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THE ECONOMIC SELECTION OF MAIN AND AUXILIARY MACHINERY

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The Economic Selection of Main and Auxiliary Machinery

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SYNOPSIS

The authors use a comprehensive method (Refs 1 and 2) of economic assessment of machinery arrangement alternatives for a Panamax-size bulk carrier of approximately 70 000 tdwt. Slow- and medium-speed diesel engines are investigated in the MCR power ranges 5500-6500 kW (Group 1), 8500–9500 kW (Group 2) and 13 000–14 000 kW (Group 3), and a comparison figure of cost per tonne mile for an assumed voyage profile is calculated. A detailed breakdown of the auxiliary electrical and steam heating power requirements of a bulk carrier is used to analyse the application of variable-speed pumps, direct from outboard main engine air supplies, exhaust gas waste heat recovery, shaft-driven alternators and blended fuel to an engine in the group which offered the optimum cost per tonne mile of cargo carried. It is concluded that slow- and medium-speed engines in the installed power range 8500–9500 kW present the most favourable economic return over a 15-year life cycle but that this relatively low installed power, combined with reduced exhaust temperatures in the latest series of slow-speed engines, means that the at-sea electrical load could not be satisfied using an exhaust gas waste heat boiler turbogenerator unit. Operating diesel generators on cheaper grades of fuel would be more advantageous under the assumed economic conditions than fitting a shaft generator.

INTRODUCTION

The major part of any total economic package is concerned with maximizing propulsive efficiency. Auxiliary power on most vessels forms a relatively minor part of the overall, at-sea, daily fuel consumption; hence effort must be concentrated initially on high propulsive efficiency, using optimized engine–propeller matching within the constraints of ship type and size.

A number of different techniques are available to establish the economic worth of alternative propulsion machinery packages. These methods can also be applied to determine advantages, or otherwise, of modifications to new or existing machinery installation with a view to reducing operational costs, e.g. where these costs may be directly related to energy saving.

In general, it is advisable to use measures of economic worth which adjust money values on an overall time basis. These measures include net present value (NPV) and required freight rate (RFR), both of which depend on the standard discounted cash flow (DCF) techniques (Ref. 1).

An alternative, often used in advertising and sales literature, is the payback period. This does not use time adjustment to establish economic worth and generally is of limited value although, in some circumstances, comparisons obtained using this parameter may provide useful information for further, more detailed, investigations.

The above time-adjusted economic criteria based on lifetime costs nevertheless require annual costs to be established, both for operating and capital charges. Where a relatively large number of alternatives for propulsion plant is available, choices may be narrowed down by initial consideration of annual costs only before using the more complex life cycle relationships.

Life cycle methods depend upon a large number of economic predictions and many have been used in the preparation of this paper. Recent history has illustrated that the accuracy with which economic forecasting can be made is, to say the least, dubious. On a strictly annual basis the relative income and expenditure can be more precisely estimated.

The following section outlines a generally applicable method for the determination of the most economical power plant for any particular vessel, the example used throughout being a Panamax-size bulker. The work concentrates on diesel engines rather than steam plant. It would appear that, with the exception of certain specialized areas, steam plant remains uncompetitive for this application.

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MAIN ENGINE CHOICE

Concentration on diesel engines produces two general categories, all elements of which have some inherent advantages and disadvantages. The categories are:

(a) Slow-speed diesel installations:
- (i) single engine—direct drive;
- (ii) twin engine—direct drive from twin input/single output gearbox;
- (iii) long-stroke engines;
- (iv) derated engines for slow steaming.

(b) Medium-speed diesel installations:
- (i) single-geared engines;
- (ii) multiple-geared engines.

In order to optimize the power and speed requirements, both technically and economically for the chosen vessel, three power ranges were considered, in the region of 6 MW, 9 MW and 13.5 MW (Groups 1, 2 and 3, respectively) at maximum continuous rating (MCR).

Propeller size was calculated with a maximum diameter of 7.0 m as a constraint on the lower limits of propeller speed, and a working diameter fixed by matching each engine considered for speed and delivered power using derived propeller curves (Fig. 1).

For each approximate power range (± 500 kW), a number of suitable engines can be identified. At the time of writing this paper, competition between at least two of the world's leading marine engine licensors has led to a large number of alternatives being available. Considerable overlap exists in layout diagrams between bore sizes, numbers of cylinders and, particularly, the derated modes of operation.

Basically, derated engines operate on lower BMEP with an adjusted fuel-injection timing to retain maximum cylinder firing pressure. This leads to a reduction in power, a reduction in rev/min (advantageous from the propulsive efficiency standpoint) and a reduction of the order of 3% in the specific fuel consumption.

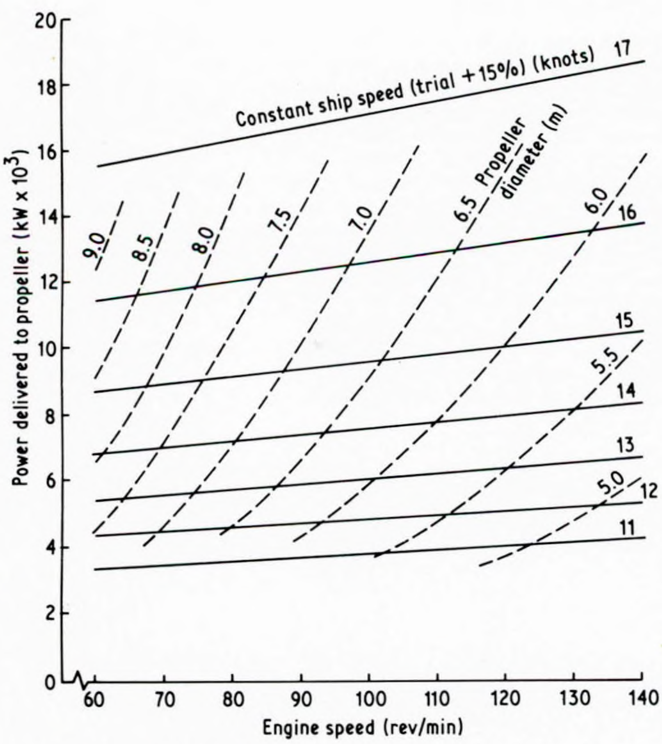
Clearly, when dealing with derated modes it is even more important to investigate the relationship between operating costs (particularly fuel) and capital costs. It could be a mistake to penalize a vessel by installing a larger engine operating in the derated mode, albeit more efficiently, when a smaller, cheaper, lighter engine is available for the same duty.

PARAMETERS INCLUDED IN THE STUDY

Voyage profiles

This is clearly a variable parameter. Where the profile is known and likely to be reasonably constant then round trip length, port time and port costs can be incorporated directly into the analysis. The assumptions made in this particular study are a round trip pattern of 12 000 nautical miles, with a total of 12 days in port per round trip.

Different voyage patterns have, in fact, been investigated but the effect on ultimate choice is negligible.



Length between perpendiculars, L_{PP}	190 m
Draught, T	12.5 m
Block coefficient, C_B	0.8
Location of centre of buoyancy	2% for'd
Displacement	62 826 tsw

FIG. 1 Power delivered to propeller/engine speed/ship speed/propeller diameter

Technical data

Power, fuel and lubricating oil consumption, engine weights, etc. were taken from manufacturers' published data. Arbitrary power deductions were assumed to be 2% for shaft transmission losses and a further 2% for gearbox losses (where fitted).

Propeller speed and diameter and ship speed in both loaded and ballast condition were then obtained from Fig. 1. Where gearboxes were used, the maximum propeller diameter of 7.0 m was assumed and the gear ratio optimized for the required delivered power.

Overall machinery weight is always a difficult parameter to assess accurately without detailed design work. For the purposes of a comparative analysis it has been found useful to take auxiliary weight to be the same for each installation in a given power range, so that differences in machinery weight, and the consequent effect on earning capacity, are attributable to differences in main engine weight and bunkers carried.

As well as the weight of the auxiliary machinery, the energy used for auxiliary power generation must also be included. Whilst it is recognized that this latter will vary, particularly when energy-saving principles are applied, it can be assumed initially that no electrical load is supplied by waste heat recovery and, in the example quoted, figures of 3.0 tonnes/day and 1.5 tonnes/day were used to represent diesel oil used in generators at sea and in port respectively. It will be seen later that these figures are modified when particular installations are being considered.

Operational data

The typical round-trip voyage pattern chosen has been mentioned earlier. The proportion of time spent in ballast was taken as 40%, a figure typifying the annual average for the vessel under consideration.

Bunkering patterns have taken on some importance recently and are a subject for research in their own right. For the purposes of the study it was assumed that bunkers were taken at the loading port for a typical out and return voyage with 5 days' steaming reserve of main engine and auxiliary fuel.

Economic data

Costs of machinery installations were obtained directly from engine builders and gearbox manufacturers. Similar problems exist in estimation of total plant cost as those previously referred to for total plant weight. A survey showed that for the higher power range considered the cost of auxiliary equipment, pipework, etc. is approximately equivalent to main engine cost. For comparison purposes it is clearly unfair to penalize a more expensive main engine with a more expensive set of auxiliaries. Where possible, therefore, the price of ancillary equipment was regarded as being fixed over a particular power range.

Maintenance and repair cost is another parameter which is difficult to quantify, since much depends upon the methods adopted by the operator. Whilst these costs clearly form part of the overall operating costs, changes in methods, and hence costs, of maintenance and repair do not contribute significantly to comparative differences.

It is noteworthy that main engine maintenance costs will be reduced for a derated engine as compared to the same engine operating at or near its designed continuous service rating (CSR). Conversely, higher maintenance costs will be associated with higher speed multi-cylinder engines, generally due to the increased numbers of cylinders.

Crew costs depend primarily upon the nationality of the personnel used and the number considered necessary for adequate functioning of the ship. These numbers are not significantly altered by choice of machinery, particularly when only alternative diesel plants are being considered.

Other costs included in the analysis are those associated with insurance, administration, classification charges, etc. Costs attributed to loading and discharge facilities and harbour dues tend to be more difficult to quantify. However, since all engine alternatives will incur very similar port costs, any figure chosen will have minimal influence on variations of overall costs between them.

Correlation of data

Each engine system considered was investigated for an annual operation typical of the first year. This is essentially a fairly coarse filter, since lifetime costs are regarded as a more reliable measure.

Table I: Analysis of main engine choice

MCR (kW)	9000
Engine speed (rev/min)	106
Round trip (nautical miles)	12 000
Cargo carried/annum (tonnes)	446 870
Annual running costs (includes maintenance and repair, crew, insurance, etc.) (£)	1 116 000
Annual fuel and lube oil costs (£)	999 500
Annual port costs (£)	225 900
Total operating costs (£)	2 341 400
Annual capital charges (1st year) (£)	2 622 000
Total annual costs (£)	4 964 000
Tonne miles/annum × 10^6	2681
Cost/tonne mile (operating) (p)	0.0873
Cost/tonne mile (total annual) (p)	0.1852

Table II: Required freight rate over the 15-year ship life

		NPV OF 15 YEAR COSTS (£)	CARGO PER ANNUM (tonnes)	RFR (£/tonne)
Group 1 (5500–6500 kW)	Engine A	28.77 × 10^6	407 860	9.28
	Engine B	27.84 × 10^6	403 730	9.06
Group 2 (8500–9500 kW)	Engine C	30.87 × 10^6	446 790	9.08
	Engine D	30.77 × 10^6	446 870	9.05

Table III: Auxiliary power requirement at sea

	ELECTRICAL POWER (kW)	% OF TOTAL
Main engine pumps	109.1	26.7
Engine room vent fans	37.6	8.8
Galley	33.6	7.9
Air conditioning compressor	46.4	10.9
TOTAL	226.7	53.3

Table IV: Reduction in power requirements

	GROUP 1 (5.5–6.5 MW MCR)	GROUP 2 (8.5–9.5 MW MCR)	GROUP 3 13–14 MW MCR)
1. Total auxiliary load with no savings	376	425	494
2. Main engine seawater circulating pump: normal	(24)	(35.4)	(52.0)
3. Engine room vent fans: normal	(25)	(38)	(56)
4. Main engine seawater circulating pumps: 25% power saved	6	9	13
5. Engine room vent fans: 80% power saved	20	30	45
Minimum electrical load [=1−(4+5)]	350	386	436

Total operating costs were calculated and the cost per tonne mile of cargo found. Annual capital charges (again for the first year of operation) were then found on a basis of OECD loan and interest rates, i.e. typically 80% for $8\frac{1}{2}$ years at 7.5% interest net of all charges. Repayments are to be normally in equal instalments at regular intervals of 6 months and a maximum of 12 months. This enabled total annual costs and overall cost per tonne mile of cargo to be determined.

Table I shows a typical set of data from an analysis of main engine choice for the bulk carrier. Similar analyses were performed for all competing engine plant designs. On that basis, the two or three most promising economically were then subjected to further analysis.

Full discounted cash flow calculations were performed on the chosen engines, incorporating factors allowing for inflation of the various annual costs along with an estimated rate of return on capital of approximately 10% over a 15-year expected life of the ship.

Figure 2 shows the relationship between first-year operating costs and first-year total annual costs (operating plus capital) against ship speed. Clearly, the economic speed for this type of ship will be about 13.6 knots. A comparison of required freight rate values worked out over the life of the vessel is presented in Table II for four engines, two from each of the lower power groups. In Group 1 (the lowest power group) the engine giving the best RFR value, i.e. the lowest, was more expensive than many of its competitors but proved more economic over the 15-year period because of lower operating costs.

Auxiliary power supply and demand

Reduction in the cost of auxiliary power can be approached from two directions: the power requirement can be reduced using various power-saving devices; or cheaper sources of power can be used. The economic worth of a particular method of reducing the power requirement can thus only be assessed in relation to the cost of the power it saves. If the total electrical load at sea can be satisfied using a waste heat boiler/turbogenerator system there is, of course, no economic argument for fitting devices which reduce power consumption, although it may be desirable to increase the supply/demand margin so that large, intermittently used pumps could be started without starting an additional generator.

For the purposes of the project, British Shipbuilders supplied the results of two examinations of electrical power and heating requirements of bulk carriers. The more detailed of these corresponded (in terms of installed power) with engines in Group 2 (8500–9500 kW), and indicated that over half of the electrical load at sea was imposed by the main engine pumps, engine room vent fans, galley equipment and air conditioning compressor (Table III).

In estimating the electrical load of ships in Groups 3 and 1, it is assumed that the power requirements given in Table III for the galley equipment, air conditioning compressor and the remaining 46.7% (laundry, lighting, navigational equipment, etc.) remain constant, but that engine-related items are in direct proportion to the installed power. This gives the figures shown in line 1 of Table IV.

POWER-SAVING DEVICES

Variable-speed pumps

The sea water cooling capacity for ships' main engines is designed to permit full rated output at a sea water temperature of 30°C. If a ship spends a substantial proportion of its time in temperate climates where the sea water temperature is well below 30°C, the sea water flowrate and hence pumping power can be reduced.

Various methods are available and Ref. 3 compares schemes incorporating, respectively: two-speed motors with throttling on low speed; stepless variable speed using an eddy current coupling, and stepless variable speed using a variable-frequency controller with a constant-speed motor with throttling. Two possible duty cycles were assumed: A, in which 75% of the running hours were at 100% flowrate with 25% at 50% flowrate; and B, in which 50% running took place at 100% flowrate and 50% at 50% flowrate.

The analysis showed that both stepless variable-speed methods involved substantial increases in capital costs, but that two-speed motors with throttling on low speed when applied to duty cycles A and

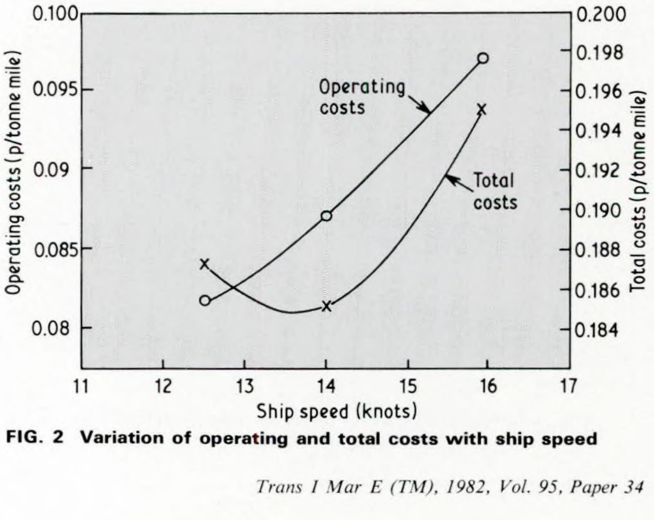


FIG. 2 Variation of operating and total costs with ship speed

Table V: Application of power savings

	GROUP 1		GROUP 2		GROUP 3	
Sea days/round trip	39.4		34.5		31.5	
Round trips/annum	6.81		7.53		8.1	
Sea days/annum	268		260		255	
Hours/annum	6432		6240		6124	
SAVINGS	SEAWATER PUMPS	OUTBOARD AIR SUPPLY	SEAWATER PUMPS	OUTBOARD AIR SUPPLY	SEAWATER PUMPS	OUTBOARD AIR SUPPLY
Power saved (kW)	6	20	9	30	13	45
Cost saved/annum (£/annum)	1460	4868	2125	7084	3013	10428
Present worth of cost saved (£)	11103	37019	16160	53871	22912	79300
Extra cost (£):						
65 kW motor					2678	
Net present value (£)					20234	
Benefit cost ratio					8.56	

Table VI: Application of waste heat recovery

MCR (kW)	9000
Exhaust gas flowrate at 85% MCR (kg/h)	62 500
Temperature (°C)	290
Power in exhaust (kW)	2301
A Auxiliary steam consumption (kW)	724
Power for superheat generation (kW)	1577
Electrical power available (kW)	263
B Auxiliary steam consumption (kW)	478
Power for superheat generation (kW)	1823
Electrical power available (kW)	304
C Auxiliary steam consumption (kW)	0
Power for superheat generation (kW)	2301
Electrical power available (kW)	384
Assumed electrical load at sea (kW)	425
Electrical load including power saving (kW)	386
Steam and exhaust conditions:	
Feed temperature (°C)	50
Steam pressure (bar)	8
Superheat temperature (°C)	260
Boiler efficiency	0.97
Exhaust gas specific heat (kJ/kg°C)	1.05
Turbogenerator specific steam consumption (kg/kWh)	7.8

Table VII: Typical at-sea steam heating requirement (kW)

1. Heavy oil and lube oil purifier heaters	224
2. Heavy oil preheater	228
3. Air conditioning	26
4. Double bottom, settling and service tanks	246
TOTAL	724

B gave payback times of, respectively 2.6 and 1.2 years. Taking the more optimistic duty cycle B, an overall power saving of 25% is obtained which yields the figures in line 4 of Table IV.

Table V shows the two-speed motor system applied to an engine selected from each group. The extra cost of the system taken from Ref. 3 is appropriate to the Group 3 engine and, over the assumed 15-year life of the ship, the NPV of £20 234 and the benefit cost ratio (BCR) of 8.56 indicate a worthwhile investment, based on electrical power generation using diesel-fuelled generators and duty cycle B.

Direct air supplies

It has been suggested that the main engine could draw its air supply directly from outboard, thus reducing the power required for the engine room vent fans by up to 80%. No estimates for the additional cost of this system have been attempted but, if diesel generation is the only source of power, Table V shows that it is likely that direct air supplies would merit further investigation for particular designs.

POWER SUPPLY

Waste heat recovery

Broadly speaking, the greater the installed propulsion power, the lower the auxiliary power as a fraction of propulsion power. It is thus more likely that higher powered ships can be made self-sufficient electrically using a waste heat boiler/turbogenerator system than those of lower installed power. As fuel costs rise, transport theory shows that the economic speed decreases, and hence the installed power decreases. The increase in fuel costs, therefore, by which waste heat recovery becomes economic, may also have reduced the installed power to the point where the electrical energy requirement exceeds the supply available from a waste heat turbogenerator unit.

In their report to British Shipbuilders in January 1981 (Ref. 2) the authors concluded that some engines in Groups 2 and 3 could be self-sufficient electrically using a waste heat unit without employing any power-saving devices, although the use of the latter did increase the excess of supply over demand. As it made power available notionally free, a waste heat unit was considered more attractive than a shaft generator. However, the original report was based on Sulzer RLB and B & W LGFCA series slow-speed engines; and since January 1981 the RLB has been modified and the RTA and LGB/GBE engines introduced. Of course, the objective of these engines is to maximize propulsion efficiency but, in relation to waste heat recovery, the penalty is a reduction in exhaust gas temperature.

Detailed information on exhaust gas and scavenge air heat utilization is now available for the LGB/GBE engines, and under the steam cycle assumptions shown in Table VI even the present Group 3 engines are unlikely to produce sufficient exhaust gas energy to make a waste heat recovery unit viable.

Table VI shows the application of a simple single-pressure steam cycle waste heat recovery unit to a 4L80 GBE (Group 2) engine. In calculating the exhaust power available for electrical generation, account must be taken of the ship's saturated steam heating requirements, and the extent to which scavenge air heat may be utilized for this duty is also considered.

The electrical power and heating analysis provided by British Shipbuilders concluded that a typical 'at sea' steam heating requirement would be as shown in Table VII.

The availability of scavenge air heat depends on individual circumstances noting, for example, that at 85% engine power the available scavenge air heat may be only half that available at 100% MCR. However, if all or part of the ship's steam heating requirements can be satisfied using scavenge air heat, the greater the output of superheated steam and hence electrical power.

Case A in Table VI, therefore, represents the base condition assuming no scavenge air heat recovery. Case B assumes that scavenge air heat satisfies the double bottom, settling and service heat load (Table VII, at a lower temperature than the purifier heaters and preheater) only; and Case C assumes that the total steam heating load could be satisfied using scavenge air heat. It can be seen that, even under the most favourable circumstances of Case C, there is insufficient power available to satisfy the minimum electrical demand.

Ideally, of course, a substantial margin of supply over demand would be required for viable operation. Although it may be tempting to increase the output of the turbogenerator by supplementary oil firing of the exhaust gas boiler, these units are only attractive because the supply of energy from the exhaust gas is free: their specific fuel consumption, when directly fired for use in port or on supplementary firing, can exceed 0.5 kg/kWh; and, at present-day price ratios of distillate fuel/boiler fuel, the generation of electrical power at such a low efficiency using cheaper fuel is less economical than burning high-grade distillate fuel in a diesel generator at much higher efficiency.

Shaft-driven alternators

The use of shaft generator systems in conjunction with medium-speed engines and controllable-pitch propellers, where the alternator may be driven via the reduction gearing, is well established. Frequency variations can be controlled within close limits even when crash astern manoeuvres have taken place.

The application to slow-speed diesel engines driving fixed-pitch propellers is a more difficult problem, although these technical difficulties have in a large part been overcome. The main advantages of such a system are:

(i) Electrical energy is generated using main engine fuel rather than the expensive diesel oil used in most generating sets.
(ii) Reduction of maintenance costs for the independent diesel generators.

A major disadvantage is that extra capital costs are usually involved, although some of these may be offset by the omission of one conventional diesel engine driven alternator. Clearly, a decision must be made either to increase the size of the main engine by an appropriate amount to allow for the extra power take-off; or accept a reduced delivered power at the propeller and the consequent reduction in ship speed and earning capacity.

The plant considered for the following example was a slow-speed diesel engine in Group 2 with an MCR of 9 MW. This engine necessitates provision for a power take-off from the main shaft. It was assumed that one diesel engine for the supply of auxiliary power would not be required, although in general it may be that the remaining alternators would need to be increased in size to allow one engine to cope with maximum port load when working cargo.

The at-sea electrical power requirement was taken to be 425 kW, although this figure could be reduced by application of energy-saving systems. On this basis the auxiliary fuel requirements were taken as 2.25 tonnes/day of marine diesel oil (MDO).

Table VIII indicates the present worth of fuel cost saved over a 15-year period discounted at 10%. This is compared to the standard case of the same ship using data from the basic analysis mentioned in the first section of this paper. The reduction in cargo tonne miles is also included to indicate the losses in revenue incurred. In this case an NPV of £106 730 indicates the permissible first cost which may be incurred on installation of the shaft generator system to give a 10% rate of return on the investment.

A similar analysis can be undertaken for the second alternative, i.e. maintaining ship speed but installing a larger main engine to supply the necessary extra power.

Blended fuel for diesel alternators

Engine manufacturers have in the past given assurances that their generator engines can burn heavy oil of viscosity as high as 1500 s Redwood No. 1. Accepting that maintenance costs will increase and that extra capital costs will accrue, the advantages to be gained are large when the reduction in fuel price is considered.

The authors recognize that technical problems exist with quick-running trunk piston diesel engines when operating on such fuel, but maintain that conversion to burn a blended fuel of about 27 cSt at 50°C (200 s Redwood No. 1 at 100°F) is a viable proposition. This fuel could be produced in an in-line blender from 60% residual fuel and 40% marine diesel oil. The price of this blended fuel would be $£(0.4 \times 172)+ £(0.6 \times 100)=£129$/tonne.

The annual fuel cost saving can be calculated for the basic ship generating all auxiliary electrical power by means of diesel alternators with a loading pattern as outlined below:

At sea	425 kW
Manoeuvring	530 kW
Port (working cargo)	900 kW
(not working cargo)	340 kW

As before, the at-sea requirements for auxiliary fuel will be 2.25 tonnes/day. An accurate assessment of port fuel usage, including manoeuvring and cargo working for the voyage pattern assumed, worked out at 31 tonnes per round trip. Annual fuel cost savings when using blended fuel in generators are as follows:

Fuel oil saved per annum: at sea (tonnes)	585
port (tonnes)	233
Fuel cost saving	£35 170

The NPV of annual savings of the above magnitude leaves little doubt that this is a worthwhile exercise where diesel generators are used as the main source of auxiliary power generation.

INTEGRATION OF SYSTEMS

Energy-saving and energy-recovery options do not necessarily apply to all ships and all engine power ranges, nor indeed do they always apply to different engines within the same power group. Again only one engine is considered in this section, taken from the Group 2 power range. The following stages of system integration can be identified.

Stage 1: Basic ship using only well-established systems, e.g. exhaust gas economizer, jacket water evaporator plus diesel generators running on MDO. This represents the system considered in the general analysis mentioned earlier in the paper.

Stage 2: Ship incorporating a modest amount of energy-saving technology, e.g. exhaust gas economizer, jacket water evaporator, diesel generators running on blended fuel, outboard air supply and variable-speed pump.

Stage 3: Ship incorporating all appropriate energy-saving systems, i.e. as Stage 2 plus shaft generator.

It has already been established that the engine considered would not be self-sufficient electrically using a waste heat turbogenerator unit. The power available from this source can be nevertheless used for other purposes such as bunker heating, etc.

The economic analysis was carried out on the same basis as outlined in the first part of the paper. The following refinements and assumptions were added:

- Auxiliary firing of exhaust gas economizer to supply port steam heating requirements uses 0.8 tonnes of fuel oil/day.
- Port electrical loading taken as in the previous section.
- At-sea electrical loading where diesel generators are used taken initially as 425 kW (Stage 1) and reduced to 385 kW by energy-saving methods.

The following adjustments were made to the initial capital cost of the ship to allow for the extra items of energy-saving equipment fitted.

Variable speed pumps and controls:	£5000
In-line fuel blender and engine modification:	£11 000
Outboard air supply:	£18 000

In view of the possibility of high-peak, in-port demands for electrical power, it is proposed that two generator sets, each of 900–1000 kW, be fitted when the shaft generator is used. Extra costs associated with this latter item are, therefore, reduced by the removal of one diesel alternator, although increasing the size of the other two. This further cost involved is estimated to be £120 000.

Table IX gives a comparison of annual costs associated with the three stages of auxiliary modification outlined above, with a base of 100% for Stage 1.

It can be seen from Table IX that the annual operating costs, i.e. repair and maintenance, crew, fuel and port costs, fall progressively as a result of fuel cost savings, but that the extra capital costs and charges involved make the Stage 3 scenario (i.e. the shaft generator application) a doubtful choice when overall costs are considered.

To establish the long-term benefits, if any, a full DCF calculation was performed for Stage 3 since it must be borne in mind that fuel savings accrue for the lifetime of the ship, whilst capital repayment and interest cease after, say 8 years. For the particular plant considered, the required freight rate index for a 15-year life cycle with an approximate rate of return of 10% was:

	RFR index (£/tonne)
Base ship (Stage 1)	9.014
Shaft generator, etc. (Stage 3)	8.99

Clearly, only marginal differences exist and the effect of long-term fuel savings has just, in effect, countered the extra capital costs involved.

Table VIII

Present worth of fuel saved (£)	725 270
Required freight rate (£/tonne)	9.05
Present worth of cargo lost (£)	618 540
Net present value (£)	106 730

Table IX: Annual results (first year) for integrated energy-saving systems (base 100%)

	STAGE 1	STAGE 2	STAGE 3
Cargo carried/annum (tonnes)	100	100	98
Annual running costs	100	100	100
Annual fuel and lube oil costs	100	95.6	89.3
Annual port costs	100	100	97.8
Total operating costs	100	98.1	95.3
Annual capital charges (first year)	100	100.2	100.9
Total annual costs	100	99.2	98.3
Tonne miles/annum	100	100	98.0
Cost/tonne mile: (operating)	100	98	97.2
(total annual)	100	99.1	100.3

CONCLUSION

Under the assumed operational and economic conditions, engines in the range 8500–9500 kW show the most favourable performance in terms of cost per tonne mile at an average speed of 13.6 knots. It appears unlikely that the at-sea auxiliary load could be satisfied entirely by a waste heat turbogenerator unit, due to the relatively low installed power and the reduced exhaust temperatures of the latest engine designs. The available exhaust heat would satisfy the steam heating load using a conventional waste heat boiler and there is thus little to support the use of scavenge air heat for this purpose.

A shaft generator in this application yields only marginal benefits over the life of the ship when compared to the base ship where only the minimum energy recovery technology is used. The greatest economic advantage is obtained by burning cheaper grades of fuel in conventional generators.

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Discussion

D. A. HAWKER (Pump & Compressor Division, Hamworthy Engineering Limited): On the subject of fuel economy in relation to motor-driven centrifugal pumps for seawater cooling service, the authors conclude that a two-speed motor can currently be a worthwhile investment and I am in agreement with their conclusion. There has, however, been sufficient interest recently in variable-speed pumps to warrant a few comments as follows.

Fuel economy should follow from a reduction in speed of rotation of a pump. A flowrate of 50% of normal will usually result in a theoretical power input to a pump shaft of 12.5% of normal. Fuel consumption will not be 12.5% of normal, however, because of a change in overall efficiency from pump to motor, to speed-changing device, to generator, to prime mover. The change in overall efficiency can be considerable.

Stepless speed variation, to control the flowrate from a centrifugal pump, is an elegant engineering practice and there have been some excellent industrial applications. Solid-state, variable-frequency controllers are, however, questionable when there is suggestion of increased profit from a ship. Before simply relating the rate of flow from a pump to ambient seawater temperature and showing an impressive annual saving of kilowatts, there are a few aspects that warrant investigation. For example:

1. The manufacturer of the main engine may have something to say. One said recently that he wanted his specified flowrate maintained, that he wanted the coldest possible seawater for his air cooler and that an increase of 10 °K in air temperature would lead to an increase in fuel consumption of 1 g/bhph.
2. The cooler manufacturer may have something to say about the simple variation of flowrate in proportion to temperature. There may be a minimum velocity below which a lack of turbulence will result in 'hot spots'.
3. The shipbuilder may have something to say about the minimum velocity below which marine growth will rapidly foul his seaboxes and pipework.
4. The shipbuilder may also have something to say about the minimum head of pressure which is required to fill his system layout and to keep it filled at all times. At 50% of normal speed, a centrifugal pump will generate only 25% of normal head. Most seawater cooling systems are syphonic with the pump head simply matching the system friction but the pump has to be capable of raising water from sea level to the top of the system. Any air which is entrained during low-speed operation of the pump could break the syphon. A correctly placed sensor would restore high speed but any foreseen circumstance in which flow could cease is probably best avoided.
5. It may be recognized that variable-speed pumping is being applied to a cooling system that has an excessive demand for energy. A typical pipework system of 200 mm diameter can demand three times the energy of one constructed from 250 mm diameter pipework.
6. It should be recognized that any investment calculation has to be based upon a realistic apportionment of total running hours to the various modes of operation and that maintenance costs may be applicable to any additional equipment.

Having considered the foregoing points, a variable-frequency controller may prove to be a sound investment but, as yet, I have not seen proof. There are ways of conserving fuel, in relation to seawater cooling pumps, which involve lower expenditure of capital and some may be of interest:

(a) The 'running' and 'standby' pump of a two-pump system need not, necessarily, be of the same rating.

(b) A two-speed motor can be fitted to one pump as already mentioned in the paper.

(c) A three or more pump system can be fitted for operation singly or in parallel. Although there may be some disagreement with the following statement, pumps are relatively low-cost items. One false economy, still too often seen, is the combination of a low-head and a high-head duty on a single pump, especially when appreciable running hours are involved.

(d) A replacement pump element can be supplied, by some pump-makers, to suit a specific long-term charter or a revised operating condition or simply to correct the discovery of an excessive flowrate. In a recent example of this the power supplied to a pump was reduced by 50% and by this simple approach the small amount of capital was expected to be recovered in about 150 days of operation.

A. J. WEST (M.A.N. – B & W Diesel Department): Over the last 10 years the proportion of the engine costs to total ship costs has risen from 25% to its present level of 50%.

At the same time, the influence of the fuel cost has risen from 45% of the engine cost to around 80% of the engine costs. For engine designers the message was clear: to retain or increase market share, it is necessary to reduce fuel oil consumption without increasing first cost too much.

This was achieved first by increasing the bore/stroke ratio and also by adopting the constant-pressure turbocharging system. This led to a reduction in specific fuel oil consumption (SFOC) from approximately 155 g/bhph to 133 g/bhph for a 900 mm bore engine, operating at its maximum continuous rating (MCR).

The M.A.N. – B & W uniflow scavenged 2-stroke engine has a wide range in the choice of power and rev/min. Also, it is possible to maintain the firing pressure at its 100% MCR value over a wide range of powers, which will give a higher thermal efficiency and, therefore, a lower SFOC.

This flexibility of the power and rev/min combination makes it possible to adapt the engine to the ship to achieve the optimum economic installation possible. The flexibility is limited by the maximum permissible revolutions of the engine, the nominal mean effective pressure and the engine bearing loads.

Considering the M.A.N. – B & W range of super long-stroke L-MC and long-stroke L-GB engines, covering from 2000 to 56 000 bhp with a revolution spectrum of 60–200 rev/min, it can be seen that the owner is offered many possibilities from which to choose the best solution. In fact, for engines adjusted for maximum economy and operating at part-load, SFOCs below 120 g/bhph can be offered.

Turning to the part of the paper covering auxiliary machinery, I would agree that due to the increasing thermal efficiency of the main engine the heat available for recovery is much reduced. In particular, the heat recovered from the exhaust gas will not in many cases be able to support the engine's electrical load unless it is augmented, for example, by passing a proportion of the exhaust gas around the turbochargers or by oil-firing of the auxiliary boilers; and it is possible that shaft generators, probably direct-coupled, will gain favour as they are able to burn the lowest-grade fuels at the lowest specific fuel oil consumption.

It is possible to recover heat from the air coolers and, for engines running at high loads, bunker and central heating could be provided by this means.

Finally, regarding diesel alternators, I agree that an economic benefit is gained by running these with degraded fuels and, with today's engines, the true uniflow ship is now a reality.

S. N. CLAYTON (Lloyd's Register of Shipping): The authors have shown that integration of systems can lead to effective savings and have indicated that a shaft generator may, in certain circumstances, also bring advantages. This prompts me to question whether they have considered the use of an integrated propulsion system.

It will be recalled that, in general, such a system is arranged for the main propelling prime mover to provide the power not only for the electricity supply but also for the pumps and other auxiliary services. A separate diesel engine is used for power purposes in port but can also provide for emergency propulsion through the main engine gearing. The savings from such a system obviously come from the use of a main engine, using a residual fuel, to provide all the power requirements.

The authors suggest the use of blended fuel for diesel alternators. The provision of in-line blenders and the tankage and piping required would increase the cost of the installation but no doubt the authors have taken these additional costs into consideration. It is felt that it might be more advantageous, if onboard blending is to be supplied, to aim for a one-fuel ship with the main and auxiliary engines using the same fuel, particularly when one notes the proportionate cost of fuel shown in Table I.

As regards the economic data mentioned in the paper, while the repair costs may be difficult to quantify and are a comparatively small proportion when compared with the full investment in the ship, it would, nevertheless, be of interest to learn whether any further breakdown of costs was available to the authors. It can often be the case that excessive repair costs may destroy economic stability.

M. R. WALL (Dept of Marine Technology and Naval Architecture, Southampton College of Technology): The economic tools used in this paper, i.e. net present value and discounted cash flows, involve the setting of a discount rate. The level at which this is set will predict whether an investment will be more or less profitable or, as in the case of this paper, whether a project is economically viable.

Earlier this year a colleague of the authors read an interesting paper on techno-economic selection techniques applied to fuel-saving projects, in which he assumed discount rates of 10% and 15% for his scenarios. I believe that the authors of this paper have set the level at 10% and would like to ask how, and why, this level was set? If, as suspected, inflation drops further, linked with possible static crew and fuel costs, would this discount rate still appear reasonable?

E. J. BANNISTER (Shell International Marine Limited): During the presentation of the paper, the authors described in some detail a system of economic evaluation and examples of its use were given. Their calculations assume loans with repayment schedules and interest rates based on approximately OECD terms. There are however, apparently no provisions for tax payments or allowances.

Normally, economic calculations have two main purposes:

(a) to compare alternative investments and determine the best one, and/or

(b) to determine whether a potential investment is a viable one by whatever criteria may be considered appropriate.

In the former case simplified calculations can be used, it only being necessary to highlight differences between alternatives, not absolute values. In the latter case, more precise calculations are required. I assume from the use to which the authors put the calculations that the applications of both (a) and (b) are intended.

If this is the case, it is surprising that they do not apply taxation regimes as these can often vary considerably from shipowner to shipowner in different countries with different flags, whereas loans are generally relatively similar, being determined more by world-wide commercial conditions.

I should be grateful if the authors would clarify the position. I hope they are not implying that in the long term shipowners are not hoping to be in a profit-making but, regretfully, tax-paying position.

J. C. HAMMOND (Hart, Fenton & Co. Limited): The example used in the paper, that of a Panamax bulk carrier, offers a predictable trading pattern and operation. Some of the benefits due to energy-saving measures, which often increase first cost, are marginal and clear conclusions may not be available for each measure considered.

For many types of ship the voyage details and operational data are not known at the time the basic design work is carried out. The charter arrangements and period of ownership may not be known. In some cases the ship may be sold before delivery. Assumptions must then be made on the trading pattern of the vessel. Substantial additional costs incurred in energy-saving measures must be reflected in charter rates and/or resale price.

The capital cost may often be the leading economic criterion for the design. Economy of operation in later years will not raise more capital to pay for the energy-saving measures. It is thus necessary to minimize the capital cost and maximize the revenue-earning capacity of the vessel. Additional expense may be justified in adding features which improve cargo efficiency (and hence revenue) or in providing flexibility to give a wider charter or resale value.

The selection of main and auxiliary machinery on an integrated basis may well lead to conclusions different to those obtained from the approach of reducing the possible system early in the program by deciding on a particular main engine on the basis of the engine's merits alone. For example, the slow-speed two-stroke and medium-speed four-stroke diesel engines offer different exhaust conditions and electrical/auxiliary load requirements. These conditions and requirements should be taken into account at the time of selection of the main engine.

DR I. L. BUXTON (Dept of Naval Architecture and Shipbuilding, University of Newcastle upon Tyne): The authors have presented a very succinct paper which is based on a much more detailed study. Clearly, such economic evaluations are becoming even more important with the range of alternative main engines, auxiliary machinery and propulsion devices which are available for new ships.

Economic evaluations are of most use to engineers when comparing alternatives; it is not usually our decision whether it is worth investing in ships at all. If one does analyse the overall profitability of shipping, one finds that relatively low rates of return are yielded in practice: rarely over 10% in money terms which, after allowing for inflation, may not even be a positive rate in real terms.

The problems for the analyst are then first to decide whether to work in real or in money terms (which latter explicitly recognizes cost escalation, loan terms and charters without escalation clauses); and, second, whether to use a target discount rate based on expected rates of return typically found in shipping, or the rather higher rates of return usually found in alternative investments ashore. Such considerations alter the balance between capital and operating costs, so influencing the decision whether to spend more (e.g. on machinery) or to save more (e.g. on fuel). An indication of the discount rates and escalation rates the authors have used would be of interest.

The study of the shaft-driven alternator shows it to be closely matched to the alternatives. Of course, the benefit is a function of number of days at sea per annum, so a sensitivity study can indicate whether the ranking will change for other assumptions. Perhaps also the high in-port electrical load assumed has influenced the comparison. Panamax bulk carriers are rarely fitted with cargo-handling gear and even those ships which are so fitted generally use them only intermittently; few ports are so well organized that gear at all holds would be used simultaneously and continuously throughout the day. The job for the engineer is to discover under what range of operating circumstances Equipment A is better than Equipment B, and then to weigh up the probabilities of each circumstance occurring. Fortunately the availability of computer programs makes such economic analysis easier, but the underlying engineering analysis needs to be done thoroughly as well.

Authors' Reply

We thank Mr Hawker for his helpful comments on the application of variable-speed pumps for cooling water circulation.

It is clear that much can be achieved by good detailed design of particular systems and substantially more by design of the propulsion system as a whole as opposed to individual components. If, as he suggests, there is a number of different criteria to satisfy, stimulated from different sources, i.e. engine manufacturer, cooler manufacturer and shipbuilder, then full discussions prior to the design must take place. This can then lead to an integrated system affording maximum economy.

Mr West is associated with one of the marine engine builders who have clearly responded to the call for more efficient main engines in the face of ever-rising fuel prices. His organization has developed a series of engines which can only be described as remarkable in their fuel economy. He also comments on the problems associated with the provision of auxiliary power and, in particular, the reduction in energy available in the exhaust gas from the main engine.

The example quoted in the paper was for a specific case and it must be reiterated that provision of shaft generation may indeed be worthwhile in other applications. Indeed, in the case study presented, if port time were substantially reduced and annual at-sea time increased, it is likely that a shaft-driven alternator would prove a better alternative.

A worthwhile compromise may well be to reduce the at-sea electrical load to the point where exhaust gas/turbo-generator sets once again become viable. This could be done by using engine-driven pumps for the main-engine cooling and lubrication services at very little extra cost in providing a larger main engine.

The above points may also answer some of the queries raised by Mr Clayton. In our view, an integrated propulsion system should utilize as much waste heat as possible. We have suggested various ways in which this may be achieved and other workers have suggested many more energy-saving methods. Nevertheless, it must always be borne in mind that whilst auxiliary load, and hence fuel cost, is a significant proportion of the total fuel bill, considerable investment may be required to make relatively small economies. It is for this reason that some of the more sophisticated and complex systems that have been suggested were not in fact considered in our paper.

We agree that progress towards the one-fuel ship is a useful concept but we must again point out that the cost of the main engine's fuel is of much greater significance and small percentage increases in fuel price to allow a one-fuel ship could easily overwhelm the savings made on auxiliary power generation.

Maintenance and repair costs are traditionally difficult to quantify, depending as they do on the methods adopted by individual companies to undertake M & R. No further breakdown of costs is immediately available but, as Mr Clayton points out, these costs form a small proportion of total operational outgoings. We do not visualize any circumstance of normal operation which could destroy economic stability. Clearly, a major breakdown producing excessive repair costs may cause serious problems in any one year but we have yet to come across a manufacturer of machinery who suggests allowing for such a happening in any future economic scenario.

Mr Wall has asked for information on the discount rate used for the case study presented. The discount rate was, in fact, 10% and at the time this work was undertaken that figure was regarded in Government circles as representing a reasonable rate of return. In fact, as Mr Wall suggests, this rate can be varied according to whatever circumstances dictate and the effect considered on the overall analysis. Inflation levels do not materially affect this rate of return. Indeed, were all expenditure and income subject to a constant level of inflation, then inflation need not enter into the equation at all.

It is not our brief to comment on whether, given the scenario suggested by Mr Wall, a discount rate of 10% would still appear reasonable. As used in the paper it represents a genuine rate of return on investment.

Mr Bannister is right in his assumption that no provision has been made for tax payments or allowances. The method of analysis we outlined in the paper is primarily used to compare alternatives for ships' machinery installations, within a number of constraints, and to determine which system would prove to offer the most economic operation. It should, nevertheless, be regarded only as one of a number of tools available to the ship's designer in his deliberations.

Taxation regimes do vary, as do subsidies and allowances. Nevertheless, it is not unreasonable to assume that any variations in these parameters, whilst perhaps affecting the overall viability of a major capital investment, do not bear on the decision to install the most economic machinery system possible.

Mr Hammond queries the route pattern quoted in the paper. It must be stressed that in the paper we are really concerned with the method of analysis and not specifically with the one example quoted in the text. Obviously, assumptions must be made but it is always possible to incorporate any specific trading pattern or indeed to produce a mapping of a wide range of trade routes if necessary. We would agree with his comments on the importance of first cost and its minimization, bearing in mind that the cheapest engine is not always the most efficient.

Mr Hammond also comments on the advisability of basing integrated designs on an initial coarse filter of main-engine efficiency. This is a valid point but we have found that, since main engine fuel costs form by far the major proportion of total energy costs, it is a reasonable way to proceed. In fact, for some scenarios that have been investigated, medium-speed engines prove a better proposition than slow-speed engines.

Dr Buxton partially answers some of Mr Bannister's points, i.e. economic evaluations are useful in comparing alternatives and they are not intended to be the final arbiter in the decision on whether it is worth investing in ships.

For the example shown in the paper, a general level of inflation of 8% was assumed and this was applied to crew costs, fuel and lubricating oil costs and port costs. Maintenance costs were assumed to rise at a rate of 3% above the normal inflationary levels. Because of these differences, and also the variation of payments of interest on loan repayments, it was decided to incorporate all of these factors in the cash flow analysis along with a discount rate of approximately 10%.

Mention has already been made of the variations which may be evident when basic trade patterns are altered and the effects this variation may have on the viability or otherwise of shaft-driven generators.

In conclusion, we should like to thank all who contributed to our paper. Our studies have led us to the conclusions that the method of analysis outlined in the paper provides a useful tool in the decision-making process involved in machinery installation design. Much has yet to be done. Main-engine builders have responded magnificently to the challenge of reduction of specific fuel consumption but the area of auxiliary installation and integration requires further study. Reduction of at-sea electrical power requirements is a particularly important area worth investigation.