REDUCING SHIP EMISSIONS: A REVIEW OF POTENTIAL PRACTICAL IMPROVEMENTS IN THE PROPULSIVE EFFICIENCY OF FUTURE SHIPS

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SUMMARY

Environmental issues such as the emission of greenhouse gases, pollution, wash and noise are having an increasing impact on the design and operation of ships. These environmental issues together with economic factors, such as rising fuel costs, all ultimately lead to the need to minimise ship propulsive power. Various methods and devices for reducing propulsive power are reviewed and discussed. The most favourable methods, from a feasible and practical point of view, are identified and quantified. It is found that potential reductions in the resistance of existing good hull forms are relatively small, but optimising hull-propeller-rudder interaction offers very promising prospects for improvement. The biggest potential savings in power arise from optimised operational strategies such as the use of optimum trim, speed and weather routeing. Potential conflicts of interest when considering both economic and environmental requirements are investigated and discussed. Suitable design methodologies and procedures, taking into account economic and environmental factors, are suggested for the design of future ships.

NOMENCLATURE

A	Propeller disc area (m^2) [$\pi D^2/4$]
a	Axial inflow factor
a'	Circumferential (rotational) inflow factor
B	Breadth (m)
BAR	Blade area ratio
C	Capacity (tonnes)
C_F	CO_2 conversion factor
C_B	Block coefficient
C_T	Propeller thrust coefficient [$T/½\rho AV^2$]
CRF	Capital recovery factor
D	Propeller diameter (m)
EEDI	Energy efficiency design index
J	Propeller advance ratio [Va/nD]
K_T	Propeller thrust coefficient [$T/\rho n^2D^4$]
L	Length (m)
LCB	Longitudinal centre of buoyancy
n	Propeller rate of revolution (rps)
NPV	Net present value
P	Propulsive power (kW) or propeller pitch (m)
P_D	Delivered power (kW)
P_E	Effective power (kW)
r	Propeller local radius (m)
R	Resistance (kN)
RFR	Required freight rate (cost/tonne)
sfc	Specific fuel consumption (kg/kW.hr)
T	Thrust (kN)
t	Thrust deduction factor
V	Ship speed (m/s)
Va	Propeller advance speed (m/s)
w_T	Wake fraction
η_D	Quasi propulsive coefficient
η_H	Hull efficiency
η_0	Open water efficiency
η_R	Relative rotative efficiency
η_a	Ideal efficiency or axial efficiency
η_r	Rotational efficiency
η_f	Frictional efficiency
∇	Displacement volume (m^3)
Δ	Displacement (tonne)
ρ	Density, sea water (kg/m^3)

1. INTRODUCTION

The design of merchant ships has always had to be centred on economic viability. The main economic drivers amount to the construction costs, crew costs, disposal costs and, in particular, fuel cost as it relates to the chosen operational speed. These need to be combined in such a way that the shipowner makes an adequate rate of return on the investment with a given level of risk. The IMO in 2012 [1], [2] highlighted the urgent need to reduce CO_2 emissions, as already global shipping accounts for 3 – 4% of anthropomorphic emissions, and this proportion will rise if these emissions are not controlled, although such concerns are not new, [3]. Other environmental concerns relate to operational pollution, underwater noise, anti-foulings, ballast water exchange and wave wash. Economic and environmental pressures thus combine to create the need for a fresh appraisal of the estimation of ship propulsive power and the choice of suitable machinery, as well as ship hull design for new-builds. Both issues present the need to minimise propulsive power. Minimising propulsive power can be addressed at the design stage, in terms of hull form design and propulsor design, and during operation which can include the use of suitable changes in trim, route changes and slow steaming.

One of the challenges for ship operators is associated with the difficulty in assessing the actual benefit of retrofit technologies, whereas for a new build, increased investment in vessel design through computational and experimental techniques can help optimise hull shape compared with the more traditional shape compromises driven by construction costs. Thus it can be expected that the economic driver of higher fuel costs will target lower fuel usage and thus reduce emissions. The life span of large ships, typically 20-30 years, works against rapid reductions in emissions. For retrofit, however, it is likely that some form of additional flow control may improve propulsive efficiency, [4], but whether such devices will be cost-effective in generating payback periods of 4 to 5 years will determine their take-up by shipowners. Indeed, the ability to design such devices so that, across the typical operational profile of a specific ship, fuel savings can be guaranteed is still very much an open question.

The aim of the work presented is to provide a systematic evaluation as to the means of reducing CO_2 emissions by reducing required propulsive power and on developing a design methodology that will take account of both economic and environmental issues.

2. QUANTIFYING THE ENVIRONMENTAL IMPACT OF SHIP PROPULSION

The emissions from ships include NOx, SOx and CO_2, a greenhouse gas. NOx and SOx emissions have a relatively local impact and their production and control depends mainly on fuel and engine types. In areas where many ships operate, such as the English Channel and the North Sea, these can cause relatively high concentrations and legislation, through the IMO, is introducing specific operational requirements to minimise these emissions, [5], [6]. CO_2 emissions have a global climate impact and a concentrated effort is being made worldwide towards their reduction. In order to monitor and quantify CO_2 emissions, the International Maritime Organisation (IMO) has developed an Energy Efficiency Design Index, IMO [1], [2].

The fundamental form of the Index is:

$$\text{EEDI} = \frac{CO_2\ emission}{Transport\ work} \tag{1}$$

The general form of the Index, as proposed by IMO, is as follows:

$$\text{EEDI} = \frac{P \times sfc \times C_F}{C \times V} \quad \text{gmCO}_2\text{/tonne.mile} \tag{2}$$

where P is power (kW), *sfc* is specific fuel consumption (gm/kW.hr), C_F is a CO_2 conversion (tonne CO_2/tonne fuel), C is the capacity of the ship (deadweight tonnes or Gross Tonnage) and V the speed (nautical miles /hr (knots), or km/hr). As such, the Energy Efficiency Design Index can be seen as a measure of a ship's CO_2 efficiency. This is very much the general, or generic, form of the equation as the power will be made up of the propulsive and auxiliary power, the capacity C of the ship will in the main be deadweight tonnes; passenger ships will use gross tonnage. Speed has to be clearly defined as it could be taken as the design speed, or some average speed expected in operation. Similarly, power may be the design calm water propulsive power, or power taking into account average increases due to weather.

When considering the overall form of the Energy Efficiency Design Index it is clear that in order to reduce the index for a given ship design proposal at a given speed, a decrease in propulsive power must be achieved and/or improvements made in engine efficiency with a reduction in *sfc*. Improving the basic efficiency of the ship design by maximising deadweight capacity (C) for a given displacement, hence power (P), should also be explored.

For explanatory and comparative purposes, this paper uses the general form of the index, Equation (2), with P as the service propulsive power, capacity C as deadweight tonnes and V the service speed in knots. The example cargo/container ship shown in Table 1 with assumed sfc = 190 gm/kW.hr and C_F = 3.17 tonne CO_2/tonne fuel (IMO [1]) would have a Energy Efficiency Design Index = 12.89 gm/tonne.mile.

Table 1: Particulars of example cargo/container ship

L	145.0 m
B	24.0 m
T	10.7 m
C_B	0.710
Δ	27100 tonnes
Deadweight	20500 tonnes
V service	16 knots
Ps service power	6680 kW

A form of CO_2 emissions control has been introduced and a limit has been set on the Energy Efficiency Design Index for new builds, for some ship types, which entered into force in 2012. This immediately sets great importance on the specific definition of each of the components in Equation (2), Reference [1], together with future design procedures and decisions. It should be noted that as the power (P) is related to the installed power, there may be a drive to reduce assumed powering margins, with potential safety issues such as inability to station keep in extreme seas.

3. POWERING

3.1 OVERALL CONCEPT

The overall purpose of the powering system is to convert the energy of the fuel into useful thrust (T) to match the ship resistance (R) at the required speed (V), Figure 1.

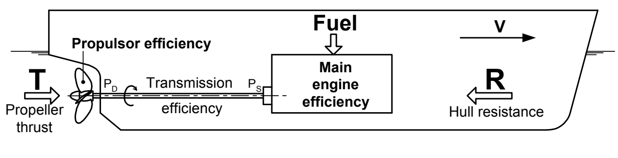

Figure 1: Overall concept of energy conversion in ship propulsion

The overall efficiency of the propulsion system will depend on:

- fuel type, properties and quality;
- the efficiency of the engine in converting the fuel energy into useful transmittable power; and
- the efficiency of the propulsor in converting the power (usually rotational) into useful thrust (T).

The present study concentrates on the performance of the hull and propulsor, primarily considering, for a given set of constraints, how resistance (R) may be reduced and thrust (T) may be increased.

For a ship of given displacement travelling at a constant speed in a calm sea, there will be no net force acting on the hull, propeller and superstructure when the surface pressure and shear stress are integrated over all these surfaces. Energy is only supplied to sustain propulsion via the propeller shaft. The presence of devices which are designed to enhance overall efficiency can only be assessed when operating in the presence of all the other components.

Available fuel and engine types are summarised later. Detailed accounts of propulsion engines may be found in sources such as Woodyard [7] and Molland [8].

3.2 COMPONENTS OF POWERING

The main components of powering may be identified as follows:

3.2(a) Propulsive power

The power delivered to the propeller, delivered power (P_D), may be defined as:

Delivered power (P_D)

$$= \frac{\textit{Effective power } (P_E)}{\textit{Quasi propulsive coefficient } (\eta_D)} \quad (3)$$

$$\text{Effective power } (P_E) = R \,.\, V \quad (4)$$

where R is total resistance (kN) of the naked hull and appendages, together with above water air drag of the hull and superstructure. V is ship speed (m/s).

The total naked hull resistance is made up of friction, viscous pressure (or form) and wave components. These basic hull resistance components are applicable to displacement ships and most semi-displacement ships. Further components are appendage drag and air drag, both of which are discussed later. For faster vessels, other resistance components arise such as transom, spray and induced drag.

3.2(b) Relative levels of powering components for different ship types

A breakdown of the hull resistance components, as a proportion of total, has been made for representative ship types, namely tankers, bulk carriers, container ships and a high speed catamaran passenger and vehicle ferry. These are summarised in Table 2. This breakdown identifies likely targets for savings in hull resistance. It is interesting to note from Table 2 how the slower hull form tankers and bulk carriers have a high proportion of viscous drag (friction plus form), whilst for the higher speed container ships with the finer hulls, wave resistance plays a more important part. For the fast ferry, the most significant component is the wave resistance, and much research has been carried out pursuing a reduction in this component, for example by increasing length displacement ratio or altering the spacing of catamaran hulls to reduce wave interference, Molland et al. [9], [10].

Table 2: Approximate distribution of resistance components. Air drag is shown as a percentage of total resistance, i.e. total hull plus appendages plus air.

Type	Lbp (m)	C_B	Dw (tonnes)	Service speed (Knots)	Service power (kW)	Fr	Hull resistance component: Friction %	Form %	Wave %	Air Drag % total
Tanker	330	0.84	250000	15	24000	0.136	66	26	8	2.0
Tanker	174	0.80	41000	14.5	7300	0.181	65	25	10	3.0
Bulk carrier	290	0.83	170000	15	15800	0.145	66	24	10	2.5
Bulk carrier	180	0.80	45000	14	7200	0.171	65	25	10	3.0
Container	334	0.64	100000 10000 TEU	26	62000	0.234	63	12	25	4.5
Container	232	0.65	37000 3500 TEU	23.5	29000	0.250	60	10	30	4.0
Catamaran ferry	80	0.47	650 pass 150 cars	36	23500	0.700	30	10	60	4.0

3.3 REDUCTION IN PROPULSIVE POWER

The main areas with the potential for reducing the power in a feasible and practical manner are summarised in Table 3. There are many optimistic claims on levels of savings for these various topics and methods. The following sections analyse and discuss likely achievable reductions in power during the design stage and during operation, noting that an improvement in one component may well detract from the performance of the others.

4. POWER SAVINGS DURING DESIGN

4.1 HULL FORM

Hull resistance is dominated by the principal hull parameters such as $L/\nabla^{1/3}$, C_B, B/T and LCB. Local detail, such as the use of 'V' or 'U' shaped sections forward and/or aft, will have an effect, as will the use of bulbous bows. A useful review of the techniques used for minimising hull resistance, including the use of experiments and CFD, are given in [11]. Investigations into aft body shape are described in [12]. The use of bulbous bows should be made with caution in that there are relatively specific areas where they can be used to advantage. Suitable areas for the application of bulbous bows can be found in [13] and from the work of Kracht [14]. It is found that the choice, and cost, of employing a bulbous bow is design specific. Hochkirch and Bertram [15], for example, report on a specific investigation, using CFD, into the design and re-design of bulbous bows for container ships when slow steaming. Vortex generators can be employed to re-align the aft end flow and delay separation. This is often done to provide a cleaner flow into the propeller, rather than necessarily reducing resistance, Anon [16].

The savings by 'optimising' hull form depend on the datum hull or starting point. If the datum hull is based on existing good practice, using published information for the influences on resistance of the main hull parameters and local hull shape, then the indications are that further optimisation studies can derive overall savings of up to about 5%.

4.2 HULL SURFACE FINISH

It is noted from Table 2 that frictional resistance is 60% - 70% of total hull resistance for tankers, bulk carriers and container ships and any reduction in this component can have significant benefits. Hull surface finish is fundamental to the levels of hull skin friction resistance. A smooth surface, with low roughness, will normally lead to lower frictional and viscous pressure resistance. From a hydrodynamic point of view, the underlying objective is to provide a smooth hull surface finish when the vessel is constructed and to maintain a clean smooth surface in service. This may be achievable using advanced marine coatings. For example, research by Candries and Atlar [17] indicates that reductions in skin friction resistance of the order of 2% to 3% may be achieved with foul release coatings. Much research has been carried out to demonstrate the benefits of a good surface finish, for example Townsin et al. [18], [19], [20]. Significant increases in resistance due to roughness and fouling can occur in service. The frequency of docking to clean the hull has normally been assessed on economic grounds. If an emissions trading scheme, or some form of carbon 'subsidy' were introduced, then the emphasis might change to a reduction in power, driven by a reduction in CO_2 emissions, rather than solely for economic purposes.

4.3 APPENDAGES

Appendages, such as bilge keels, shaft brackets and rudders require careful design. This might entail flow visualisation tests or CFD investigations to optimise the alignment of bilge keels and shaft brackets. Rudders should be considered as part of the propeller-rudder combination in respect of thrust deduction and propulsive efficiency changes, Molland and Turnock [21], Anon [16]. Total appendage drag is typically up to about 5% of

Table 3 Main areas for potential reductions in power

Reduce vessel resistance	Hull: shape, surface finish Appendages: low drag design Superstructure (air drag): low drag design
Improve efficiency of propulsors	Choice of design parameters, surface finish Adaptation to actual hull wake
Optimise hull/propeller/rudder interaction	Optimise wake distribution Minimise thrust deduction Upstream flow conditioning Recovery of rotational energy
Optimise strategy for operation	Speed, including slow steaming Trim: monitor/optimise Weather routeing Hull/propeller cleaning

total resistance for single screw ships and 8% - 15% for twin screw ships. There is, therefore, the potential using careful design to achieve some savings. A particular challenge is that of assessing appendage drag at model scale when appendages often may well be in a flow regime that is different to that at full scale, [22].

4.4 AIR DRAG

Air drag of the above water hull and superstructure is generally a relatively small proportion of the total resistance for tankers and bulk carriers although it can be significant for container ships and fast ferries. However, for a large vessel, in absolute terms, any reductions in air drag may be worth pursuing. It should also be noted that air drag will rise significantly in any form of head wind. Air drag values for commercial ships can typically be found in Isherwood [23], van Berlekom [24], Gould [25] and Molland and Barbeau [26]. Improvements in the superstructure drag of commercial vessels with box-shaped superstructures may be made by rounding the corners, leading to reductions in drag. It is found that the rounding of sharp corners can be beneficial, particularly for box - shaped bluff bodies, Hoerner [27] and Hucho [28]. However, a rounding of at least r/B_S=0.05 (where r is the rounding radius and B_S is the breadth of the superstructure) is necessary before there is a significant impact on the drag. At and above this rounding, decreases in air drag of the order of 15% – 20% can be achieved for rectangular box shapes, although it is unlikely such decreases can be achieved with shapes which are already fairly streamlined. It is noted that this procedure would conflict with design for production, and the use of 'box type' superstructure modules.

Investigations by Molland and Barbeau [26] on the superstucture drag of large fast ferries indicated a reduction in air drag coefficient (based on frontal area) from about 0.8 for a relatively bluff fore end down to 0.5 for a well streamlined fore end, a decrease in air drag of about 38%. If this change were applied to the ferry in Table 2, this would lead to a decrease in overall power of about 1.5%.

4.5 PROPULSIVE EFFICIENCY

4.5(a) Propulsive efficiency

The components of quasi propulsive coefficient (η_D) may be written

$$\eta_D = \eta_0 \cdot \eta_H \cdot \eta_R \tag{5}$$

where η_0 is the open water efficiency of the propeller, η_H is the hull efficiency and η_R is the relative rotative efficiency.

η_R takes account of the differences between the propeller in the open water condition and when behind the hull, and lies typically between 0.98 to 1.02.

η_H takes account of the interaction between the hull and propeller and is defined as:

$$\eta_H = \frac{(1-t)}{(1-w_T)} \tag{6}$$

where t is the thrust deduction factor and w_T the wake fraction. η_H lies typically between 1.0 and 1.25 for displacement ships. The formula indicates how changes in thrust deduction (t) due, for example, to the presence of a rudder or other device will influence overall propeller efficiency. Similarly, the influence of wake fraction (w_T) can be seen and quantified.

η_0 is the open water efficiency of the propeller and will depend on the propeller parameters and operating conditions.

4.5(b) Individual components of propeller open water efficiency:

For a fixed set of propeller parameters, η_0 can be considered as being made up of:

$$\eta_0 = \eta_a \cdot \eta_r \cdot \eta_f \tag{7}$$

where η_a is the ideal (or axial) efficiency, η_r accounts for losses due to fluid rotation induced by the propeller and η_f accounts for losses due to blade friction drag, Dyne [29], [30], Molland et al [31].

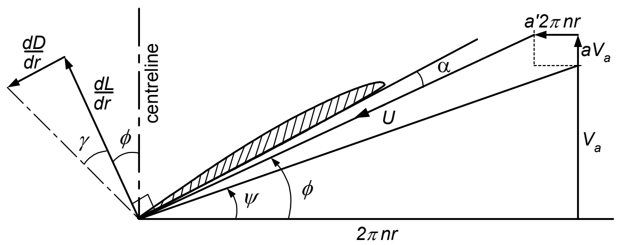

Figure 3: Propeller blade element diagram

An investigation has been carried out to determine the likely values of these three components of efficiency. Blade element-momentum theory was used, [31], [32] and, based on the blade element diagram, Figure 3, it can be shown that:

$$\eta_a = \frac{1}{(1+a)} \tag{8}$$

$$\eta_r = (1-a') \tag{9}$$

$$\eta_f = \frac{\tan\phi}{\tan(\phi+\gamma)} \tag{10}$$

where a and a' are the axial and rotational inflow factors, derived from momentum considerations and corrected for finite number of blades using Goldstein correction factors [31].

The investigation used a propeller with a pitch ratio *P*/*D* = 1.0, *BAR* = 0.700 and 4 blades for a range of *J* values, hence thrust loading, C_T, as shown in Table 4.

Table 4: Range of thrust loadings investigated

J	C_T
0.25	23.04
0.35	10.32
0.45	5.34
0.55	2.94
0.65	1.64
0.75	0.86
0.85	0.38
0.90	0.20

The thrust loading coefficient C_T is defined, and related to K_T/J^2, as follows:

$$C_T = \frac{T}{0.5\rho \frac{\pi D^2}{4} Va^2} = \frac{K_T}{J^2}.\frac{8}{\pi} \tag{11}$$

For a fixed pitch, decrease in *J* leads to an increase in thrust loading K_T/J^2, or C_T.

The results of the investigation are shown in Figure 4. It can be noted that the η_0 curve closely replicates the level of that for a Wageningen B4.70 propeller. Working from a low *J* (high thrust loading C_T) to higher *J* (lower thrust loading) it is seen that the rotational losses decrease, the frictional losses increase and there is a significant decrease in the axial losses. At a typical design condition of say $J = 0.75$ ($C_T = 0.86$) it is seen that the losses are typically 60% axial, 10% rotational and 30% frictional. At a lower *J*, higher thrust loading, of $J = 0.35$ ($C_T = 10.32$) the losses are typically 80% axial, 15% rotational and 5% frictional.

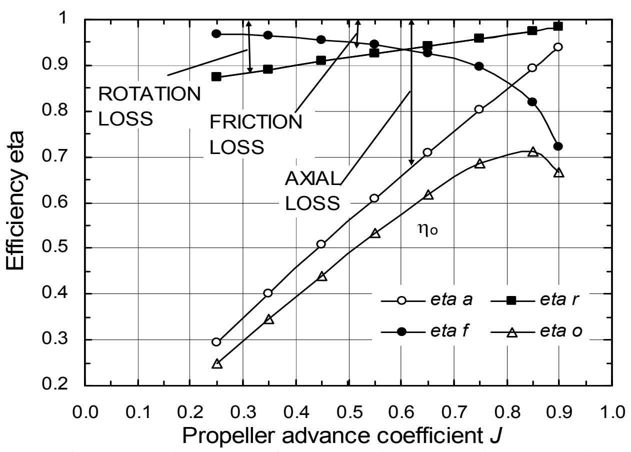

Figure 4: Components of propeller efficiency

This breakdown of the individual components of η_0, Equation (7) and Figure 4, is important as it indicates where potential savings might be made to maximise the recovery of lost energy. The following comments are made on some practical methods used to improve the efficiency of each component:

(i) η_f Savings in friction can be achieved by using the minimum blade thickness consistent with strength considerations and minimum blade area consistent with cavitation requirements. Reduction in friction can also be achieved by decreasing the local inflow velocity (by reducing revolutions) with an appropriate increase in diameter. Friction loss may also be reduced by reducing revolutions and increasing pitch, although this will lead to increased rotational losses which may have to be compensated by stators downstream. Surface finish influences friction, particularly during operation. Indications of the potential savings were derived using the propeller blade element-momentum theory with $J = 0.75$, *P*/*D* = 1.0 and *BAR* = 0.700. It was found that a 10% change in blade thickness led to about 1% - 2% change in η_0, a decrease in *BAR* from 0.700 to 0.600 led to an increase in η_0 of about 2% and an increase in drag coefficient of 20% due to say roughness and fouling led to a decrease in η_0 of 2% - 4%.

(ii) η_r Recovery of rotational losses can be achieved in various ways. The most effective way is to employ contra-rotating propellers, where much of the flow rotation loss can be removed. In the absence of such propellers the most common way is by the use of pre- and post-swirl stators. The rudder (downstream of a propeller) acts as a post-swirl stator, but also blocks the flow, resulting in pressure (axial) losses which can negate much of the rotational savings. Pre-swirl (upstream) stators can entail fins, while post swirl downstream can entail fins attached to the rudder. Asymmetric sterns can be employed which put pre-rotation into the propeller inflow. Levels of savings in power for these various devices are discussed in Section 4.6. It should be noted that pre- and post-swirl fins and asymmetric sterns can increase the resistance, hence reducing some of the effective savings in propeller efficiency.

(iii) η_a Axial losses are by far the largest, Figure 4. Theory and practice indicate that an increase in diameter with commensurate changes in *P*/*D* and rpm will lead to improvements in axial efficiency (together with some improvement in frictional efficiency). Maximising diameter is therefore of fundamental importance. Accelerating ducts may be used to advantage in conditions of high thrust loading, although duct friction will tend to remove any savings at moderate or low thrust loadings. An upstream semi-duct has been employed to improve the axial efficiency by directing part of the frictional wake to inside the propeller diameter.

4.5(c) Effect of propeller diameter

In order to quantify the influence of propeller diameter on propulsive efficiency, a practical study was carried out on the small cargo/container ship whose particulars are given in Table 1. A survey of container ships indicated that the choice of propeller diameter was between 65% and 74% of the design load draught. The lower values are presumably applied where operation is expected at draughts significantly less than the design load case. This can create a significant power penalty. For example, when this range of diameters is applied to the 145m vessel in Table 1, then the propeller diameter would be between 6.9m and 7.9m. If this were transformed into propeller efficiency improvements, then the order of increases are shown in Figure 5, which include changes in w_T and t (hence η_H) with change in diameter. With the propeller efficiency η_D, Equation (5), improving from 0.726 to 0.765, there is an improvement of some 5%. To be able to incorporate such a large increase in diameter is unlikely in a particular design situation, but the attraction of applying any increase in diameter is apparent.

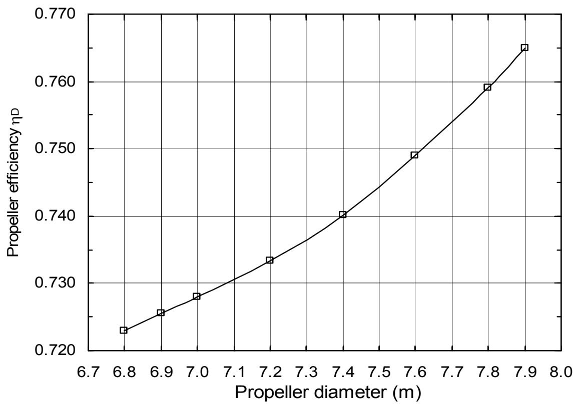

Figure 5: Change in propeller efficiency η_D with change in propeller diameter

4.5(d) Means of increasing propeller diameter

(i) Minimising clearances
Propeller tip clearances will normally limit the maximum diameter. Clearances are typically 15% to 20% of the diameter and can be up to 25% to 30% diameter for high powered vessels such as large container ships. For single screw vessels, the stern aperture will be shaped appropriately to accommodate the propeller, but closeness of the propeller tip to the water surface, say in a ballast condition, may be the limiting factor. The use of skew will normally allow some decrease in the clearances, increase in diameter and improvement in efficiency.

(ii) Tunnel stern
Tunnel sterns have been successfully employed on shallow draught vessels, such as those found on inland waterways. The use of the tunnel allows some increase in propeller diameter. Care must be taken to make sure there is adequate immersion of the propeller and adequate vertical structure outboard of the propeller in order to avoid ventilation of the propeller around the side of the hull. The use of tunnels is described in Carlton [32] and Harbaugh and Blount [33].

(iii) Inclined keel
In this case, the keel is inclined (equivalent to designing in trim) and a significantly larger propeller can be employed, [34], [35], [36]. This is similar to the approach used for conventional tugs and trawlers. In the case of a larger vessel, such as a container ship, the draught amidships would be the design draught and the ship would ballast back to level keel if required by port draught limitations. As an example, if the 145m cargo/container ship in Table 1 had a 2.0m trim by the stern, and assuming this could be transformed (by the redesign of the aft end) into an increase of 1.0m in propeller diameter then, using Figure 5, this would suggest an expected increase in propeller efficiency of about 5%. There may be some increase in resistance with an inclined keel, but the indications are that the gains to be made from the increased propeller diameter are greater than the losses due to the increase in resistance. For example, the inclined keel investigation carried out by Seo et al. [36] indicated an overall power saving of the order of 4%. The inclined keel is a feasible and practical proposition and these findings would suggest that the concept deserves further consideration.

(iv) Propeller tip below baseline
This is a ploy used in some warships. Increased diameter can be achieved, but it leaves the propeller more vulnerable to damage and creates added difficulties during drydocking.

(v) Rudder aft of ship
This concept employs what is effectively a transom hung rudder. This allows the propeller to be moved aft and its diameter increased significantly. Such a layout is being investigated in the EU STREAMLINE Project [37] for tankers and RO-RO vessels, and improvements in total propulsive efficiency of the order of 15% are indicated. There are, however, some severe practical limitations for such a layout, including the risk of propeller

ventilation and loss of thrust in waves and the vulnerability of the rudder and propeller during manoeuvring and docking.

4.5(e) Detailed modifications to propeller

There are a number of detailed modifications that can be made to the simple solid fixed-pitch propeller, including the use of tip fins, tip rake and boss cap fins. However, compared say with the influence of changes in diameter, such modifications generally lead to relatively small improvements to a propeller already designed to existing best practice.

4.5(f) Alternative propulsors

Alternatives to the simple solid fixed-pitch propeller may be summarised as ducted, controllable pitch, contra-rotating, podded units and cycloidal propellers. Generally, these are employed for specific applications where improvements in propulsive efficiency and/or manoeuvring characteristics can be made, noting that for ocean-going merchant ships such units must be robust, reliable and safe. Based on the need for robustness and reliability, these alternative propulsors are unlikely to have significant applications or impact on overall emissions reduction for large ocean going ships such as tankers, bulk carriers and container ships.

4.6 PROPELLER-HULL INTERACTION

This is an area that can have a significant effect on the overall propulsive efficiency. For example, examination of Equation (6) indicates how thrust deduction (t) and wake fraction (w_T) affect hull efficiency, whilst Equation (7) and Figure 4 include the rotational losses η_r for the propeller which might be recovered by the application of suitable devices. The propeller-hull interaction is dominated by propeller hull clearances and aft end hull shape, for example fineness of waterline endings, depending on C_B and LCB, and/or the use of 'U' or 'V' sections upstream of the propeller, [12]. This is modified by the possible presence of shaft brackets and rudders. Fundamental also is propeller rudder-interaction, having an influence on thrust deduction and some recovery of propeller induced rotation of the flow, [21]. A further basic change would be the use of a 'bulbous' stern, with or without asymmetry. Beyond these fundamental aspects are detailed devices that can contribute to improvements in efficiency. These include vortex generators, which are claimed to have led to 4% - 6% reduction in fuel consumption, Anon [16], and a duct upstream of the propeller, which is claimed to save up to 4% of power for large full form vessels, Anon [38]. Savings of between 2% - 4% might be expected from the application of pre and/or post swirl stators. An integrated twisted rudder, bulb and propeller hubcap is described in Anon [39] and it is suggested that savings in power of up to 10% might be achieved with careful integrated design of hull, propeller and rudder.

4.7 PROPULSION MACHINERY AND FUELS

Although not directly part of the power saving budget, a brief review is made of propulsion machinery and fuels, and their contributions to reducing emissions.

4.7(a) Propulsion machinery

The main propulsion machinery is responsible for converting the energy in the fuel into useful mechanical power, Figure 1. The main types of engine, suitable for the propulsion of commercial ships may be summarised as:

- Low, medium and high speed diesel engines;
- Gas turbines;
- Electric motor, inboard or within a podded drive.
- Steam turbines.

The principal properties of the various propulsion engines, such as size, mass, fuel consumption and emissions are described in some detail in Woodyard [7] and Molland [8]. It should be noted that engine manufacturers have made significant improvements in overall engine efficiency in recent years, leading to reductions in the fuel consumption and emissions.

4.7(b) Alternative fuels

A number of alternative fuels are under consideration which would reduce the emission of greenhouse gases and reduce the dependence on oil, ECSA [40]. These include bio fuels, nuclear power, LNG and fuel cells. Bio fuel does not contain sulphur and reduces the emission of CO_2. It does, however, have a high price and may not be available in suitable quantities for shipping. Nuclear power has a proven track record for naval ships and icebreakers. The mass and size of nuclear units has decreased significantly and the application of nuclear power to merchant ships is being revisited, [41]. The use of LNG would reduce CO_2 emissions and its application is the subject of investigation, [42]. The large volume of stowage required for LNG tends to make it less viable for large ocean-going ships, although it has several suitable applications for small ships. Fuel cells may become viable in the future but, at present energy efficiency levels, are not suitable for the propulsion of large ships.

5. POWER SAVINGS DURING OPERATION

5.1 SPEED

For most displacement ships, propulsive power varies approximately as speed cubed. Any reduction in speed can therefore offer significant reductions in power and the emission of greenhouse gases. On an economic basis, the reduction in speed leads to a saving in fuel but a loss of earnings and there is a fine balance between them to derive the 'optimum economic' speed. If the physical changes are examined, it is found that, initially, starting from a low speed, as speed is increased the increase in earnings increases at a greater rate than the power and fuel costs. This continues until a speed is reached when the increase in fuel costs is greater than the increase in earnings. This is shown schematically in Figure 6, where the economic criterion is the required freight rate, *RFR*.

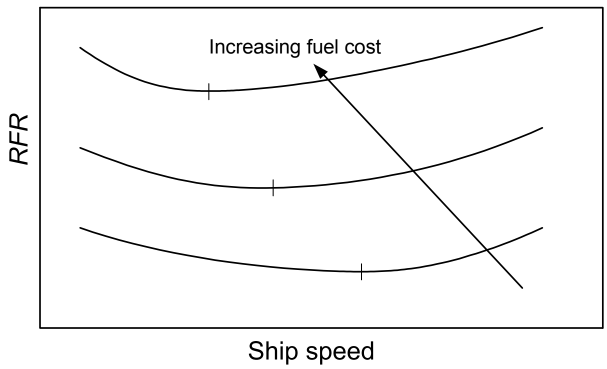

Figure 6: Change in *RFR* with change in speed and fuel cost

It is found that optimum speed decreases with increase in fuel costs and provides a reason for the use of lower speeds, or operational slow steaming, in periods of high fuel costs. It is important to note that, for displacement ships, power varies (approximately) as speed cubed, and a reduction in speed will lead to a reduction in the EEDI (CO_2 index), Equation (2), according to speed squared. For example, if the speed of the ship in Table 1 is reduced from 16 to 14 knots, then there is a significant reduction in the EEDI from 12.89 to 9.87 gm/tonne.mile. Thus the easiest way to reduce EEDI is to decrease speed and, in order to meet EEDI limits, this method is being applied to existing designs by a number of shipbuilders and operators. In many cases, further gains may be made by fitting, or retrofitting to an existing ship, a propeller designed for the reduced speed. It is clear that a reduction in speed leads to significant reductions in power, although decisions on levels of speed reduction are also likely to depend on the overall operation of a number of ships to transport a certain amount of cargo.

5.2 EFFECTS OF TRIM ON HULL RESISTANCE

Merchant ships are normally designed for level trim in the load condition and some trim by the stern in a ballast condition. This will normally ensure adequate propeller immersion in the ballast case together with forefoot immersion. The effects of trim on hull resistance have been investigated using data from the BSRA Series [43]. The results are for the standard BSRA vessel with

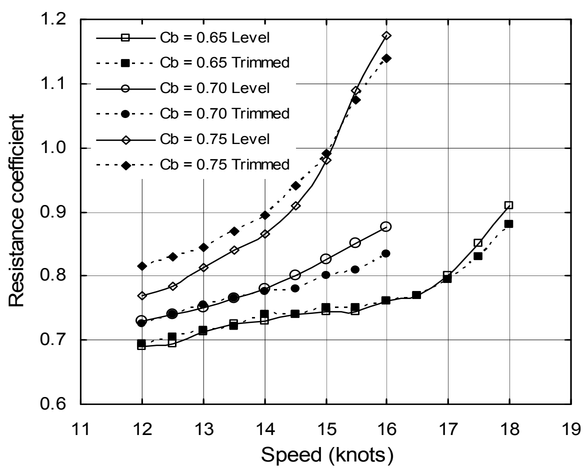

Figure 7: Effect of trim on hull resistance

L = 122m and B = 16.8m. The ballast condition was tested at a draught equivalent to 4.9m both at level keel and with a trim of 2.4m by the stern. The results over a range of speeds for three block coefficients are shown in Figure 7. It is seen from Figure 7 that significant changes in hull resistance can occur with change in trim. In the case of the C_B = 0.65 vessel, the major changes occur at higher speeds, where up to 3.5% decrease in resistance is observed. The C_B = 0.70 case shows up to 5% reduction in resistance at higher speeds. For C_B = 0.75, the resistance in the trimmed condition is up to 6% higher at low speeds and up to 3% lower at higher speeds. The results in Figure 7 serve to illustrate levels of change in hull resistance with change in trim. At the same time, change in trim can change hull efficiency factors such as wake fraction, with consequent change in overall propulsive efficiency. An overall investigation should take such effects into account. Larsen et al [44] provide an excellent account of the sources of changes in power due to changes in trim. Their investigation found that most of the changed propulsive power originates in the residual resistance coefficient. The effects of trim on hull resistance for a particular vessel can be determined at the model tank testing stage, and/or by the use of CFD, which can provide guidance to the ship operator. Alternatively, investigations can be carried out on the ship in service by monitoring say power or fuel consumption (F) over a period of time for different amounts of trim. In a manner similar to voyage analysis [31], changes due to trim might be monitored using a factor F_C, such as described in Equation (12), which can also correct for any changes in displacement (Δ) and speed (V).

$$F_C = \frac{\Delta^{2/3} V^3}{F} \tag{12}$$

Hansen and Freund [45] describe a detailed study into the derivation of the effects of trim and application to ships in operation. There are now a number of commercial software packages available to ship operators that can calculate optimum trim and ballasting alternatives. It is claimed that such packages can lead to typical overall savings of up to 5%.

5.3 WEATHER ROUTEING

This is now a well practised procedure by many shipping companies. There are many commercial software packages available and weather routeing services which facilitate the procedure. It entails trading a relative decrease in fuel consumption for an increase in distance to travel around bad weather. To work effectively, knowledge is required of the performance of the ship in a seaway, in particular, speed losses in the various forecasted sea conditions. Such procedures are, for example, described by Satchwell [46]. The practice should lead to the overall savings in power and the emission of less greenhouse gases.

5.4 HULL/PROPELLER CLEANING

Hull cleaning is known to decrease overall power, but has usually been carried out on a strictly economic basis, see Townsin et al. [18], [19], [20]. Indicative levels of efficiency change with roughness are given in Section 4.2 and 4.5(b). The decrease in CO_2 emissions, and possible emissions trading for increases in maintenance costs, could provide the operator with the incentive to clean the hull and propeller over shorter intervals of time. It can also be noted that propeller coating applications have been growing over the past few years, with increasing use of foul release coatings, especially on the propellers of large cargo vessels, [17], [47].

6. AUXILIARY PROPULSION DEVICES

There are a number of devices that provide propulsive power using renewable energy. The energy sources are wind, wave and solar. Devices using these sources are described in references such as [48], [49], [50], [51], [52] and [53].

Whilst a number of the devices may be impractical as far as propulsion is concerned, some, such as wind turbines and solar panels, may be used to provide supplementary power to the auxiliary generators. This will lead to a decrease in *overall* power (propulsion and auxiliary electrical generation) and an overall reduction in emitted greenhouse gases.

7. ECONOMIC AND ENVIRONMENTAL ISSUES

The factors driving current research and investigation into improving the overall efficiency of propulsion of ships are both economic and environmental. Fundamentally, improvements in efficiency of propulsion should lead directly to improvements in the economic return and a decrease in greenhouse gas emissions. This means there is a double incentive to pursue such efficiency improvements. There are, however, some possible technical changes that will decrease emissions, but which may not be economically viable. For example, the use of controllable pitch propellers (for off-design improvements) or contra-rotating propellers to improve efficiency and decrease emissions, are both likely to incur increases in first and maintenance costs, detracting from the economic efficiency. Many of the auxiliary powering devices, using renewable energy sources, and enhanced hull coatings, are likely to come into this category. There are suggestions that emissions trading for ships or, in effect, some form of 'subsidy' for decreasing emissions, may be introduced in the future. If this is the case, all means of improvement in powering and reduction in greenhouse gas emissions should be explored and assessed, even if such improvements may not be directly economically viable.

Studies have been carried out over many years to derive the most suitable combination of hull parameters for a particular vessel at a particular speed with a given fuel cost. Analysis is usually based on some economic measure of merit, such as NPV, yield or required freight rate, *RFR*. The resulting dimensions will depend on speed, build cost and fuel cost. For example, if speed is reduced, the vessel will tend to be shorter and construction costs will reduce, whilst for higher fuel costs, optimum length and *L/B* tend to be larger, the decrease in power and fuel offsetting the increase in build cost. An example of such an investigation is given in [54] where parametric changes in main hull dimensions for tankers were carried out by a leading oil company, providing indications of what savings in power might be achieved.

A study has been made into the effects of parametric changes in hull parameters for the small cargo/container ship described in Table 1. This entailed running the ship at 16 knots with 18 voyages/year and changing *L/B* ratio in a methodical manner. The ship design software ShipDes, described by Molland et al. [53], was used for the investigation. ShipDes is primarily a technical design program which evaluates ship primary dimensions for given input values of deadweight, speed and range. It also carries out a simplified economic analysis to evaluate required freight rate, *RFR*. This entails estimating the operating costs, including maintenance, crew and fuel, and capital costs using an estimate of the construction costs and a capital recovery factor, *CRF*. The results are shown in Figure 8. Changes in the construction costs/annual charges and fuel cost changes follow expected trends, namely, as *L/B* increases, construction costs and annual charges increase and fuel costs decrease. Observation of the *RFR* results in Figure 8 indicate that with fuel at \$300/tonne the *L/B* should be about 6.7. Figure 8 also illustrates how higher *L/B* and decreasing power leads to a lower CO_2 index (EEDI). However, above *L/B* of about 6.7, the *RFR* tends to increase, leading to a decrease in economic efficiency. This illustrates the conflicting demands of environmental efficiency and economic efficiency. What is important to note is that, with high fuel prices, and pressure to reduce emissions and power, it may well be necessary to move to higher *L/B* ratios than is currently the practice. On the same basis, suitable values for the other hull parameters, such as *B/T*, C_B and *LCB*, should also be re-visited. It is apparent that the combined influences of fuel costs *and* CO_2 emissions are likely to take a more important role in the choice of the overall hull parameters for future tonnage.

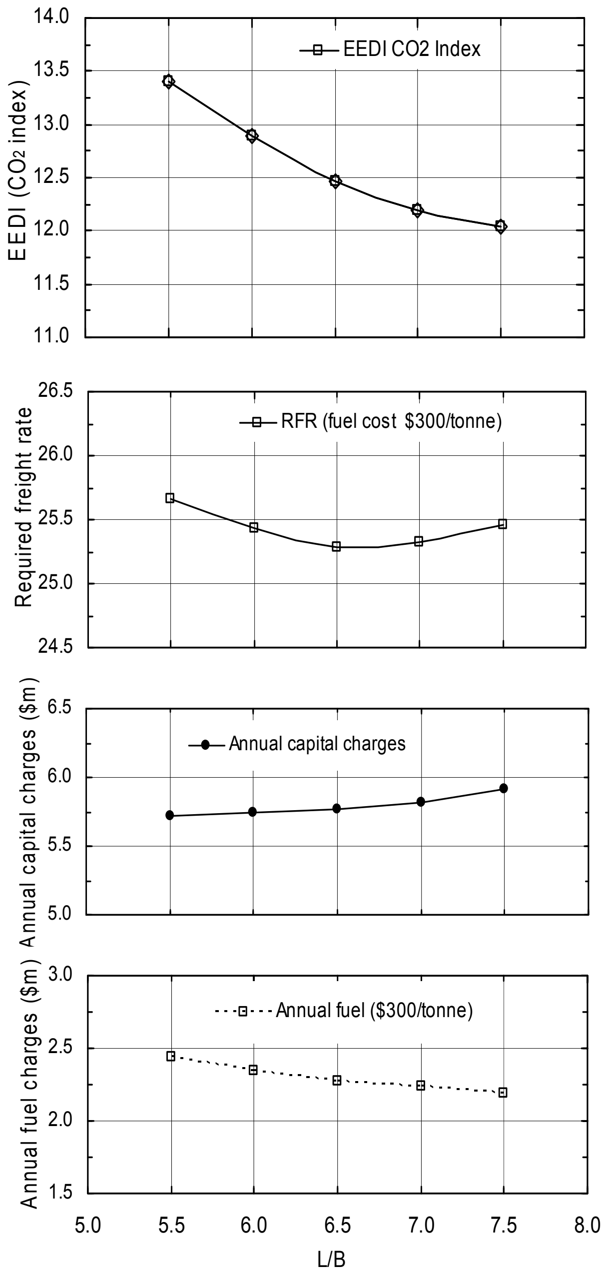

Figure 8: Influence of *L/B* on Annual charges and fuel, Required Freight Rate and CO_2 index (EEDI)

8. DESIGN PROCEDURES

It is clear from the earlier Sections that procedures for quantifying the impact of greenhouse gas emissions need to be incorporated in the ship design process. This could, for example, entail the incorporation of the EEDI (Equation (2)) as an objective function. Figure 9 shows a traditional ship design approach where the objective function, or measure of merit, is some economic criterion such as *NPV* or *RFR*, Molland [8], Schneekluth and Bertram [55], Watson [56].

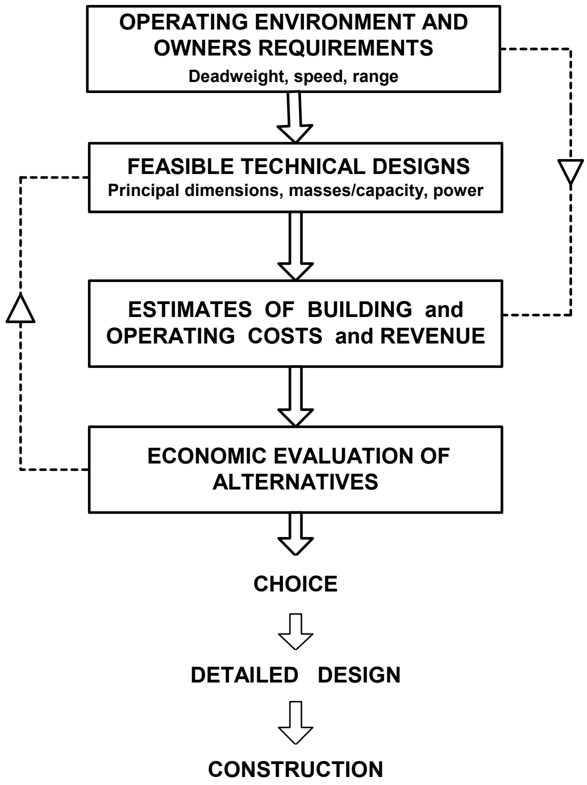

Figure 9: Overall design flow path

Figure 10 indicates how the environmental effects may be incorporated in the ship design process. The use of such an approach allows design changes, technical innovation and auxiliary power devices to be incorporated in the feasible technical design, and a cost benefit analysis of these changes carried out in the usual way, Schneekluth and Bertram [55]. Thus the objective function for optimising on an economic basis might be NPV or RFR, whilst the environmental 'optimum' might be to achieve the lowest EEDI. Earlier examples, such as that illustrated in Figure 8, have indicated that the economic and environmental optima may not coincide.

The design path now becomes a multiple criteria problem, see for example Sen [57] and Schneekluth and Bertram [55]. Weightings will have to be applied depending on what financial incentives might be given, directly or indirectly, to arrive at an environmental optimum which is not necessarily the economic optimum. The weightings are likely to depend on fuel cost levels, changes to achieve a required EEDI and incentives in carbon trading schemes.

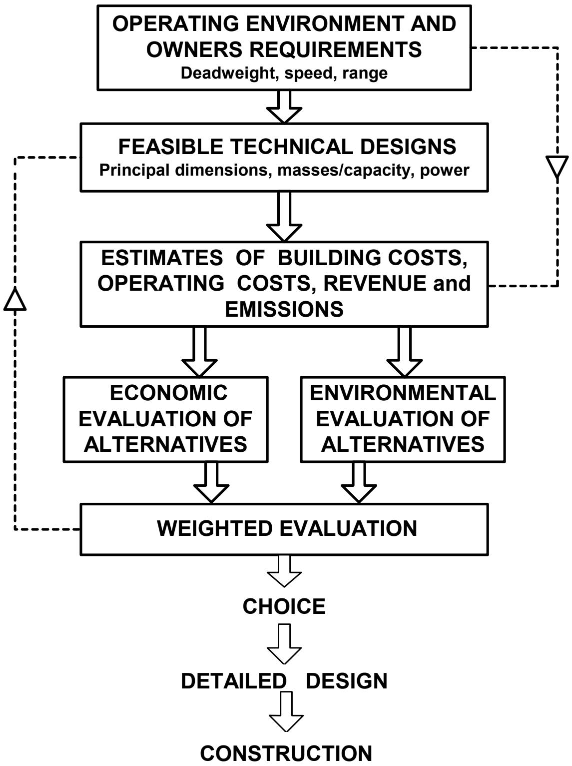

Figure 10: Overall design flow path incorporating environmental effects

9. CONCLUSIONS

9.1 GENERAL

A number of areas have been identified where initial design changes and investment at the construction stage can lead to savings in propulsive power, fuel consumption and emission of greenhouse gases. Changes may be made at the design/construction stage, or modifications carried out whilst the ship is in service. Whatever changes are made and energy saving devices proposed, these must be practical, robust, reliable and safe.

9.2 RESISTANCE

Several areas have been identified where overall propulsive performance may be improved. In terms of resistance, optimisation of overall hull shape parameters can be investigated, together with attention to the fore end in terms of bulbous bows and local section shape, and to the aft end in terms of section shape and the interaction of the wake with the propeller. CFD is being usefully employed to develop suitable hull shapes for particular operational conditions. However, the findings indicate that the achievable overall reductions in hull resistance can be relatively small when compared with existing good practice.

9.3 PROPELLER EFFICIENCY

Small local improvements can be made to a propeller already designed to existing best practice, but the overall efficiency is dominated by diameter, with gains of up to 5% being possible when going from a small diameter to maximum diameter. Ways of maximising diameter have been identified including the use of an inclined keel.

9.4 HULL-PROPELLER-RUDDER INTERACTION

Attention to hull-propeller-rudder interaction offers scope for significant reductions in power. Reductions of 5% - 10% are claimed. Techniques include adapting the hull aft end using asymmetric and bulbous sterns, flow conditioning upstream of propeller using pre-swirl devices and recovery of rotational energy downstream of the propeller using twisted rudders and post-swirl devices. CFD is being usefully applied to complement model tests for such hull-propeller-rudder interaction effects.

9.5 OPERATION

It is found that the most favourable savings in power come from optimised operational strategies, such as the use of optimum trim, speed and weather routeing. Operators have reported typical overall savings of up to 5% by adopting such techniques.

9.6 SAVINGS

In reacting to the pressure to reduce propulsive power, the designer will need to investigate every feasible possibility. This might entail deriving small improvements from a number of the component parts which, collectively, should provide worthwhile savings in overall power and a reduction in the emission of greenhouse gases.

9.7 ECONOMIC VIABILITY

With the increased pressure from the environmental point of view and with the possible future introduction of emissions trading schemes, reductions in power and emissions might be achieved with design changes and investment in fuel saving devices which are not necessarily the best economic solution. Conflicting demands can therefore exist when attempting to achieve both economic and environmental efficiency.

9.8 DESIGN PROCEDURES

The design process should be adapted to take account of the changing emphasis between economic viability and environmental factors, such as greenhouse gas emissions. The process will include some economic objective function, such as NPV or RFR, and an environmental objective function which could be the EEDI. A multiple criteria approach will be necessary, with weightings between the criteria depending on levels of fuel cost and on what financial incentives might arise in order to persuade ship operators to reduce emissions.

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