1. INTRODUCTION

1.1. Ships, main machinery and auxiliary marine systems

Ships are marine vehicles made of many different systems of large dimensions and high levels of technical complexity. These systems must be robust and self-sustaining in their marine environment – characterized by harsh conditions - for long periods with a high degree of reliability in order to assure safe operations. Therefore, ship design and construction covers different technological areas and involves a wide field of expertise, in terms of applied engineering. In general, there are two main areas of skill, those of the naval architect and the marine engineer. In general, the naval architect is concerned with structural aspects of the ship's hull and superstructure. Namely, naval architects deal with definition of hull forms, in order to optimize ship's hydrodynamic performance, hull structural design, in order to assure ability to endure its environment during the entire ship's life cycle, and superstructure layout, in order to provide adequate habitability conditions and accommodate all the required operational spaces. After design stage, naval architects are also involved on technical assistance to ship's construction (manufacturing and erection).

On the other hand, the marine engineer (specialized in mechanical, electrical or automation) is responsible for the various main machinery and auxiliary marine systems which propel and operate the ship, respectively. More specifically, this means that marine engineers have to deal with operation and maintenance aspects of all the machinery required for propulsion, power generation and its distribution, steering gears, deck equipment for anchoring and ship securing, cargo handling, and air conditioning and ventilation, etc..

In practice, some overlap in responsibilities occurs between naval architects and marine engineers when working either in shipyards or ship design offices in areas such as propeller design, the reduction of noise and vibration in the ship's structure, and other engineering services provided to considerable areas of the ship.

On these notes, considering main machinery and auxiliary marine systems is a very wide field of expertise, topics more related to the role of naval architect as a design or construction project manager will be privileged. However, it should be stressed that the responsibilities of the marine engineer are rarely confined to the machinery space, and thus the knowledge required and the duties to be performed by the marine engineer requires robust training and education. In fact, the various duties of a marine engineer involve not only operation, but also preventive maintenance and corrective actions in many different fields: mechanical, electrical, refrigeration and air conditioning, fresh water production, all of them installed on a self-sustaining floating platform exposed to a corrosive environment.

A ship might reasonably be divided into three distinct areas: the cargo-carrying holds or tanks, the accommodation and the machinery space. Depending upon the type each ship will assume varying proportions and functions. An oil tanker with double-bottom and double-hull, for instance, will have the cargo-carrying region divided into tanks by a longitudinal bulkhead and several transverse bulkheads. As shown in Figure 1.1, there will be considerable quantities of cargo and ballast piping both above and below decks.

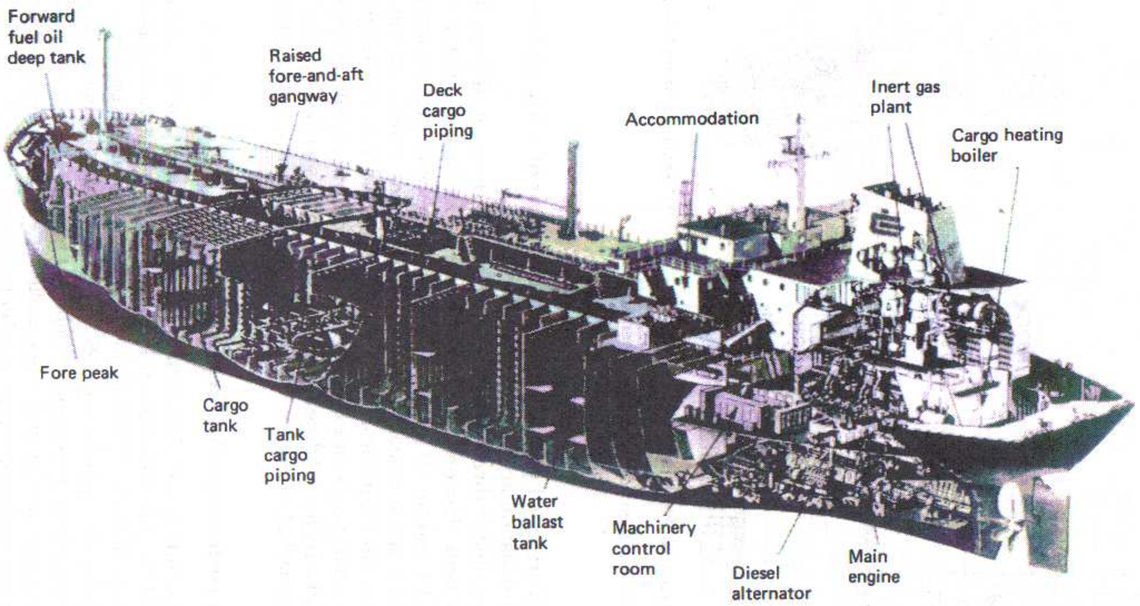

Fig. 1.1 – Cutaway drawing of a typical oil tanker.

On the other hand, a general cargo ship will have various cargo holds which are usually the full width of the vessel and formed by transverse bulkheads along the ship's length. Cargo handling equipment will be arranged on deck and there will be large hatch openings closed with steel hatch covers. The accommodation areas in each of these ship types will be sufficient to meet the requirements for the ship's crew, provide a navigating bridge area and a communications centre. The machinery space size will be decided by the particular machinery installed and the auxiliary equipment necessary. A passenger ship, however, would have a large accommodation area, since this might be considered the 'cargo space'. Machinery space requirements will probably be larger because of sanitary water treatment plant, air conditioning equipment, roll stabilization system, and many other types of equipment related to transportation of passengers in adequate safe and comfortable conditions.

1.1.1. Ship's mission, requirements and technical specification

Before a naval architect can begin the basic design of a vessel, it is important to work closely with the owner to understand and define the mission. The study which should be undertaken will result in the definition of required size and speed and many other mission requirements. Here, the naval architect must interact with the owner to ensure that the emerging missions are such that they can be fulfilled in terms of a practical and economical vessel. Therefore, the existence of a certain vessel can be justified essentially by its own mission. Several examples of missions are as follows:

a) Transportation:

a.1) Cargo:

a.1.1) Dry cargo;

a.1.2) Liquid cargo.

a.2) Unitized containers:

a.2.1) Containers;

a.2.2) Palettes;

a.2.3) Piece-by-piece;

a.2.4) Roll-On/Roll-Off (RORO).

a.3) Passengers:

a.3.1) Ferry-boats;

a.3.2) Cruise liners;

b) Services and industrial vessels:

b.1) Scientific and oceanographic survey;

b.2) Fisheries and legal protection;

b.3) Military;

b.4) Fishing;

b.5) Pipe lying;

b.6) Tow and tug;

b.7) Pilot;

b.8) Suction dredges;

b.9) Ice-breaker;

b.10) Vessels for prospecting oil and other mineral resources.

Owner requirements are determined by mission analysis. Moreover, owner requirements do represent a list of requirements that must be satisfied by the vessel in order to effectively and economically accomplish its mission. These requirements, such as the nature of the cargo and/or passengers to be transported, have a powerful influence on the ship's design. An understanding of the entire design sequence is therefore essential to anyone seeking to develop a basic design. The four steps involved are illustrated in the design spiral, Evans (1959), as an iterative process working from mission requirements to a detail design, Figure 1.2.

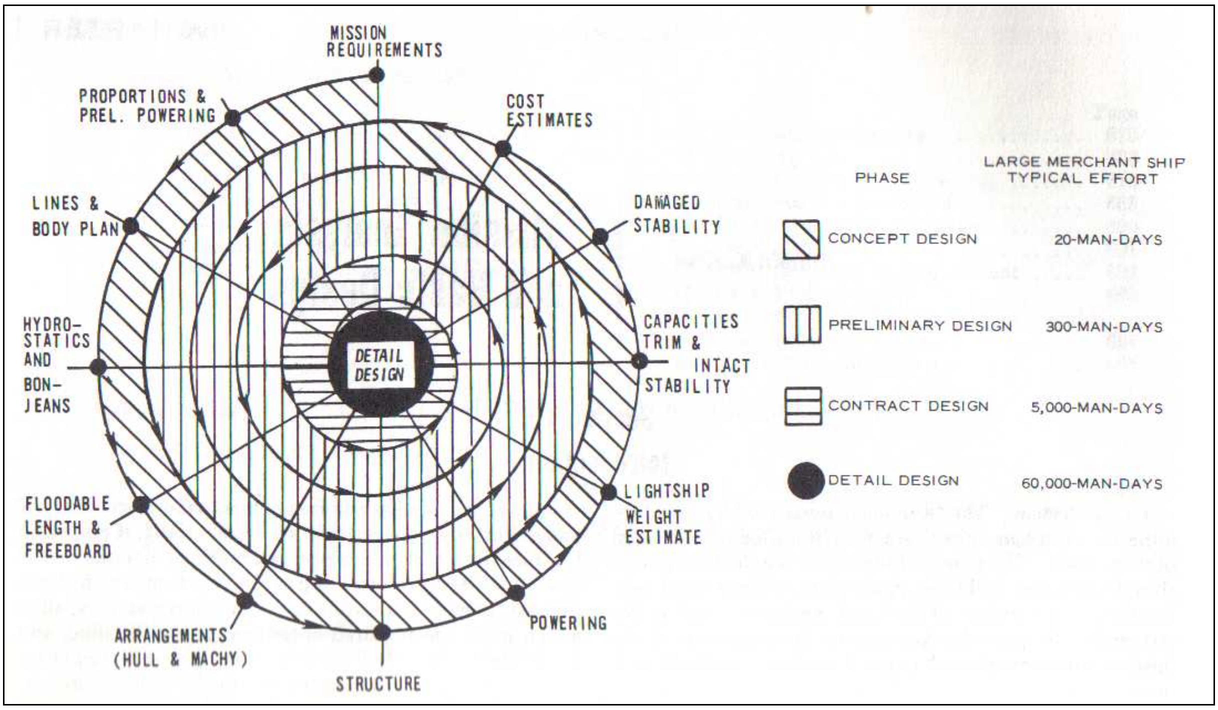

Fig. 1.2 – Basic design spiral.

A set of plan and specifications produced by the shipyard, designated as technical specifications, and which form an integral part of the shipbuilding contract document, are the outcome of the interpretation and refinement process of the owner requirements. Therefore, naval architects and marine engineers responsible for basic design should be able to first interpret owner requirements, taking then (during the contract design phase) also into account all the safety and operation rules and regulations applicable to the vessel.

The accompanying technical specifications, as suggested by its own name, delineate quality standards of hull and outfit and the anticipated performance for each item of machinery and equipment in order to obtain a practical and economical vessel for investors. They also describe the tests and trials that shall be performed successfully in order that the vessel will be considered accepted.

The most important aspects that should be considered when writing technical specification are as follows:

a) Integration and well-balanced solutions;

b) Structural robustness (sound ship's structural design);

c) Nautical capabilities (hull forms, weight distribution, seakeeping and possible installation of roll stabilization devices, etc.);

d) Mobility (propulsion and manoeuvrability);

e) Habitability and spaces functional relationship (ergonomics and spaces layout).

The final stage of ship design is the development of detailed working plans. These plans are the installation and construction instructions to the ship fitters, welders, outfitters, metal workers, machinery vendors, pipefitters, etc. As such, they are not considered to be part of the basic design process.

1.1.2. Ship costs

In respect to many different possible technical solutions, those which are really adopted do result from economical analysis. In fact, the technical solutions commonly adopted for a certain vessel are those which result in an efficient vessel with the requisite performance criteria while satisfying the predefined economical criteria (price range).

To conduct this economical analysis, it will be first necessary to determine the ship's costs adopting a systematic approach, as described below:

a) Initial or acquisition cost (C_{i0});

b) Operating cost:

b.1) Fixed costs (independent from operational activity);

b.2) Variable costs (directly dependent from operational activity);

Operating costs are listed bellow:

b.1) Fixed cost (C_f):

b.1.1) Crew (partial);

b.1.2) Maintenance (partial);

b.1.3) Insurance;

b.1.4) Owner administrative or miscellaneous costs.

b.2) Variable cost also known as daily running cost (C_o):

b.2.1) Fuel;

b.2.2) Crew's consumables (e.g. food and drinks);

b.2.3) Port cost.

Expected profitability of the vessel is then calculated from the difference between the annual income (revenue) and expenditure (all annual cost including the investment cost).

Annual cost (*CC*) is given by the summation of the operating cost plus cost of capital recovery (C_i), which means, the amount of initial cost that should be annually received in order to recover the capital cost and the interest rate of the loan. Mathematically, annual cost is given by:

$$CC = C_i + C_f + C_o \qquad (1)$$

Note should be given to the fact that operation cost can be estimated based on fuel consumption of main machinery and auxiliary systems, as follows:

$$C_o = CAC + COD.Z \qquad (2)$$

, where:

$CAC = Z.D.q_{mi}.(1+k).PC$ = Cost of fuel and lubricating oil per year consumed at a given ship's speed;

COD = Diverse operational costs per trip;

$Z = \frac{P_o}{TVR}$ = Nr of trips per year, where P_o is the nr of operation hours per year.

In respect to formulae presented above, it is still convenient to explain their meaning and units:

$q_{mi} = \frac{p.P_B}{V}$ = Ship's fuel consumption in [kg/mi], where p is the main machinery fuel consumption in [kg/kW.hr] and V represents the ship's speed;

k = Factor representing the relation between the cost of fuel and lubricating oil consumed by auxiliary systems relatively to the cost of fuel and lubricating oil consumed by main machinery;

$TVR = T_N + T_P$ = Round trip time, given by the summation of the navigation time (T_N) and the stop time on ports (T_P). Moreover, the navigation time in hours can be obtained from the following expression: $T_N = \frac{D}{V}$;

D = Distance of one round trip [mi/trip];

PC = Unitary cost of fuel in [Currency/Kg].

Annual revenue (RR) is given by summation of all the incomes due to chartered services provided by the vessel. Income is generated from the product of cargo carried per annum times average freight rate. However, since freight rates vary widely with supply and demand and inflation, the annual revenue of the vessel should be estimated based on a probabilistic approach, as follows:

$$RR = P_i.Z.CDW.F \tag{3}$$

, where:

P_i = Probability of obtaining cargo in the charters market, expressed in terms of [hr/year];

CDW = Ship's cargo deadweight per hour;

F = Unitary cost of the freight [currency/ton];

Therefore, expected profitability (PR) can be obtained from the difference between the annual revenue and cost, simply given by:

$$PR = RR - CC \tag{4}$$

1.1.3. Economical velocity and minimum required freight rate

The most economic ship's speed is the speed at which expected profitability (*PR*) of the ship is maximized. Therefore, the speed at which fuel consumption per mile is minimal might well not be corresponding to economical velocity.

In practice, it is difficult to establish precisely the most economical ship's speed, and often a range of economical speeds has been utilized to identify the ship's enhanced economical performance.

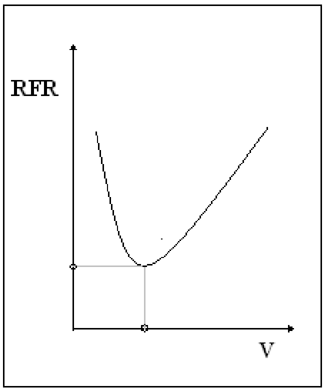

Fig. 1.3 – Minimum required freight rate and most economical ship's speed.

Another possibility to find the most economical ship's speed is to make a calculation of the required freight rate (*RFR*) versus ship's speed, and then from this curve conduct a trend analysis in order to find out its minimum value corresponding to the most economical ship's speed (see Figure 1.3).

Finally, it is recalled that by definition minimum required freight rate (*MRFR*), is given by:

$$MRFR = \min\left(\frac{CC}{Z.CDW}\right) \tag{5}$$

, which is expressed in [currency/ton].

1.1.4. Transport efficiency

Transport efficiency (Ω) is defined as.

$$\Omega = \frac{W.V}{P} \tag{6}$$

, where:

W = Ship's total weight in [N];

V = Ship's speed in [kts];

P = Power installed onboard [W].

Hence, high values of transport efficiency correspond to the most favorable situation, where installed power onboard is more efficiently utilized.

Transport efficiency (Ω) of various modes of transport versus ship's speed is shown in Figure 1.4.

Transport efficiency (Ω) of different types of vessels versus ship's forward speed is shown in Figure 1.5.

Propulsion efficiency (η_o) of different types of propulsor versus ship's forward speed is shown in Figure 1.6.

Normalized fuel cost of various modes of transport versus payload ratio is shown in Figure 1.7.

Although economics of transportation means is a topic covered by a different discipline, naval architects and marine engineers should recognize the significant impact of selection of a propulsion system in terms of energy savings and this is the reason why this topic was brought in here. Moreover, while selecting a certain transportation mean or a vessel's propulsion system, other operational aspects such as the value of the cargo to be transported or how fast the cargo (either passengers or goods) should be transported to its final destination must be also taken into account.

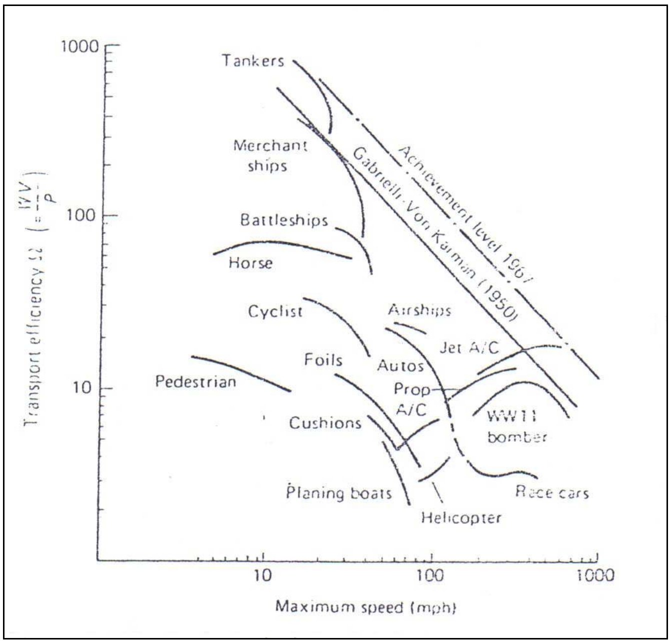

Fig. 1.4 – Equivalent of the Gabrielli-von Karman (1950) chart showing transport efficiency of various modes of transport as a function of maximum speed. Also shown is the limit of performance given by Mantle (1976).

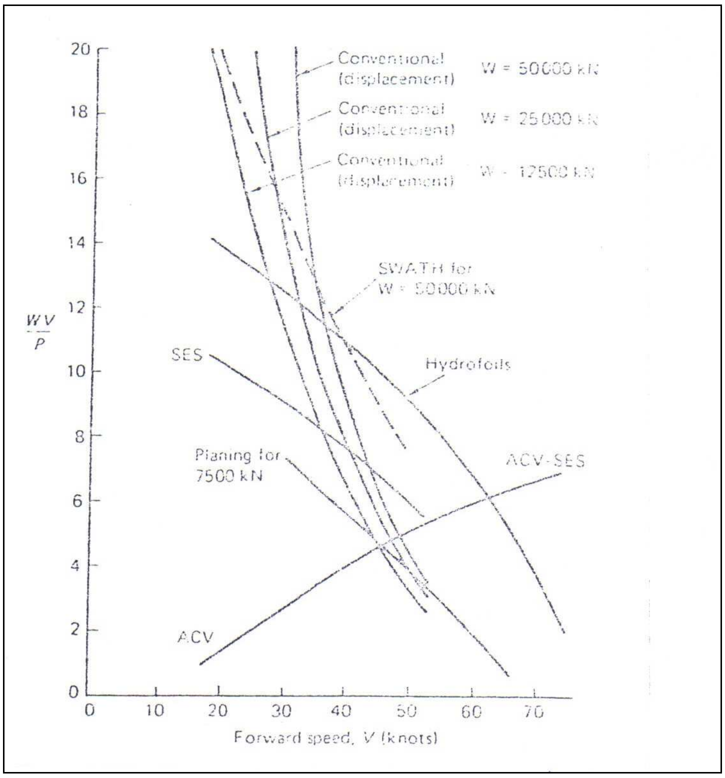

Fig. 1.5 – Transport efficiency of some conventional and high speed craft as a function of ship's speed (after Oossanen, 1987).

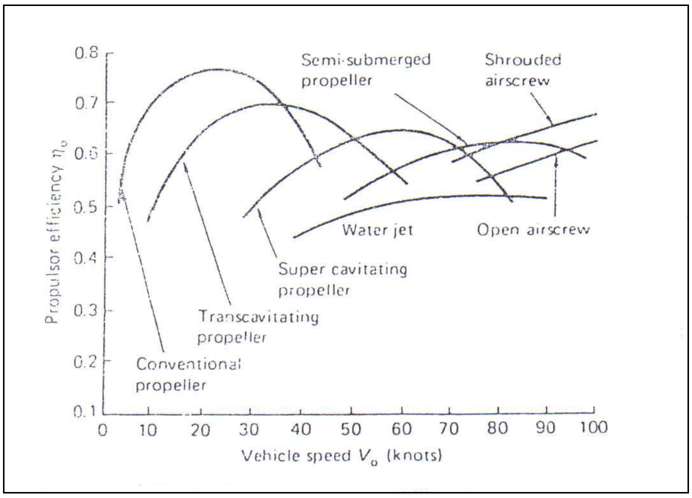

Fig. 1.6 – Highest achievable values of open water efficiency of different types of propulsor as a function of forward speed in open water (after Oossanen, 1987).

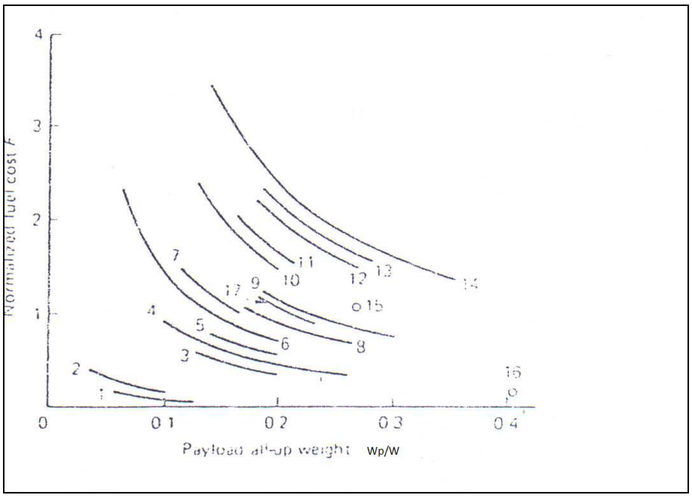

Fig. 1.7 – Normalized fuel cost as a function of payload ratio. Key: 1-Monohull displacement ferry; 2-High speed passenger train; 3-SWATH ship of 15MN (15000 tonnef) weight displacement and 28 knots operating speed; 4-Modern passenger aircraft; 5-SWATH ship as 2, but at 33 knots; 6-Jet surveillance craft; 7-Surface piercing hydrofoil; 8-SES; 9-ACV; 10-Diesel fast patrol boat; 11-Jetfoil; 12-Slender planing boat; 13-Gas turbine fast patrol boat; 14-Helicopters; 15-Medium sized family car; 16-Motor coach; 17-Catamaran.

1.1.5. Characterization of onboard systems

Resulting from the above mentioned technical and economical requirements, ship systems should be analyzed during ship design appraisal stage in respect to:

a) Energy conversion efficiency:

a.1) Propulsion system;

a.2) Other auxiliary systems.

b) Interaction with environment;

c) Interaction with land structures and other vessels;

d) Habitability conditions;

e) Mission specific performance aspects;

f) Safety conditions.

1.1.6. Most important topics in the realm of main machinery and auxiliary marine systems

Based upon the above mentioned technical and economical requirements, the most important aspects to be considered in the realm of main machinery and auxiliary marine systems during basic ship design phase are as follows:

a) Choice of the internal combustion engines;

b) General requirements for machinery pressure piping systems;

c) Air conditioning, refrigeration and ventilation;

d) Pollution abatement systems and equipment;

e) Interaction between machinery and the vessel;

f) Automation;

g) Fuel consumption (increased efficiency, recovery of dissipated energy and reduction of energy losses);

h) Maintainability of equipments and materials and ship's reliability and availability.

In respect to maintainability and systems reliability, it is important to introduce the concept maintenance cycle and time between overhauls. Figure 1.8 shows a typical curve of failure rate time history of a diesel engine.

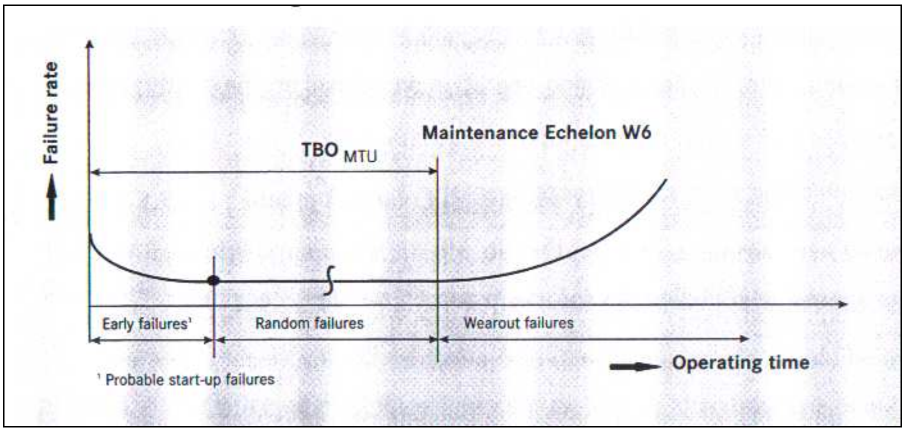

Fig. 1.8 – Definition of maintenance cycle and Time Between Overhauls (TBO).

As shown above, the TBO might be defined as the time span in which operation without major failure is ensured, i.e. it precludes wear related damage requiring a major overhaul or diesel engine replacement. For this engine manufacturer (MTU), this time span is theoretically reached, if a probability of wear-out failures exceeds 1%. This means that an MTU diesel engine can still provide full and unlimited service until the last operating hour before the scheduled overhaul. One of the major criteria for merchant ships is availability and thus the reliability of the propulsion. Based on this, this manufacturer decided to limit the statistical wear-out failure rate to 1% only. Moreover, this type of major preventive maintenance actions on a ship's propulsion or power generation system will require some planning and the operation might need to be interrupted. Therefore, maintenance cycles of a ship should be defined at an early design stage when machinery and materials are selected.

1.2. Main machinery

The main propulsion machinery installed will influence the machinery layout and determine the equipment and auxiliaries installed. This will further determine the operational and maintenance requirements for the ship and thus the knowledge required and the duties to be performed by the engineering personnel.

Three principal types of machinery installation are to be found at sea today. Their individual merits change with technological advances and improvements and economic factors such as the change in oil prices. It is intended therefore only to describe the layouts from an engineering point of view. The three layouts involve the use of direct-coupled slow-speed diesel engines, medium-speed diesels with a gearbox, and the steam turbine with a gearbox drive to the propeller.

A propeller, in order to operate efficiently, must rotate at a relatively low speed. Thus, regardless of the rotational speed of the prime mover, the propeller shaft must rotate at about 80 to 100 [rev/min]. The slow-speed diesel engine rotates at this low speed and the crankshaft is thus directly coupled to the propeller shafting. The medium-speed diesel engine operates in the range 250-750 [rpm] and cannot therefore be directly coupled to the propeller shaft. A gearbox is used to provide a low-speed drive for the propeller shaft. The steam turbine rotates at a very high speed, in the order of 6000 [rpm]. Again, a gearbox must be used to provide a low-speed drive for the propeller shaft.

1.3. Auxiliary marine systems

Despite main machinery also have auxiliary service systems associated, the term auxiliary marine systems designate those systems related to ship service.

The machinery service systems are usually installed inside the machinery space, and are necessary for the main machinery and for generators in addition to their circulating systems (e.g. sea water cooling, lubricating oil, fuel oil, and compressed air).

On the other hand, auxiliary marine systems are exclusively dedicated to servicing the ship in general and providing amenities for personnel or passengers. Thus the ballast system is available to move liquid ballast along the vessel or overboard in order to make weight distribution corrections on ship's transverse or longitudinal plan. The bilge system is available to clear oil, water leakage and residues from machinery and other spaces. Moreover, each of these two ship's servicing systems can be utilized as well as to provide an emergency pumping capability in case of flooding. Still in respect to ship's servicing, usually there are also available onboard air conditioning and ventilation, domestic water, and sewage systems to provide amenities for personnel.