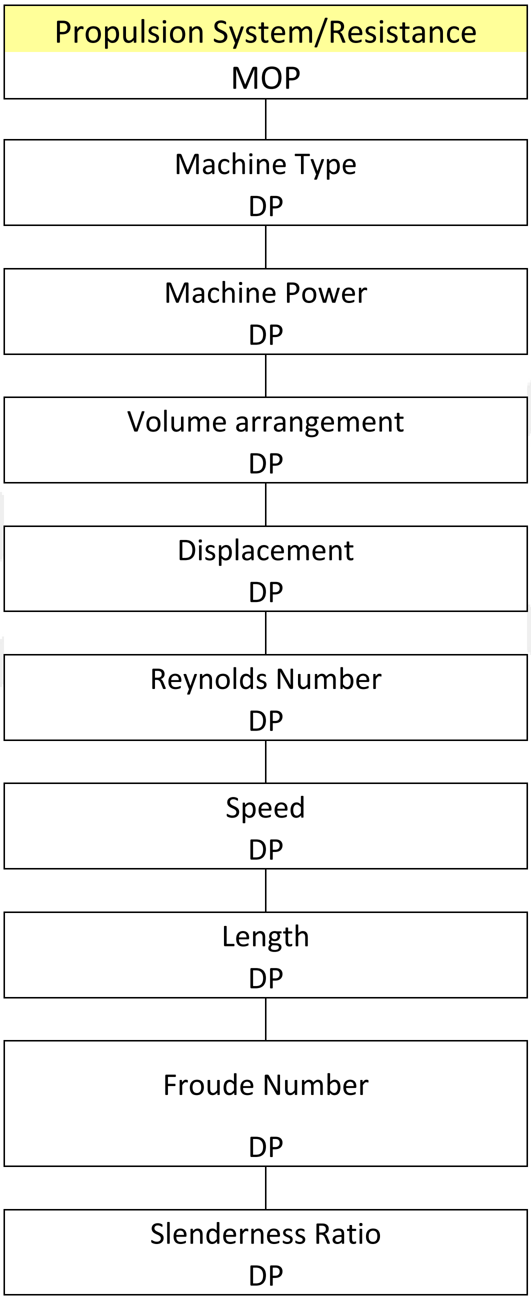
The term sustainability refers to enduring at all times. RAMS analysis is used to calculate sustainability. RAMS is an acronym for Reliability, Availability, Maintainability and Safety. It is a frequent term used in engineering in order to distinguish a product or system. Reliability is the competency to execute a particular function's and/or design reliability or operational reliability. Availability is the competency to continue performing under given circumstances. Maintainability is the competence to be on time and maintainable which also involves servicing, inspection, check, repair and/or modification). Lastly, safety is the competence to be harmless to individuals, environment or other resources in its entire life time.

To be more precise in detail; the chance of being functional after a certain time the unit or system operates is referred as reliability. Failure density and uptime patterns are reliability's concerns. On the contrary, maintainability is about downtime patterns and refers to the unit/system repair timings. Availability is the ratio of uptime through the planning horizon and is concluded by reliability as well as maintainability.

The importance of RAM analysis is due to being crucial to profitability analysis of a system, subsystem or equipment in a particular operable and committable condition when a mission is inducted and/or when the mission is demanded at any given time. Basically, a system's condition where it is still operable is known as availability. Availability and reliability have a positive correlation as they both fluctuate in a parallel manner.

Considering the fact that avoiding a failure is the foundation of everything, reliability can be stated as the most substantial concern of availability.

6.2.7. Propulsion System / Resistance



Resistance created due to ship motions and engine capacity required to power the ship and reach certain speeds on missions are highly related. Size of the engine, speed of the vessel and range will determine the size of fuel tanks and hence the weight of fuel carried, effecting volume arrangements on board.

Total resistance effecting the hull is the sum of viscous and wave resistance. Formulas and parameters effecting resistance are;

$$R_{TOTAL} = R_{VISCOUS} + R_{WAVE} \quad (6.5)$$

$$R_{VISCOUS} = (1+k)\, R_{FRICTION} \quad (6.6)$$

$$R_{FRICTION} = ½\, \rho . WSA . V^2 . Cf\, ITTC'57 \quad (6.7)$$

$$ITTC_{1957}\, Cf = \frac{0{,}075}{[\log 10 Rn - 2]^2} \quad (6.8)$$

$$R_{WAVE} = ½\, \rho . WSA . V^2 . Cwave \quad (6.9)$$

$$C_{WAVE} = a.Fn^n \quad (6.10)$$

where a is a constant and n equals 4.

‘Effective Power’ or ‘Installed Power’ (P) equals total resistance of the hull multiplied with speed of the vessel.

$$P = R_T \text{ x } v \quad (6.11)$$

where R_T is the total resistance and v is the vessels speed.

According to Schmitke and Murdey’s work [2], length and beam must be chosen on the basis of arrangement and powering considerations. After selection of beam, adjust draft accordingly to the beam, so beam/draft ratio satisfies stability requirements in early design phase. Keeping block coefficient, C_B, low will provide low resistance and good sea keeping for the warship. High fore waterplane area coefficient C_{WF} ensures best sea keeping capabilities. To be able to meet machinery and system arrangements and powering requirements for the warship choosing aft waterplane area coefficient C_{WA} precisely during early design phase hastens the process [2].

R.T Schmitke and D. C Murdey built on the foundation laid Bales's paper, mentioned above in $MOP_{SEAKEEPING}$, and addressed to sea keeping and resistance trade-offs arising in frigate hull form design in their "Seakeeping and Resistance Trade-Offs in Frigate Hull Form Design" paper. They added the fact that warship designers are always interested in achieving higher speeds, without any penalty regarding resistance, stability or sea keeping of the ship. Schmitke and Murdey decided to continue on their assessment by selecting the most important motions during deployment on sea of frigates. Pitch, heave, vertical accelerations and roll came forward as the main effecting parameters of warships sea keeping quality. Sea keeping and resistance parameters they found crucial are displacement of the frigate, Δ, length, L, beam, B, draft, T, length/displacement ratio, $L/\nabla^{1/3}$, beam/draft ratio, B/T, block coefficient, C_B and waterplane area coefficients for fore and aft, C_W.

Mobility is utmost important out of all other MOE's forming Survivability OMOE. In case a vessel doesn't have or cannot maintain its mobility ability in a given scenario, advantaging capabilities of the friendly vessel against enemy and their threats becomes closer to failure. Rest of the MOE's such as susceptibility, vulnerability and recoverability might be eliminated if a mobility kill happens. Environmental conditions may lead to losing the ship too, as fighting capabilities against sea and weather states will become more difficult to tolerate. In the end, combining all the MOPs for MOE mobility, MOE formula becomes;

$$MOE_{MOBILITY} = (MOP_{SPEED} \cup MOP_{ENDURANCE} \cup MOP_{SEAKEEPING} \cup MOP_{MANOEUVRABILITY} \cup MOP_{STABILITY} \cup MOP_{SUSTAINABILITY} \cup MOP_{RESISTANCE}) - (MOP_{SPEED} \cap MOP_{ENDURANCE} \cap MOP_{SEAKEEPING} \cap MOP_{MANOEUVRABILITY} \cap MOP_{STABILITY} \cap MOP_{SUSTAINABILITY} \cap MOP_{RESISTANCE})$$

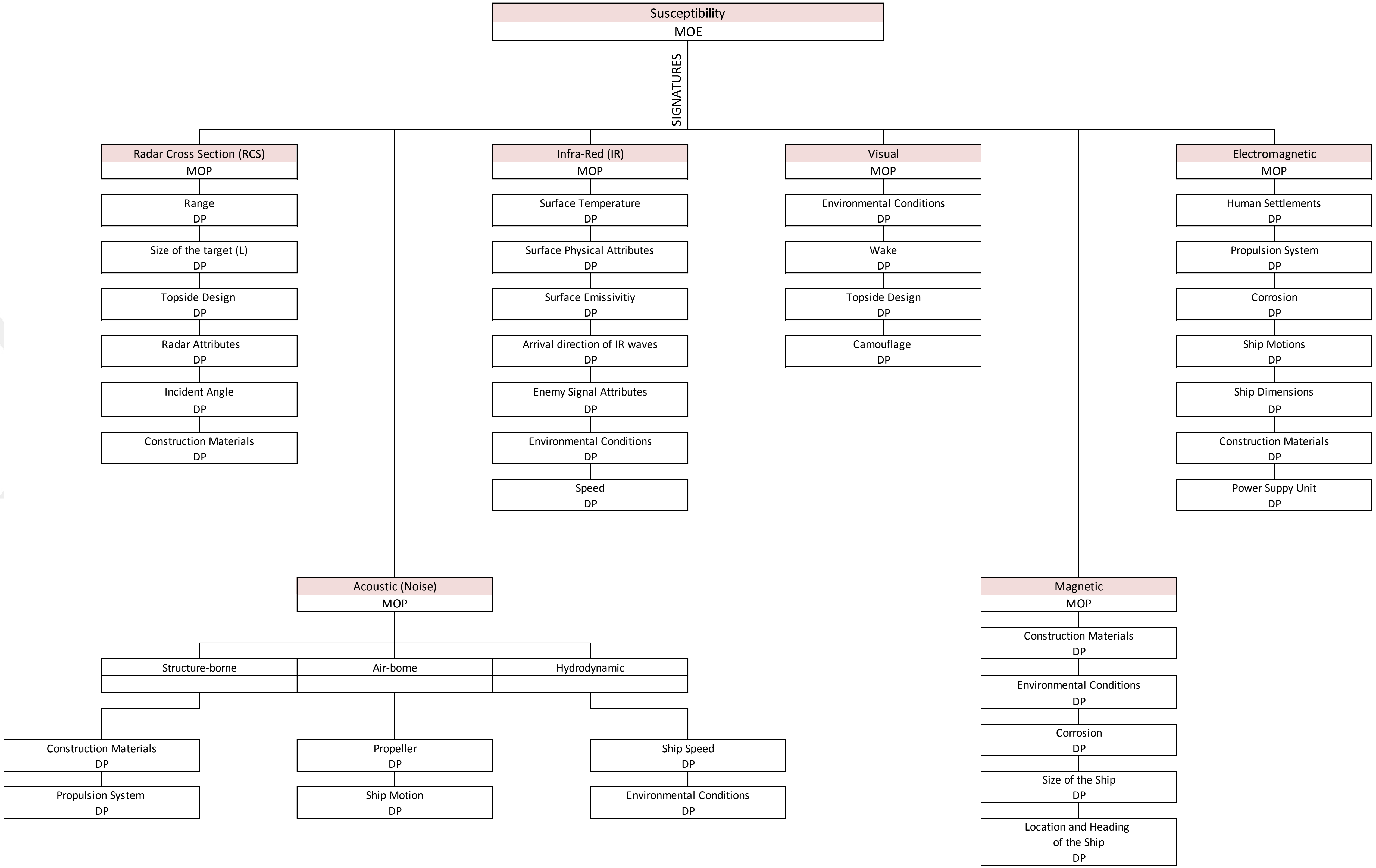
$$MOE_{MOBILITY} = (MOP_{SPEED} + MOP_{ENDURANCE} + MOP_{SEAKEEPING} + MOP_{MANOEUVRABILITY} + MOP_{STABILITY} + MOP_{SUSTAINABILITY} + MOP_{RESISTANCE}) - (MOP_{SPEED} * MOP_{ENDURANCE} * MOP_{SEAKEEPING} * MOP_{MANOEUVRABILITY} * MOP_{STABILITY} * MOP_{SUSTAINABILITY} * MOP_{RESISTANCE})$$

6.3. Susceptibility

Designing a modern naval vessel revolves around implementing technologies that aspire to minimize the ship's reflected and transmitted energies to avoid being identified, located, tracked and attacked by a hostile force. There are numerous energies and their corresponding signatures that has to be minimized. Reducing those signatures increases the vessels survivability since lowering the signatures make it harder for the opponent to detect, identify and classify the vessel. The point of every stealth technology is to reduce a signature while avoiding increasing another.

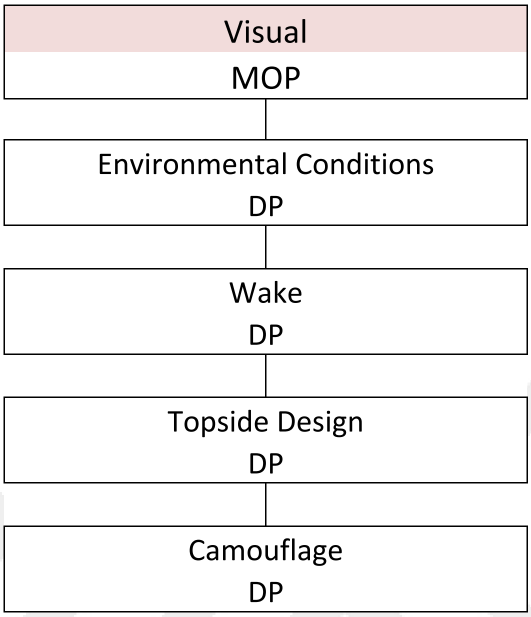
To be able to reduce susceptibility of a warship, enhanced detection avoidance is vital. Susceptibility of a warship is focused around signatures. These are radar, infra-red, noise/acoustic, electromagnetic/magnetic and pressure and wake as visual signatures. If the ship has been seen on any of the enemy's monitors, this means it has been detected but not necessarily as a target. Therefore second step of the scenario – camouflage and manipulation earns precedence and reduction techniques play significant roles. For example, deceiving the enemy into thinking friendly warship is a commercial or private vessel.

Questions asked are "What is the signature?" and "How to reduce the created signature?"



MOE$_{SUSCEPTIBILITY}$

6.3.1. Visual Signature



Visual signature is dependent on environmental conditions the combatant is operating in. They must avoid detection by human eye. Visual detection is possible in two ways, either the ship itself can be detected during the day by human eye from surface and/or air, or the wake the ship creates, which is unfortunately long lasting and is also visible for air detection. Therefore performing missions during night time is the easiest way to reduce visual detection. Also any technique that lowers wake signature is helpful. To be able to reduce the chance of being detected, height of the superstructure of the ship should be kept to the minimum required and camouflage paint can be used.

Wake is dependent on shape of the hull, propeller location and size, speed of the vessel and depth of the water in operation zone. During design phase, design should progress in achieving a hull form capable of creating shorter and/or less persisting wake effect. Wake is created after the vessel exceeds critical speed.

Critical Speed of water is;

$$vp = \sqrt{(g.d)} \quad (6.12)$$

where;

Vp is the phase velocity, g is gravity, d is the water depth.

Difference in speed, expressed as a percentage of the ship speed is known as the wake fraction coefficient, w, seen below in the equation (6.13);

$$w = \frac{(V - Va)}{V}$$

W is the wake fraction coefficient

V is the speed of the vessel

Va is the speed of advance of the propeller Va relative to the water in which it is working is lower than the observed speed of the vessel v.

For a stealth warship, visual detection range to enemy visual detection range ratio must be as low as possible, meaning allied combatant shouldn't be seen till it is impossible for enemy not to see the warship.

It is possible to calculate the range between two targets via the line of sight formula;

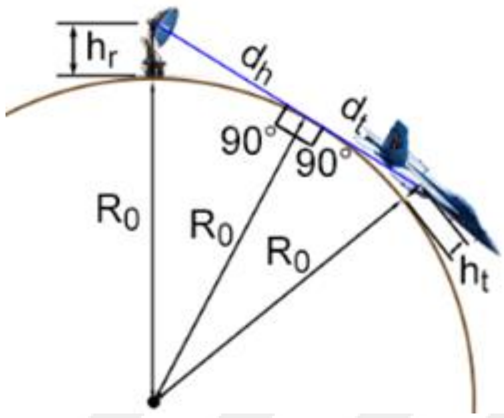


Figure 6.7 – Line of Sight Schema [54]

h_r is the radar antenna height;

h_t is the target height,

d_h is the radar horizon distance,

d_t is the distance from the point of tangency to the target,

$D=d_h+d_t$ is the target visibility distance and R_0 is the mean radius of the Earth.

$$d_h = \sqrt{2R^0hr} \quad (6.14)$$

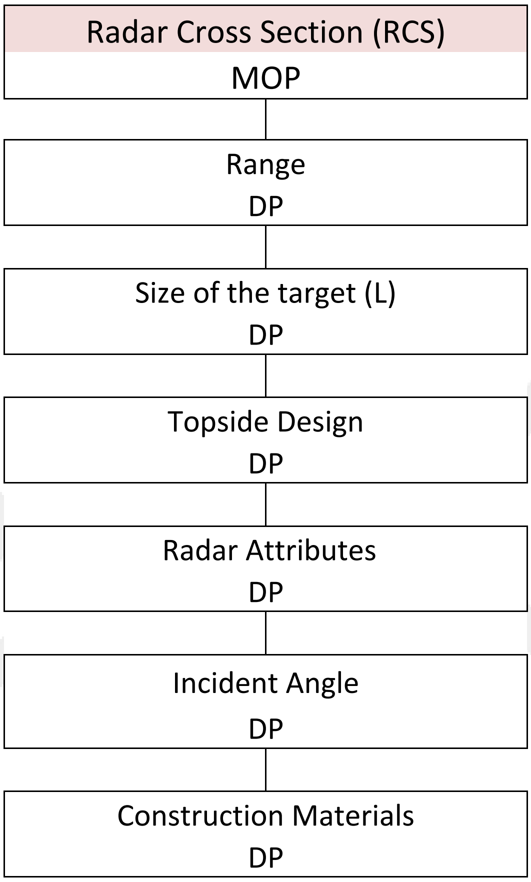
$$d_t = \sqrt{2R^0ht} \quad (6.15)$$

$$D_g = d_h + d_t = \sqrt{2R^0hr} + \sqrt{2R^0ht} \quad (6.16)$$

All units in the formula has to be in the same units of length and distance.

Input parameters are environmental conditions and speed.

6.3.2. Radar Signature (RCS)



Radar is an acronym, used by USA during Second World War, for "Radio Assisted Detection And Ranging", meaning first letters of the words create the word, "radar" even though it has been invented by the British and was called RD/RF (Radio Direction and Range Finding). According to Merriam-Webster dictionary, radar is "a device or system consisting usually of a synchronized radio transmitter and receiver that emits radio waves and processes their reflections for display and is used especially for detecting and locating objects (such as aircraft) or surface features (as of a planet)."

Radar signature is defined by Radar Cross Section (RCS) of the warship. Aim here is to reflect a limited amount of radar energy back to its sender by absorbing or dissipating the most of it. Different factors determine how much electromagnetic energy returns to the source. These factors are absolute size of the target (length), materials used in building the ship, relative size of the target in relation to the wavelength of the illuminating radar, the incident angle which the radar beam hits a particular portion of target that depends upon shape of the target and its relative orientation to the source, the angle which the reflected beam leaves the part of the target hit and polarization of transmitted and received radiation in respect to the orientation of the target.   To be able to control radar signature and proceed with full stealth potential, meaning not to be classified by enemy, upper deck and superstructure of warships are carefully designed. Sectional shaping, micro-geometry reduction, radar absorbent materials (RAM) and active/passive cancelations are some of the methods for achieving the goal.

Application of enhanced topside design for lowering susceptibility on warships are done by using one or more of the methods which are; constructing ship from large flat panels, angling topside panels at least 7 degrees to vertical line of the ship, avoiding reflective dihedrals, setting all internal angles on structure bigger than 97 degrees and ensuring bridge windows are also radar reflective.

Nowadays, it is impossible for a warship to not be seen on ships passive survivability equipment as the technology hasn't gone that far yet. Nevertheless, it is possible to manipulate enemy's vision. This is where micro-geometry reduction and radar absorbent materials (RAM) come in.

Micro-geometry reduction allows warship to be camouflaged into a e.g fishing boat or to be seen different than it actually is. To achieve this, methods are installing an integrated mast to gather up all system sensors instead of generally located loosely, enclose/screen decks, relocating active survivability upper deck equipment inside the superstructure which was designed to have junction boxes only for this purpose, installing bulwarks to hide equipment that cannot be relocated and are nailed to the upper deck and using radar transparent material for deception. Screen openings/doors should be covered with mesh to be able to avoid radar beams and control reflection angles.

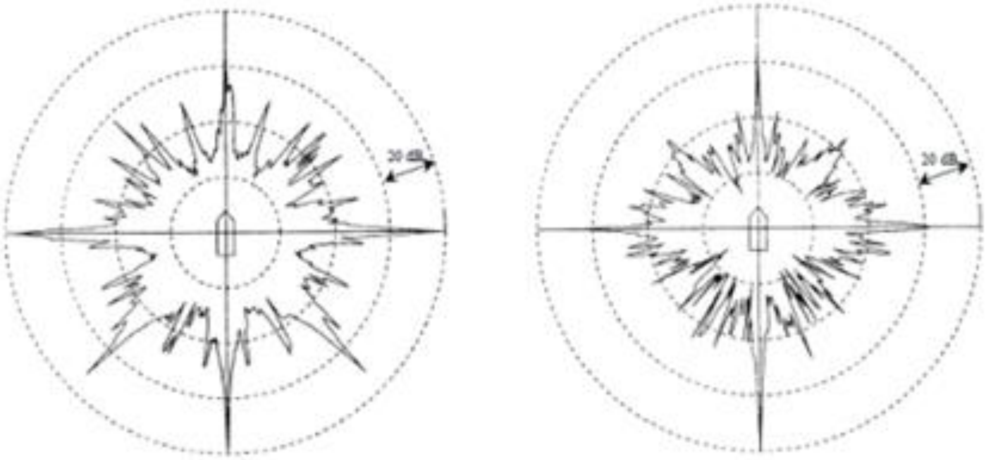


Figure 6.8 - RCS Profiles with and without shaping [11]

As mentioned earlier RCS is dependent on the smoothness of the projected surface. By reducing clutters on the surface and topside design surfaces of the ship, and installing angled bulwarks on applicable equipment on the topside design such as antenna, weapons, mast and arrays, the reflection angles going back to the sender can be controlled and reflections strength can be reduced. Surfaces should avoid having corners and two surfaces shouldn't be aligned at 90 degrees to prevent strong radar reflection back to the sender.

Radar absorbent materials (RAM) or paints can be used to coat whole warship but it is very cost effective. These materials are able to absorb radar energy and trap the energy in a medium that will dissipate its microwave energy as heat and thereby eliminate most of the radar reflection. The amount reflected depends on the impedance (the square root of the ratio between each materials permeability and permittivity. The greater the impedance change, the more energy is reflected before it can be absorbed, so RAM design must balance absorptivity with surface reflectivity to maximize absorption. Therefore, in applications where high radar energies radar absorbing material involved, cooling fans are used to exhaust the heat generated [14].

One of the disadvantages of RAM is that it adds additional weight on ship and can affect ships stability and sea keeping ability. So during design phase, just like the principle of armouring sacrificial angles mentioned above, locations and conciliatory points that need RAM material coverage can be observed and marked to assign the material and redo the stability and sea keeping calculations based on the new design with additional structural weight to see if the main parameters undergo a significant change.

In the end, need of RAM is in accordance with topside shaping, ship's need for RAM decreases sufficiently when efficiency of micro-geometry reduction by structure shaping increases, as there won't be any need for extra materials and therefore extra weight of the vessel.

Radar Signature of a combatant is dependent on range, size of the target, topside design, radar attributes, incident angle and construction materials. Composite/aluminium constructions are more effective on RCS reduction as steel construction can be recognized easier but are very cost effective as well as structural strength is not as much as steel constructions.

There are formulas to be able to calculate preliminary RCS of a ship, though the real measures will be known after computer aided, model or trial tests. To be able to produce a low RCS design, computer aided model tests are favoured.

Skolnik's Formula [16] is;

$$\sigma = Ap \times R_{Reflect} \times D_{Direct} \quad (6.17)$$

where;

σ is RCS in m^2.

A_P is the projected object surface

$R_{Reflect}$ is Reflectivity, re-radiated fraction of intercepted power, dependent on material.

D_{Direct} is Directivity, ratio of the maximum intensity of the radiator to the intensity of an isotropic source, dependent on shape of the object.

Another empirical formula is;

$$\sigma = 52 \, . \, f^{1/2} \, . \, \Delta^{3/2} \quad (6.18)$$

where;

σ is RCS in m^2.

f is the Frequency, incident radar frequency in MHz.

Δ is the displacement; ships displacement in kilotons.

When a ship sails away from a radar station, then the obtainable radar range is determined by three physical facts which are the visibility of the target, horizon and radars detection range. The formula for the radar horizon / target visibility range is;

$$\frac{R}{km} = 2.23 \text{ x } \left(\sqrt{\frac{ha}{m}} + \sqrt{\frac{ht}{m}} \right) \quad (6.19)$$

Where;

ha is the antenna height

ht is target height

For obtaining the radar horizon ht is equal 0, and for obtaining the radar target visibility range ht should have a bigger value than 0.

As mentioned earlier, maximum range of detection is vital for RCS calculations. The maximum radar range equation for detection can be written as;

$$Rmax = \sqrt[4]{\frac{PT^2\lambda^2\sigma}{(4\pi)^3 kTsBFL(SNR)o\ min}} \quad (6.20)$$

Where;

R_{max} is the maximum range of radar detection

P_T is the peak transmitted power

G is the antenna gain

λ is the radar operating wavelength

σ is the radar cross section (RCS) parameter

4π coming from $4\pi R^2$, surface area of a sphere with a radius of R

k is the Boltzmann's constant.

T_S is total effective system noise temperature in Kelvin

B is the radar operating bandwidth.

F is the noise figur

L is the radar losses

SNR_{Omin} is the signal to noise ratio at the output of the receiver also called S/N by Kim et al. which is;

$$S/N = \left[\frac{PG^2\lambda^2\sigma}{(4\pi)^3R^4FkTBnL}\right] \quad (6.21)$$

kTB_n value indicates the noise power.

N(noise power) = kTB_n

Or for Rmax, the below calculation can be used;

$$R_{max} = \left[\frac{PtG^2\lambda^2\sigma}{(4\pi)^3Pmin}\right]^{1/4} \quad (6.22)$$

Rmax is the maximum detection range

Pt is the peak transmitters power

G is the antenna gain

λ is radars operating wavelength

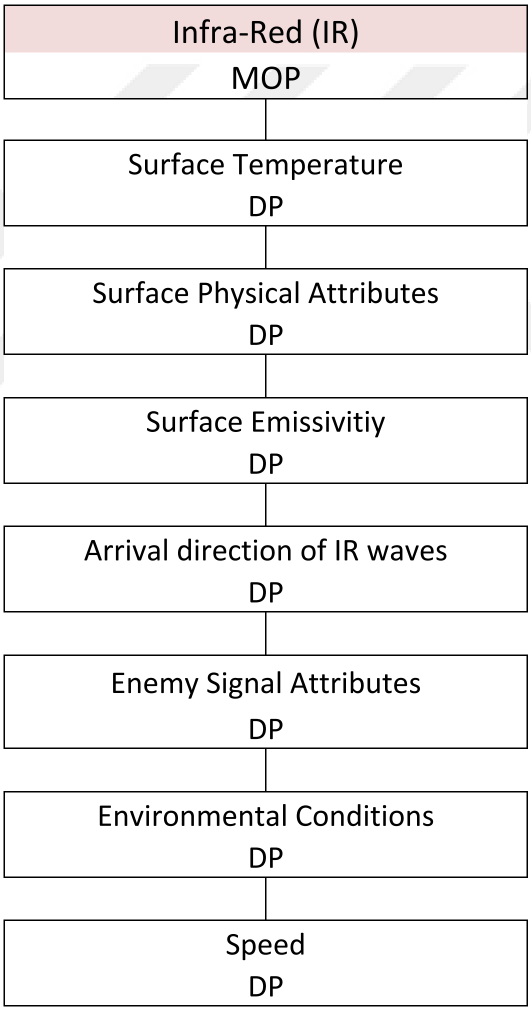
σ is RCS

4π is coming from $4\pi R^2$, surface area of a sphere with a radius R.

Pmin is the minimum detectable received signal from the enemy's sensor

For OMOE analysis input parameters are L, B, F, topside design features and radar characteristics.

6.3.3. Infra-Red Signature



A ships IR signature consists of two main components, which are the heat created by the ship itself and the effect of heat sources of ship's surroundings. Heat rising is caused by thermal radiation in the electromagnetic spectrum particularly in wavelengths. All objects emit IR radiation although hotter objects emit IR with greater intensity. The amount of radiation that is emitted is dependent on the temperature and the emissivity of the body. A hotter body emits more and a rough-surface emits more than a smoother one [20]. Factors that increase IR signature include rejected heat from the engines, every running machinery or vital system equipment, e.g exhaust products of exhaust, and waste air from ventilation systems and/or solar, sky radiance, and sea radiance absorption and reflection by the ship's surfaces as stated by Thompson [21,22]. The primary internal IR sources are the main machinery on board and drive engines and electrical generators.

The infrared signature of a ship at sea will have three prominent features; the imperfect grey body emission of the ship's structure, the characteristic continuum of the hot water from the overboard discharges or the creation of wake and discrete spectral lines from the gases that compose the stack effluent. Imaging systems collect the total amount of infrared energy emitted into the instantaneous field of view solid angle viewed by the detector element in its spectral bandwidth. A spectral system looks at the energy emitted as a function of frequency in the viewed solid angle. The signature of each feature will vary with both changing environmental conditions and ship controlled parameters such as speed and internal temperature [23]. In addition, IR signature is dependent on surface temperature, arrival direction of the IR waves from the source and wavelength of the signal.

Imperfect Grey Body Emission

A grey body can be defined as an imperfect black body whose absorptivity is limited due to measure and wavelength of the incident radiation. The actual radiant existence of the ship's structure will depend only on the thermodynamic temperature of its surface and the emissivity of that surface [23]. Factors that affect these parameters are; physical condition of the structural surface, meteorological conditions, the ocean conditions and time of the day and year. Several properties of black body theory are critical to the development of the ideas of the ship's structure as an infrared emitter. 'Black body' is defined as an idealized object that absorbs all incident radiated energy, not discerning between wavelengths nor directions. These properties are first the intensity of the radiation that a body emits, which is a function of the physical condition of its surface and second, the intensity of the radiation that a body emits depends on the thermodynamic temperature of the surface of the object. If the object is in thermal contact with variable heat sources such as the wind and waves, the amount of radiation emitted by the body will vary as a function of its changing environment [23].

To be able to calculate ship temperature, the description of the spectral intensity of the black body as given by Planck is;

$$W_0\lambda = (2\pi hc^2/\lambda^5) \text{ x } [\exp(hc/\lambda kT) - 1]^{-1} \quad (6.23)$$

Where;
$W_0\lambda$ is spectral radiant emittance (erg/cm²-cm⁻¹)
h is Plank's Constant (6.63exp(-27) erg-sec)
λ is wavelength in cm
k is Boltzmann's Constant (1.38exp(-17) erg/deg)
T is thermodynamic temperature in Kelvin
c is the speed of light (2.99exp(+10) cm/sec)

The formulation of the black body emission must be reduced by emissivity, ε, for the particular surface condition [23]:

$$W = \varepsilon \, w_0 \quad (6.24)$$

Transmission Formula; Transmission of the signal is;

$$T_{TRANS} = \exp(-(a+s)\, r) \quad (6.25)$$

Where;

T_{TRANS}	Transmittance
a	absorbtion coefficient
s	scattering coefficient

r distance of travel of the signal

Emission Formula is;

$$E = \sigma \cdot T^4 \quad (6.26)$$

E	Total Energy Emitted	
σ	Stefan Boltzmann Coefficient	5.67exp
T	Thermodynamic Temperature Kelvin+	

Ratio that can be put in MOP_{IR} for ship temperature is;

$$\frac{\text{ship temperature}}{\text{background temperature}}$$

Which can be calculated at a specific time during a mission, the difference between the ship temperature and background environmental temperature.

Wake

The water that is pumped overboard will be around $65^{O}C$ - $80^{O}C$ and the wake will be a few degrees warmer than ambient, naming them hot water dischargers of the warship. The significant mechanisms that contribute to the cooling of the hot water discharge are; convective and evaporative cooling by the wind, conductive and convective cooling by the ocean water and the emission of photons in cooling. The signal produced by the hot water in the overboard discharge is detectable only if viewed against the background of the lower temperature of the ocean. The detectability of the signal will last as long as a temperature difference exists between the discharge stream and the cool ocean water [22].

This in the OMOE system function can be written as;

$$\frac{\text{wake temperature}}{\text{background temperature}}$$

Exhaust

The exhaust gases from the combustion process exit the stack at a temperature of 150^{O}C-200^{O}C at a height of about 20 - 45 meter above the waterline. These gases exit the stack with a velocity dictated by the stack geometry, ship speed and fuel consumption. The stack effluent is immediately subjected to the forces of the wind. Cooling mechanisms for the stack gases are convective between the atmosphere and the stack stream, mixing between the stack stream and the atmosphere and radiated decay of the vibrational excited molecules of the stack stream. It is the radiated decay process that provides the signal for detection by the infrared system [22].

This in the OMOE system function can be written as;

$$\frac{\text{gas temperature}}{\text{background temperature}}$$

To be able to control IR signature, existent ship systems installed on board should be utilised. Techniques and options to reduce IR signature consists of; application of insulation on warships sides and decks instead of only insulating machinery spaces**,** solar or infra-red reflective paints to reflect heat, application of direct or water injected exhaust cooling systems to reduce increased exhaust temperature and also application of proper ventilation and insulation to exterior bulkheads to reduce outer skin temperatures to an acceptable contrast temperature.

Another technique is the sea water wash-down system to cool the hot surfaces of the ship, and a water mist system to blanket the ship in a thick cloud of mist, hiding the ship from the view of IR seekers [21] and also cool the hot parts of the ship's surface. To be most effective, a water wash system must be carefully designed to cool the entire surface of the ship to ±5^{O}C contrast from +10 to +30^{O}C. The wetting system should be designed to distribute water uniformly over the subject area so that no hot spots remain. The variation in the surface temperature after cooling should be less than 5^{O}C [22].

Input parameters are temperature of surfaces and outputs as well as speed of the combatant.

6.3.4. Acoustic (Noise) Signature

Warships are being detected by enemy forces by the noise they emit in the acoustic frequency region. The acoustic signature of a particular ship is the combination of all noises created by the ship itself or effects on its surrounding while ship is afloat. These noises can be machinery-borne noise inside the warship, propeller-borne noise created by popping air bubbles outside the ship through cavitation, hydrodynamic noise due to irregular and fluctuating flow of water passing the moving hull and noise originating from water inlet and outlets.

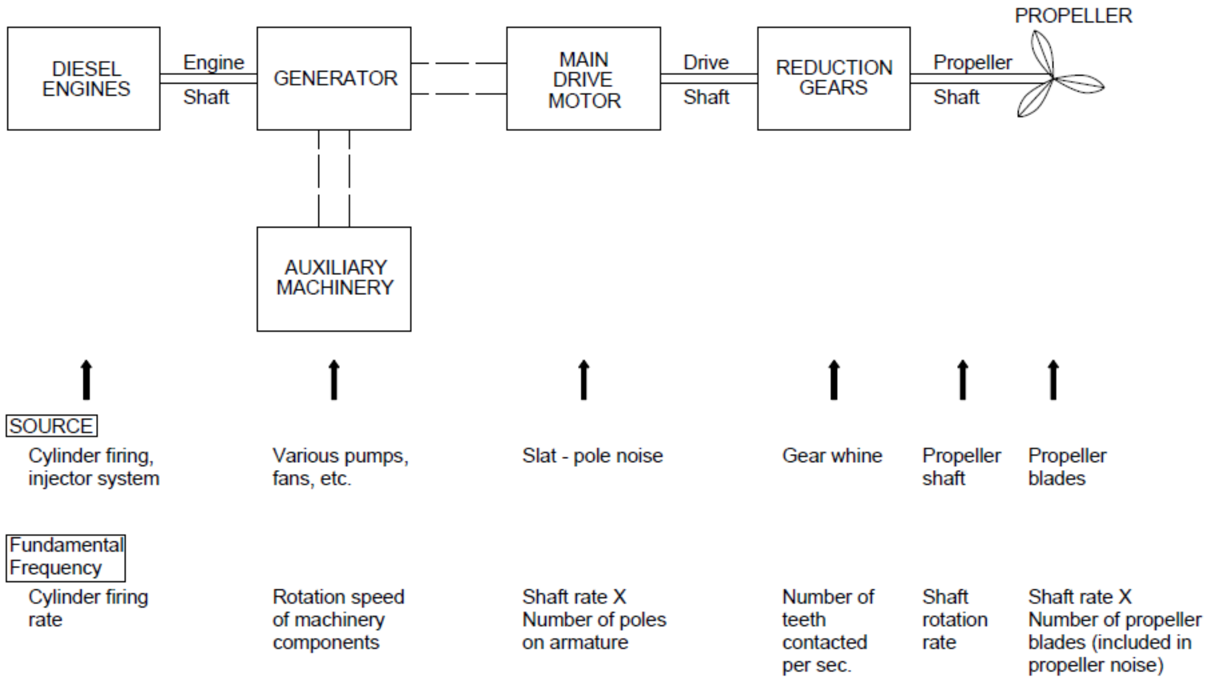
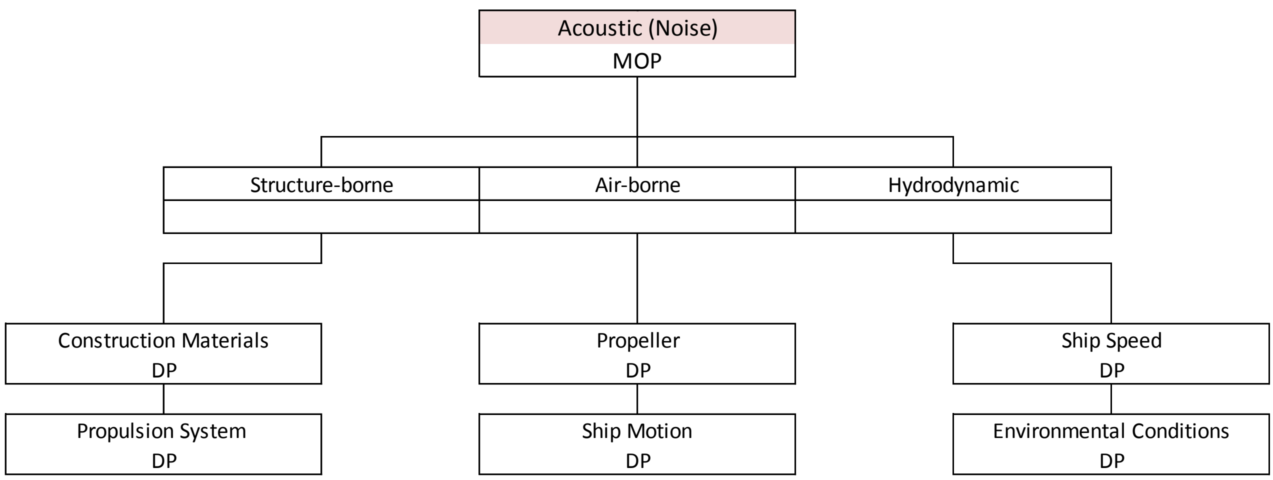


Figure 6.9 - Schematic Visual of Machinery-borne Noise [24]



To avoid detection by the enemy, reduction of main sources of radiated noise underwater should be the aim as sound waves are created on or below sea can be picked up by a hydrophone as it travels. Reducing radiating noise sources and installing acoustic insulation or enclosures to existent noise sources on board can be done to lower the airborne acoustic signature. Isolating rotating machinery using flexible mounts and considering double mounting equipment on rafts are a way to reduce structure borne signatures.

Finally, eliminating unsteady flow around hull in early design phase by avoiding knuckles and steps in hull form to minimise motion on water, taking in consideration the flow around sea inlets, thruster tunnels and sonars to make sure all hull appendages are precisely aligned with the local flow can be done to reduce acoustic signature. Last but not least, eliminating unsteady fluid flow within system pipework is also notable as when fluid flows through pipes, it generates noise. If this flow becomes turbulent, noise increases.

To be able to reduce the signature, the noise generated within the warship should be kept to a minimum and refrained to be transmitted to the environment to reduce the chance of being detected by passive sonar. Since active sonar relies on the sound waves reflected from the target, this reflection should be minimized to avoid detection. Techniques of minimizing reflection of sound waves include; creating a wall of air bubbles enveloping the hull of the ship and anechoic tiles.

Masker air system creates a wall of air bubbles that surround the hull. This method is based on the principle that sound waves travel at different speeds through air and water. This difference of impedance acts as an acoustic insulation and reduces the chance of detection by active sonar. The penalty is that this technique generates a visible and long lasting wake above water by disrupting the water surface, thus reducing visual susceptibility of the warship.

Just like RAM in RCS reduction, anechoic tiles can be used to reduce acoustic signature. They work in two ways. Firstly, they can act as mufflers and absorb warships own machinery noise transmissions through the hull and diminishes the chance of detection by an enemy passive sonar. Secondly, they can absorb sound waves of active sonar by making sound waves pass through the air cavities of tiles and lose some of their energy, therefore lessening the travel distance of the sound waves. Their disadvantage is that just like RAM, they add more weight to the ship and their need for maintenance is too high.

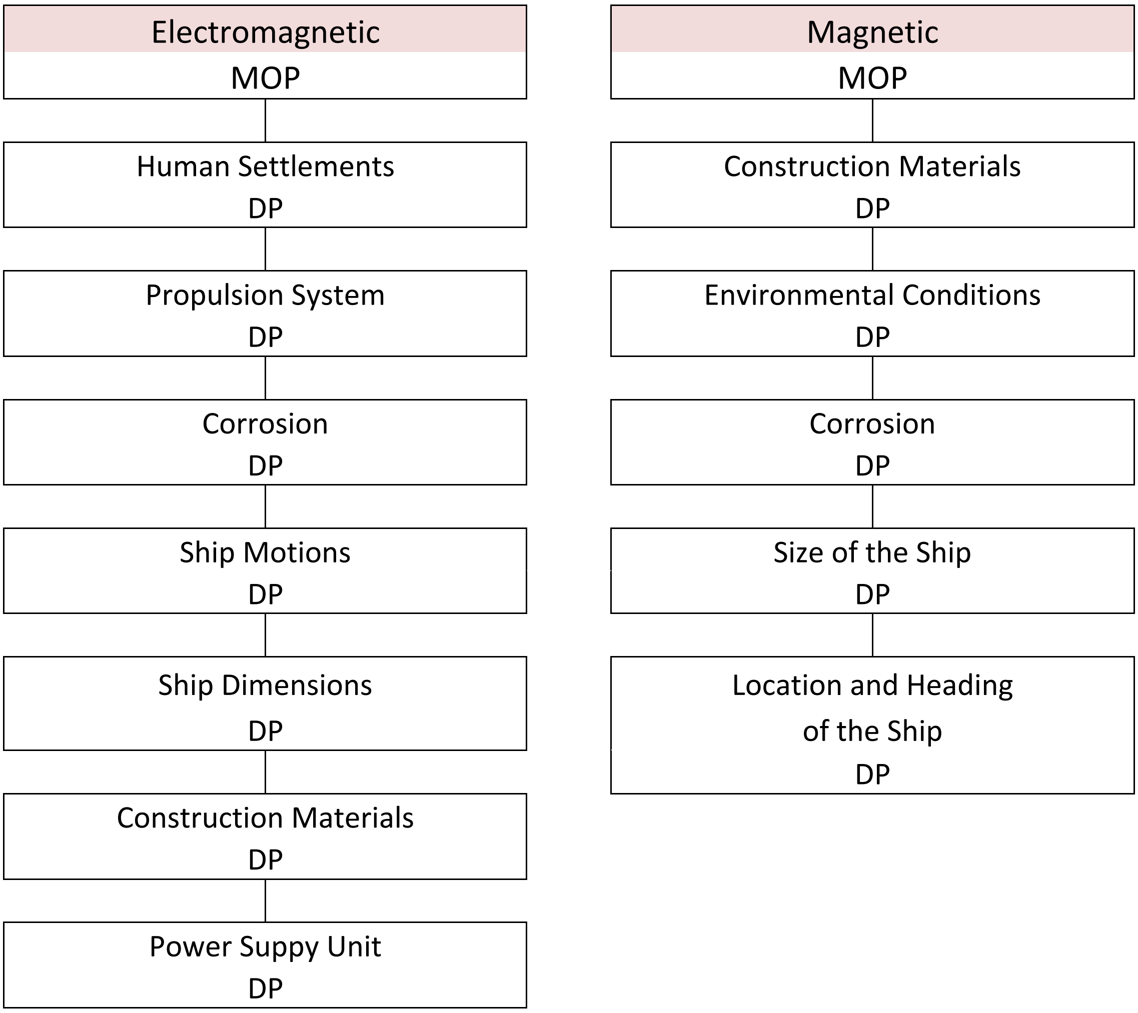
They’re not commonly used anymore as they cannot completely cancel acoustic signature and they are very expensive, which leaves them an unpractical technique for application.

The acoustic signature can be reduced by fitting of machinery with the best possible mechanical tolerances and machinery to be designed to produce a minimum of noise. Propellers can be redesigned to reduce cavitation, which led to the development of large slow turning propellers.

Input parameters for analysis are; L, B, T, v and propulsion system.

6.3.5. Magnetic And Electromagnetic Signature

Environmental physics explains the birth of magnetic activity on earth itself, solar flares and electrical storms which excite resounces and create magnetic activity. It is a common knowledge that earth has its own magnetic field. Therefore, anything that consists of ferrous materials in its presence has magnetism. Ferrous materials used for constructing warships are induced with magnetism by earth at all times, therefore creating a magnetic signature. Same principle applies to electrically conducting materials, whether they are magnetic or non-magnetic. Currents flowing through active circuits aboard and the presence of a strong electric field that surrounds the warship generate a detectable and traceable magnetic and electronic signature.



There are two effects of motionally induced electric field, magnetic and electric respectively. Flow velocity and magnetic field creates the magnetic, where the induced electric fields due to the motion of conducting seawater in the earth's magnetic field creates the electric effect.

Magnetic Signature

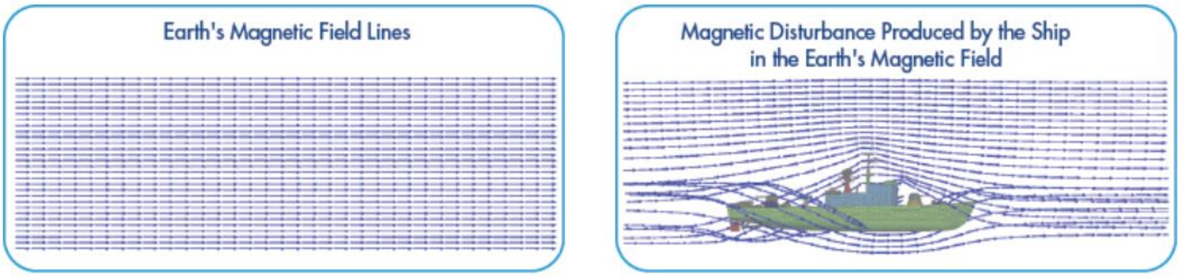


Figure 6.10 - Earth's Magnetic Field

Figure 6.10 shows the difference between uninterrupted earth's magnetic field lines and magnetic disturbance of ships [28].

Steel is ferromagnetic as it is composed mostly of iron, therefore induction with earth's magnetic field, creates magnetization. The amount of magnetic signature created depends on how much steel is used in construction, therefore size of the vessel.

To be able to reduce electromagnetic/magnetic signature caused by environment and earth gravity itself, signature reduction systems have to work together. These include magnetic treatments created to reduce the warship's signature, which are semi-permanent piping and de-perming by magnetometer or gyro controlling, active and/or passive degaussing systems, increased current cathodic protection, active shaft grounding systems to reduce alternating magnetic and electric fields generated by the interaction between the cathodic protection equipment and the rotating shaft/propeller blades. Active Shaft Grounding (ASG) unit removes the periodic modulation of the current due to the shaft frequency and virtually eliminates the alternating electric signature arising from rotating components [21].

There are passive and active reduction methods available. For passive reduction, designers desire to use non-ferrous materials during construction, but these non-ferrous materials are not sufficiently strong enough, except e.g stainless steel or duplex steel, to be used in the structural construction of the warships. Therefore usage of higher strength ferrous materials, such as steel, is increasing the magnetic signature of the warships. Reduction techniques include Deperming and Degaussing. Deperming is temporarily eliminating magnetization and degaussing is countering the induced magnetization by passing electrical currents through strategically placed on-board coils to set up an opposing field and thus null out the net field [55]. Degaussing can be done through M(vertical), L(longitudinal) and A(athwart) coils, therefore is dependent on dimensions of the vessel.

Another passive reduction technique is passive Degaussing, which is applied for reducing or removing the permanent magnetism of the warship. Reduction is achieved by wrapping heavy grade cables around the hull and superstructure so high electrical currents can flow around the ship.

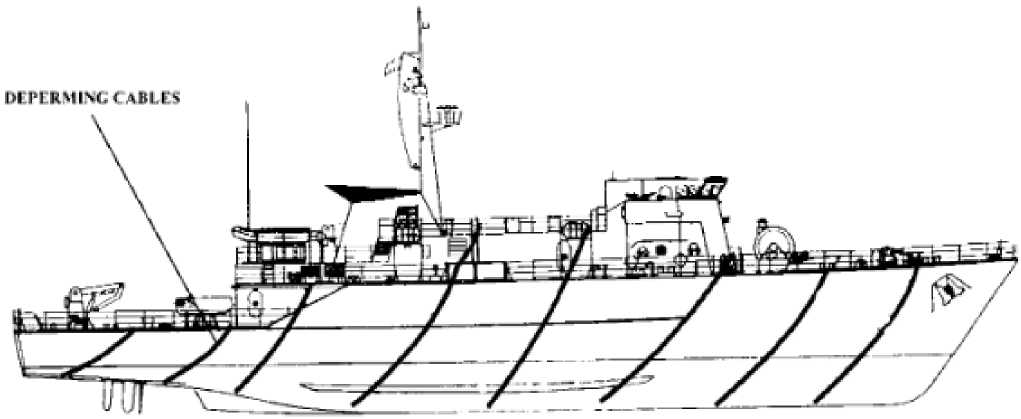


Figure 6.11 - Degaussing System [29]

Another approach for reducing magnetic signature is using active Degaussing systems. Applying direct current passing through cables mentioned above in passive degaussing, creating a field equal and opposite to the ship's own magnetic field, therefore cancelling the signature. Iron in construction has 10000 nT at beam depth at frigates, after degaussing this value decreases to 1000-2000 nT.

Electromagnetic Signature

Hull and propulsion systems relationship with seawater leads to electric currents through corrosion, creating static electric and magnetic fields. At the same time the active electronic emitters the warship radiates into the atmosphere and leaves a trace of its electronic signature. Propulsion systems lead to alternating electric fields at the shaft frequency and its harmonics. Human settlements and use of onboard electric power supplies on the vessel increases electromagnetic activity.

As McGillvray Jr. mentioned in his "Stealth Technology in Surface Warships"[27] paper, electronic signature can be silenced by turning the active equipment off, however the penalty of this action is that the ship loses its active detection and radio communication capabilities.

The electromagnetic signature of a vessel arises from the presence of a strong electric field that surrounds it, Figure 6.12. Periodic fluctuations in the field give rise to both a Static Electric (SE) component to the signature and an Alternating Electric (AE) component (also known as Extremely Low Frequency Electric or ELFE). The fluctuations in the field also induce a corresponding Alternating Magnetic (AM) field around the vessel [22].

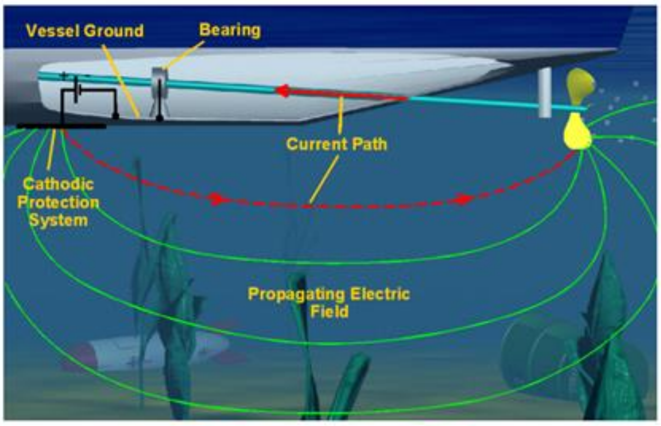


Figure 6.12 - Origin of SE/AE Signature [22]

The electric field surrounding the vessel is produced by the presence of large electric currents passed through the water by Active Cathodic Protection (ACP) systems to provide enhanced corrosion protection for the ship. In old conventional ways, electric current is passed from anodes on the hull through the propeller or hull locations that lack adequate coating protection, therefore resulting electrical signature is produced that is proportional to the current path lengths [22].

Input parameters for magnetic and electromagnetic signature are L, B, D and construction material properties.

All summarised, all signatures must be as low as possible and the designer should aspire to achieve a balance by optimizing all ship signatures keeping in mind that reducing one signature may cause another to increase. Signature management and reduction is successful only if signature self-awareness is taken into account. Susceptibility reduction is achieved by ship's own active sensors searching the environment, effective tracking, identification or classification of signatures caused by either ship itself or the enemy. Most importantly, the most sufficient susceptibility reduction system is to avoiding being targeted or being hit by an enemy.

For example shock mounting for maximising shock resistance may be detrimental to underwater radiated noise signature. Although a warship should be shock resistant, the methods include shock hardening and raft mounting as well as above-mentioned shock mounting. Avoiding use of grey cast iron and other brittle materials as well as avoiding cantilevered or overhanging components achieve shock hardening. Shaft line of the warship can be hardened for enhanced survivability to resist blast damage, which can lead to dis-alignment. For raft mounting multiple components can be placed on a single raft, which will create increased space and weight requirements. In conclusion, every improvement in a certain signature reduction may cause another to detoriate.

Hence, the overall susceptibility MOE formula for OMOE analysis becomes;

$$MOE_{SUSCEPTIBILITY} = (MOP_{RCS} \cup MOP_{IR} \cup MOP_{ACOUSTIC} \cup MOP_{VISUAL} \cup MOP_{MAGNETIC} \cup MOP_{ELECTROMAGNETIC}) - (MOP_{RCS} \cap MOP_{IR} \cap MOP_{ACOUSTIC} \cap MOP_{VISUAL} \cap MOP_{MAGNETIC} \cap MOP_{ELECTROMAGNETIC})$$

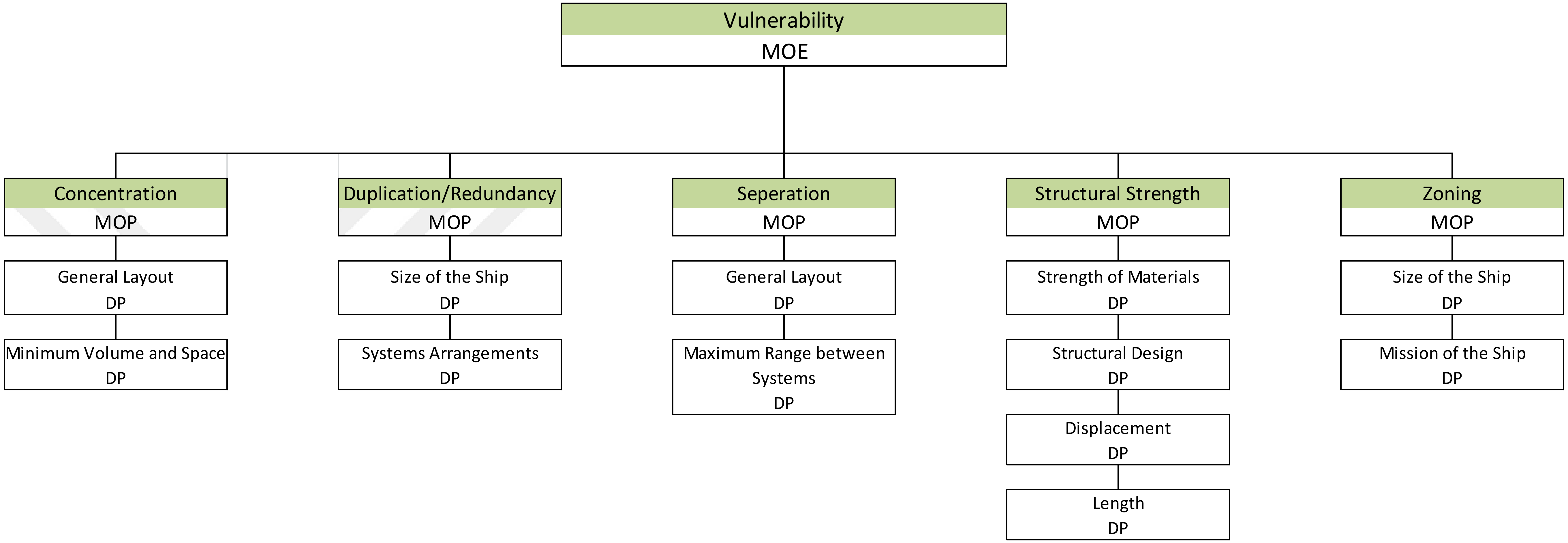
$$MOE_{SUSCEPTIBILITY} = (MOP_{RCS} + MOP_{IR} + MOP_{ACOUSTIC} + MOP_{VISUAL} + MOP_{MAGNETIC} + MOP_{ELECTROMAGNETIC}) - (MOP_{RCS} * MOP_{IR} * MOP_{ACOUSTIC} * MOP_{VISUAL} * MOP_{MAGNETIC} * MOP_{ELECTROMAGNETIC})$$

6.4. Vulnerability

Susceptibility is mostly dominated by payload and combat system capability, therefore design has to be done according to vulnerability reducing methods without any mobility penalties. Vulnerability of a combatant must be as low as possible for enhanced survivability to be able to endure any impact damage on combatant.

Vulnerability reducing methods consists of;

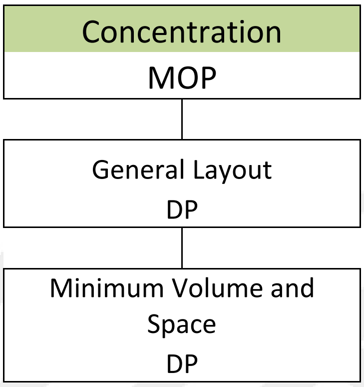
- Concentration – To lessen the chance of being hit and damaged. All systems and their components should be located in the smallest possible space and volume.
- Duplication – Installation of critical systems and sub-systems should be in parallel arrangement to be able to stay available, reliable and maintainable in case of damage to any of the components. The designer should refrain from arranging the systems in a serial manner.
- Separation – The equipment that serve the same purpose or could be substitutes for each other should be well separated from each other as to not lose the benefits or mission capability all together.
- Zoning, Protection and Hardening – Vital services and their associated equipment that are located in each zone should be protected by adequate armour and have their own fire-fighting, smoke control and ventilation systems as well as watertight compartmentations in case of flood to prevent spreading to other zones.



MOEVULNERABILITY

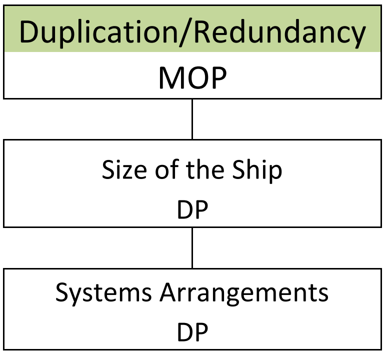
6.4.1. Concentration

Concentration is dependent on General Layout of the design, in preliminary design phase minimizing the ship space helps the survivability through making the ship a smaller target in enemy eyes.



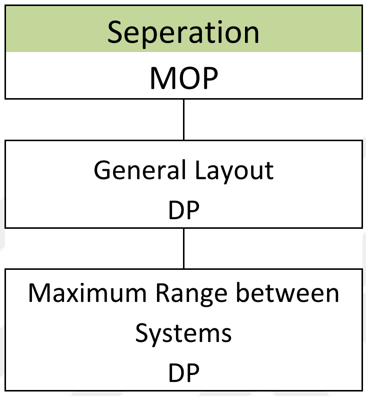
6.4.2. Duplication / Redundancy

Duplication is dependent on the size of the ship, dimensions and equipped system and equipment. Any impact harm or failure of one of the vital systems or equipment will lead to limitations of operational capability, therefore duplication of these systems and equipment through arrangement provides full redundancy of the combatant.

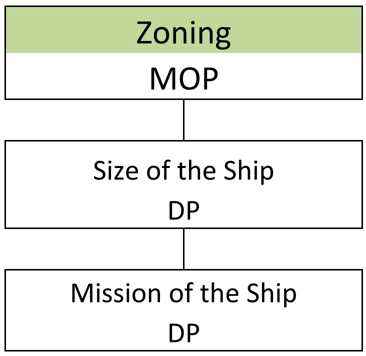


6.4.3. Seperation

Seperation is also dependent on General layout of the design and should be considered in preliminary design phase. In case of incoming damage, it is beneficial for vital systems and equipment to be as far as possible from each other without losing their operability. Seperation prevents the effect of the damage from affecting multiple systems at once.



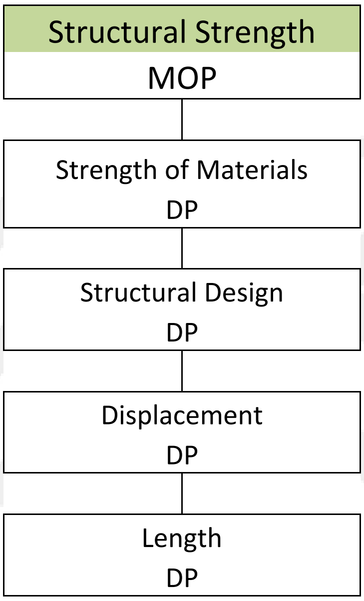
6.4.4. Zoning



Zoning is important for damage and fire control, in case of losing portions of the ship during war, it must sustain the damage and survive, therefore zoning is utmost important for warships as each zone is able to control the whole warship and its systems on its own.

6.4.5. Structural Strength

Weight of the vessel should be as low as possible, which will increase operational efficiency by easing the propulsion system and resistance. Therefore, longitudinal framing systems are commonly used in warships, as they are lighter than transversal systems. Length is a crucial parameter.



Input parameters for vulnerability MOE are; L,B, D, volume, displacement, structural construction material properties and most importantly general layout arrangement of ship systems and their components.

For OMOE analysis, vulnerability formula becomes;

$$MOE_{VULNERABILITY} = (MOP_{CONCENTRATION} \cup MOP_{REDUNDANCY} \cup MOP_{SEPERATION} \cup MOP_{STRENGTH} \cup MOP_{ZONE}) - (MOP_{CONCENTRATION} \cap MOP_{REDUNDANCY} \cap MOP_{SEPERATION} \cap MOP_{STRENGTH} \cap MOP_{ZONE})$$

$$MOE_{VULNERABILITY} = (MOP_{CONCENTRATION} + MOP_{REDUNDANCY} + MOP_{SEPERATION} + MOP_{STRENGTH} + MOP_{ZONE}) - (MOP_{CONCENTRATION} * MOP_{REDUNDANCY} * MOP_{SEPERATION} * MOP_{STRENGTH} * MOP_{ZONE})$$

A previous study concerning ship vulnerability has been done by Malakhoff et al. in 1998 [56]. Their paper is based on JJMA Ship Vulnerability Model (JJMA - SVM), which examines the ship system components that would likely be affected as a result of an occurrence as well as the degree of ship's functional capability once the occurrence takes place, through a virtual process.

Ships have some particular requirements where availability needs are asserted. These requirements should be fulfilled by the ship systems which are initially designed for. Either US Navy data banks or the related manufacturers' guidelines are used in order to conclude the system's availability as a component that accomplishes the expected performance level. In order fulfil or better the stated system requirements, component redundancy is to be granted in a sufficient manner. In such a system scenario, it is necessary to perform a vulnerability analysis to regulate the ship system's availability, which concerns the operational capability level.

The very essential ship design specifications consist of two main concepts: the optimum desired level of ship's system availability and a predefined operational environment's life cost goals.

An easier approach is applied in order to verify a high-level design's availability sensitivity towards reliability and component maintenance. The optimum down time is taken as the MMTR while the optimum uptime is taken as the MTTF. AR&M, which is explained as component optimum availability based on reliability and maintainability, is signified as below;

$$A_{R\&M} = 1 - (MTTR/(MTTF+MTTR)) \quad (6.27)$$

OR

$$A_{R\&M} = 1 – (MTTR/(MTBF)) \quad (6.28)$$

Determining a systems design that successfully fulfils availability requirements is the first and foremost action to be taken. To accomplish the same, the designer is expected to work on a single or multiple alternative that are stated below;

- More reliable (and more costly) system's components
- Greater component redundancy
- More frequent maintenance and parts replacement schedule.
- A merged RAM Life Circle to Vulnerability Simulation analysis is to be taken as a second action in order to carry out a vulnerability analysis.
- A broader separation between redundant components should be given. It is essential to use adequate separation between redundant components to make sure vulnerability is performing effectively. While including additional components would have a positive effect on system's availability, it reduces the previously mentioned vulnerability aspect.
- To preserve system's armour, shock mitigation, more robust component design etc. components should be increased based on weapon effects tolerance. This option is taken into consideration when the ship is undersized compared to the threat weapon's vulnerability area. In case exclusion armour is possessed, the component units should be a minimum number in order to restrict the target area and to have a reasonable armour weight on ship system. This scenario being quite extraordinary, if happens so, it is advised to select the steadiest components of availability and vulnerability.

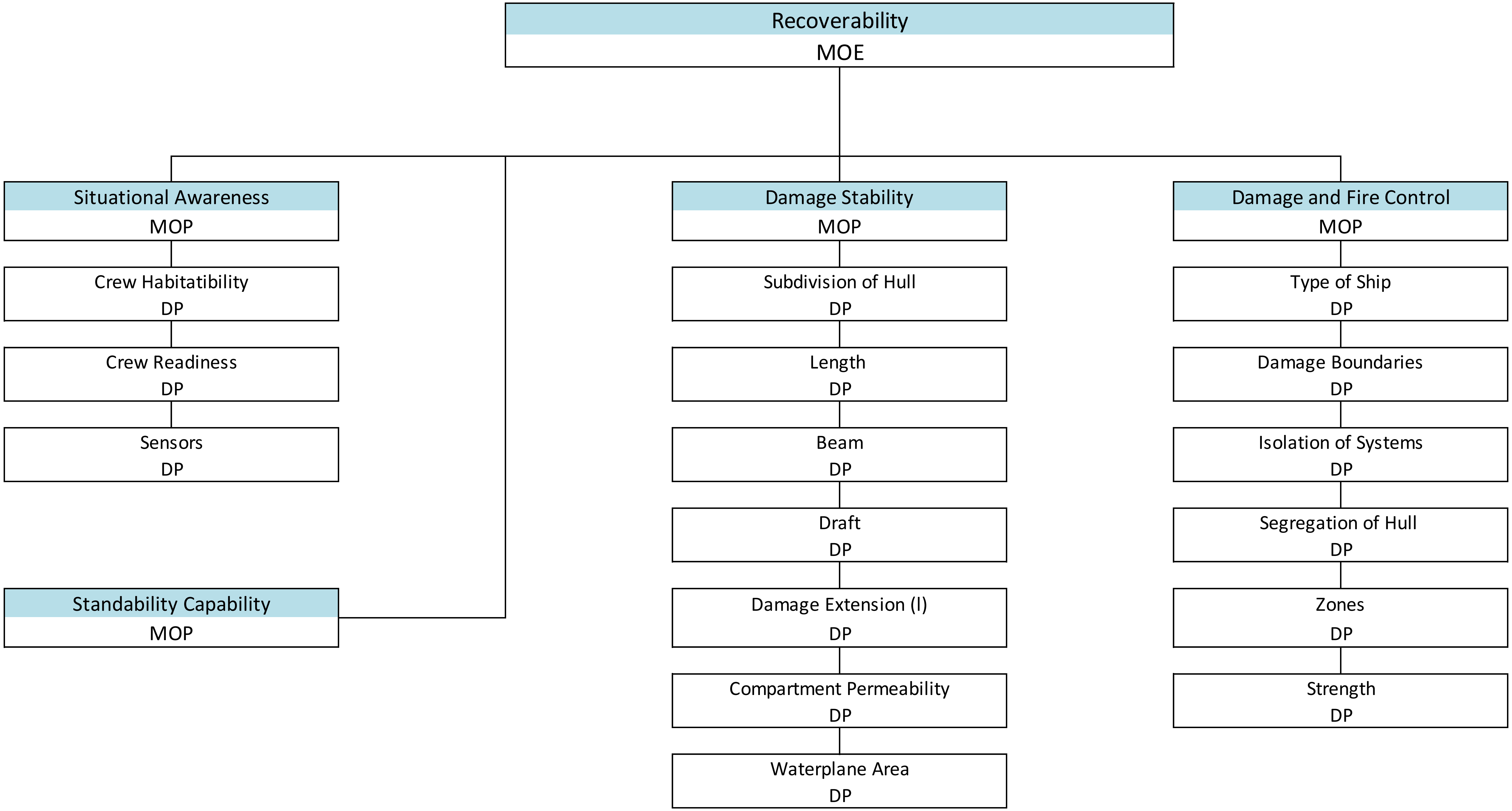
All of the above options and/or their consolidated results should be examined over the ship impact and cost in order to conclude an ideal system's design.

This study provides the aforementioned competence to ship designers through the methodology described. It is indeed required to perform a reliability analysis to ship vulnerability assessment process. System's components reliability and redundancy, redundant component separation, and component hardening and protection features can be decided rather rationally by the ship designer who would be capable to do so via this papers descriptions as well as develop an analytical competence.

6.5. Recoverability

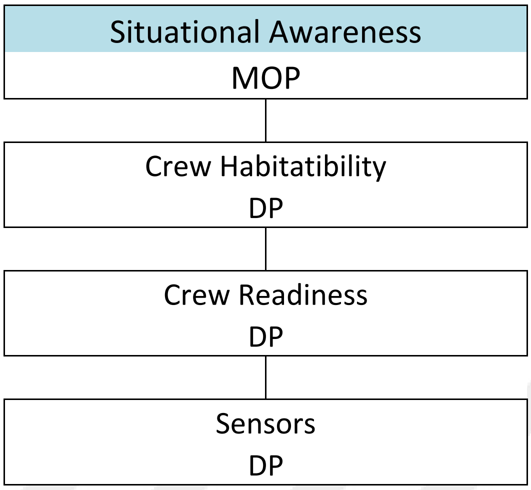
To be able to control the incoming effective damage and adapt to the environment and situation the warship is in is called recoverability. Factors to be taken in consideration must be; situational awareness, damage boundaries, damage control, recoverable systems through isolation, segregation, reconfiguration and recovery.

In the aftermath of an impact, immediate equipment damage and personnel injury analyses should be performed to determine the effect of combat damage on mission readiness and capabilities. After observing and analysing the magnitude and the type of the damage incurred, an equipment repair analysis and personnel recovery analysis should take place. These analyses will then lead to restoring the ships capabilities where available or switching to their alternatives, manning the operating positions and appointing damage control personnel to already stabilized damaged areas to start the repairing process. This also means that specific spare parts would have to be carried on board and the operators should be trained to diagnose and repair necessary systems. The recoverability as mentioned in this paper is to satisfy the minimum requirements to carry on the mission or at least get out of the battle zone, not necessarily with full capabilities but most probably at a degraded condition, although working. Total repair can only, and will be performed when the ship is docked at a friendly harbour.



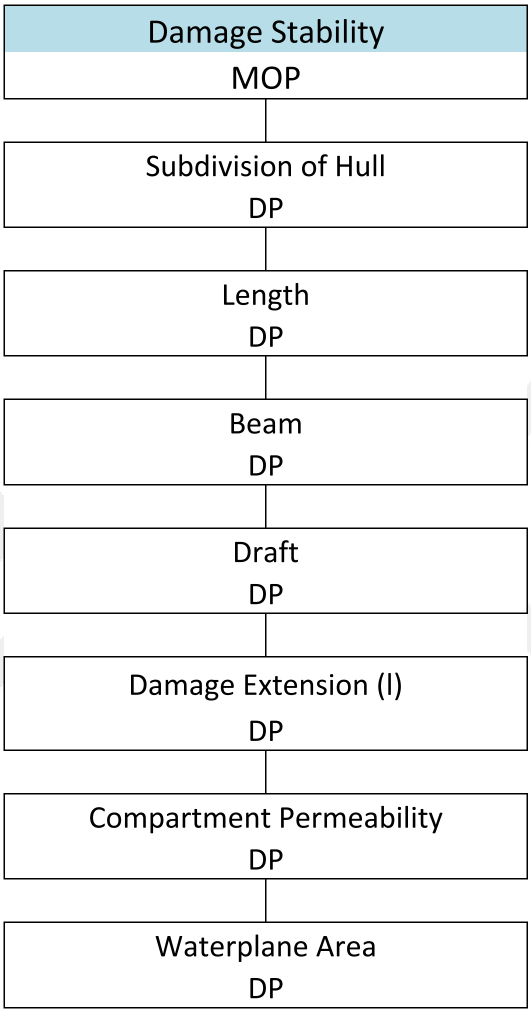
$MOE_{RECOVERABILITY}$

6.5.1. Situational Awareness



Situational awareness is dependent on crew readiness for any given circumstance and the up-time of sensors.

6.5.2. Damage Stability



Damage stability criteria must be compatible with intact stability criteria. It is very beneficial to do damage length calculations during predesign to eliminate damage stability complications. Length and number of compartments are decided upon damaged length calculations provided by class society rules.

Damage Stability criteria is based on the fundamental probabilistic damage stability concept introduced by Wendel in 1960 and IMO Resolution A.265 was derived from his work. Therefore, a probabilistic approach can be made with two probabilities of events relevant to the warships damage stability. [51, 53]

They are;

1) p_i, which is the probability of a ship compartment or group of compartments i may be flooded or damaged, under consideration p.
2) s_i, which is the probability of survival after flooding of a ship compartment or group of compartments i, under consideration s.

The overall survivability probability is expressed with "A", which is the attained subdivision index. A is the sum of products of p_i and s_i for each compartment or group of compartments i, along the length of the ship. Formula can be written as;

$$A = \sum_{i} pi \, . \, si$$

Ataseven and Yılmaz stated that; "since the index A is acceptable as a true measure of safety of ships, it is assumed that this index does not need to be supported by other deterministic conditions." [51].

Table 6.4 - Proposed Damage Stability Criteria for Warships [53]

$s_i = 1$	$\theta_{roll} = 25$ deg Wind Speed = according to DDS-079-1 $A_1 \geq 1.4\ A_2$ Min. Freeboard $\geq$ 3in + 0.5 x (H_S(0.99)- 8ft)
$s_i = P(H_S \leq 8ft)$	Ship meets DDS-079 damaged stability criteria.
$s_i = 0$	$\theta_{roll} = 10$ deg. Wind speed $\leq$ 11 knots $A_1 \leq 1.05\ A_2$ Margin line immerses.

The damage is applied anywhere within the ships length L, if there is any continuous breach in the hull of the ship caused by a combat shot or an event at the sea..

Table 6.5 - Damage Stability Criteria

Longitudinal Damage Extension	$L \leq 91{,}5$ m	The extension of damage causes the flooding of two adjacent watertight compartments
	$L \geq 91{,}5$ m	Category I – 0.15L Category II – extension of two adjacent compartments.
Vertical Damage Extension	All deck closures and platforms within the damaged area are destroyed.	
Transversal Damage Extension	The damage may reach the centre line of the ship without nevertheless including it.	

Minimum Length of a Compartment and main watertight compartment has to be;

- 3m + %3 Lbp for a ships length between perpendiculars less than 250 m.
- 10,5 m for ships of length between perpendiculars not less than 250 m.

In case of flooding after the breach, cross-flooding and equalisations has to be done in;

a) For cross-flooding conditions that are accepted are;

   1) Self-acting cross connection
   2) The system is independent without any power supply
   3) The controlled flooding is to be completed in time;

   - $D < 4500$ t - less than 2 mins
   - $4500t < D < 10000t$ - less than $0{,}1(D/1000)^2$ mins
   - $D > 10000$ t - less than 10 mins

b) For passive equalisation; manually operated controls from the above the damage control deck should be used. These controls should be operable with a maximum heel angle of 20^{O} and the control system has to be independent from any power supply. Time needed may not exceed 15 minutes.

c) For active equalisation mechanically driven systems may be used after passive equalisation in order to right the ship, if it is not prohibited by the stability manual.

Survival Condition defined after flooding according to criteria is that;

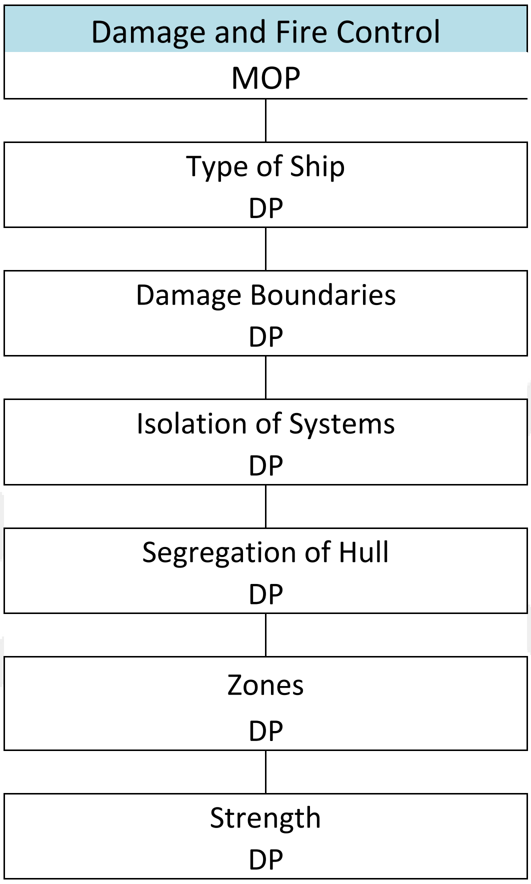
1) θ_e Equilibrium heeling angle after damage should not exceed 20^{O}.
2) After passive equalisation θ_e should not exceed 15^{O}.
3) The initial metacentric height value at a null angle has to be positive.

Recalculated stability criteria should be in accordance with;

1) GMcorr > 0
2) GZmax – GZheel > 0 – before equalisation, never to capsize.
3) GZmax – GZheel > 0.08m

Input parameters that effect damage stability calculations are L, B, T, damaged length ‘l’ and displacement.

6.5.3. Damage And Fire Control



Damage control phase comes right after the ship had suffered damage from an impact. The worst two scenarios that can arise are fire and flooding that can lead to total kill. The main objective of fire fighting is to prevent the fire from spreading to explosive equipment or substances such as fuel or gas lines, tanks and ammunition. Fire spreading to power lines and other connections to vital systems of the ship such as combat or navigation systems may increase the damage further. The flooding of the ship may change the stability and sea keeping parameters, leading to hindered mobility and ultimately causing the ship to sink, loss of asset and crew to total kill. Such as with the fire, flooding may also disrupt electrical systems on board if not controlled and lead to a primary or combat system kill or a HM&E support system kill, rendering the vessel useless. It is beneficial for a ship to have automated recoverability services, such as automatic water or powder spray systems during fire and emergency stop systems to isolate the flammable media. Traditionally, a ship is divided longitudinally into a number of watertight compartments to restrict the flooding to one or more compartments in case of damage. This prevents flooding across the entire ship's length in case of damage at any location. The compartmentalization is done by means of transverse watertight bulkheads [59].

Damage Control Head Quarters are vital for a ships survivability process. Minimum of two well separated, self-sustained DCHQ must be embedded into the ship during design phase. In case of partly damage, these damage control headquarters must be able to undertake the mission on its own. Quantity of damage control headquarters are dependent on the zones ship has been divided into. Division and sizing for zones are determined depending on ships stability calculations, weapon and command and control systems as well as length, beam, draft and general arrangement of the warship. During peacetime all zones of the ship are openly connected, but during war, ships damage control zones and watertight boundaries close down.

According to worlds navies, several damage stability criteria's are used. Such as for Royal Navy, UK Defstan 02-900, for US Navy, U.S.N DDS 079-1 and for German Navy, BV 1033.

6.5.4. Standability Capability – Capsize

Standability Capability
MOP

MOE Mobility calculation re-done for damaged ship, heel angle not to exceed 60 degrees.

Therefore all parameters effecting $MOE_{MOBILITY}$ is effecting standability capability.

Last MOE needed for OMOE function, $MOE_{RECOVERABILITY}$ becomes;

$$MOE_{RECOVERABILITY} = (MOP_{AWARENESS} \cup MOP_{DAMAGESTABILITY} \cup MOP_{DAMAGEFIRECONTROL} \cup MOP_{STANDABILITY}) - (MOP_{AWARENESS} \cap MOP_{DAMAGESTABILITY} \cap MOP_{DAMAGEFIRECONTROL} \cap MOP_{STANDABILITY})$$

$$MOE_{RECOVERABILITY} = (MOP_{AWARENESS} + MOP_{DAMAGESTABILITY} + MOP_{DAMAGEFIRECONTROL} + MOP_{STANDABILITY}) - (MOP_{AWARENESS} * MOP_{DAMAGESTABILITY} * MOP_{DAMAGEFIRECONTROL} * MOP_{STANDABILITY})$$

7. CASE STUDY

For this case study, targeted surface battle platforms were divided into four categories according to their type which are; patrol vessels, corvettes, frigates and destroyers. Main dimensions of the freeboard according to what system has been loaded on board and vessels length due to manoeuvrability and shipping performance are the qualities to come into prominence. All the naval architecture parameters and formulas concerning speed, length or displacement were checked and used in the main analysis (See Appendix A).

To be able to perform system analysis comparison between selected vessels fitting the RFI given, a total of hundred combatants from different countries have been selected to perform parametric analysis. To be exact, 23 patrol vessels, 26 corvettes, 38 frigates and 14 destroyers have been selected, which yielded the results below, ranging from 350 to 8000 tons with various mission roles and ship types.

Furthermore, RFI for a combined patrol corvette (CPC) for the replacement of existing aged fleet has been provided. In order to achieve the same, top level requirements can be seen below in the tables 11, 12 and 13.

Table 7.1 - Top Level Requirements for CPC

TOP LEVEL REQUIREMENTS FOR COMBINED PATROL CORVETTE CPC	
MISSIONS	• Anti-Submarine Warfare • Anti-Submarine patrolling in approaching waters of bases and ports • Reconnaissance and Surveillance • Control and Protection of Littoral Transportation • Base and Port Defence
OPERATION AREAS	• Black Sea • Aegean Sea • Mediterranean Sea - Shall be operable in seas world-wide excluding Arctic Sea.

LIFE-CYCLE	35 years with minimum maintenance and repair.
DISPLACEMENT	Not to exceed 3000 tons.
ENDURANCE	- Range at Cruising Speed 4500NM(with %90 fuel consumption) - Provisions for 20 days at least. Fuel replenishment can be done at sea. - Range is defined for full load departure condition according to US NAVY DDS 079-1.
COMPLEMENT	180 persons. - Should be able to accomodate 195 people including helicopter persons.
SEAKEEPING	SEA STATE 5 o Helicopter Operations : SEA STATE 4
MANOUEUVERABILITY	- Steady Turning Circle Diameter < 5 Lwl, rudder at 35 degrees - Astern Speed not less than 8 knots - Crash Stopping < 5 Lwl, < 70 seconds, All calculations made with maximum speed.
ACCELERATION	0 knots to maximum speed in 90 seconds.
TOP LEVEL REQUIREMENTS FOR COMBINED PATROL CORVETTE CPC	
SPEED	Cruising : 22+ knots Quite : 15+ knots Sustained : 30+ knots Sprint : 32+ knots (for minimum 30 mins)
COMPARTMENTS	5
DAMAGE CONTROL ZONES	3
Maximum SPEED and ENDURANCE for Beaufort 2, Sea State 2, Waterdepth minimum 75 meters.	

Table 7.2 - Top Level Requirements for CPC

Minimum speed with no restriction by the motions given below;	15 knots
Significant Roll (degrees)	8 knots
Significant Pitch (degrees)	3 knots
Significant Vertical Accelerations at CIC	0.4g
Slamming occurences per hour	20
Deck wetness occurences per hour	30

Significant Roll (degrees)	5 knots
Significant Pitch (degrees)	2 knots
Significant Vertical Velocity at Flight deck (m/sec)	1,4-2

Table 7.3 - Operational Areas Wave Characteristics for CPC

Sea State	Significant Wave Height (m)	Black Sea Modal Wave Period (sec)	Mediterranean Modal Wave Period (sec)	Aegean Sea Modal Wave Period (sec)
3	0,5-1,25	4 - 5	6 - 7	4 - 5
4	1,25-2,50	7 - 8	8 - 9	6 - 7
5	2,50-4	8 - 9	10 - 11	7 - 8

Four (4) frigates were selected for system analysis and measure of merit calculations, which are similar and suitable for the RFI characteristics provided. The comparison enables one to analyse and understand which areas need further improvement for the latest design. All aspects and areas required for the designing phase as well as building the combatant will be covered through system breakdown and be ranked according to the performance of its associated parameters. Evaluation of these parameters is further explained in Appendix A.

Characteristics of ships assessed for system analysis comparison can be seen below in the tables 14 and 15.

Table 7.4 - Main Dimensions and Parameters

	Vessel (Class)			
	Frigate A	Frigate B	Frigate C	Frigate D
Length Overall	115,50	118,00	118,80	123,00
Length Waterline	110,88	113,28	114,05	118,08
Beam	14,20	14,80	17,60	13,20
Draft	4,10	4,30	4,30	3,80
Freeboard	4,44	4,53	4,56	4,72
Depth Minimum	8,54	8,83	8,86	8,52
Volume	2893,7	3350,2	3272,2	2907,3
Displacement	2966,00	3434,00	3354,00	2980,00
Maximum Speed	27	32	40	29
Endurance Speed	18	18	18	18
Range	4100	4100	3500	4000
Installed Power	22000,0	53430,0	84800,0	20700,0
Propulsion System	CODAD	CODOG	CODAG	CODAD
Complement	180	196	50	202

Table 7.5 - Additional Parameters

	Vessel (Class)			
	Frigate A	Frigate B	Frigate C	Frigate D
Cb	0,448	0,465	0,379	0,491
Cm	0,945	0,946	0,938	0,949
Cp	0,474	0,491	0,404	0,517
Cvp	0,653	0,668	0,583	0,692
Cwa	0,687	0,695	0,650	0,709
WSA	1480,437	1608,772	1595,970	1535,230
L/B	7,605	7,455	6,311	8,710
L/T	27,044	26,344	26,523	31,070
L/D	12,991	12,827	12,869	13,850
B/T	3,463	3,442	4,093	3,470
B/D	1,664	1,676	1,986	1,549
Slenderness Ratio (L)	7,781	7,570	7,682	8,273
Slenderness Ratio (B)	0,996	0,989	1,185	0,925
Froude No	1,319	1,547	1,927	1,373
GM/B	0,082	0,080	0,199	0,042
Gzmax	7,140	7,600	7,486	6,935
Bales 'R' factor	5,822	5,450	5,547	7,637
Sfc	4070,000	9884,000	15688,000	3829,500
RCS	4199,814	5232,073	5050,309	4229,585

Thresholds of additional parameters taken from charts can accelerate the design phase by knowing the safety zone values for preliminary design. Thresholds are considered as logarithmic functions of associated values to give more precise values of safety zones, set according to the 100 ships taken into account in parametric analysis for this thesis.

If different ships are added to the list, the thresholds in question may vary. All parameters are plotted against displacement. (See Appendix B)

Table 7.6 - Thresholds of Parameters

Parameter	Threshold				
	Patrol Vessels	Corvettes	Frigates	Destroyers	Average
Cb	0,37	0,385	0,4	0,4	0,410-0,450
Cm	0,937	0,938	0,94	0,94	0,941-0,945
Cp	0,395	0,41	0,43	0,437	0,430-0,450
Cvp	0,57	0,585	0,6	0,61	0,610-0,650
Cwa	0,65	0,655	0,665	0,67	0,665-0,680
L/B	6,2	5,7	7,4	7,2	6,2-8,2
L/T	20,5	22,5	22,8	23	22-25,5
L/D	11,2	11,75	12,9	12,95	11,6-12,5
B/T	3,22	3	3,05	3	3,05-3,5
B/D	1,75	1,48	1,52	1,4	1,5-1,85
Slenderness Ratio (L)	7	7	7,58	7,5	6,98-7,85
Slenderness Ratio (B)	1,07	0,88	0,925	0,895	0,93-1,12
Froude No	> 1,1				
GM/B	positive	positive	positive	positive	0,03-0,14
Gzmax	3,6	3,7	5,7	7,6	3,25-8,75
Bales 'R' factor	> 1	> 1	> 1	> 1	1,00 - 10,00

Design parameters, their descriptions and their rankings, can be seen in the below in table 7.7, which have been prepared for this case study through experience and collective data available. For parameters that can neither be calculated with an empirical formula nor with any given ratios, the number stated were attained through know-how and collected through the research done for this thesis. These ranks have been assigned to their assumed ratios between 0 and 1. For analysis, threshold and goal values have been set for each aspect by assessing the data that is obtained from parametric analysis tables.

MOE	Design Parameter	Description	Threshold	Goal	Ratios
Mobility	Speed	Between 0,9-1; If maximum speed exceeds given goal speed, =1 If maximum speed is below goal speed, ratio between them is them is used if it is between 0,9-1. Less than 0,9 is rejected.	Maximum Speed in knots	30 knots or more	$\frac{\text{Maximum Speed}}{30}$
	Endurance • Range/Fuel Capacity	1- 7000 nm 2- 5500 nm 3- 4000 nm 4- 2500 nm	Minimum 2500 nm	7000nm or more	$\frac{\text{Total Range Endurance}}{4500}$
	Endurance • Storage	1- 60 days 2- 45 days 3- 30 days 4- 20 days	Minimum 20 days	20 days or more	$\frac{\text{Total Storage Endurance}}{20}$
	Endurance • Combat	1- 5 days 2- 3 days 3- 1 day	Minimum 1 day	5 days or more	$\frac{\text{Total Combat Endurance}}{5}$
	Seakeeping	Bales 'R' Factor, between 1-10, ratio of the calculated factor between 0-1	1	10	$\frac{\text{Bales'R'Factor}}{10}$
	Manoeuvrability • Turning Circle • Initial Turning Ability • Crash Stopping • Astern Speed	Between 0-1; Between 0-1; Succeeded or Failed; Minimum of 7 knots according to DIN Standards.	6,7L 3,5L - 7 knots	3L 2L depending on the angle < 5 LWL, in less than 70 secs. 8 knots	$\frac{\text{Turning Circle Distance}}{\text{LWL}}$ $\frac{\text{Initial Turning Ability}}{\text{LWL}}$ $\frac{\text{Crash Stopping Time}}{\text{70 secs}}$ $\frac{\text{Crash Stopping Distance}}{\text{5 x Lwl}}$ $\frac{\text{Astern Speed}}{\text{8 knots}}$
	Stability	In accordance with Stability Criterias for Naval Ships. 1- Passed with elegance 2- Passed with limits 3- Failed	2	1	1 = 1 2 = 0,50 3 = 0
	Sustainability	1- Full redundancy of all systems and self-sustained ship. 2- Semi Redundant with vital systems covered. 3- None or no-effective redundancy of systems.	2	1	1 = 1 2 = 0,50 3 = 0
	Propulsion System /	1- Efficient Hull Form with high efficiency and less sfc. 3- Low Efficient Hull Form with high sfc.	3	1	1 = 1 2 = 0,75 3 = 0,50
Susceptibility	Visual Signature	1- Full stealth with minimum wake and camouflage. 2- Full stealth with camouflage. 3- Semi-stealth with camouflage. 4- Easily visible by human-eye, wake persistent form.	4	1	1 = 0,95 2 = 0,85 3 = 0,50 4 = 0,10
	Radar Signature	Between 0-1, closer to 1 means the ratio between reduced RCS and actual RCS has a smaller value.	<1	≥ 0	1 = ~%10 = 0,90 2 = ~%30 = 0,70 3 = ~%50 = 0,50 4 = ~%75 = 0,25 5 = ~%90+ = 0,10 OR
	Radar Signature	Actual ratio at the given time;	0,9	0,1+	$\frac{\text{reduced RCS}}{\text{Actual RCS}}$
	Infra-Red Signature	1- Temperature difference doesn't exist. 2- Temperature difference is acceptable. 3- Temperature difference is rather different.	2	1	1 = 0,95 2 = 0,60 3 = 0,30 OR
	Infra-Red Signature	Actual ratios at the given time;	0,50	1	$\frac{\text{Gas Temperature}}{\text{Background Temperature}}$ $\frac{\text{Wake Temperature}}{\text{Background Temperature}}$ $\frac{\text{Ship Surface Temperature}}{\text{Background Temperature}}$
	Acoustic Signature	1- Isolated structure with resilient mounted equipment. 2- Resilient mounted equipment without isolation. 3- Isolated structure without resilient mounted equipment. 4- Non-isolated structure.	0,30	0,95	1 = 0,95 2 = 0,70 3 = 0,60 4 = 0,30
	Magnetic/Electromagnetic Signature	1- Avoiding usage of ferromagnetic materials on vessel and/or 2- Cathodic protection of hull 3- Degaussing	0,50	0,95	1 = 0,95 2 = 0,70 3 = 0,50
Vulnerability	Concentration	1- Minimum operational volume achieved with compact systems. 2- Conventional layout	0,50	1	1 = 1 2 = 0,50
	Duplication / Redundancy / Seperation	1- Full redundancy of all systems. 2- Full redundancy of vital systems only. 3- Redundancy for propulsion system only.	0,30	1	1 = 1 2 = 0,60 3 = 0,30
	Structural Strength	1- Usage of High Strength Material with Longitudinal Framing. 2- Longitudinal Framing 3- Transversal Framing	0,50	1	1 = 1 2 = 0,75 3 = 0,50
	Zoning	1- 3 zone 2- 2 zone 3- 1 zone	3	3	$\frac{\text{Current Zone Number}}{\text{Goal Zone Number}}$
Recoverability	Situational Awareness	1- Crew trained and well-in-order for mission. 2- Crew trained for mission. 3- Crew not ready for mission requirements in given time.	0,60	1	1 = 1 2 = 0,60 3 = 0,15
	Damage Stability	In accordance with Damage Stability Criterias for Naval Ships. 1- Passed with elegance 2- Passed with limits 3- Failed	0,50	1	1 = 1 2 = 0,50 3 = 0
	Damage and Fire Control	1- 3 zone 2- 2 zone 3- 1 zone	3	3	$\frac{\text{Current Zone Number}}{\text{Goal Zone Number}}$
	Standability Capability	1- None of the above. Survived all. 2- Hull, Machinery, Electrical System Kill 3- Primary/Secondary System Kill 4- Mission Area Kill 5- Mobility Kill 6- Total Kill	0,30	1	1 = 1 2 = 0,75 3 = 0,50 4 = 0,30 5 = 0,15 6 = 0

Table 7.7 - Design Parameters, Descriptions and Ranks

A radar with characteristics seen below in Table 17 has been selected for radar cross section in $MOE_{SUSCEPTIBILITY}$ calculations taken from [4], which is a A Band NATO approved radar with 1,20m wavelength. Radar related parameters are based on this value for all equations.

Table 7.8 - A Band Radar [4]

Property	**Value**	**Dimension**
Receiver Sensitivity	IE-14	W(m)
Operation Frequency	0,25	[GHz]
Distance from radar	25	[m]
Angle	90	[θ]
Noise Factor	2,50E-16	[w]
Temperature	195	[F]

As cited on the Table 7.6, some ships have negative GM/B values. Eames and Drummond's [57] 1975 paper is the primary source that has been referred while calculating preliminary stability calculations. The paper is focusing on preliminary empirical formulas covering small warship design. The results obtained are values based on these formulas and may vary with actual data calculated through tests of already-been-built combatants. Author believes that functioning real life ships may not have negative GM values unlike the results shown in the below chart.

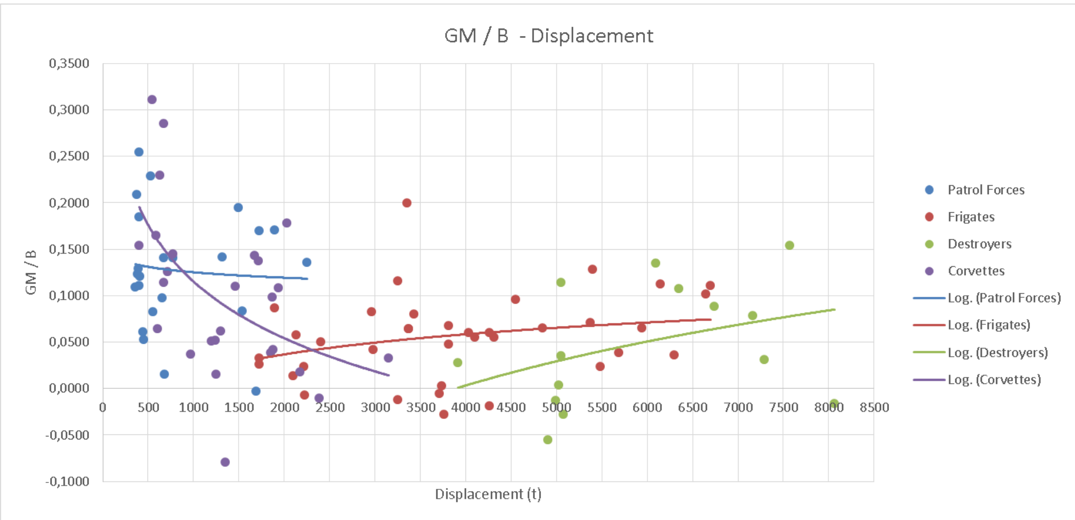


Figure 7.1- GM Chart

This has proven that the results in this thesis are not necessarily correct due to all listed ships are belonging to naval forces with very restricted and limited accessible data available used. Therefore, theoretical assumptions related to empirical formulas along with the collective data are the main sources while advancing on the case study process. For example, to be able to estimate 'Seakeeping Rank 'R' Factor', all combatants in parametric analysis have been given a C_{WF} of 0,95, C_{WA} of 0,65, C_{VPF} of 0,75 and C_{VPA} of 0,69.

If there is any given scenario at a given time for a mission, $\frac{\text{remaining value}}{\text{maximum value}}$ and/or $\frac{\text{actual occurance}}{\text{maximum allowable occurance}}$ can be used for parameters within a given ratio instead of rankings. This will lead to a better OMOE result, as real numerator and denominator will be present for the MOP function. The MOP result is to provide the exact value for that given time.

The final formulas for MOE's are concluded as;

Mobility -

$$MOE_{MOBILITY} = \Big(\frac{\text{maximum speed}}{30} \cup \Big(\frac{\text{total range endurance}}{4500} \text{ x } \frac{\text{total storage endurance}}{20} \text{ x } \frac{\text{total combat endurance}}{5}\Big) \cup \frac{\text{Bales R Factor}}{10} \cup \Big(\frac{\text{Turning Circle Distance}}{\text{Lwl}} \text{ x } \frac{\text{Initial Turning Ability}}{\text{Lwl}} \text{ x } \frac{\text{Crash Stopping Time}}{70} \text{ x } \frac{\text{Crash Stopping Distance}}{5\text{Lwl}} \text{ x } \frac{\text{Astern Speed}}{8}\Big) \cup \text{stability rank ratio} \cup \text{sustainability rank ratio} \cup \text{resistance rank ratio}\Big) - \Big(\frac{\text{maximum speed}}{30} \cap \Big(\frac{\text{total range endurance}}{4500} \text{ x } \frac{\text{total storage endurance}}{20} \text{ x } \frac{\text{total combat endurance}}{5}\Big) \cap \frac{\text{Bales R Factor}}{10} \cap \Big(\frac{\text{Turning Circle Distance}}{\text{Lwl}} \text{ x } \frac{\text{Initial Turning Ability}}{\text{Lwl}} \text{ x } \frac{\text{Crash Stopping Time}}{70} \text{ x } \frac{\text{Crash Stopping Distance}}{5\text{Lwl}} \text{ x } \frac{\text{Astern Speed}}{8}\Big) \cap \text{stability rank ratio} \cap \text{sustainability rank ratio} \cap \text{resistance rank ratio}\Big)$$

$$MOE_{MOBILITY} = \left(\frac{\text{maximum speed}}{30} + \left(\frac{\text{total range endurance}}{4500} \text{ x } \frac{\text{total storage endurance}}{20} \text{ x } \frac{\text{total combat endurance}}{5}\right) + \frac{\text{Bales R Factor}}{10} * \left(\frac{\text{Turning Circle Distance}}{\text{Lwl}} \text{ x } \frac{\text{Initial Turning Ability}}{\text{Lwl}} \text{ x } \frac{\text{Crash Stopping Time}}{70} \text{ x } \frac{\text{Crash Stopping Distance}}{5\text{Lwl}} \text{ x } \frac{\text{Astern Speed}}{8}\right) + \text{stability rank ratio} + \text{sustainability rank ratio} + \text{resistance rank ratio}\right) - \left(\frac{\text{maximum speed}}{30} * \left(\frac{\text{total range endurance}}{4500} \text{ x } \frac{\text{total storage endurance}}{20} \text{ x } \frac{\text{total combat endurance}}{5}\right) * \frac{\text{Bales R Factor}}{10} * \left(\frac{\text{Turning Circle Distance}}{\text{Lwl}} \text{ x } \frac{\text{Initial Turning Ability}}{\text{Lwl}} \text{ x } \frac{\text{Crash Stopping Time}}{70} \text{ x } \frac{\text{Crash Stopping Distance}}{5\text{Lwl}} \text{ x } \frac{\text{Astern Speed}}{8}\right) * \text{stability rank ratio} * \text{sustainability rank ratio} * \text{resistance rank ratio}\right)$$

Susceptibility -

$$MOE_{SUSCEPTIBILITY} = \left(\text{RCS rank ratio OR } \frac{\text{Reduced RCS}}{\text{Actual RCS}} \cup \text{IR rank ratio OR } \left(\frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}\right) \cup \text{acoustic rank ratio} \cup \text{visual rank ratio} \cup \text{e/m rank ratio}\right) - \left(\text{RCS rank ratio OR } \frac{\text{Reduced RCS}}{\text{Actual RCS}} \cap \text{IR rank ratio OR } \left(\frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}\right) \cap \text{acoustic rank ratio} \cap \text{visual rank ratio} \cap \text{e/m rank ratio}\right)$$

$$MOE_{SUSCEPTIBILITY} = \left(\text{RCS rank ratio OR } \frac{\text{Reduced RCS}}{\text{Actual RCS}} + \text{IR rank ratio OR } \left(\frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}\right) + \text{acoustic rank ratio} + \text{visual rank ratio} + \text{e/m rank ratio}\right) - \left(\text{RCS rank ratio OR } \frac{\text{Reduced RCS}}{\text{Actual RCS}} * \text{IR rank ratio OR } \left(\frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}\right) * \text{acoustic rank ratio} * \text{visual rank ratio} * \text{e/m rank ratio}\right)$$

Vulnerability -

$$MOE_{VULNERABILITY} = (\text{concentration rank ratio} \cup \text{duplication/redundancy/separation rank ratio} \cup \text{structural strength rank ratio} \cup \frac{\text{Current Zone Number}}{\text{Goal Zone Number}}) - (\text{concentration rank ratio} \cap \text{duplication/redundancy/separation rank ratio} \cap \text{structural strength rank ratio} \cap \frac{\text{Current Zone Number}}{\text{Goal Zone Number}})$$

$$MOE_{VULNERABILITY} = (\text{concentration rank ratio} + \text{duplication/redundancy/separation rank ratio} + \text{structural strength rank ratio} + \frac{\text{Current Zone Number}}{\text{Goal Zone Number}}) - (\text{concentration rank ratio} * \text{duplication/redundancy/separation rank ratio} * \text{structural strength rank ratio} * \frac{\text{Current Zone Number}}{\text{Goal Zone Number}})$$

Recoverability -

$$MOE_{RECOVERABILITY} = (\text{situational awareness rank ratio} \cup \text{damage stability rank ratio} \cup \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} \cup \text{standability rank ratio}) - (\text{situational awareness rank ratio} \cap \text{damage stability rank ratio} \cap \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} \cap \text{standability rank ratio})$$

$$MOE_{RECOVERABILITY} = (\text{situational awareness rank ratio} + \text{damage stability rank ratio} + \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} + \text{standability rank ratio}) - (\text{situational awareness rank ratio} * \text{damage stability rank ratio} * \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} * \text{standability rank ratio})$$

Checking Brown's MOP weights chart (Figure 3.6), it is visible that IR Signature, Acoustic Signature, Redundancy, Hull and Topside RCS, Reliability (Sustainability), Stores Duration, Range, Speed and Seakeeping MOP's that both studies have referred. Therefore, weights of these ratios have been added to the respective MOE estimation formula.

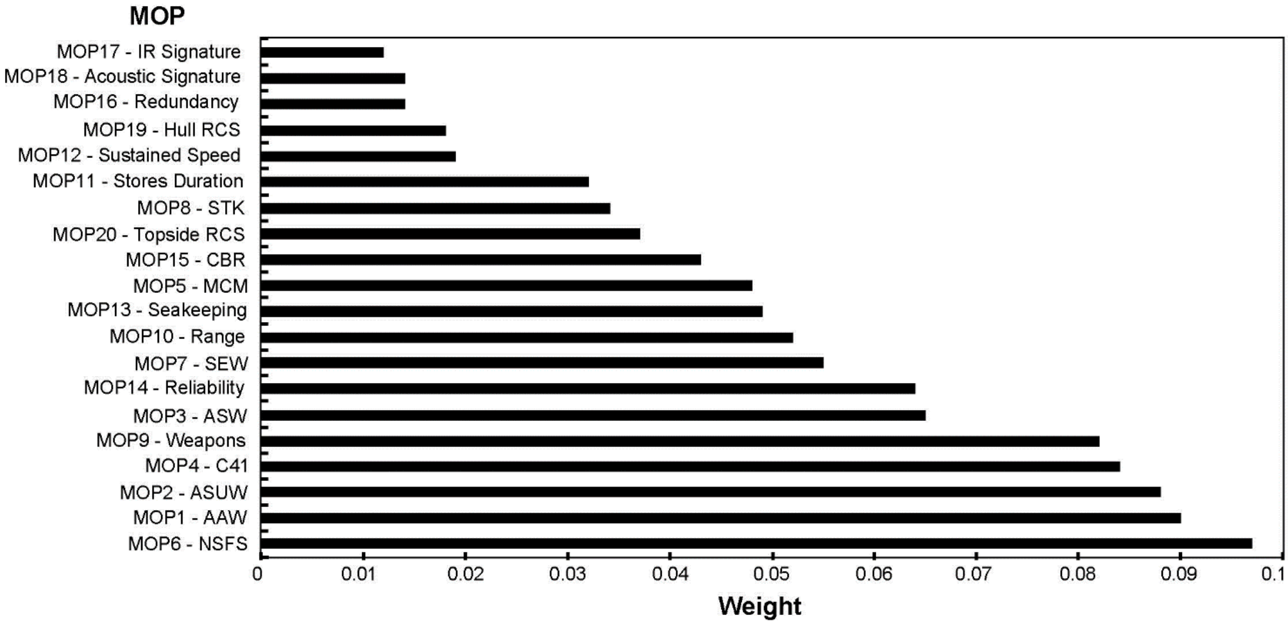


Figure 3.6 - Measure of Performance (MOP) Weights [36]

New formulas become;

Mobility -

$$MOE_{MOBILITY} = (0{,}02\ x\ \frac{\text{maximum speed}}{30} \cup (0{,}054\ x\ \frac{\text{total range endurance}}{4500}\ \text{x}\ 0{,}033\ x\ \frac{\text{total storage endurance}}{20}\ \text{x}\ 0{,}033\ x\ \frac{\text{total combat endurance}}{5}) \cup 0{,}05\ x\ \frac{\text{Bales R Factor}}{10} \cup (\frac{\text{Turning Circle Distance}}{\text{Lwl}}\ \text{x}\ \frac{\text{Initial Turning Ability}}{\text{Lwl}}\ \text{x}\ \frac{\text{Crash Stopping Time}}{70}\ \text{x}\ \frac{\text{Crash Stopping Distance}}{5\text{Lwl}}\ \text{x}\ \frac{\text{Astern Speed}}{8}) \cup \text{stability rank ratio} \cup 0{,}064\ \text{x sustainability rank ratio} \cup \text{resistance rank ratio}) - (0{,}02\ x\ \frac{\text{maximum speed}}{30} \cap (0{,}054\ x\ \frac{\text{total range endurance}}{4500}\ \text{x}\ 0{,}033\ x\ \frac{\text{total storage endurance}}{20}\ \text{x}\ 0{,}033\ x\ \frac{\text{total combat endurance}}{5}) \cap 0{,}05\ x\ \frac{\text{Bales R Factor}}{10} \cap (\frac{\text{Turning Circle Distance}}{\text{Lwl}}\ \text{x}\ \frac{\text{Initial Turning Ability}}{\text{Lwl}}\ \text{x}\ \frac{\text{Crash Stopping Time}}{70}\ \text{x}\ \frac{\text{Crash Stopping Distance}}{5\text{Lwl}}\ \text{x}\ \frac{\text{Astern Speed}}{8}) \cap \text{stability rank ratio} \cap 0{,}064\ \text{x sustainability rank ratio} \cap \text{resistance rank ratio})$$

$$MOE_{MOBILITY} = (0{,}02\ x\ \frac{\text{maximum speed}}{30} + (0{,}054\ x\ \frac{\text{total range endurance}}{4500}\ \text{x}\ 0{,}033\ x\ \frac{\text{total storage endurance}}{20}\ \text{x}\ 0{,}033\ x\ \frac{\text{total combat endurance}}{5}) + 0{,}05\ x\ \frac{\text{Bales R Factor}}{10} + (\frac{\text{Turning Circle Distance}}{\text{Lwl}}\ \text{x}\ \frac{\text{Initial Turning Ability}}{\text{Lwl}}\ \text{x}\ \frac{\text{Crash Stopping Time}}{70}\ \text{x}\ \frac{\text{Crash Stopping Distance}}{5\text{Lwl}}\ \text{x}\ \frac{\text{Astern Speed}}{8}) + \text{stability rank ratio} + 0{,}064\ \text{x sustainability rank ratio} + \text{resistance rank ratio}) - (0{,}02\ x\ \frac{\text{maximum speed}}{30} * (0{,}054\ x\ \frac{\text{total range endurance}}{4500}\ \text{x}\ 0{,}033\ x\ \frac{\text{total storage endurance}}{20}\ \text{x}\ 0{,}033\ x\ \frac{\text{total combat endurance}}{5}) * 0{,}05\ x\ \frac{\text{Bales R Factor}}{10} * (\frac{\text{Turning Circle Distance}}{\text{Lwl}}\ \text{x}\ \frac{\text{Initial Turning Ability}}{\text{Lwl}}\ \text{x}\ \frac{\text{Crash Stopping Time}}{70}\ \text{x}\ \frac{\text{Crash Stopping Distance}}{5\text{Lwl}}\ \text{x}\ \frac{\text{Astern Speed}}{8}) * \text{stability rank ratio} * 0{,}064\ \text{x sustainability rank ratio} * \text{resistance rank ratio})$$

Susceptibility -

$$MOE_{SUSCEPTIBILITY} = (0{,}058 \text{ x RCS rank ratio OR } 0{,}058\text{x}\frac{\text{Reduced RCS}}{\text{Actual RCS}} \cup 0{,}014 \text{ x IR rank ratio OR } (0{,}014\, x \frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}) \cup 0{,}018 \text{ x acoustic rank ratio } \cup \text{ visual rank ratio } \cup \text{ e/m rank ratio}) - (0{,}058 \text{ x RCS rank ratio OR } 0{,}058\text{x}\frac{\text{Reduced RCS}}{\text{Actual RCS}} \cap 0{,}014 \text{ x IR rank ratio OR } (0{,}014\, x \frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}) \cap 0{,}018 \text{ x acoustic rank ratio } \cap \text{ visual rank ratio } \cap \text{ e/m rank ratio})$$

$$MOE_{SUSCEPTIBILITY} = (0{,}058 \text{ x RCS rank ratio OR } 0{,}058\text{x}\frac{\text{Reduced RCS}}{\text{Actual RCS}} + 0{,}014 \text{ x IR rank ratio OR } (0{,}014\, x \frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}) + 0{,}018 \text{ x acoustic rank ratio } + \text{ visual rank ratio } + \text{ e/m rank ratio}) - (0{,}058 \text{ x RCS rank ratio OR } 0{,}058\text{x}\frac{\text{Reduced RCS}}{\text{Actual RCS}} * 0{,}014 \text{ x IR rank ratio OR } (0{,}014\, x \frac{\text{Gas temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Wake temperature}}{\text{Background Temperature}} \text{ x } \frac{\text{Ship surface temperature}}{\text{Background Temperature}}) * 0{,}018 \text{ x acoustic rank ratio } * \text{ visual rank ratio } * \text{ e/m rank ratio})$$

Vulnerability -

$$\text{MOE}_{\text{VULNERABILITY}} = (\text{concentration rank ratio } \cup 0{,}018 \text{ x duplication/redundancy/separation rank ratio } \cup \text{ structural strength rank ratio} \cup \frac{\text{Current Zone Number}}{\text{Goal Zone Number}}) - (\text{concentration rank ratio } \cap 0{,}018 \text{ x duplication/redundancy/separation rank ratio } \cap \text{ structural strength rank ratio} \cap \frac{\text{Current Zone Number}}{\text{Goal Zone Number}})$$

$$\text{MOE}_{\text{VULNERABILITY}} = (\text{concentration rank ratio } + 0{,}018\text{x duplication/redundancy/separation rank ratio } + \text{ structural strength rank ratio} + \frac{\text{Current Zone Number}}{\text{Goal Zone Number}}) - (\text{concentration rank ratio } * 0{,}018\text{x duplication/redundancy/separation rank ratio } * \text{ structural strength rank ratio} * \frac{\text{Current Zone Number}}{\text{Goal Zone Number}})$$

Recoverability -

$$\text{MOE}_{\text{RECOVERABILITY}} = (\text{situational awareness rank ratio } \cup \text{ damage stability rank ratio } \cup \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} \cup \text{ standability rank ratio}) - (\text{situational awareness rank ratio } \cap \text{ damage stability rank ratio } \cap \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} \cap \text{ standability rank ratio})$$

$$\text{MOE}_{\text{RECOVERABILITY}} = (\text{situational awareness rank ratio } + \text{ damage stability rank ratio } + \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} + \text{ standability rank ratio}) - (\text{situational awareness rank ratio } * \text{ damage stability rank ratio } * \frac{\text{Current Zone Number}}{\text{Goal Zone Number}} * \text{ standability rank ratio})$$

This stage onwards, the ship design matrix - chromosome table, for selected four ships can be developed with their respective input design parameter rankings and/or ratios. Design chromosomes for each frigate are;

FRIGATE A				
MOP_{SPEED}	$MOP_{ENDURANCE}$	$MOP_{SEAKEEPING}$	$MOP_{MANOEUVRABILITY}$	$MOP_{STABILITY}$
0,9	0,91	0,582	0,8	1
$MOP_{SUSTAINABILITY}$	$MOP_{RESISTANCE}$	MOP_{RCS}	MOP_{IR}	$MOP_{ACOUSTIC}$
1	1	0,9	0,95	0,95
MOP_{VISUAL}	$MOP_{M/E}$	$MOP_{CONCENTRATION}$	$MOP_{REDUNDANCY}$	$MOP_{STRENGTH}$
0,95	0,95	1	1	1
MOP_{ZONE}	$MOP_{AWARENESS}$	$MOP_{DAMAGESTABILITY}$	$MOP_{FIRECONTROL}$	$MOP_{STANDABILITY}$
1	1	1	1	1

Figure 7.2 - Design Parameter Chromosome of Frigate A

FRIGATE B				
MOP_{SPEED}	$MOP_{ENDURANCE}$	$MOP_{SEAKEEPING}$	$MOP_{MANOEUVRABILITY}$	$MOP_{STABILITY}$
1	0,91	0,545	0,9	1
$MOP_{SUSTAINABILITY}$	$MOP_{RESISTANCE}$	MOP_{RCS}	MOP_{IR}	$MOP_{ACOUSTIC}$
1	1	0,9	0,95	0,95
MOP_{VISUAL}	$MOP_{M/E}$	$MOP_{CONCENTRATION}$	$MOP_{REDUNDANCY}$	$MOP_{STRENGTH}$
0,95	0,95	1	1	1
MOP_{ZONE}	$MOP_{AWARENESS}$	$MOP_{DAMAGESTABILITY}$	$MOP_{FIRECONTROL}$	$MOP_{STANDABILITY}$
1	1	1	1	1

Figure 7.3 - Design Parameter Chromosome of Frigate B

FRIGATE C				
MOP_{SPEED}	$MOP_{ENDURANCE}$	$MOP_{SEAKEEPING}$	$MOP_{MANOEUVRABILITY}$	$MOP_{STABILITY}$
1	0,7	0,547	1	1
$MOP_{SUSTAINABILITY}$	$MOP_{RESISTANCE}$	MOP_{RCS}	MOP_{IR}	$MOP_{ACOUSTIC}$
1	1	0,9	0,6	0,7
MOP_{VISUAL}	$MOP_{M/E}$	$MOP_{CONCENTRATION}$	$MOP_{REDUNDANCY}$	$MOP_{STRENGTH}$
0,95	0,95	1	1	0,75
MOP_{ZONE}	$MOP_{AWARENESS}$	$MOP_{DAMAGESTABILITY}$	$MOP_{FIRECONTROL}$	$MOP_{STANDABILITY}$
1	1	1	1	1

Figure 7.4 - Design Parameter Chromosome of Frigate C

FRIGATE D				
MOP_{SPEED}	$MOP_{ENDURANCE}$	$MOP_{SEAKEEPING}$	$MOP_{MANOEUVRABILITY}$	$MOP_{STABILITY}$
0,96	0,88	0,763	0,95	1
$MOP_{SUSTAINABILITY}$	$MOP_{RESISTANCE}$	MOP_{RCS}	MOP_{IR}	$MOP_{ACOUSTIC}$
1	0,75	0,7	0,6	0,7
MOP_{VISUAL}	$MOP_{M/E}$	$MOP_{CONCENTRATION}$	$MOP_{REDUNDANCY}$	$MOP_{STRENGTH}$
0,95	0,5	1	0,6	0,75
MOP_{ZONE}	$MOP_{AWARENESS}$	$MOP_{DAMAGESTABILITY}$	$MOP_{FIRECONTROL}$	$MOP_{STANDABILITY}$
1	0,6	1	1	0,75

Figure 7.5 - Design Parameter Chromosome of Frigate D

The only remaining step is to find each OMOE function of each combatant. Based on these calculations, below table is achieved;

OMOE			
Frigate A	Frigate B	Frigate C	Frigate D
0,979	0,985	0,947	0,865

Table 7.9 - OMOE Results

8. RESULTS

Although it is not possible to attain a realistic OSE while omitting the factor of cost and combat system capabilities, the OSE found in this paper is just an indicator of the effects of the survivability design features on the overall design efficiency.

According to calculated OMOE functions of each ship, the best result has been provided by Frigate B. If final best result is the expected achievement, it is safe to say Frigate B has better survivability features compared to other four ships, but chromosome also shows each survivability feature on its own in case any of them needs improvement. If designer is looking for a specific feature and its corresponding value or ranking ratio comparison, system breakdown analysis gives opportunity to compare and iterate the feature with other already-been-built designs. For the new design to be made, areas that need improvement are evident and improving these areas will result in a design with enhanced survivability combining with evaluation of parameters implemented in a measure of effectiveness theory based system breakdown.

Any naval information that exists regarding these listed combatants in parametric analysis are classified, therefore obtainable source and data are limited. In order to explain and exemplify on how the system works, assumptions have been made for further calculations and empirical formulas have been used depending on the limited available data and sole predictions. Therefore, results may vary with the actual results calculated through trial or model tests of already-been-built vessels that is archived by nations of the associated navies around the world.

For any ratio exceeding 1, the result has been taken as 1, and is assumed to be successful, as it has achieved the desired goal in such cases where the goal is the minimum to be compatible with the RFI. It is worth mentioning that MOP weights were not added into the OSE results found, as the values became too diminutive.

As a consequence, ‘Overall Measure of Effectiveness’ formula arises as;

$$OMOE_{(SURVIVABILITY)} = (MOE_{MOBILITY} \cup MOE_{SUSCEPTIBILITY} \cup MOE_{VULNERABILITY} \cup MOE_{RECOVERABILITY}) - (MOE_{MOBILITY} \cap MOE_{SUSCEPTIBILITY} \cap MOE_{VULNERABILITY} \cap MOE_{RECOVERABILITY})$$

Which becomes;

$$OMOE_{(SURVIVABILITY)} = (MOE_{MOBILITY} + MOE_{SUSCEPTIBILITY} + MOE_{VULNERABILITY} + MOE_{RECOVERABILITY}) - (MOE_{MOBILITY} * MOE_{SUSCEPTIBILITY} * MOE_{VULNERABILITY} * MOE_{RECOVERABILITY})$$

Each MOE is an indicator of a particular survivability attribute and they are independent from each other. MOE’s consist of their associated MOP’s which may include common DP’s. Although each MOE, therefore MOP is independent from each other, a change in a shared DP may change multiple outcomes which in turn affect the OMOE. OMOE has to be denoted as a ratio to obtain a meaningful result between 0 and 1. In this case study, OMOE ratio can be written as $\frac{\text{achieved value}}{\text{maximum achievable value}}$. Achieved value of each ship is derived from its ship chromosome. Maximum achievable value is the denominator of the ratio, which can be written as;

$$MAV = (1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+1+1)-1^{20}$$

$$MAV = (1*20)- 1^{20} = 19$$

For this case study with 20 independent MOP’s forming the chromosome, maximum achievable value is 19.

In conclusion, the diagram below can summarize the whole system analysis;

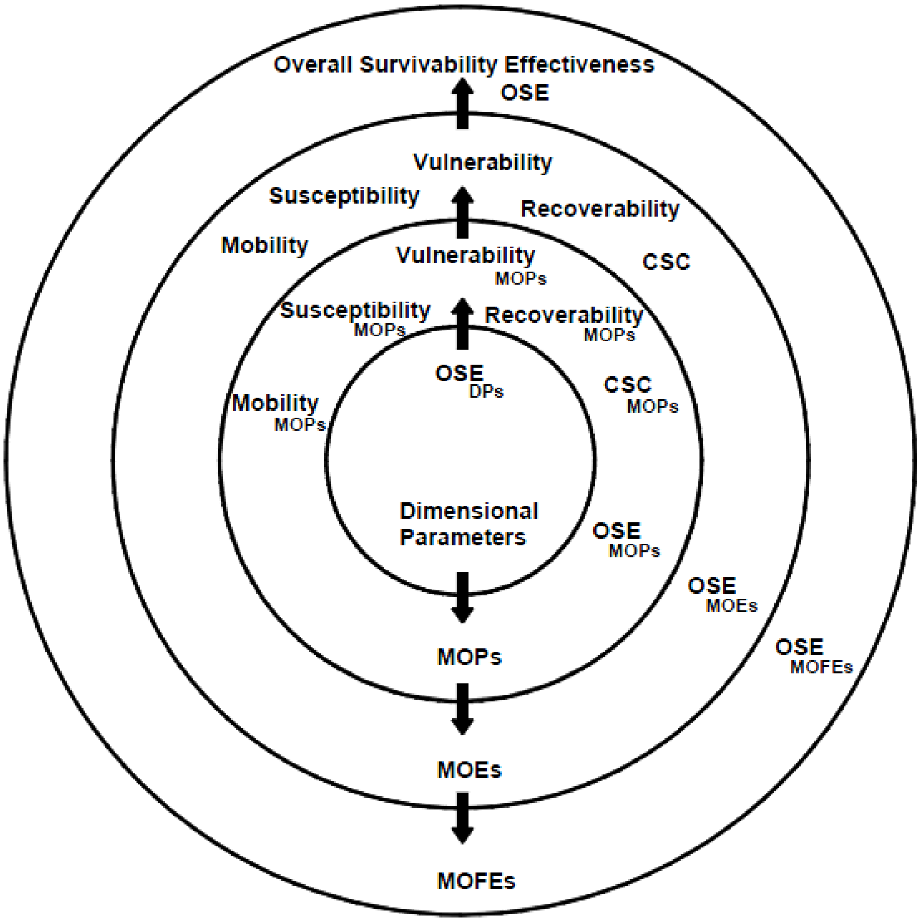
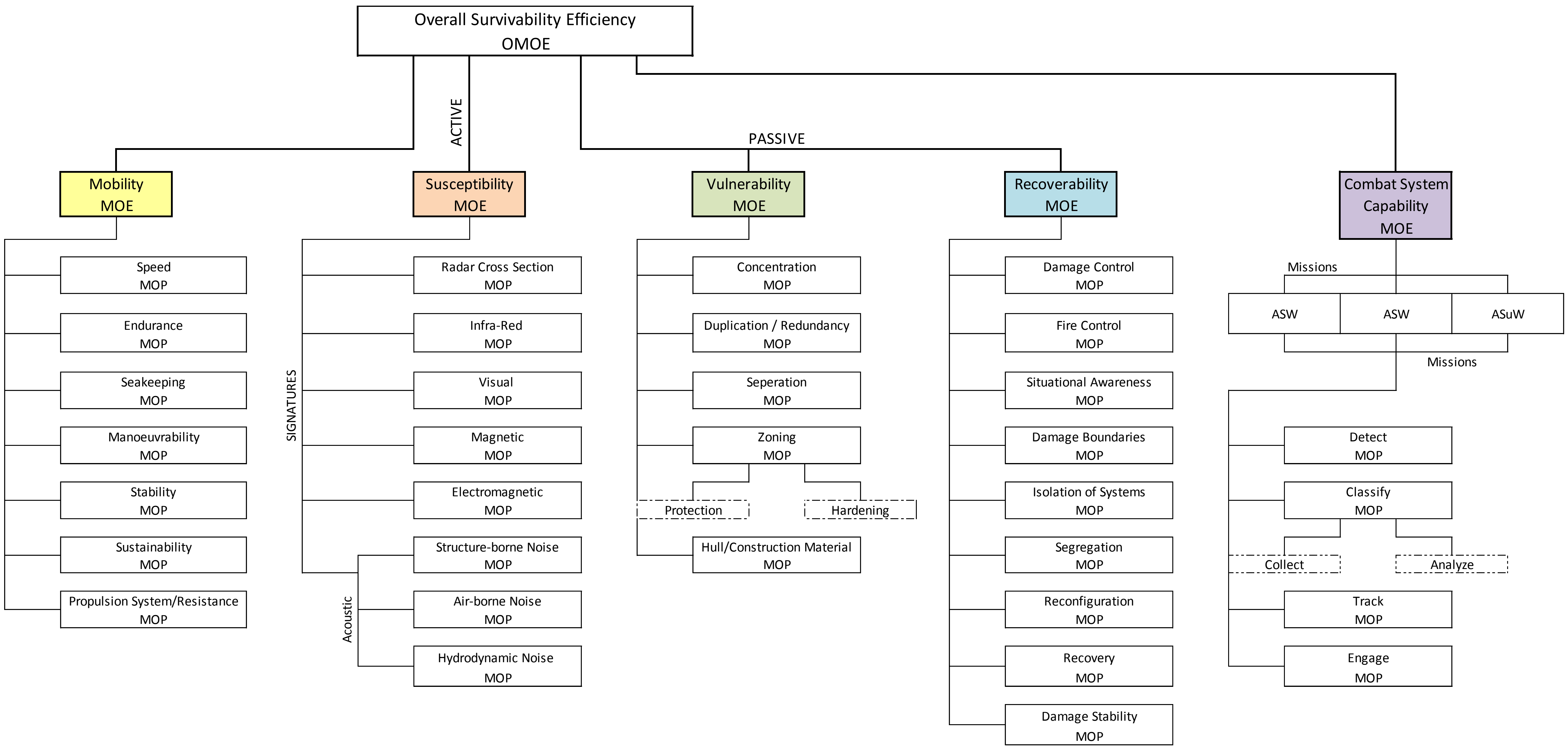


Figure 8.1 - Schematic Representation of OSE

Overall Survivability Effectiveness, OSE, comprises all MOE's that are combinations of MOP's that have been shaped by DPs.


Overall Survivability Efficiency
OMOE
ACTIVE
PASSIVE
Mobility
MOE
Susceptibility
MOE
Vulnerability
MOE
Recoverability
MOE
Combat System
Capability
MOE
Speed
MOP
Endurance
MOP
Seakeeping
MOP
Manoeuvrability
MOP
Stability
MOP
Sustainability
MOP
Propulsion System/Resistance
MOP
SIGNATURES
Radar Cross Section
MOP
Infra-Red
MOP
Visual
MOP
Magnetic
MOP
Electromagnetic
MOP
Acoustic
Structure-borne Noise
MOP
Air-borne Noise
MOP
Hydrodynamic Noise
MOP
Concentration
MOP
Duplication / Redundancy
MOP
Seperation
MOP
Zoning
MOP
Protection
Hardening
Hull/Construction Material
MOP
Damage Control
MOP
Fire Control
MOP
Situational Awareness
MOP
Damage Boundaries
MOP
Isolation of Systems
MOP
Segregation
MOP
Reconfiguration
MOP
Recovery
MOP
Damage Stability
MOP
Missions
ASW
ASW
ASuW
Missions
Detect
MOP
Classify
MOP
Collect
Analyze
Track
MOP
Engage
MOP

9. CONCLUSIONS

A take on systematic approach to survivability has been concluded. Using basic naval architecture formulas, rules and criteria, components of survivability has been selected and analysed. The relationship between branches of the systematic approach has been defined by their selected design parameters. Therefore the study will shed light on the preliminary design phase from the survivability point of view.

All design processes contain an iterative element, where the design is tested against final design requirements during the development phase, and adjustments are made to achieve the desired end result. This is achieved by asking the questions about main parameters such as weight, power required, speed, endurance ranges, cost etc.

Survivability is acquired in the pre-design phase and based on the combatant's top-level requirements where its overall measure of effectiveness formula arises as;

$$OMOE_{(survivability)} = (MOE_{MOBILITY} \cup MOE_{SUSCEPTIBILITY} \cup MOE_{VULNERABILITY} \cup MOE_{RECOVERABILITY} \cup MOE_{CSC}) - (MOE_{MOBILITY} \cap MOE_{SUSCEPTIBILITY} \cap MOE_{VULNERABILITY} \cap MOE_{RECOVERABILITY} \cap MOE_{CSC})$$

Which becomes;

$$OMOE_{(survivability)} = (MOE_{MOBILITY} + MOE_{SUSCEPTIBILITY} + MOE_{VULNERABILITY} + MOE_{RECOVERABILITY} + MOE_{CSC}) - (MOE_{MOBILITY} * MOE_{SUSCEPTIBILITY} * MOE_{VULNERABILITY} * MOE_{RECOVERABILITY} * MOE_{CSC})$$

Main aim of general ship design is to carry its payload/cargo on a certain speed from point A to point B [55]. In warships, this can be translated into carrying and protecting the payload and habitability on board while travelling from point A to point B, defending either point or any point in between, or invasion of any point around the world during peace or war on seas. Therefore, as warships take years and capital to be designed and built, they are not easily replaceable. The goal is to preserve the vessel as good as possible. Hence while designing a combatant, the utmost important feature that comes to mind is survivability. A way of designing the ship from survivability point of view applies to this study through design spiral method.

All naval architects start their design with producing alternative ways to implement owner’s requests into one optimum design. This approach leads to selection of operational and mission necessities as well as setting and/or analysing estimated first look at performance limits. Finding the perfect design is an iterative process and is best explained or visualized by the design spiral method. Author has prepared a survivability point of view design spiral, which can be seen below in Figure 9.1.

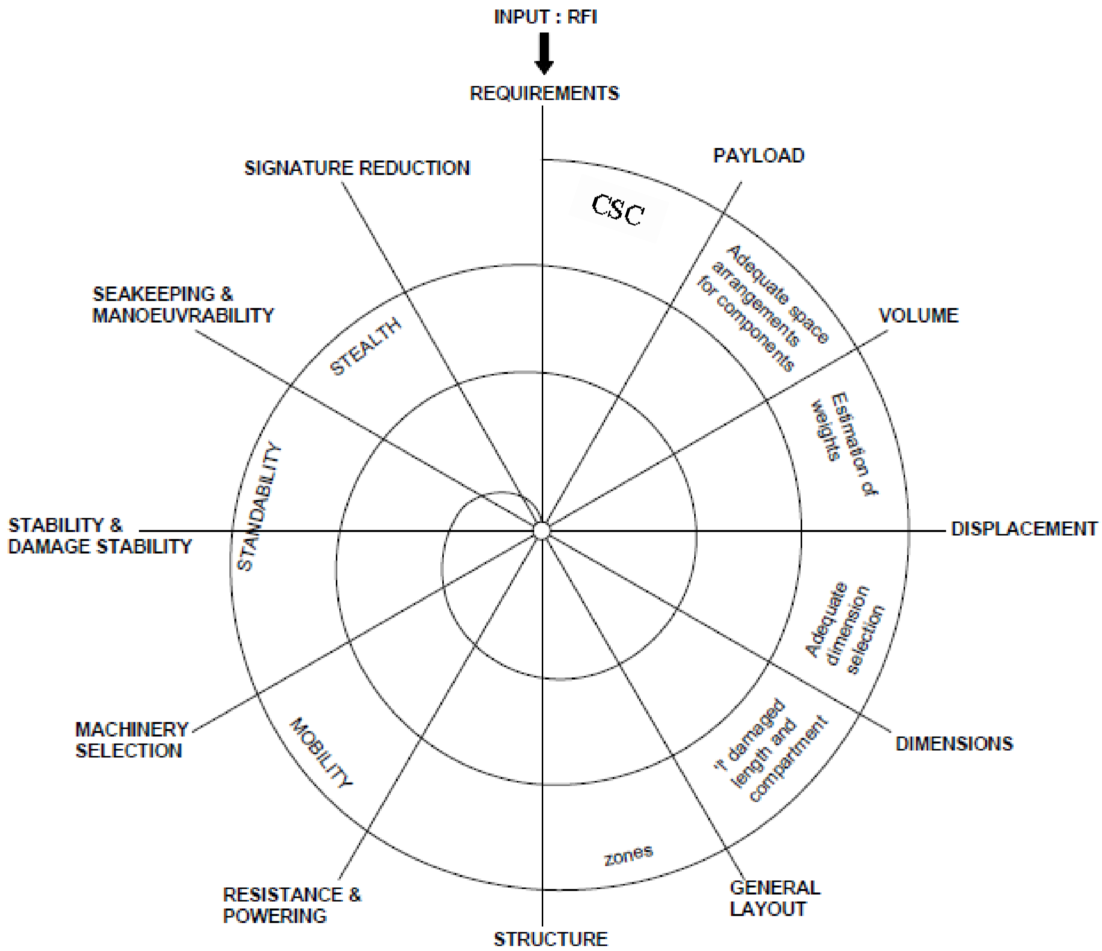


Figure 9.1 - Survivability Design Spiral

To be able to fill the spiral, designer must decide on the top-level importance areas of the ship design. Mobility is the first thing in mind, when survivability is in question. A combatant without mobility is like an unstable island located in open seas. Mobility enhances attack (offensive) and defensive power and crew survivability from enemies. This leads the vessel to provide good seaworthiness and be stable for crew habitability. Therefore resistance and powering calculations leading to machinery and propulsion system selection as well as stability and seakeeping calculations are essential. Nowadays, modern warships rely on electrical and mechanical systems, therefore self-sustainability for systems that run the ship are vital.

After proving the vessel is mobile, for enhancing survivability purposes, ship must not be easily detected by enemy forces for increased mission success against threats. The most desired characteristic is to be invisible to enemy eyes. This is where susceptibility and signature management come into play. Signature reduction methods consists of shaping, which manipulates well-known sharp looking exterior design of commercial ships, additional systems for cooling or demagnetising the structure, protection and hardening of machinery components, adding extra coats of special materials on exterior surfaces to match impedance of enemy sensor waves in any forms etc. Even though these systems can later be installed on board, they require volume and weight allowance in displacement to be applied perfectly. Only way to achieve maximum reduction of signatures is to take them into consideration while planning the general layout of the combatant. Third aspect vulnerability follows the same path. Vulnerability of a ship must be minimised and this can only be done in preliminary design phase, therefore while designing for survivability, vulnerability is the second most important feature as the eliminating techniques depend heavily upon volume, displacement, structural construction and general layout. General layout can be changed but structural construction is not easily altered after the ship has been commissioned.

Recoverability comes to surface after the combatant suffers damage. It consists of damage and fire control aboard. Effective parameters are crew and sensors, their readiness and damage stability calculations to see if the vessel will survive the lethal environment while harmed. Most important parameter in recoverability is the ‘*l*’, the distance of allowable damaged length on any point of the hull set by class societies. ‘*l*’ defines compartment lengths, therefore through preparing the general layout set by compartment lengths, limitations of zones are established.

The difference between some of survivability parameters and vulnerability parameters are that the former can be modified even in later design phases, even during the operational life of the vessel (use of radar absorb materials, ram, infrared signature suppression devices and low emission paints), but the majority of the issues that affect vulnerability will most probably characterise the vessel for her entire life. Therefore, to be able to achieve enhanced survivability, minimizing the vessels vulnerability in the preliminary design stages is crucial. Worst two outcomes from war scenarios can be flooding and/or fire hazard. Therefore planning ship’s damage control and fire control in design phase are vital. An approach to start the design phase is to choose the prime aspects affecting the survivability of a combatant ship. Also, maximizing the performance of the combat system will dominate the arrangement of the topside. This arrangement consists of sensors, directors, weapon launchers, magazines, aviation systems, communication systems, command and control spaces, computer networks and architecture.

The deducible outcome is that the design process from survivability point of view isn’t sequent and all areas have their element/elements that have to be dealt with in previous steps where the designer is deciding upon payload and construction of a proper layout with adequate volume and arrangements. As known, any change in any parameter may result in effecting another component in a positive or negative way. Corrections need to be made until one optimum design merges out.

Table 19 shows aspects of survivability with their associated main design parameters.

Table 9.1 - Dimensional Parameters (DPs)

MOE			
Mobility	Susceptibility	Vulnerability	Recoverability
MOP's			
Speed Endurance Seakeeping Propulsion System / Resistance Sustainability Stability Manoeuvrability	RCS IR Signature Visual Signature Acoustic Signature Electromagnetic/Magnetic Sign.	Concentration Duplication / Redundancy Zoning Seperation Structural Strength	Standability Capability Damage Stability Damage and Fire Control Situational Awareness
DP's			
v, sfc, volume, displacement, payload, L, B, T, c, Awa, Awf, , Cwf, Cwa, Cvpf, Cvpa, F, P, η, θ, Cb, SHP	v, L, B, T, D, F, topside design, temperature, propulsion system, construction material properties	L,B, D, volume, displacement, structural construction material properties, general layout	L, B, T, crew readiness, damaged length 'l', v, volume, displacement, payload

10. RECOMMENDATIONS AND FURTHER STUDIES

While assessing the results, there might be some deficiencies due to naval data of chosen combatants are classified by their associated navy. All the datas have been collected from open literature as much as available. Results can be more precise if data is accessible and if more ships are added into consideration. Author recommends each navy to prepare their own ship database, depending on actual values calculated through trial tests and run the explained system all over again. With more data available, parameter rankings can be expanded and further incremented. Also, navy possessing its own MOP weight table according to their own hierarchical MOP importance will be most beneficial. It is be possible to use survivability parameters in the design phase in a more realistic way to obtain results in similar ship designs with real ship data.

This study and research will continue to be able to lead a start on a warship design based of survivability efficiency perfection by using measures of effectiveness approach in the future by determining real values of MOEs.

In the future, formulas can be derived for a detailed ranking equation, like Bales's seakeeping factor, R, through regression analysis of already been built ships and their actual measures of effectiveness's for ranking survivability of various ships and ship types considering all variables of components and constraints of survivability following the hierarchic survivability line up. Therefore changing one parameter during iterative design phase to improve an aspect of ship design, even if the parameter is not related to survivability features, can be investigated and measured whether or not it has any good or bad effect on ships survivability.

To be able to find a precise survivability OMOE, combat system capability and cost must be included in the system breakdown. Through the tables created about missions and their related parameters, it is made possible to determine the precedence of various reduction methods over each other depending on their trade-offs. (Table 20, 21, 22) For each mission scenario effective parameter have been marked with a '+', non-effective parameters are marked a '-'. The scenario warship should endure can be just one, combination of both or all three of them. So the warship must always sustain its 'Mission Readiness' at a high level in order to possess control over any incoming threat.

Table 10.1 - Defensive Countermeasures

Defensive Countermeasures				
		Missions		
		ASW	AAW	SW
Countermeasures	Decoys	+	+	-
	Chaffs	-	+	+
	Flares	-	+	-
	Jammers	-	+	+
	Radar	-	+	+
	Sonar	+	-	-

Table 10.2 - Offensive Threats

Offensive Threats				
		Missions		
		ASW	AAW	SW
Weapons	Missiles	+	+	+
	Guns	-	+	+
	Mines	+	-	+
	Bombs	-	+	-
	Torpedoes	+	-	+
	NBC	-	+	+

Table 10.3 - Mission Effectiveness Parameters

Mission Effectiveness Parameters				
		Missions		
		ASW	AAW	SW
Detection Parameters	Camouflage	-	+	+
	Screening or masking	-	+	+
	RCS Reduction	-	+	+
	Visual	-	+	+
	Radar	-	+	+
	Active Sonar	+	-	-
	Passive Sonar	+	-	-
	Noise	+	-	-
	Infra-Red Radiation	-	+	+
	Magnetic	+	-	+
	Electromagnetic	+	-	+
	Wake	+	+	+

In today's environment of increasingly sophisticated threats and weapons, the importance of knowing a ship's signature over a range of operating conditions is utmost important for mission success. Through signature suppressions, a ship's detectability can be significantly reduced which ultimately improves its chance of survival. Additionally, Green stated in his "Modelling the Ship as a Weapon System" paper [47], that for a successful mission performance, the focus should be on its related areas. Through the model, it is also possible to detect the aspects which may cause mission failure. Weapon system performance and naval architecture design are aimed to be closely associated as the result of a process model. Green visualized his approach by a diagram seen below;

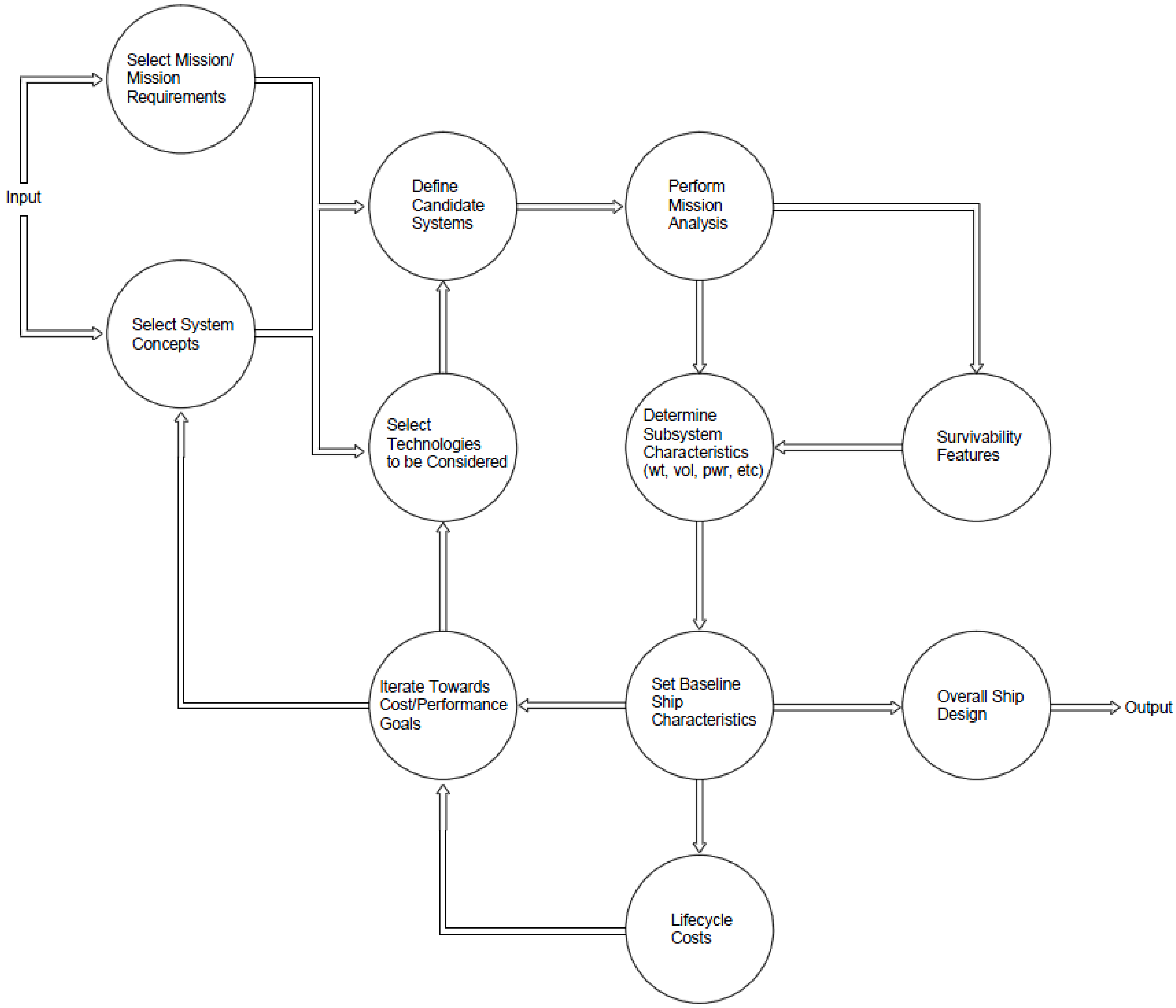


Figure 10.1 - Green's Ship as a Weapons System Diagram

Performing and surviving in the ships environment are essential concepts both. Therefore there are two perspectives to mention,

1- Offensive – Mission accomplishment
2- Defensive – Survive to accomplish the mission

Accomplishment of the mission is influenced by the below factors,

- The availability of the system for the mission
- Platform performance qualities
- Target acquisition capabilities
- Type, effectiveness and number of weapons
- Command and control capabilities
- Platform signature and countermeasures
- Tactics used and the operational environment
- The ability to take a hit and survive.

Therefore, Green came up with his "Mission Success Formula" [47] which is given as;

$$\text{Mission Success} = A_O * R_M * S * MAM \quad (10.1)$$

Where A_O is the mission availability, R_M is the mission reliability, S is for survivability, probability of ship loss. MAM is mission attainment measure; where MAM equals;

$$MAM = WSE = P_K * P_D * P_C * P_E * P_{WK} \quad (10.2)$$

Where P_K is 'Ship Killability' (a function of vulnerability and susceptibility), P_D is the probability of detection, P_C is the probability of control (correct identification, one track per target, etc.), P_E is the probability of engagement (the ability to guide the weapon to within its acquisition cone), P_{WK} is the probability of weapon kill (the ability of the weapon to achieve the desired level of kill).

In this formula, "mission availability and mission reliability follow from standard reliability theory definition but survivability and the mission attainment measure are more complex and depend on a number of factors." and survivability is measured with the degree of resistance when the damage is taken and the ability of performing on the appointed mission even while damaged.

Survivability is in direct relation with susceptibility and vulnerability. By saying that, susceptibility is expected to be successful enough to detect all the possible threats that may cause damage as well as consolidate the related factors, while vulnerability consists of the entire components that regulate the degradation of any mission area accustomed to a damage mechanism. Interfering with the kill chain is crucial for the weapons system's defensive needs.

Below three areas may decrease susceptibility if addressed:

- Decreasing the ability of the threat to detect (signature management)
- Improving the weapons systems ability to counter the target
- Disrupting the threat's ability to attack (countermeasures)

In order to reduce the vulnerability, factors that affect the damage tolerance of the system should be conducted. Accomplishing the desired reduction measures is done through ship arrangements.

- More compartments at centre of ship
- Use of redundancy
- Dispersal of resources
- More fire zones

The term active and passive hardening defines the reduction of susceptibility and vulnerability en masse. 'Active' refers to thorough defence while 'passive' refers to distributed system elements.

To analyse the subsystems as the aforementioned method enables us to create a baseline ship design. Moving from here, the design process must be checked and confirmed multiple times for any possible constraints. Using the ship design as a constraint is found less efficient compared to executing this approach combined with the conceptual ship design regarded as the ultimate objective.

Although Green has assessed 'S' in the mission success formula solely through the recoverability perspective; this paper aims to reach a conclusion on the survivability by seeking a holistic approach – which can also be implemented on mission capability. By using OSE, it has been possible to reach overall survivability that is addressed in the pre damage situations rather than post damage scenarios. The system activities of survivability design parameters have been achieved by the same, as well as the hull and ship systems were analysed and divided into subdivisions which enabled OMOE to be calculated by using MOE, MOP, DP and DF specifications.

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APPENDIX A - Evaluation of Parameters

Design parameter selection has its steps just like the system analysis. First step is to determine the payload and its required minimum displacement value. According to the set values of payload and the maximum achievable speed required, length and other main dimensions such as beam, draft and block coefficient can be found. They need to be in equilibrium with the formula;

$$\nabla = L \times B \times T \times Cb \quad (A.1)$$

Freeboard estimation can be done using Eames and Drummonds empirical formula preliminary approach for minimum allowable freeboard distance for warships.

$$F = 0{,}04L \quad (A.2)$$

With minimum freeboard value calculated and draft that satisfies volume of displacement, a first estimation of minimum depth can be found by adding freeboard and draft distances together.

$$D = F + T \quad (A.3)$$

After selecting main dimensions, rest of the hull coefficients used in ship design can be estimated through formulas.

Formulas used for hull coefficients in this study are;

- Cwa = 0,44 + 0,52 Cp (A.4)
- Cb = $\frac{\text{L X B X T}}{\nabla}$ (A.5)
- Cm = 0,9 + (0,1.Cb) (A.6)
- Cp = $\frac{\text{Cb}}{\text{Cm}}$ (A.7)
- Cvp = $\frac{\text{Cb}}{\text{Cwa}}$ (A.8)
- Slenderness Ratio (L) = $\frac{L}{\nabla^1/3}$ (A.9)
- Slenderness Ratio (B) =$\frac{B}{\nabla^1/3}$ (A.10)
- Froude Number = $\frac{v}{\sqrt{L}}$ (A.11)
- Sfc = Installed Power x 0,185 (assumption made through experience) (4)

Stability calculations were also made according to Eames and Drummonds equations which are;

- KB = T (5/6 - $\frac{\text{Cb}}{3\text{Cw}}$) (A.12)
- BM = $\frac{B^2}{\text{T Cb}}$[Cwp(0,0727Cwp+0,0106)-0,003] (A.13)
- KG = 0,65D (A.14)
- GM = KB + BM – KG (A.15)
- GZmax = $\frac{\frac{70 \text{ x } \sqrt{35\Delta}}{30}}{10 \text{ x } \sqrt{\text{Lwl}}}$ (A.16)

Almost all of the design parameters are related to each other, proven by their respective formulas. Checking main parameters for instance, length is the only parameter that affects each aspect in first degree, therefore length becomes the main parameter to be optimized. A change in 'L' length may affect wet surface area which for preliminary design has been taken as;

$$WSA = \nabla^{2/3} \text{ x } (3{,}4 + \frac{Lwl}{2 \text{ x } \nabla^{1}/3}) \qquad (A.17)$$

Increase in wet surface area will lead to an increase in viscous drag, but at the same time wave drag will decrease and propulsion efficiency losses will be less, this will also lead to the optimization of 'v' speed. For structural construction, increase in length means more usage of steel and therefore an increase in weight and cost of the vessel. Same effect occurs as minimum freeboard distance increases with the additional length, again meaning more steel usage for construction. On the positive side, increased length improves sail capability and seakeeping characteristics while battling long period sea waves. Small warships, meaning smaller length combatants have an advantage with manoeuvrability ability. In a case where displacement is constant, increase in length will decrease Cb, which will mean the ship will have to be slender. Slenderness ratio is related to volume, therefore undesired circumstances for the amount of payload carried can surface.

Ayre came up with an empirical formula that estimates a starting value for the length of a warship which is;

$$L = \Delta^{1/3} (3{,}333 + 1{,}666 \text{ Fn}) \qquad (A.18)$$

This formula is useful when the designer knows displacement and Froude number limitations for the requested design.

On the assumption that severe pitching occurs when a ship is in synchronism with waves equal or greater than its length, Lewis established an empirical formula and the maximum Froude number attainable without experiencing severe motions while traveling seas [57]. This formula binds length, displacement and speed together.

Formula is;

$$\frac{L}{\nabla^{1}/3} = 3.5 + 12.5\ Fne \quad (A.19)$$

Where Fne is the cruise speed Froude number of a given ship. As length and displacement are in linear proportion, an increase in one will lead to an increase in other. As can be seen, increase in length results in increased displacement. With increased displacement, Froude numbers decrease as the need of installed power to achieve higher speeds get much higher, resulting in bigger volume allowance for machinery, added weight and cost which in modern warship design is a big penalty to pay for additional few knots. The relationship can be seen below in the figures A.1, A.2, A.3 and A.4.

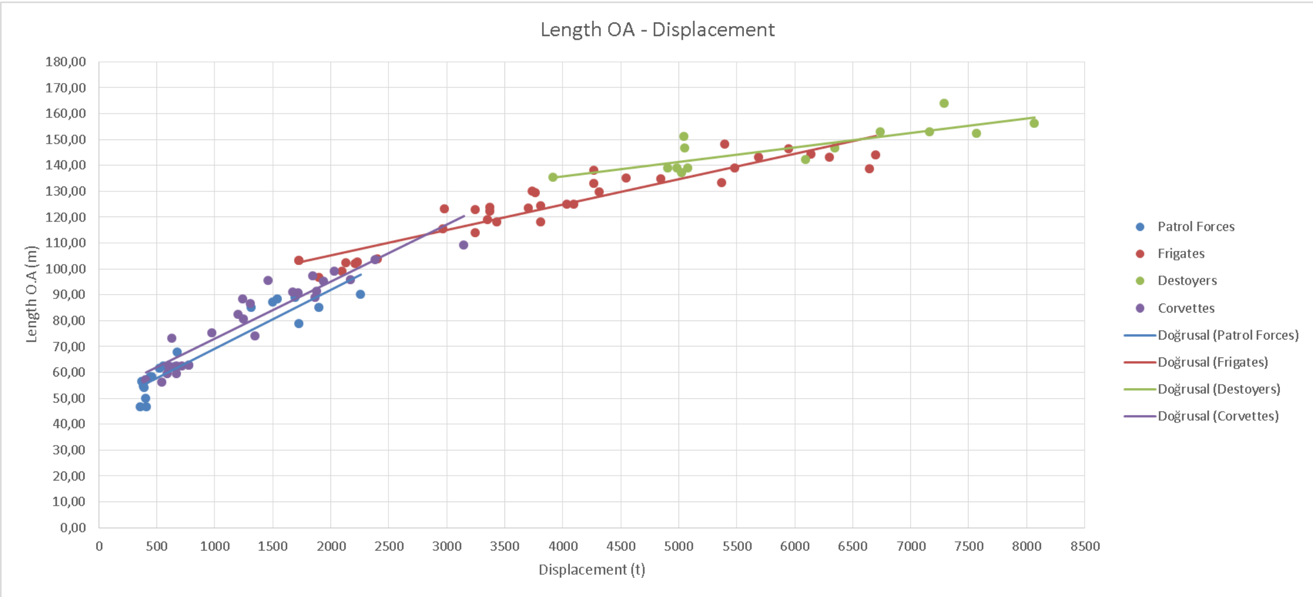


Figure A.1 - Loa / Displacement

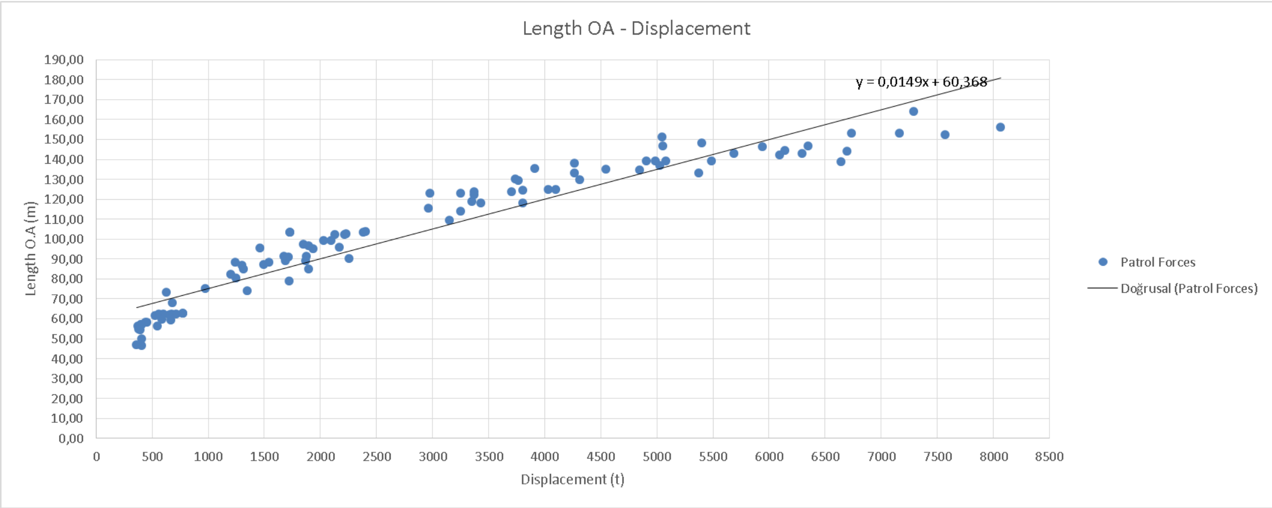


Figure A.2 - Loa/Displacement 2

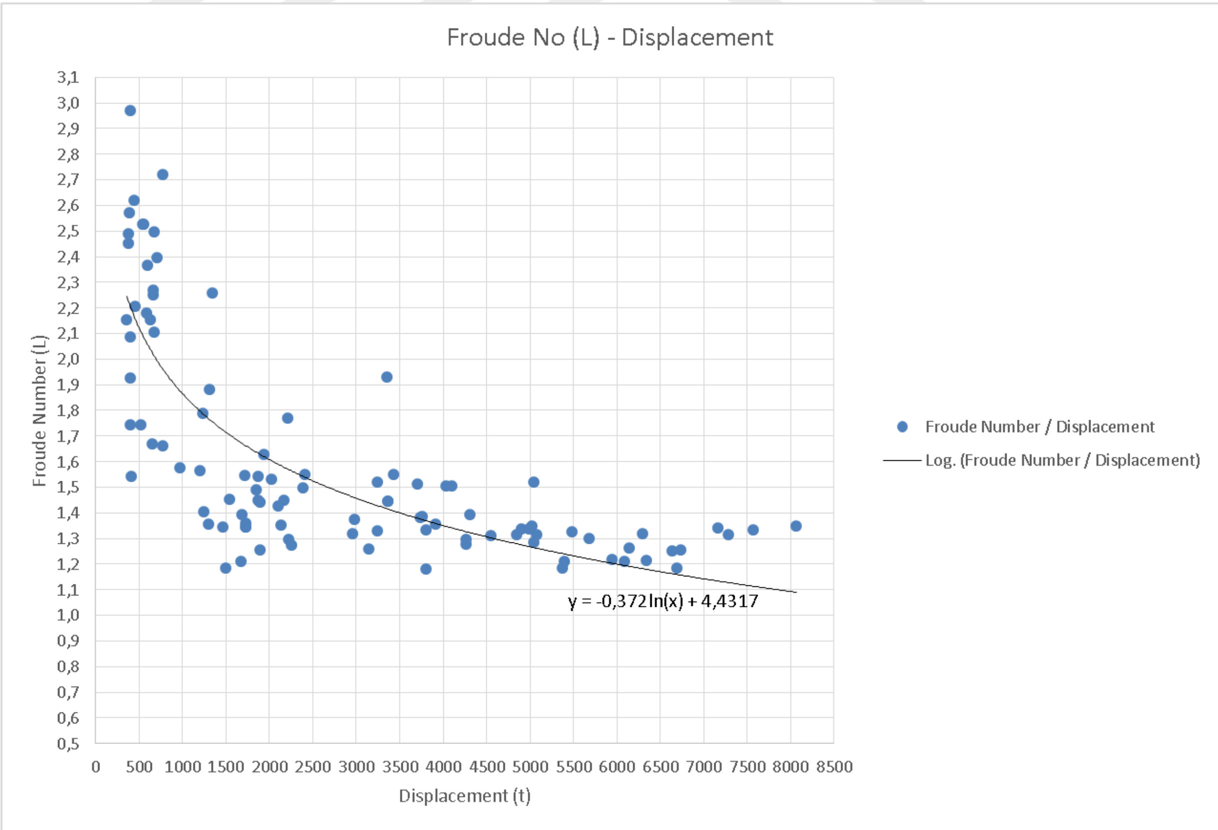


Figure A.3 - Froude Number/Displacement

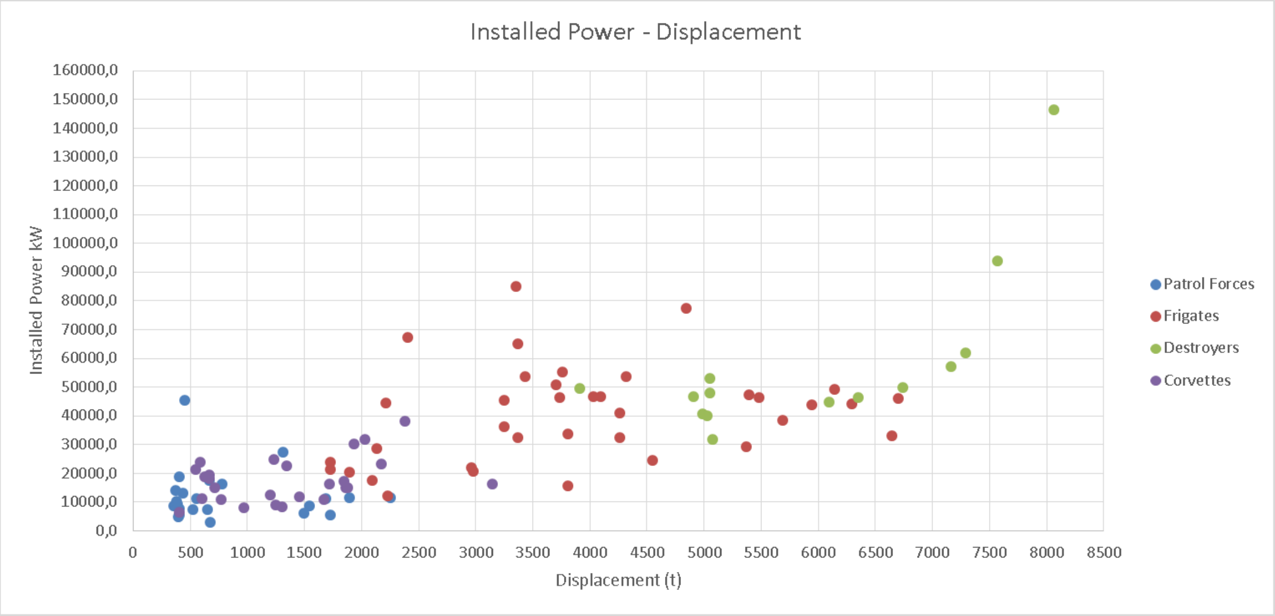
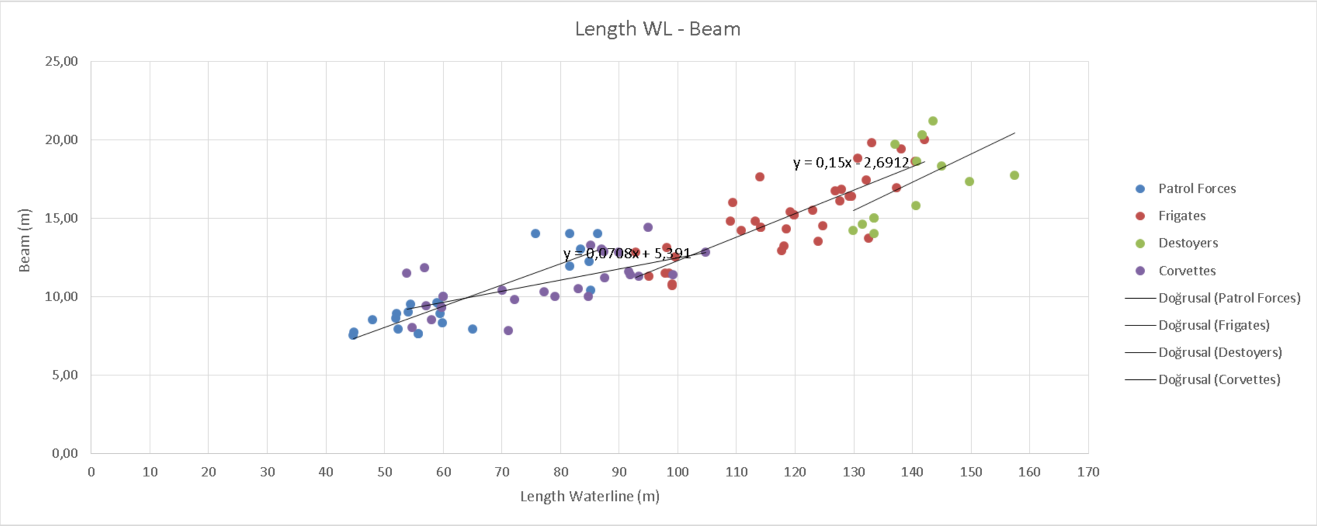


Figure A.4 - Installed Power/Displacement

After deciding upon length of the vessel, preliminary beam estimation can be found using the data from parametric analysis. The general linear function or specific linear function of the associated ship type can apply.



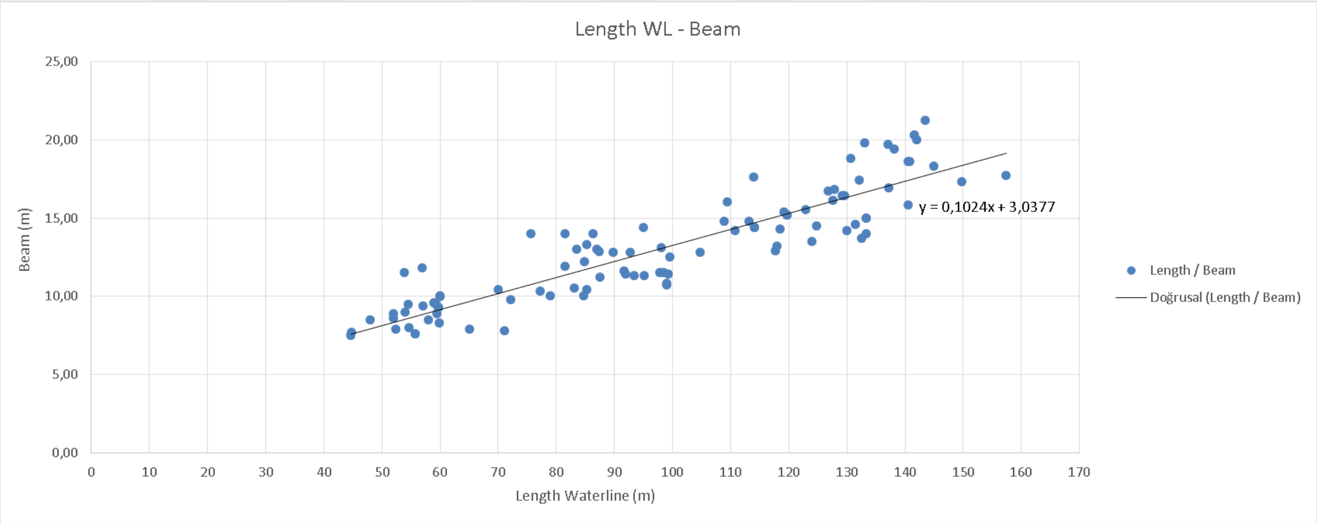


Figure A.5 - L/B Ratio

For expediting the machinery selection process, propulsion systems used for warships were plotted over speed and displacement. Designer can check which system is commonly used, therefore reasonable, at a requested speed region with chosen displacement.

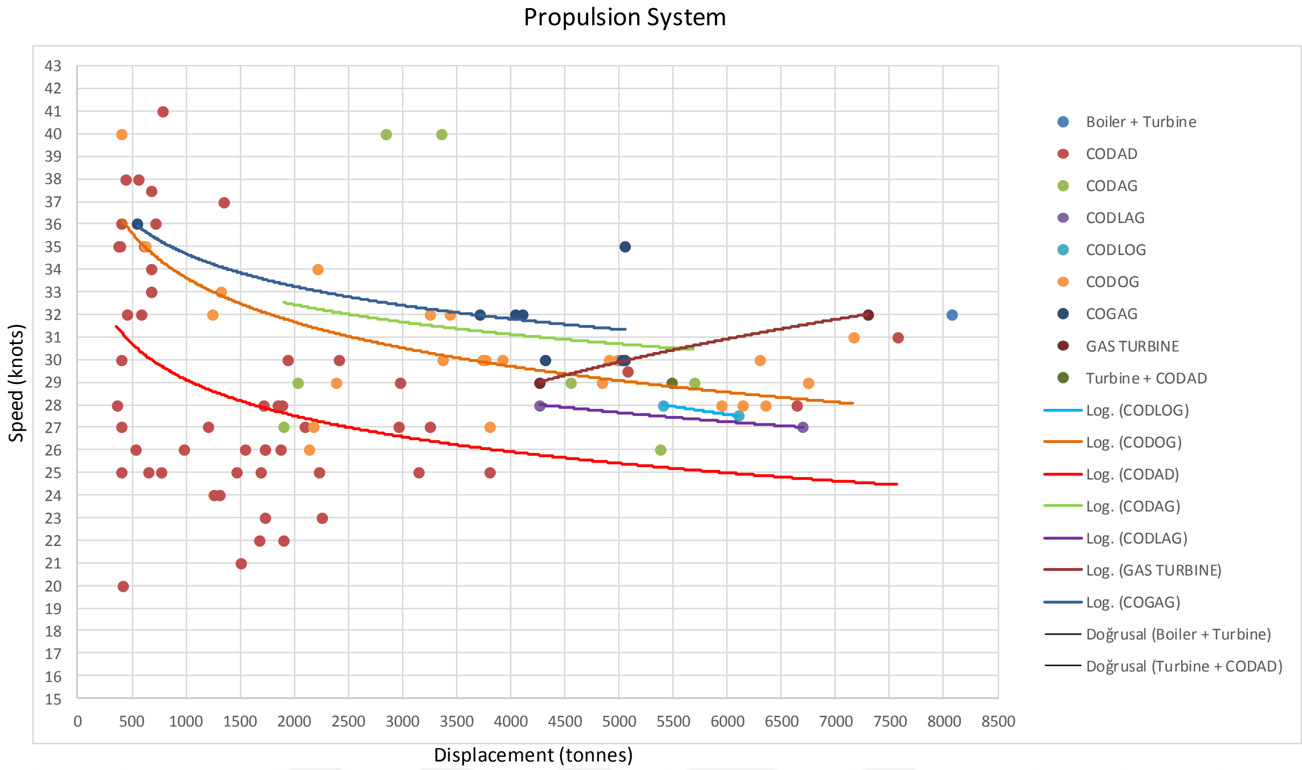


Figure A.6 - Propulsion System

A wider beam can lead to improved stability characteristics; yet affects resistance in a negative manner. With increased resistance, the required power to run the ship and its systems will also enhance. Seakeeping characteristics improve with wider beam as the roll period (T) decreases. The relationship can be seen through;

$$T = \frac{1{,}108\ K}{\sqrt{GM}} \qquad (A.21)$$

Where K is the gyration diameter and is equal to;

$$K = kB \qquad (A.22)$$

Where ‘k’ is a constant and B is beam.

Changing depth effects payload, longitudinal strength as well as stability and seakeeping as it is directly related to vertical centre of gravity (VCG). Decrease in depth will change the L/D ratio, which is related to longitudinal strength of the ship. International class societies set minimum and maximum values for this ratio [57].

Changing draft will change resistance calculations, as the draft increases, resistance of the vessel decreases due to the lower wetted area value. Thus, with a bigger propeller diameter, propulsion efficiency can be increased. [57]

When it comes to hull coefficients, block coefficient Cb is the ratio of the volume of displacement to an imaginary rectangular block with same length, beam and depth of the ship. Therefore increase in Cb has its positive and negative effects. Positive effect being the increase in payload capacity and negative effect being the increased wetness and slamming indexes for seakeeping characteristics.

Midship area coefficient, Cm, is the ratio of the midship area under waterline to an imaginary rectangle of the same beam and draft of the ship. Increase in Cm will lead to improved seakeeping as ship motions are more stable. Increasing the Cm, increases wet surface, therefore viscous drag and decreases wave drag at the same time. The equilibrium and optimization is up to the designer to decide.

Waterplane coefficient is the longitudinal waterplane area of the ship at waterline to the area of an imaginary rectangle with the same length and beam at waterline. Cwp is effective on resistance, stability and seakeeping characteristics. It also defines ships underwater form together with Cb and Cm. An increase in Cwp will lead to improved seakeeping and stability characteristics with a penalty of increased wetted surface area and resistance.

Additional comments on features can be that to improve stability characteristics, ship forms that increase KB value such as higher Cwp and lower Cp values as well as V shaped hulls will increase stability. A decrease in KG distance can lower the ships steel weight with usage of lighter materials, e.g aluminium, rather than steel for topside design. An increase in freeboard will lead to an increase in VCG, therefore decreasing stability. Desirable VCG is the lower value for improvements in the calculations. V shaped hulls result in better stability characteristics because an increase in KB leads to an increase in BM distance. The relationship can be seen by the formula;

$$GM = KB + BM - KG \quad (A.23)$$

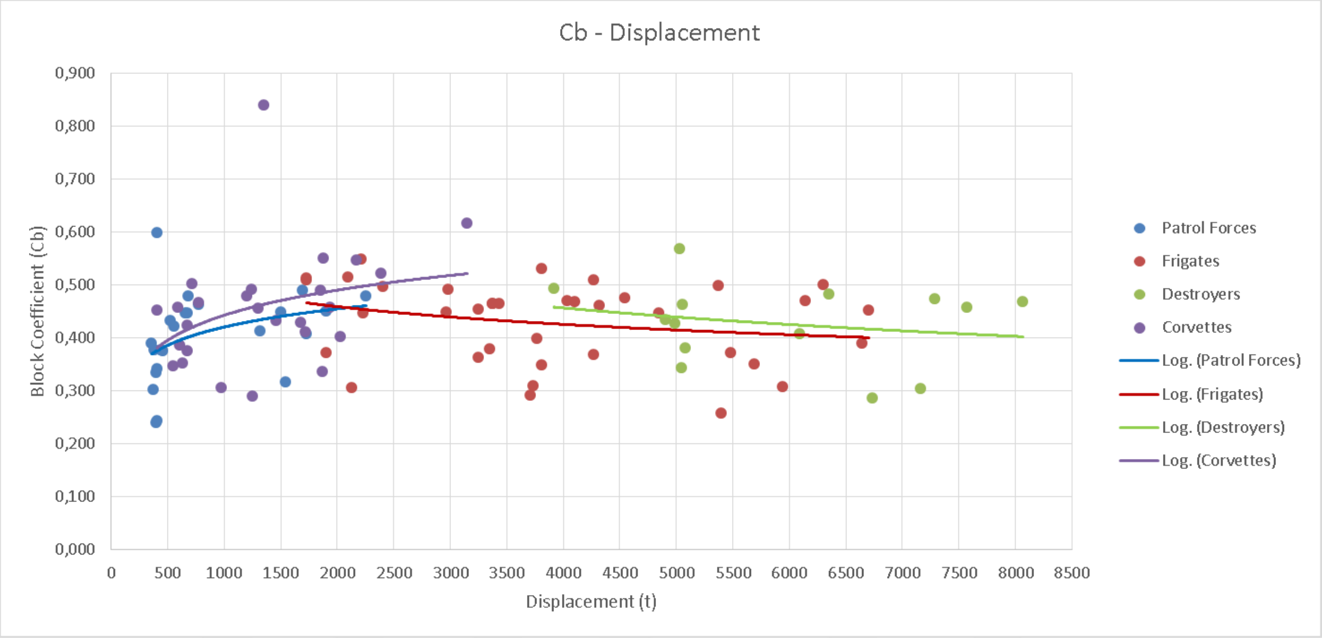
It can easily be understood through aforementioned facts, whether it's an increase or a decrease in a certain aspect; it affects another one unfavourably. Hence, it is crucial to make a wise and fully informed decision while concluding on which path to proceed.

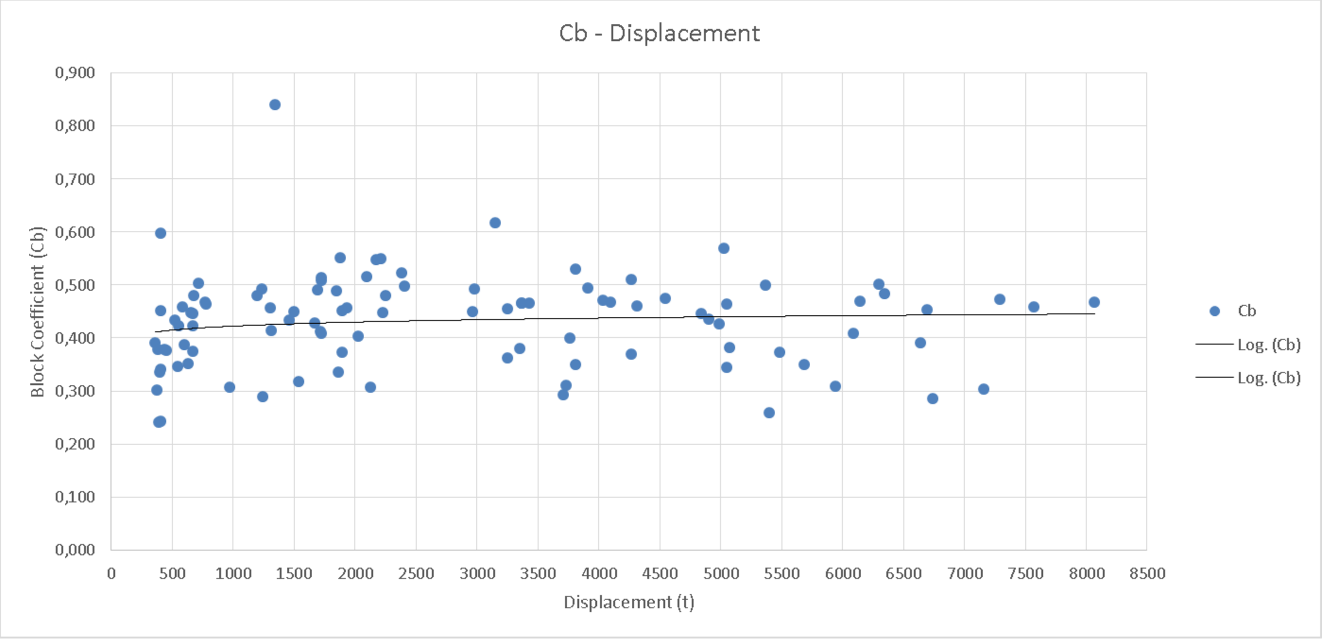
For seakeeping, the case study has taken Bales’s ‘R’ factor into consider for preliminary design calculation. For a detailed seakeeping analysis, wetness, slamming and propeller emergence can also be added into function. This will lead to adding further parameters and provides a thorough understanding.

As far as manoeuvring ability is concerned, DIN standards state that astern speed should be minimum 7 knots. While doing research, gathered data through experience shows that it should not be less than 8 knots as RFI suggests. Astern speed is calculated through trial or model tests. 3D model tests are the best choice available for preliminary design phase. By applying this method, changing the design on computer and making iterations to reach the final design is much cheaper and less tiring as the combatant would not be built as a model for towing tank tests or neither fail at the inclining test after construction.

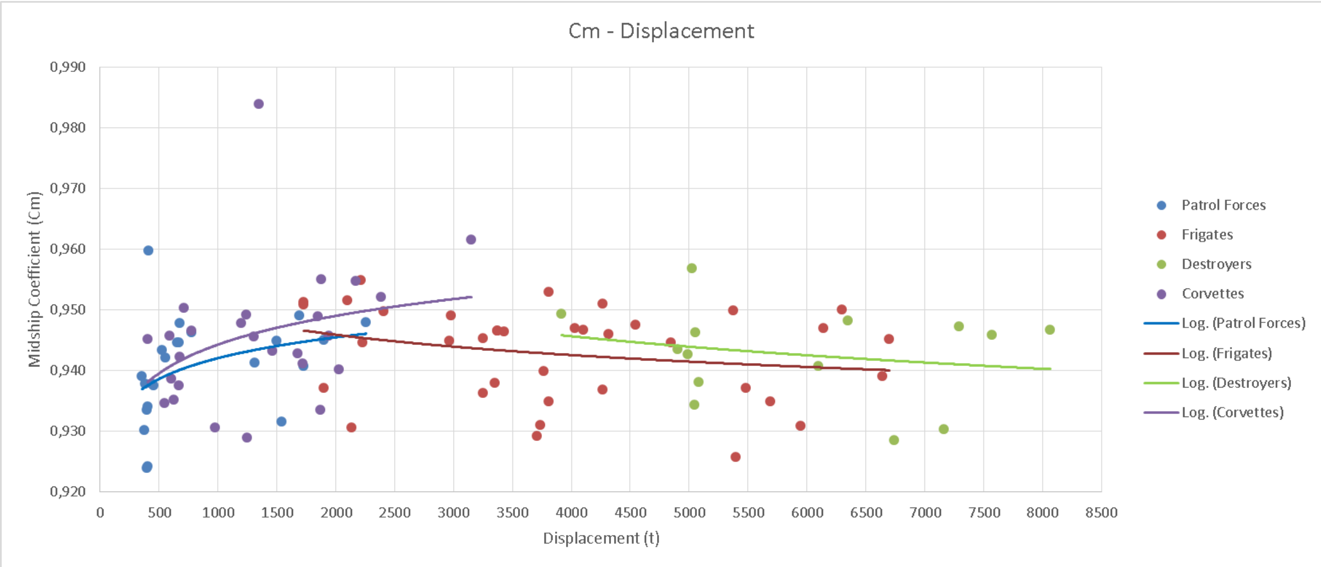
APPENDIX B

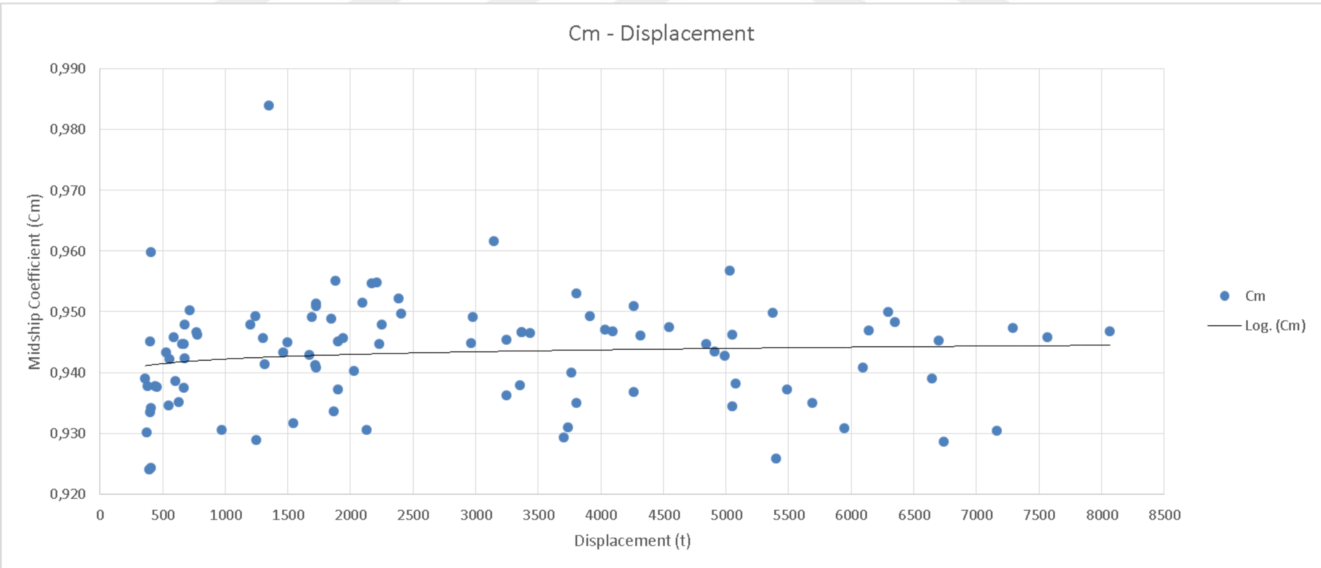
Cb – Block Coefficient



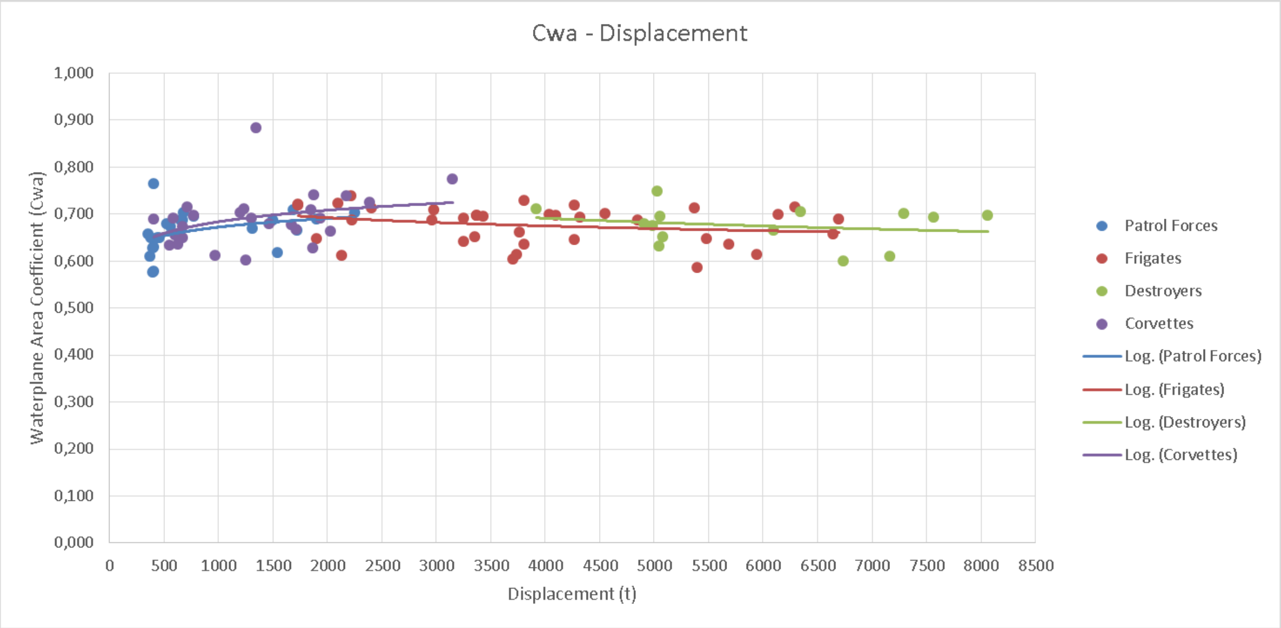


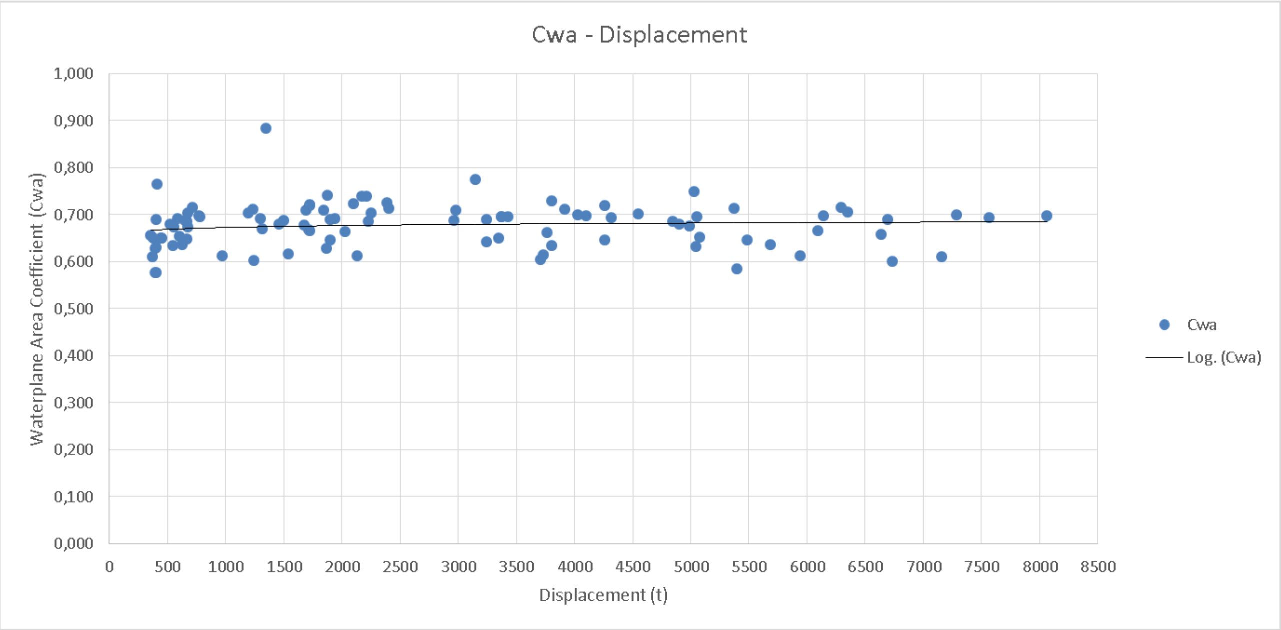
Cm – Midshiparea Coefficient



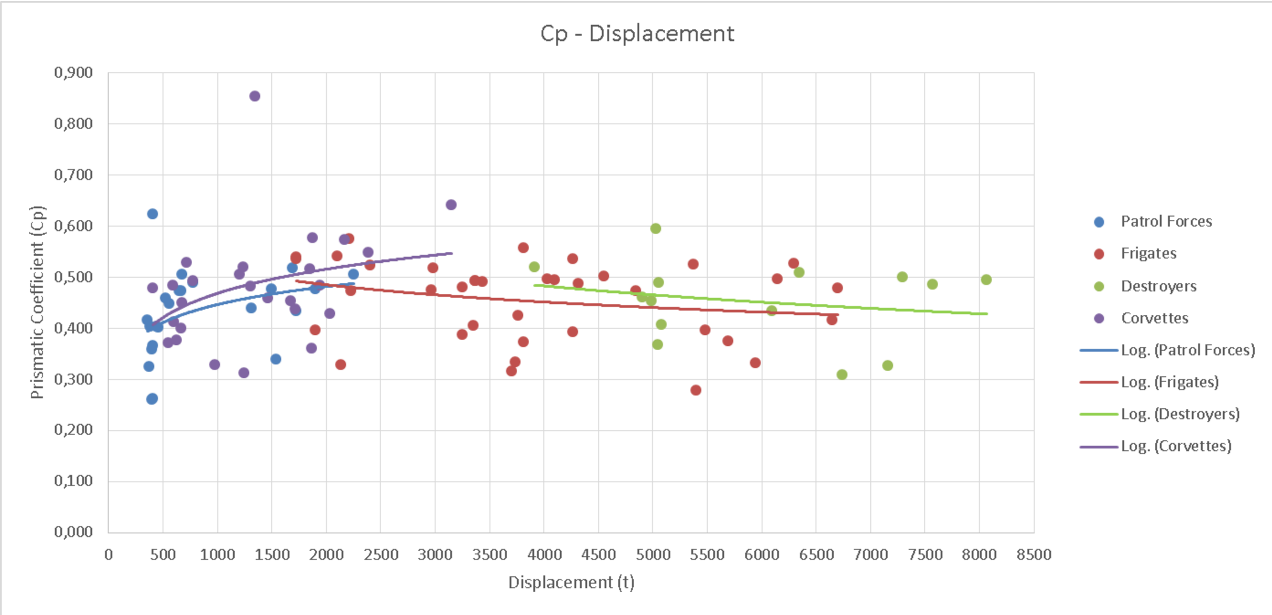


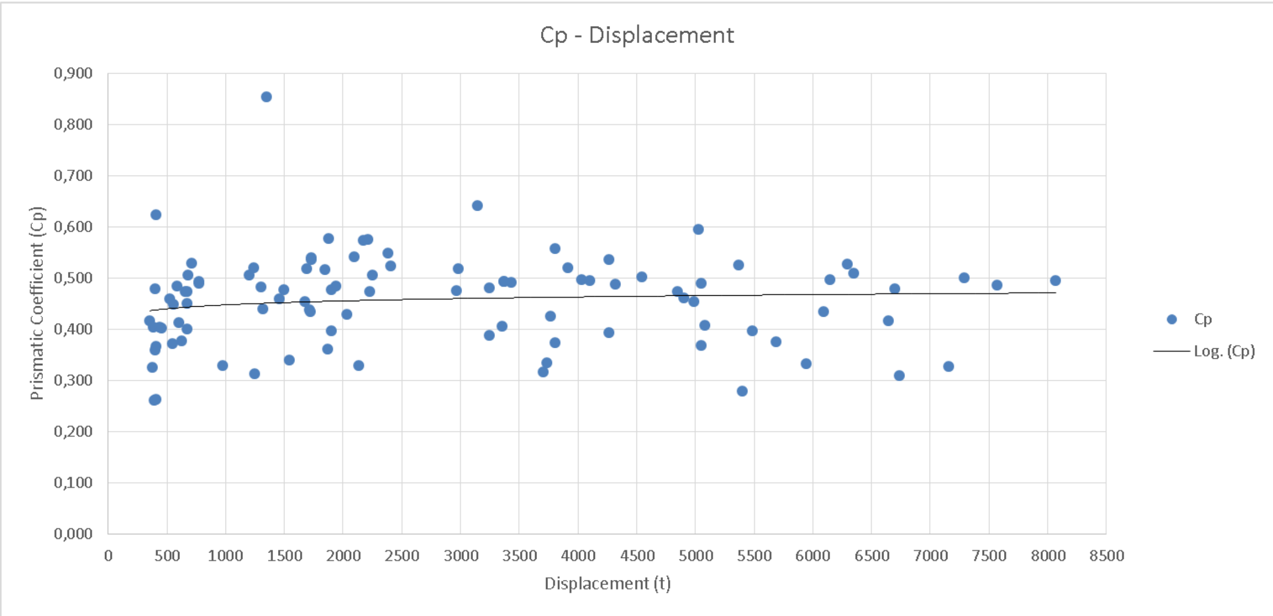
Cwa – Waterplane Area Coefficient



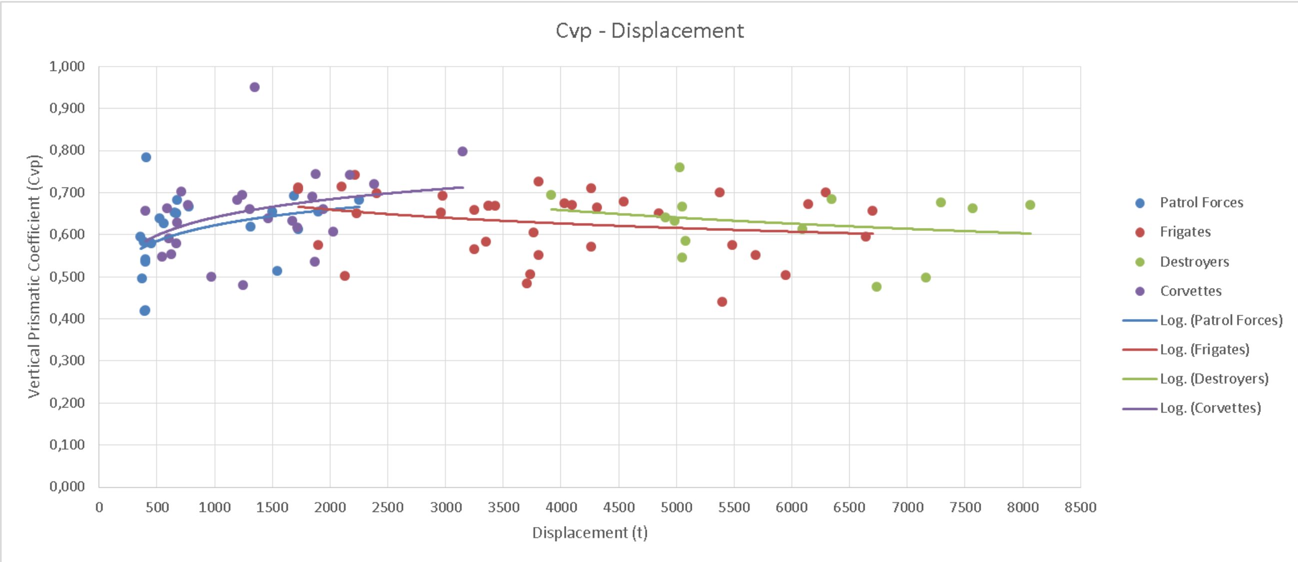


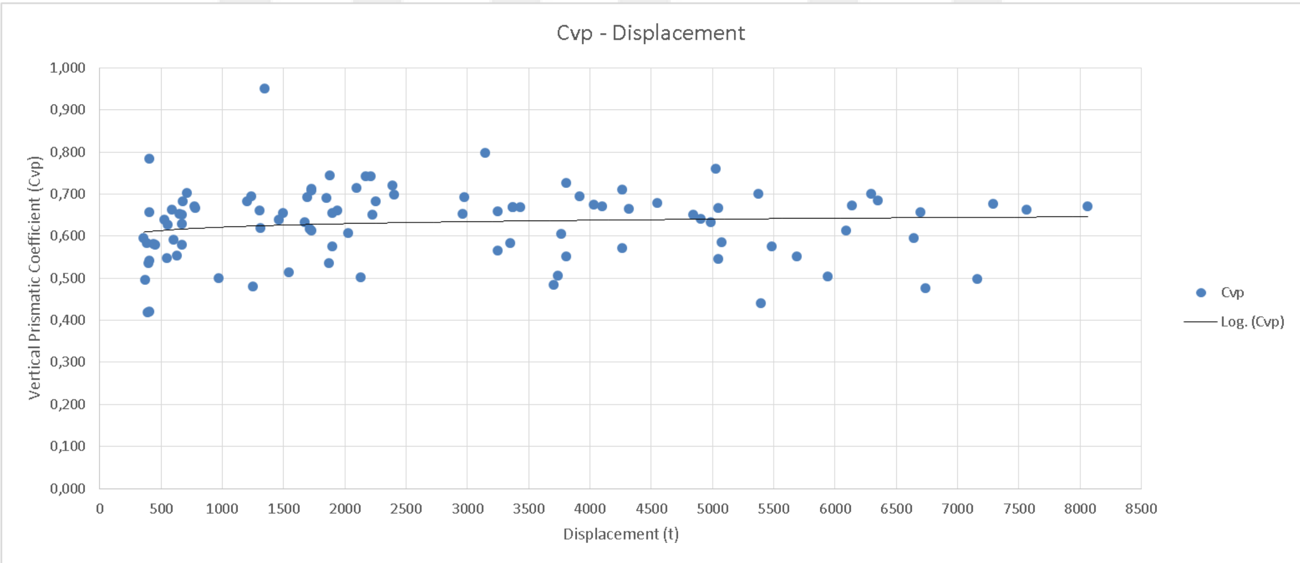
Cp – Prismatic Coefficient



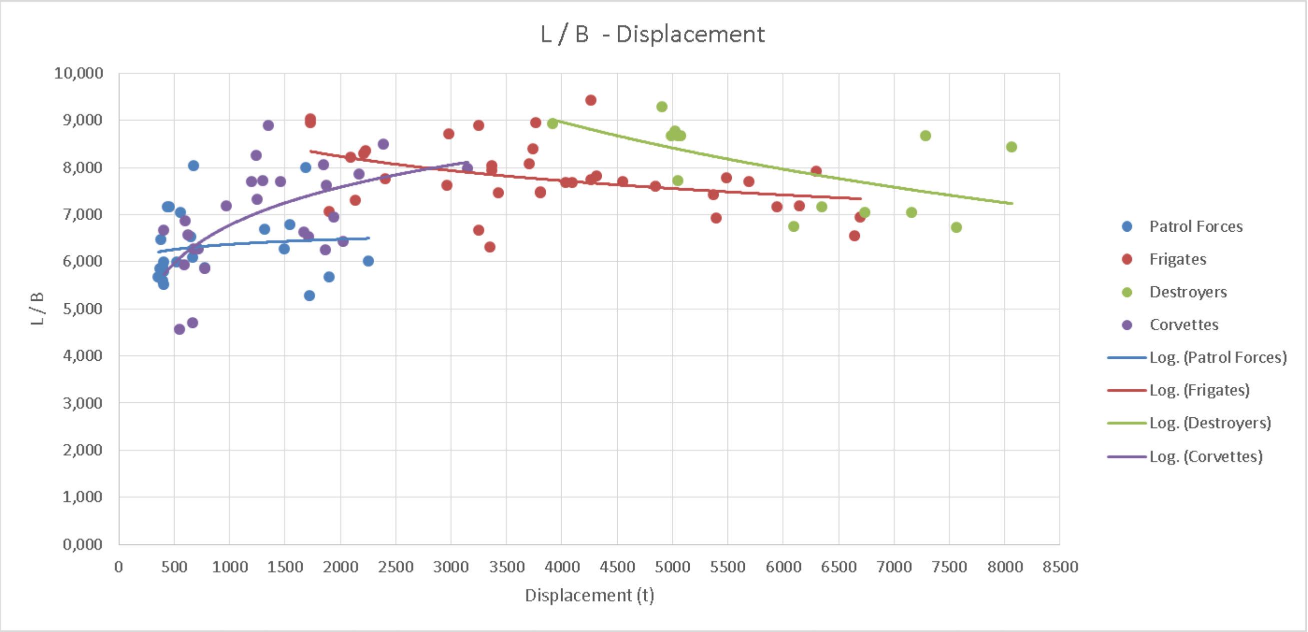


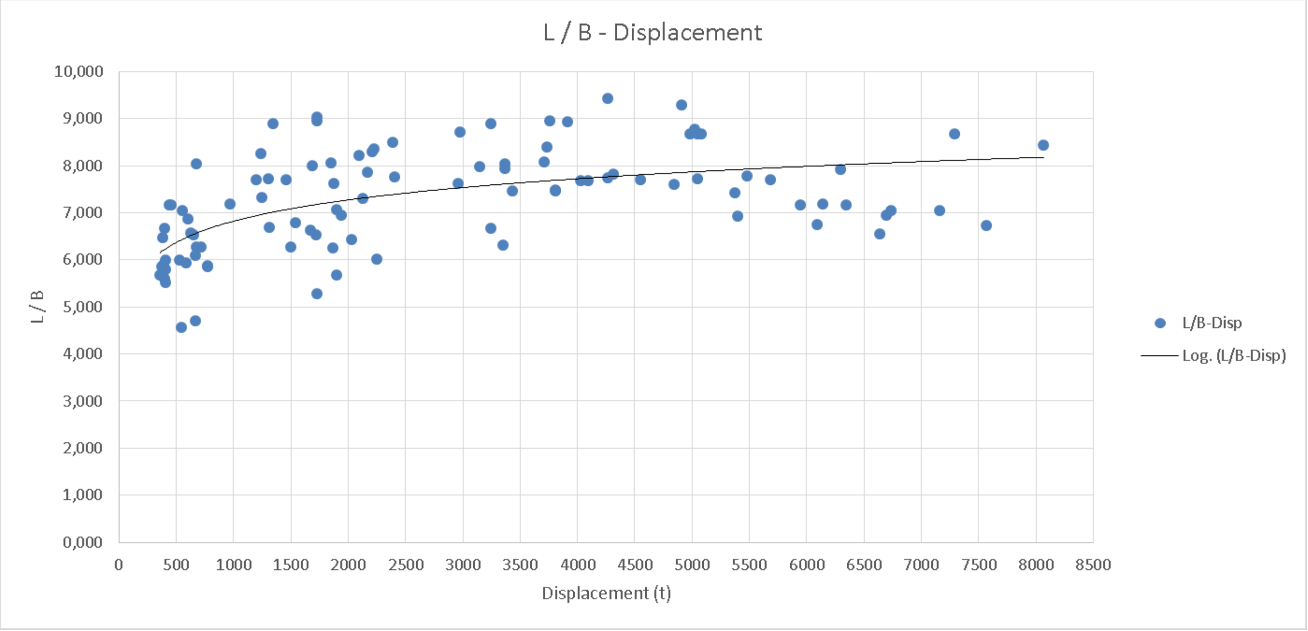
Cvp – Vertical Prismatic Coefficient



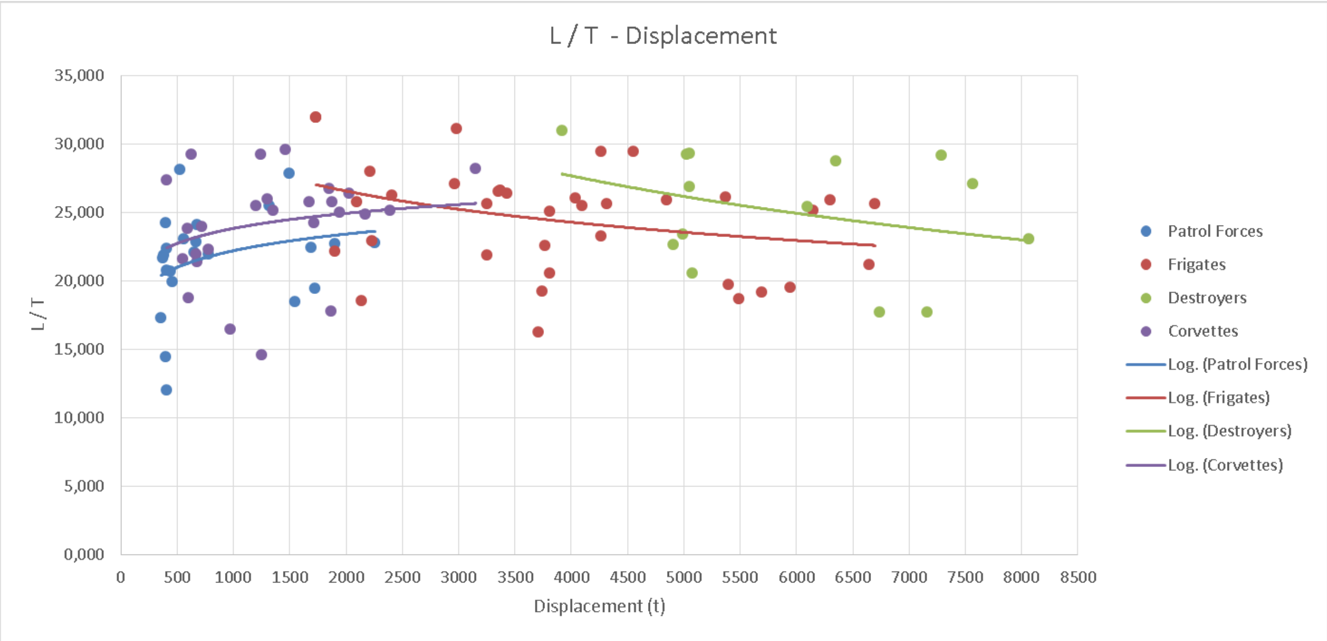


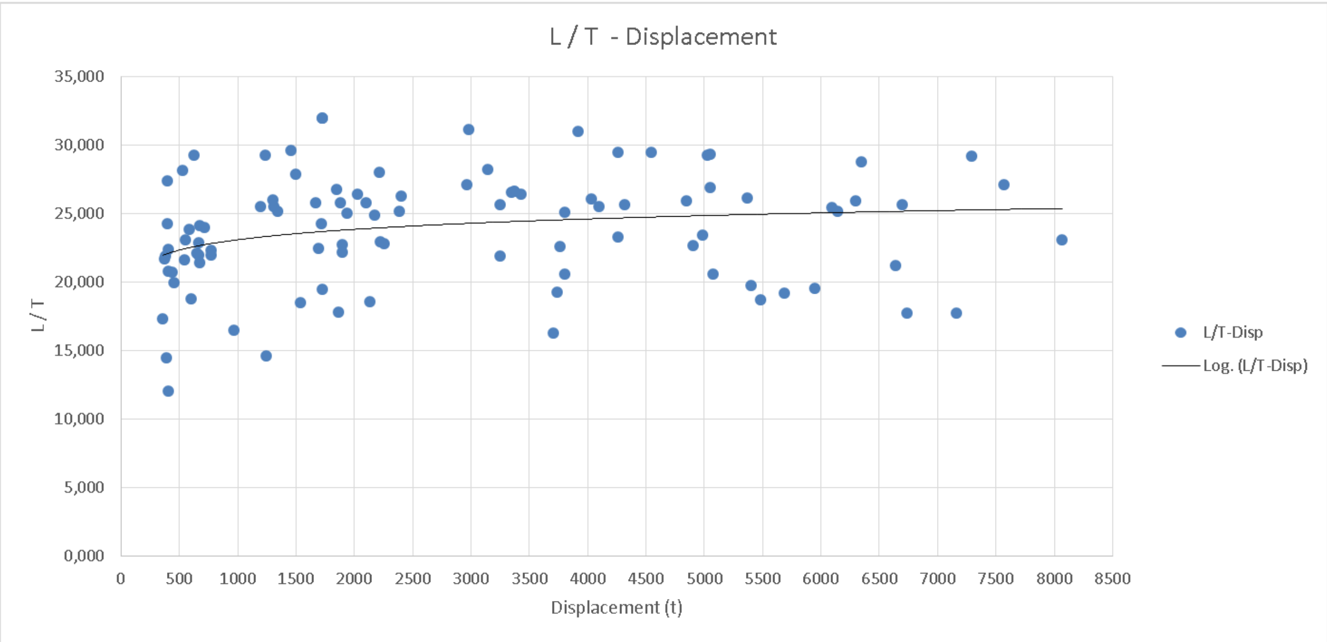
Length to Beam Ratio



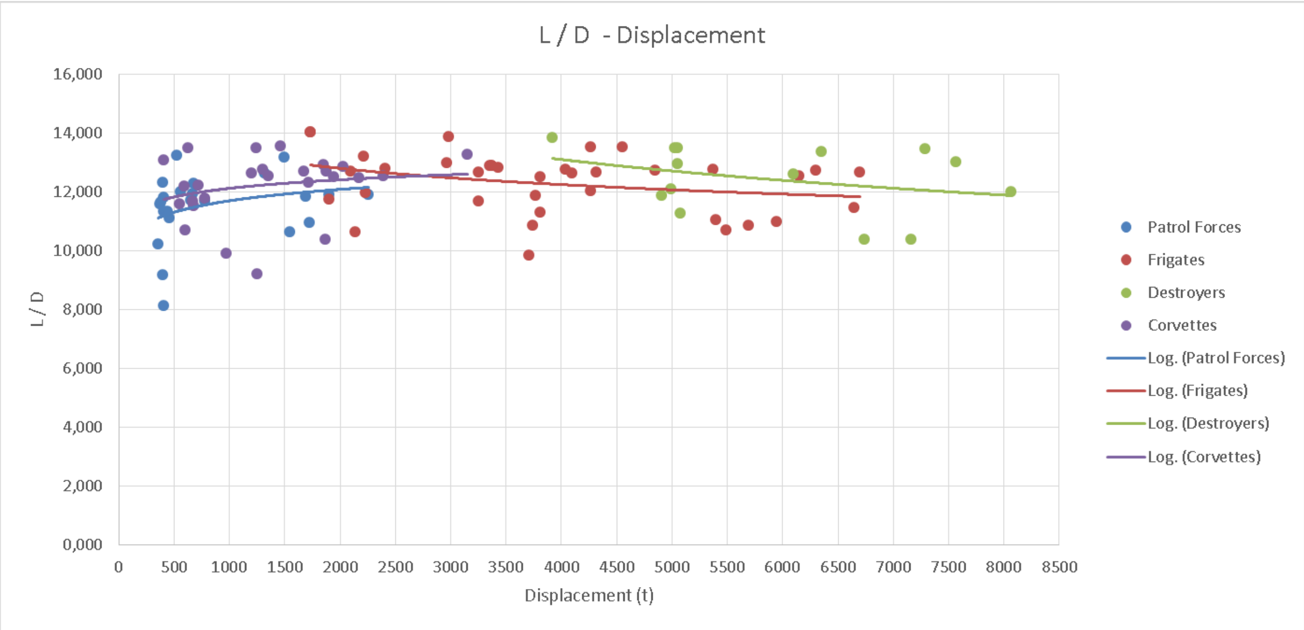


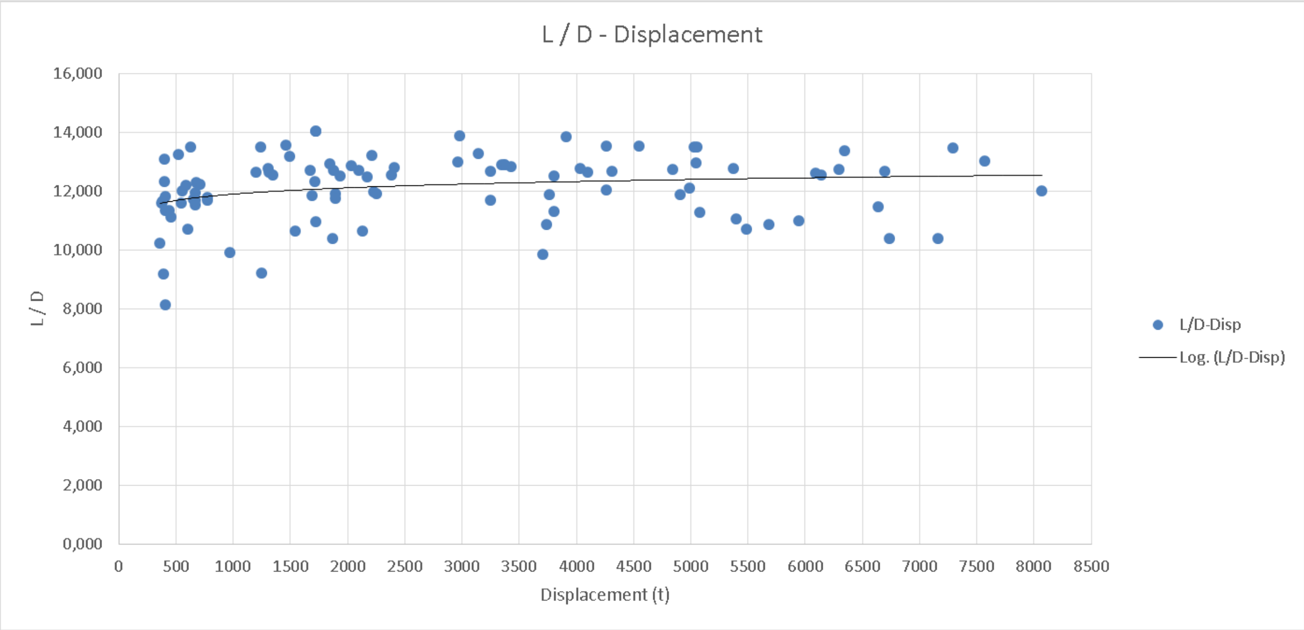
Length to Draft Ratio



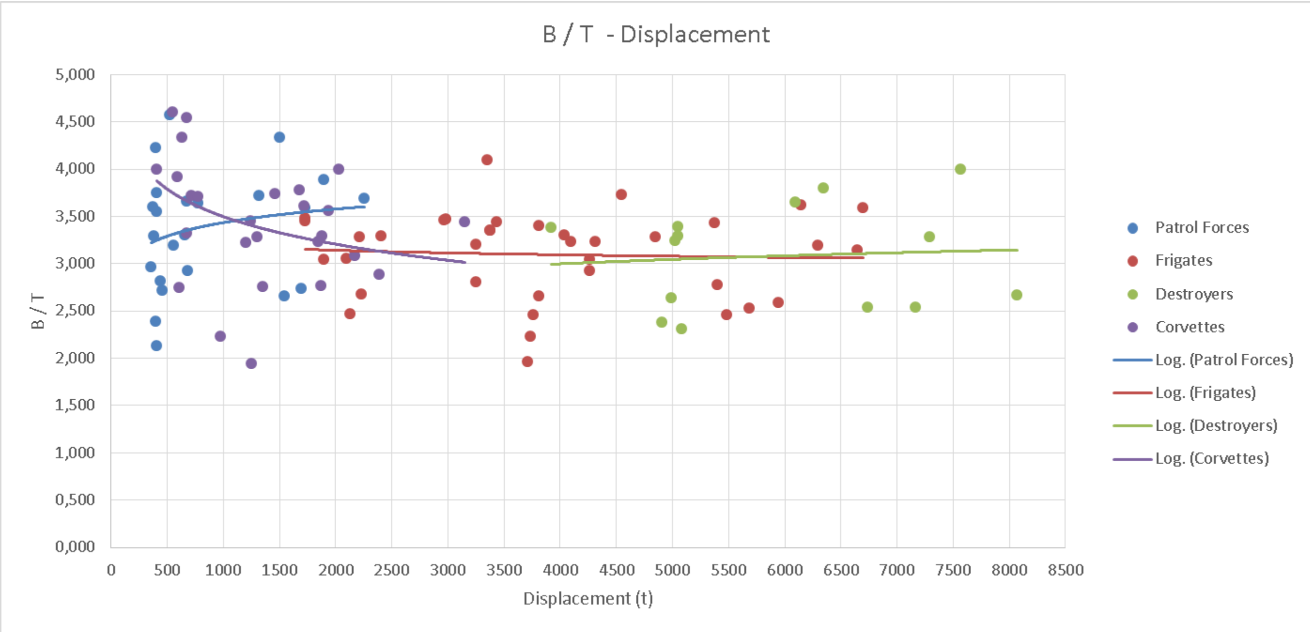


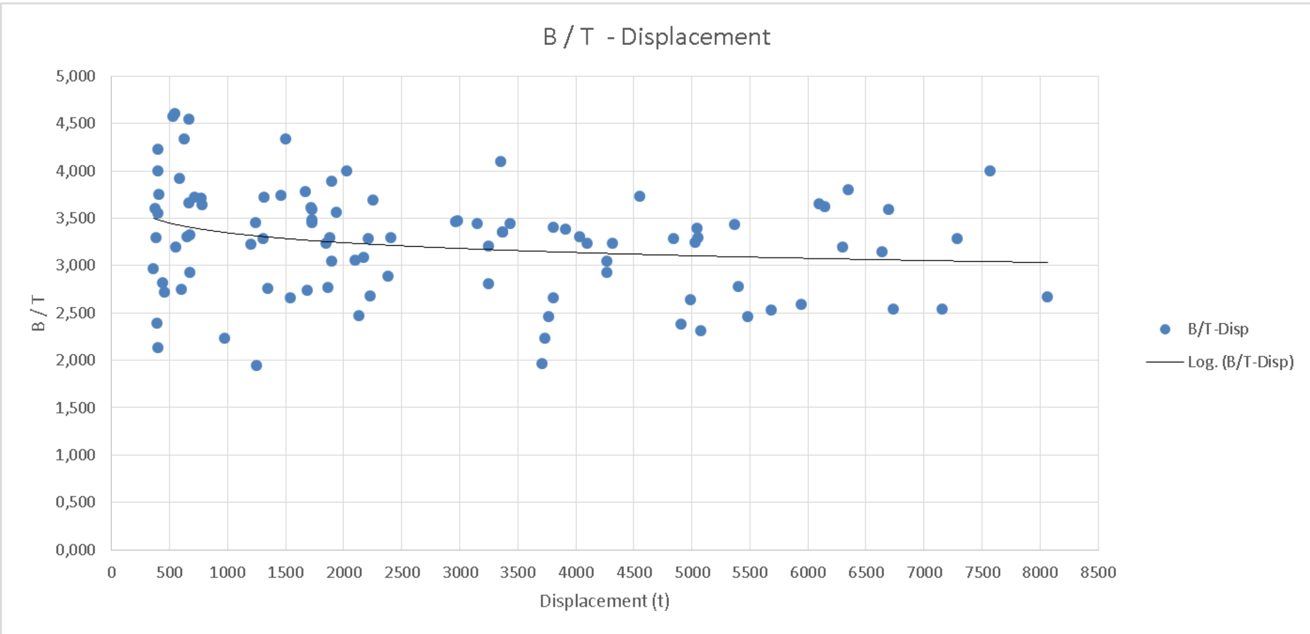
Length to Depth Ratio



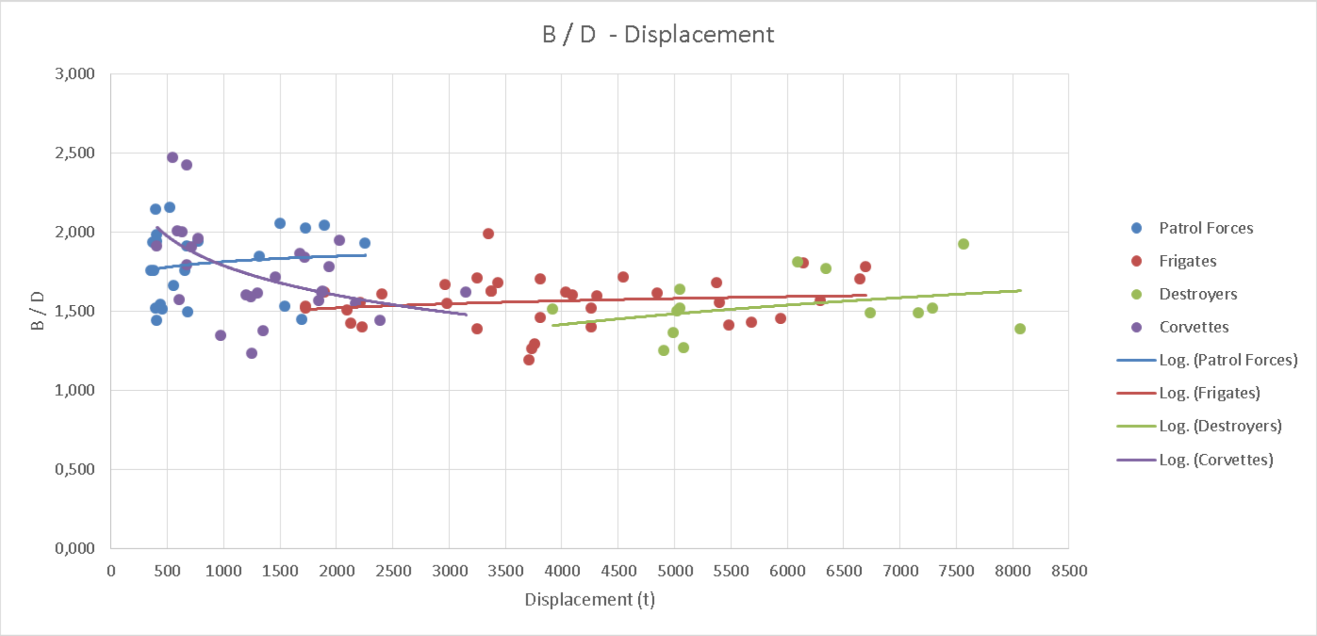


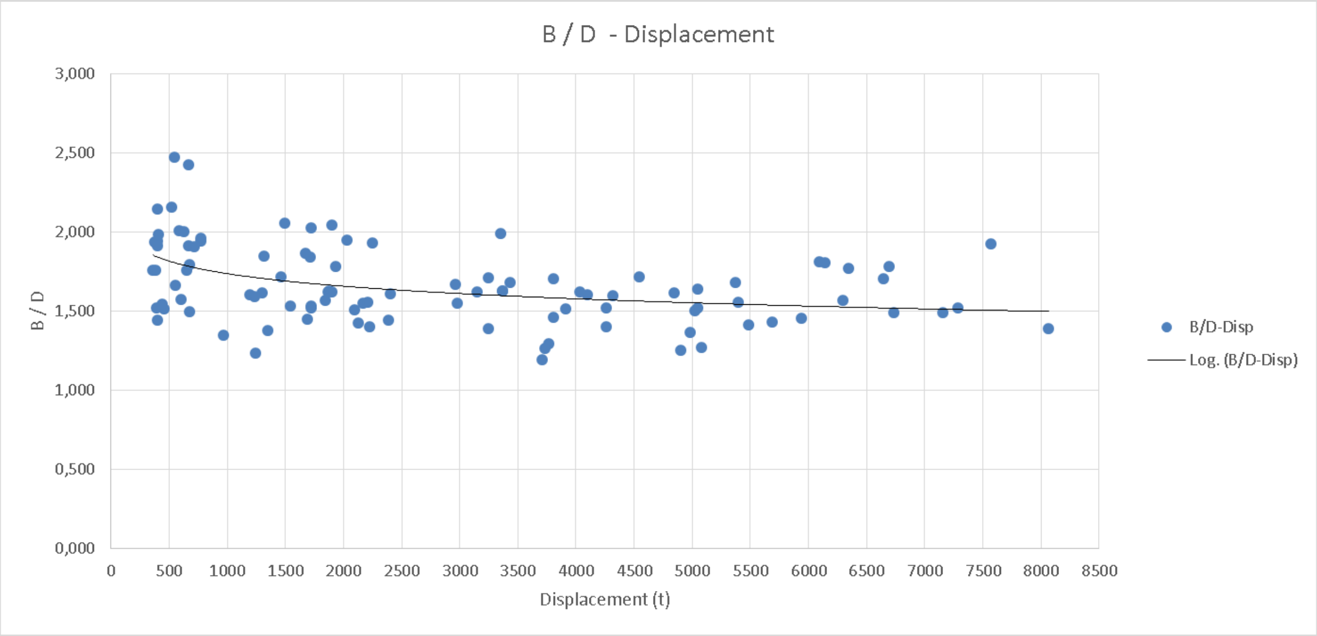
Beam to Draft Ratio



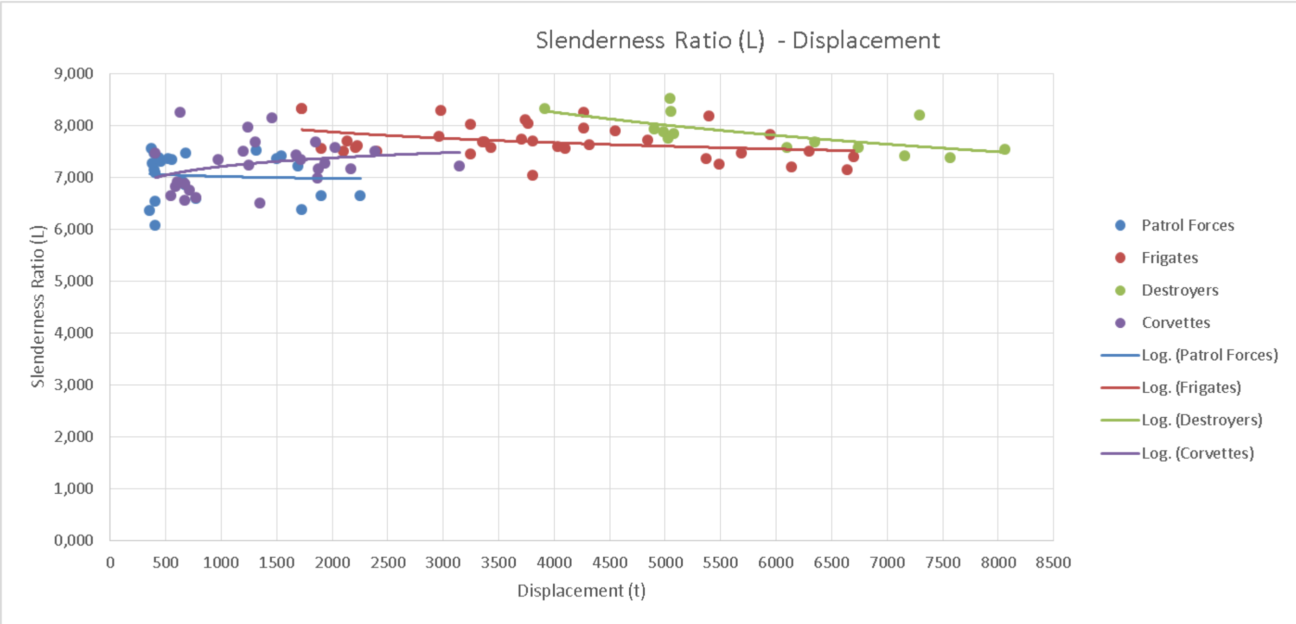


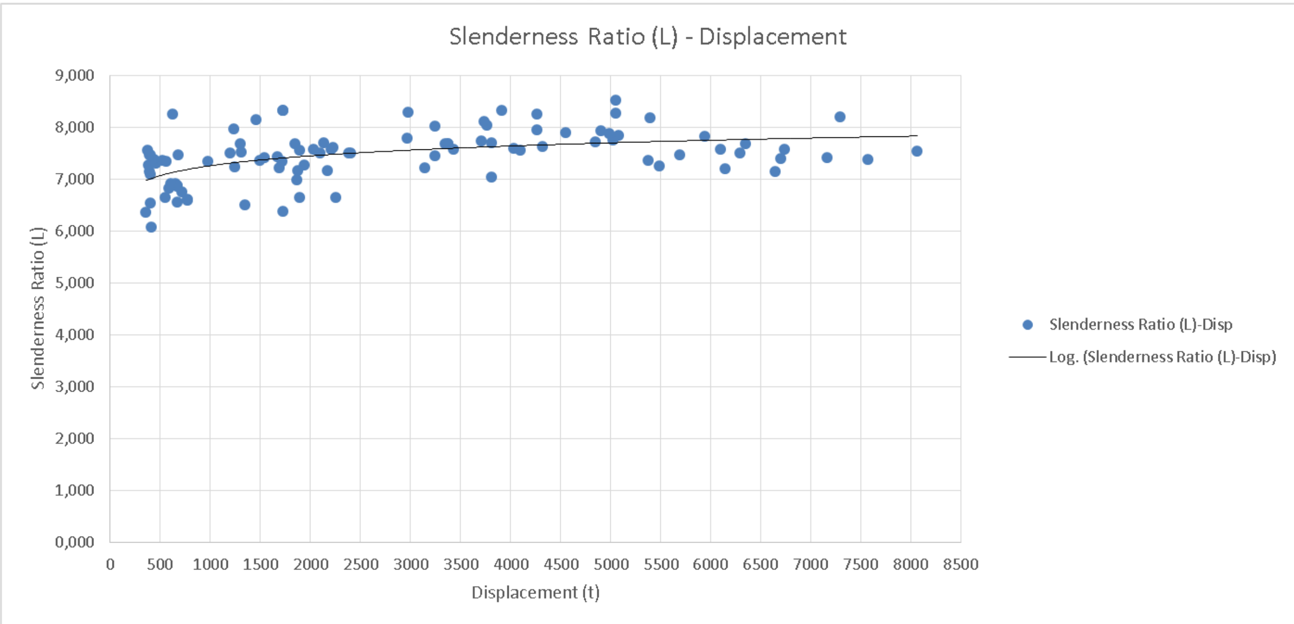
Beam to Depth Ratio



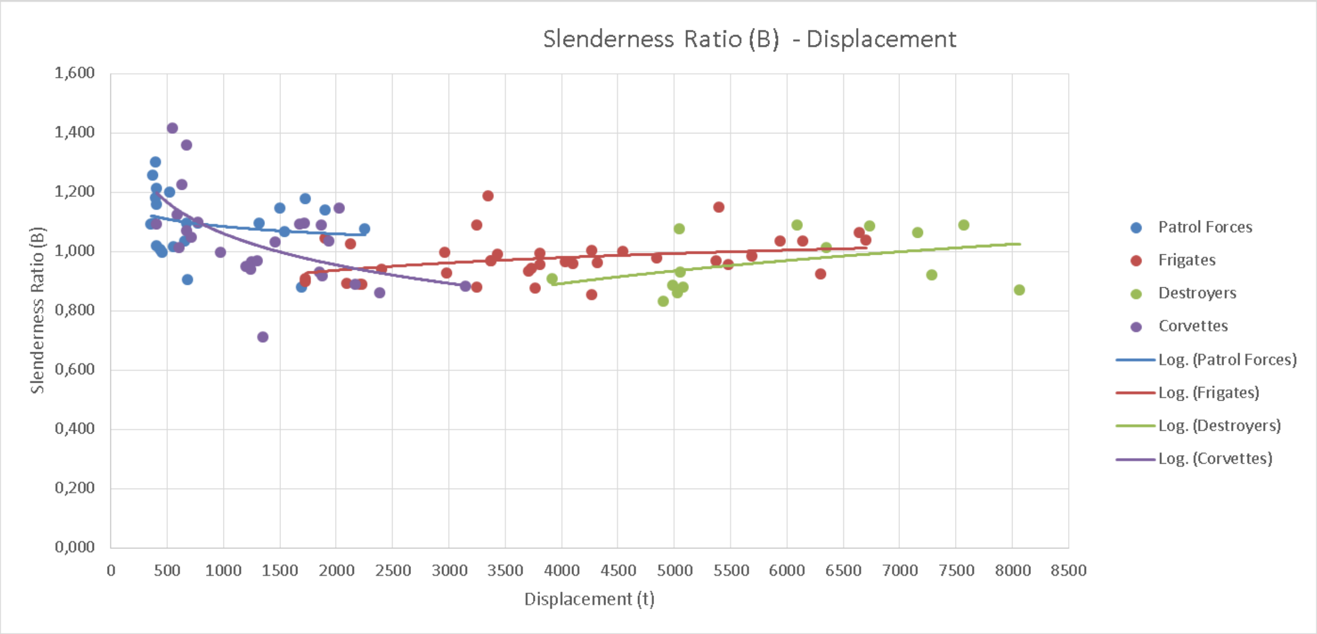


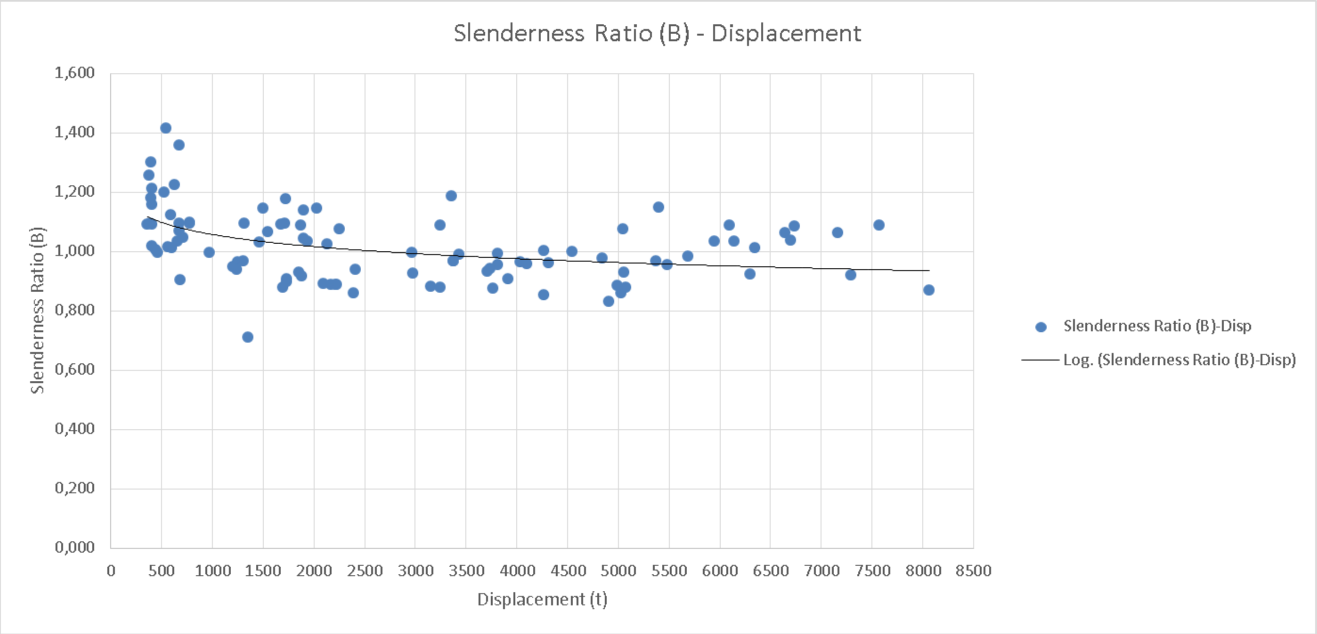
Slenderness Ratio – Length



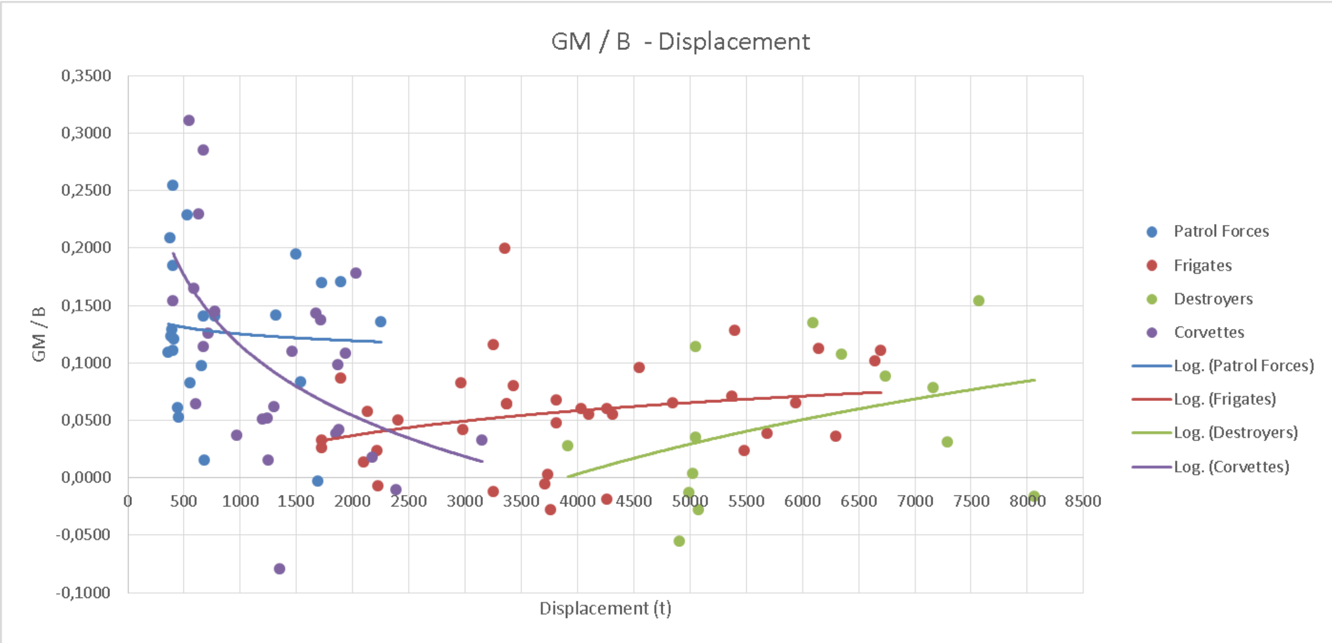


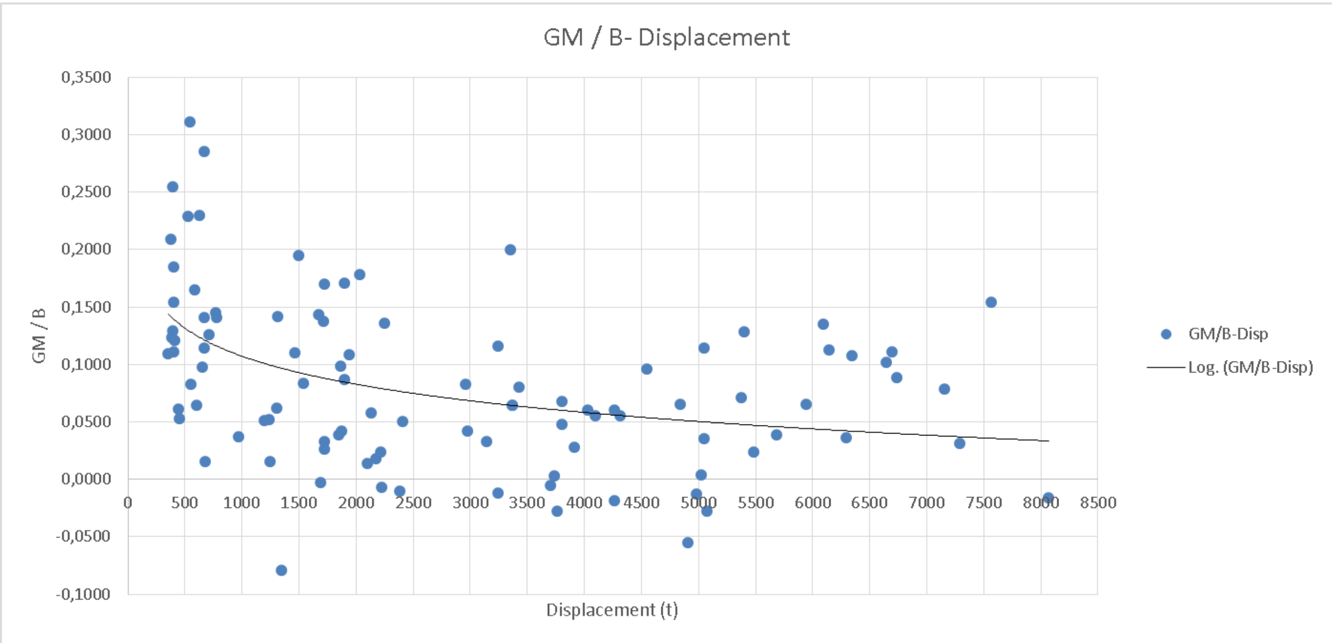
Slenderness Ratio – Beam



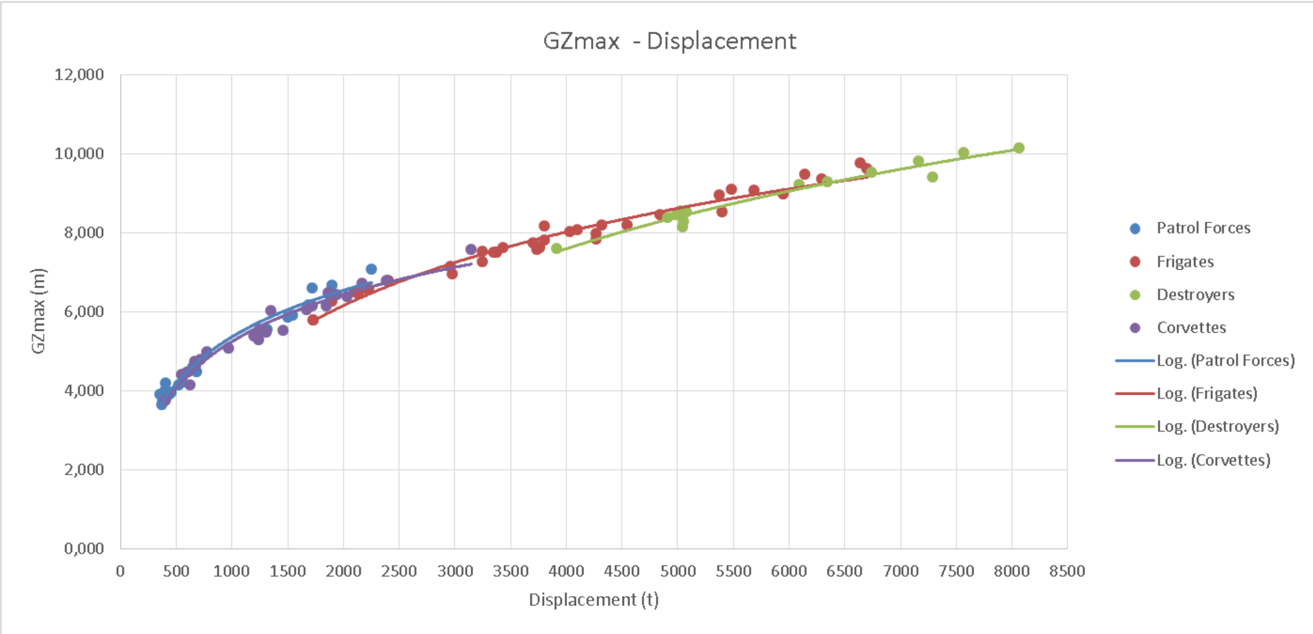


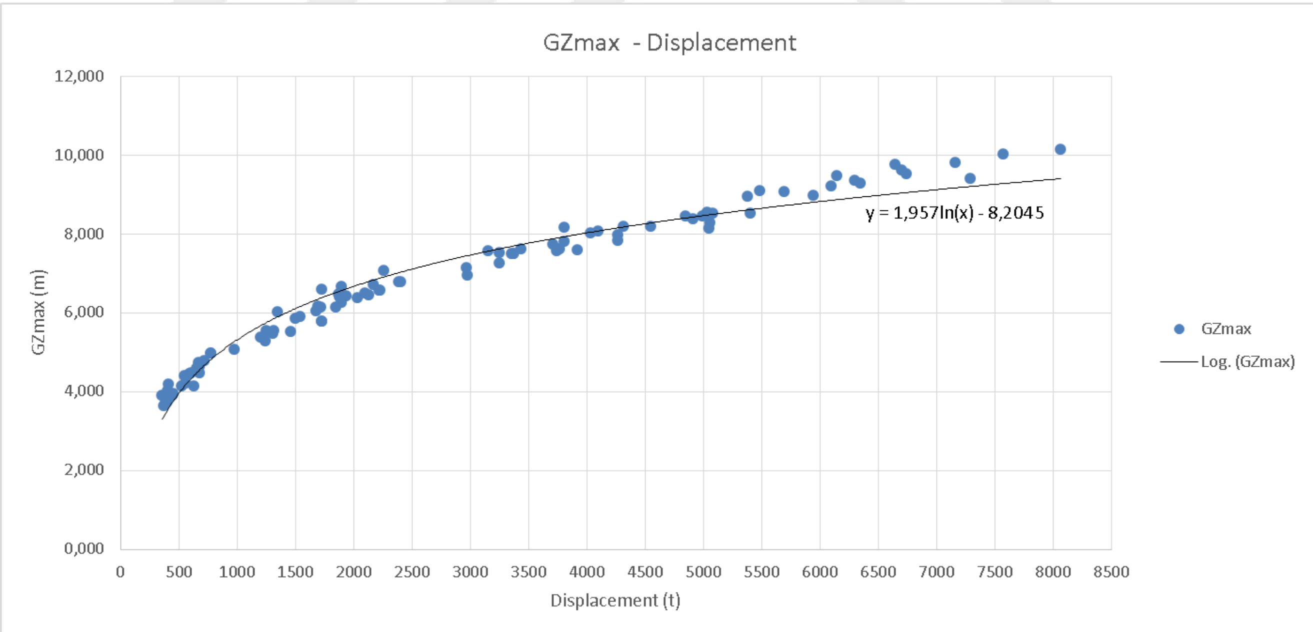
Metacentric Height to Beam Ratio





Gzmax


GZmax - Displacement
GZmax (m)
12,000
10,000
8,000
6,000
4,000
2,000
0,000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
Displacement (t)
Patrol Forces
Frigates
Destroyers
Corvettes
Log. (Patrol Forces)
Log. (Frigates)
Log. (Destroyers)
Log. (Corvettes)


GZmax - Displacement
GZmax (m)
12,000
10,000
8,000
6,000
4,000
2,000
0,000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
Displacement (t)
y = 1,957ln(x) - 8,2045
GZmax
Log. (GZmax)

Bales ‘R’ Factor