IMPROVED CONTAINER TRANSSHIPMENT UTILISING LOW CARBON FEEDER SHIPS

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ABSTRACT

Investigation of feeder ships worldwide has identified South East Asian and the Caribbean as transshipment markets open to feeder ship replacement with a need for improved operational efficiency. In response to this challenge an environmentally sustainable feeder-container ship concept has been developed for the 2020 container market. The concept utilises higher speed and larger capacity than typical feeder ships, whilst halving the fleet size. The use of low-carbon and zero-sulphur fuel (liquefied natural gas) and improvements in operational efficiency (cargo handling and scheduling) mean predicted Greenhouse gas emissions should fall by 42% and 40% in the two selected operational regions. The predicted daily cost savings are respectively 27% and 33% in South East Asian and the Caribbean. A *Multi-wing* sail system also contributes to these savings whilst providing the additional benefit of motion damping. Propulsion and manoeuvrability is provided through a contra-rotating podded drive. Performance predictions have been made based on physical testing of both hull form and sail system. Use of ship-borne gantry cranes and the podded based manoeuvrability permit reduced times in port, thus improving operational efficiency. A typical round trip voyage has been simulated taking into account: realistic wind and wave environment data; physical model testing data and a representative operational profile including port operations. The fast feeder-container ship is a proposed as a viable future method of container transshipment.

Keywords: transshipment, low carbon shipping, feeder container ship, sail system, LNG, improved efficiency

NOMENCLATURE

C_B	Block coefficient
C_C	Carbon factor
GM_T	Metacentric height
h	High speed (subscript)
l	Low speed (subscript)
N_C	Number of containers
N_S	Number of ships in fleet
P_B	Brake (installed) power
V_s	Ship speed
w	Weighting factor
AE	Auxiliary engine (superscript)
CO_2	Carbon dioxide
DWT	Deadweight
FC	Fuel consumption
ME	Main engine (superscript)
$MTEI$	Modified transport efficiency index
NO_x	Nitrogen oxides
SFC	Specific fuel consumption
TEU	Twenty-foot equivalent unit

1. INTRODUCTION

Container transshipment is essential in the transport of goods to smaller regional ports from 'mainline' ports served by larger inter-continental vessels. The transshipment market tripled between 1995 and 2005 (Ocean Shipping Consultants, 2006), a trend that is set to continue with increasing global shipping trade. Numerous efficiency improvements have been suggested for the 'feeder' container ships servicing transshipment routes namely: increasing size subject to maintaining utilisation, improved cargo handling and 'just in time' (JIT) arrival (Wärtsilä Ship Power R&D, 2009).

Shipping growth also requires improvements in energy efficiency and reduction of exhaust emissions if predicted increases of between 150% and 250% by 2050 are to be avoided (Buhaug *et al.*, 2009). Shipping already contributes approximately 3.3% of global emissions. The use of an alternative low carbon fuel (DNV Quantum 9000 (Byklum, 2010)) or renewable energy technologies (NYK Super Eco Ship 2030 (NYK, 2010)) has become popular in addressing these challenges. However, assessing the feasibility of immature technologies such as fuel cells is a difficult task. The 'fast feeder' container ship concept presented here seeks to employ mature technologies to provide both economic and environmental benefits to container transshipment operations in 2020. We adopt the approach that fewer, faster larger vessels can be more efficient than those in the existing fleet.

This paper will focus on approaches adopted to improve overall transshipment efficiency, reduce operating costs and lower emissions. A market analysis is first presented to estimate future transshipment requirements. Then a brief outline of the design development is included, covering both towing tank and wind tunnel testing. Next, a description of the performance prediction procedure carried out is included, leading to quantitative evaluation of the concept. The paper concludes by highlighting the novel features of the proposed design and discussing further work requirements.

2. MARKET ANALYSIS

It is generally accepted that 'hub and spoke' networks are more economical and environmentally sustainable than traditional distribution networks, since fewer journeys are required and containers, on average, arrive at their final destination quicker (PSA South East Asia Terminals, 2009).

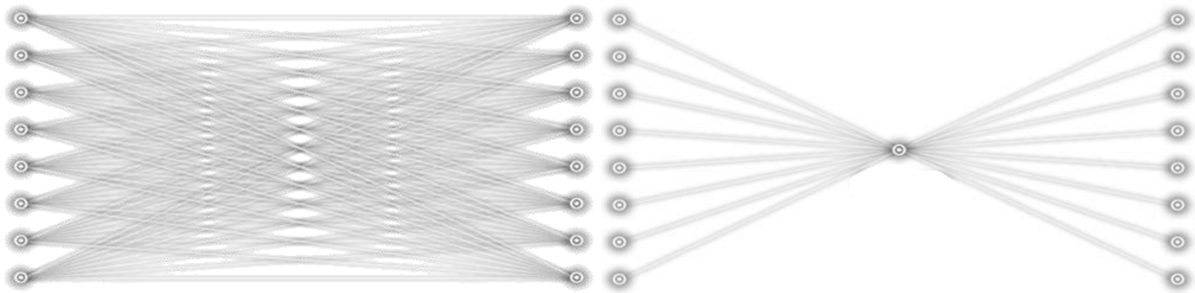

Figure 2.1 – Shipping network without (left) and with (right) transshipment [PSA South-East Asia Terminals (2009)]

A graphical representation of a hub and spoke network compared to a traditional network is given in Figure 2.1.

2.1. Regional analysis

Container throughput increases in 2020 (Degerlund, 2004; 2006; 2008) and total distance from the selected hub port to *all* spoke ports for the four regions considered appropriate is summarised in Table 2.1. US East and West coasts were not included due to well-established low cost rail transport. The predicted throughput increases are based on linear regression of 60 ports within the regions considered. The predicted throughput increase in the Far East region is considered too large to be met using the proposed approach in isolation.

Table 2.1 – Summary of minimum distance to all regional ports and predicted container throughput increase in 2020

Region	*Hub port*	*Total dist. / nm*	*Predicted increase / %*
S. E. Asia	Singapore	11836	83
Caribbean	Kingston	7870	100
Far East	Busan	5033	159
Mediterranean	Gioia Tauro	13014	67

Degerlund (2004; 2006; 2008) also provides details of port restrictions, revealing that 79% of the ports considered accept vessels with draughts of up to 10m and only 6% of ports do not accept vessels over 220m length. In addition, analysis of ship age is important as it reveals the likelihood of vessel replacement by a given date (Table 2.2). Assuming a 20 to 30 year lifespan, 47% of the current fleet (built after 1990) will require replacement by 2020.

The assessment of an appropriate operating region should also take into account typical route distances and headings. To achieve this the Dataloy voyage management system (Dataloy, 2009) was used to compile a statistical database of route-based data (see Burden *et al.* (2010a) for detailed breakdown of route information).

Table 2.2 – Summary of current vessels by year built (Degerlund, 2004; 2006; 2008)

Year built			No. of ships	% of ships
1960	→	1970	1	0.68
1971	→	1975	4	2.72
1976	→	1980	16	10.88
1981	→	1985	20	13.61
1986	→	1990	9	6.12
1991	→	1995	20	13.61
1996	→	2000	49	33.33
2001	→	2005	29	19.73

2.2. Operational analysis

Qualitative operational analysis was conducted based on discussions with feeder container ship operator Borchard Line Limited (Mash, 2009). The key considerations are:

- Manoeuvrable ships can save on high tug fees and reduce waiting times entering port;
- Congestion in port can mean waiting times of up to 5 days to use shore-side cranes, whereas shorter, beamier ships are more likely to fit into available berthing spaces, reducing wait times;
- Ships should be able to operate at constant speed up to force five conditions, although speed reductions down to 5 knots do occur in practice;

- High and low sulphur fuels must be accommodated to meet near-shore regulations as scrubbers are rarely used.

Where possible these points have been addressed in the design to achieve the sought efficiency improvements.

2.3. Economic analysis

To quantitatively identify the most appropriate region to adopt the feeder concept and derive typical vessel requirements, a flowchart analysis was carried out based on the following assumptions:

- the hub and spoke network approach to transshipment is exclusively adopted on a route;
- number of fleet sailings remains constant, with increasing ship speed and size to meet 2020 throughput increase;
- number of feeder ships on the route is halved compared to existing feeder vessels;
- port congestion is minimal and the feeder can self-load/unload;
- 10% target market share is assumed, with 90% vessel capacity utilisation.

Based on these assumptions and the accumulated data, a procedure to estimate the vessel requirements was devised (Figure 2.2).

The results of the analysis based on these assumptions are presented in Table 2.3.

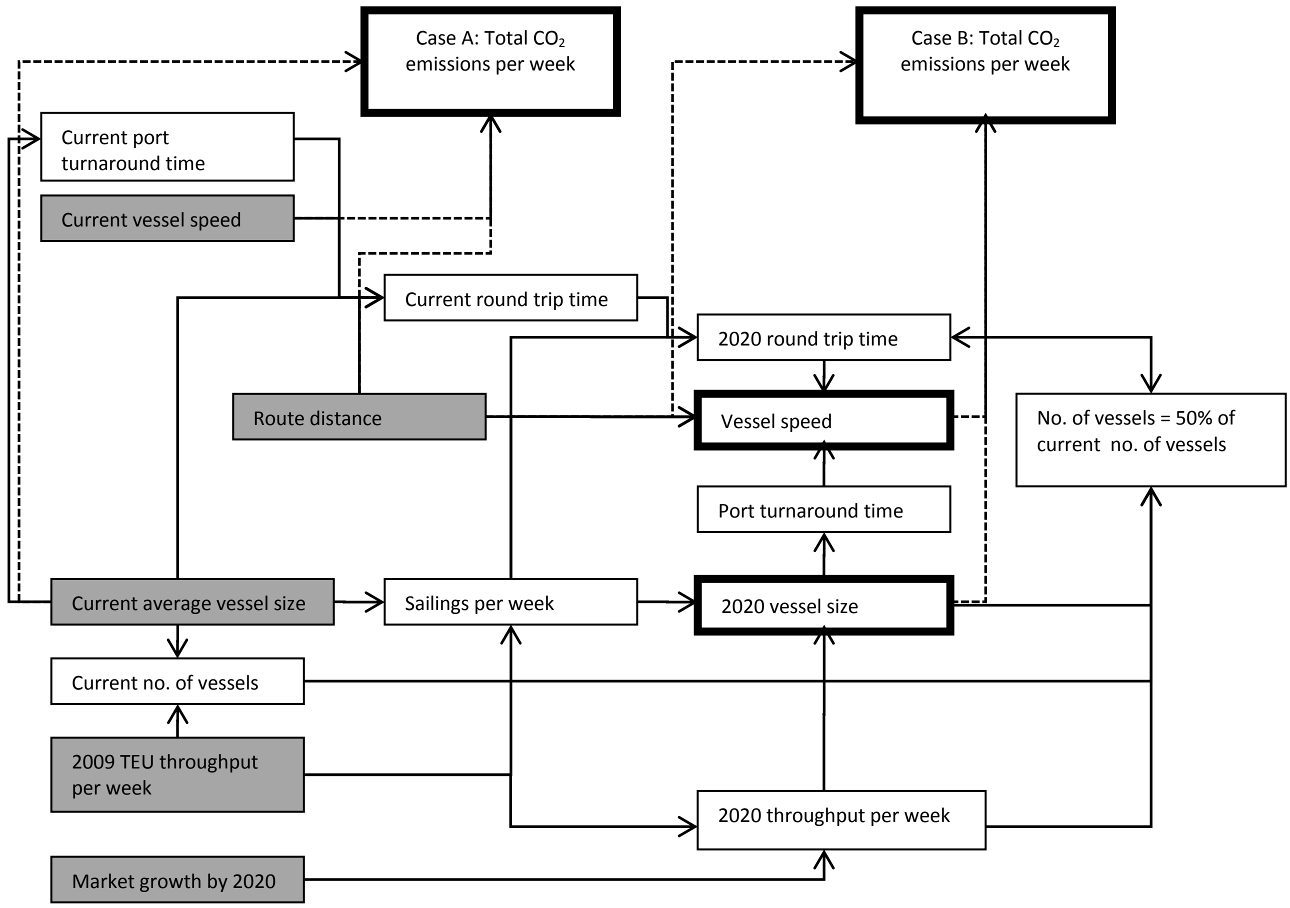

Figure 2.2 – Flow chart used to determine the required ship capacity and speed for a particular route (shaded boxes represent process inputs, bold edged boxes outputs, and other boxes intermediate steps)

Table 2.3 – Estimated increase in CO_2 emissions and reduction in total number of ships (*Case A* represents 2020 operations using the current fleet; *Case B* utilises the fast feeder ships)

Region	Tonnes CO_2 per week			No. of ships		
	Case A	*Case B*	% increase	*Case A*	*Case B*	% of *Case A*
S. E. Asia	976	1262	129	120	44	36.7
Mediterranean	609	982	161	80	45	56.3
Caribbean	244	294	121	28	12	42.9

There is a clear difference between the two cases. The significant reduction in the number of ships required to meet the projected throughput has the potential to improve efficiency by reducing both costs and port congestion. Both South East Asia and the Caribbean meet the 50% reduction target in the total number of vessels. The predicted CO_2 increase is large in all regions. At this stage, the Mediterranean was ruled out as a feasible region since the CO_2 penalty for adopting the suggested operational model was considered too large to recover, even through the use of alternative fuel technology. Tighter Mediterranean regulations results in the operators using slightly newer and smaller ships than in the other two regions.

The average feeder ship size in 2020 has been predicted to meet the increased throughput demand, resulting in 1303 and 1088 TEU in the South East Asia and Caribbean regions respectively, compared to 890 and 955 TEU in 2009. A summary of the vessel requirements is given in Table 2.4

Table 2.4 – Summary of specification for design

Spec.	*Value*
Speed / knots	25
Capacity / TEU	1300
Range / nm	1500

3. DESIGN DEVELOPMENT

Significant design development has been addressed through hull form development, towing tank and wind tunnel model testing, sea-keeping, stability and structural design to class rules including application of the common structural rules using finite element analysis. Detailed coverage of these aspects of the design is not appropriate here but can be found in Burden *et al.* (2010a; 2010b).

3.1. Initial dimensions and powering

Initial ship particulars were derived from 170 basis vessels sourced from online databases (van Duivendijk, 2009; Svendsen & Tiedemann, 2009), mass estimates were generated by empirical methods of Watson & Gilfillan (1977) and Schneekluth & Bertram (1985) and stability estimate was based on Molland (2008).

The resulting principal particulars are given in Table 3.1.

3.2. Propulsion system

Numerous novel aspects have been incorporated in the propulsion system design with the aim to improve efficiency and reduce emissions. The chosen fuel is liquefied natural gas (LNG) since it provides significant emissions reductions compared to marine diesel oil (MDO) and has lower costs (see Table 3.2). An additional benefit is the removal of any requirement to carry two fuel types due to near-shore emissions regulations (Levander, O. and Sipilä, T., 2008), as would be typical of a MDO fuelled vessel in the future under IMO legislation.

Table 3.1 – Summary of principal particulars (values in metres unless otherwise stated)

Particular	*Value*
Length overall	170.7
Length b.p.	155.4
Breadth	26.2
Depth	18.97
Draught	9.0
GM_T	1.268
C_B / -	0.57
Displacement / t	21400
DWT / t	12840
Capacity / TEU	1270
P_B / MW	25

Table 3.2 – Expected reductions in emissions and cost using LNG instead of MDO

	% reduction
CO_2	25 – 30
NO_X	85
SO_X	100
PM	99
cost[1]	28

This fuel can readily be burnt in ‘dual fuel’ medium speed engines (Wärtsilä Ship Power Technology, 2009) and is suitable for use in combination with electric power distribution systems. Thorough investigation of future LNG prices and availability has not been addressed; however DNV and MAN Diesel & Turbo (2010) predict fairly constant LNG prices over the next 25 years, thus improving cost reductions further compared to MDO, which is predicted to rise in cost significantly. It is noted that LNG terminals either exist or are proposed in both South East Asia and the Caribbean (Wärtsilä Corporation, 2009), and it is assumed these could provide appropriate bunkering facilities.

It is proposed to combine LNG with an electric distribution system and podded drive propulsor. This aims to improve power distribution efficiency and manoeuvring capability. A contra-rotating podded drive arrangement in combination with a controllable pitch propeller is specified, a propulsion layout more commonly seen on ‘Ro-Pax’ ferries (Levander, 2002), whose operating speed is similar to that of the fast feeder. This is expected to allow

[1] LNG cost 465 USD/ton (Levander, 2008); MDO cost 643 USD/ton from www.bunkerworld.com/prices/ on 23rd March 2010.

for optimal engine efficiency under different thrust loadings, such as when under sail or JIT arrival requires speed increase or reduction. A final layout of the propulsion system is indicated in the general arrangement drawing (Figure A.1) in the Appendix. Other novel features of the layout include: a forward accommodation block for maximal cargo capacity and reduced air drag; the use of rigid '*Multi-wing'* sails to provide thrust; and gantry type cranes for fast cargo handling.

3.3. Physical model testing

The hull form was developed using the *Maxsurf* software suite, allowing performance evaluation using the built-in *Hullspeed* and *Seakeeper* resistance and sea-keeping programs. In order to provide accurate resistance predictions, a 1:75 scale model was constructed using high-density foam and tested in the Southampton Solent University towing tank. Of particular importance were measurements in waves allowing realistic added resistance increases to be included in voyage modelling, and resistance contributions due to sailing at leeway and heel angles.

A 1:15 scale model of the proposed *Multi-wing* sail system was also tested in the University of Southampton wind tunnel. The results provided accurate performance estimates for the sail system at a number of apparent wind angles, accounting for interaction effects with containers, to be used as input to a performance prediction. For detailed description and analysis of the tests carried out see Burden *et al.* (2010). An artist's impression of the final design is presented in Figure A.2.

4. PERFORMANCE PREDICTION

In order to provide realistic performance estimates for the concept vessel, a program was created to estimate the thrust reduction due to the sails and estimate brake power across a typical route (see Figure 4.1). The input data included hydrodynamic calm water and added resistance, sail thrust, and wave (Hogben, 1986) and wind (US Department of Commerce, 2009) data on the simulated route. Note that the added resistance is that due to head waves only, found to be 10.7% of total voyage time based on expected headings on all routes in the South East Asia region.

The total ship resistance R_T is calculated as

$$R_T = R_U + R_A + R_W + R_H + R_I \qquad (4.1)$$

where the component subscripts represent upright, air, added wave, heeled and induced resistance respectively.

The added resistance due to waves can be scaled to any sea state by non-dimensionalising the experimental results. The assumed operational profile is assumed based on the vessel completing 3 round trips per fortnight. Thrust reduction due to the sails was calculated for both annual and seasonal (most favourable from summer or winter), as shown in Table 4.1. These values are lower than expected compared to initial estimates using empirical sail thrust coefficients. Despite the auxiliary power provided by the sails being low (high speed is a contributing factor) they do contribute to roll and yaw damping, which can provide further resistance and motion reduction. Average roll reductions of 16% and 30% due to the sails was estimated at ship speeds of 15 and 25 knots respectively, based on the method of Satchwell (1986). By estimating the yaw damping capabilities of the wing sail according to Clayton and Sinclair (1989) an estimate of the resistance reduction due to yaw damping was made (Satchwell, 1986). This equates to 1.93% and 2.14% at 15 and 25 knots in the South East Asia region (see Burden et al. for a full discussion). These potential benefits have not been modelled in the performance predictions presented here, or sea-keeping analyses, since they are purely empirical and experimental testing is required to fully quantify these effects.

5. VOYAGE MODELLING

Having estimated the performance of the sail system and thus the expected power requirement of the vessel when underway, a voyage simulation was carried out to account for port operations and to provide quantitative evaluation of the design compared to typical existing feeder vessels.

A comparison vessel was derived for each region, using empirical estimates based on the basis ships database. An operational profile was assumed from the discussion with Mash (2009). Estimates of the fast feeder manoeuvring and cargo handling durations and power requirements were made using empirical methods and manufacturer data, see Burden et al. (2010, chap. 6). This data is summarised in Tables 5.1 and 5.2.

Highlighted results in Table 5.1 indicate replacement of 2 existing feeder vessels by 1 proposed fast feeder is feasible in terms of maintaining container transports levels. Furthermore, the capacity of each ship of comparison is based on the average ship size of each region using data of 2009.

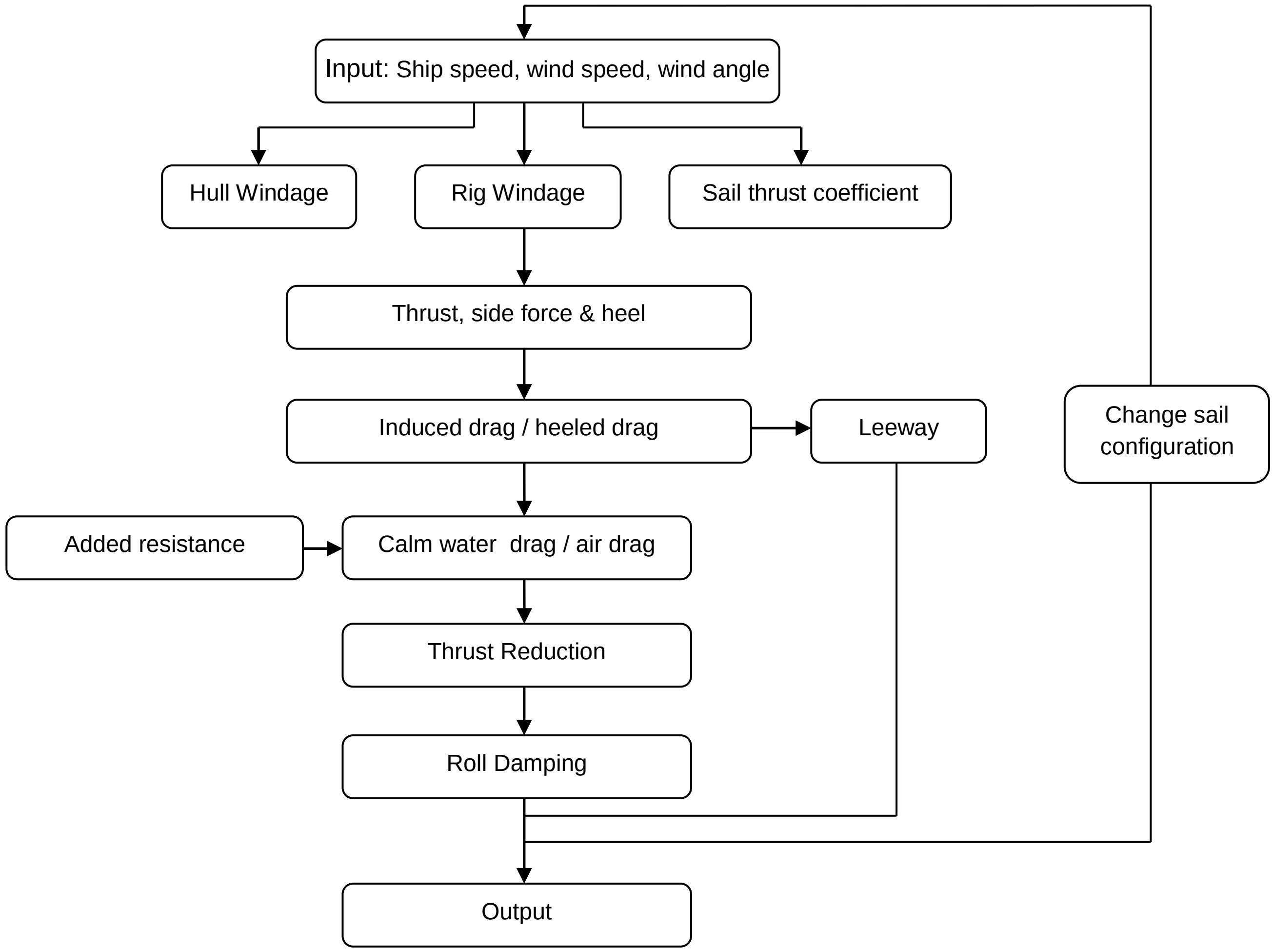

Figure 4.1 – Flowchart summary of performance prediction program used to calculate sail thrust

Table 4.1 – Thrust reduction predictions based on performance prediction program

	Singapore		*Caribbean*	
	Annual	Seasonal	Annual	Seasonal
thrust reduction / %	3.9	5.0	3.3	4.2

Table 5.1 – Summary of comparison vessels and simulated fortnightly period

	S. E. Asia comparison	Caribbean comparison	Fast feeder
TEU capacity (90% utilisation)	801	860	1143
No. of ships on route	2	2	1
No. of round trips per ship	2	2	3
Time per round trip / hours	168	168	112
Total TEU carried to/from spoke port	3204	3440	3429
Speed @ 90% MCR / knots (high speed)	15.2	17	25

Table 5.2 – Time spent and power requirement in each operating mode during fortnightly period

	S. E. Asia comparison			Caribbean comparison			Fast feeder		
Operating Mode	Time / hours	ME power / kW	AE power / kW	Time / hours	ME power / kW	AE power / kW	Time / hours	ME power / kW	AE power / kW
Cargo handling	78.0	0	591	91.7	0	591	77.3	0	-
Manoeuvre/waiting	44.2	0	591	51.2	0	591	6.7	5600	-
Low speed	53.5	5656	591	48.3	6567	591	154.6	4880	-
High speed	160.3	7272	591	144.8	8443	591	97.4	22100	-

In order to comprehensively evaluate the fast feeder design against the typical vessels, comparison has been made in three ways: fuel cost and emissions; 'efficiency index' measures; and total operating cost. The commonly used efficiency index measures are transport efficiency index (TEI) and energy efficiency design index ($EEDI$). In the context of comparisons made here, these simple indices have been modified to account for the multiple speeds and power consumptions over the simulated voyage, as well as the difference between the numbers of ships being compared. The original and modified indices are presented in Equations (5.1) to (5.4).

The basic Transport efficiency index defined as:

$$TEI = \frac{N_c V_s}{P_B} , \quad (5.1)$$

and has been modified to account for variations in ship speed and power, and the number of ships viz

$$MTEI = \frac{1}{N_s}\sum_{N_s}\frac{N_c\left(V_{s,l}w_l + V_{s,h}w_h\right)}{\left(P_{B,l}^{(ME)}w_l + P_{B,h}^{(ME)}w_h\right)}. \quad (5.2)$$

The energy efficiency design index is normally written as:

$$EEDI = \frac{\sum C_c \cdot SFC \cdot P_B}{DWT \cdot V_s} , \quad (5.3)$$

where the summation accounts for a ship burning a number of fuel types with different carbon factors. For the analysis presented here the modified energy efficiency design index ($MEEDI$) accounts for variations in ship speed, auxiliary engine usage and carbon factor, and is generalised as given in Equation (5.4).

The final results of the feasibility assessment for the fast feeder concept are presented in Table 5.3. Cost data was provided by Ocean Shipping Consultants (2010) and extrapolated as a function of TEU. Accurate cost estimates of the additional systems installed on the fast feeder, such as LNG plant and sail system, were not available; thus a conservative 50% increase in build cost is specified. It is clear that under the original TEI and EEDI definitions, the fast feeder concept is not favourable.

$$Modified\ EEDI = \frac{1}{N_s}\sum_{N_s}\frac{\sum C_c\left(P_{B,l}^{(ME)}SFC_l^{(ME)}w_l + P_{B,h}^{(ME)}SFC_h^{(ME)}w_h + P_B^{(AE)}SFC^{(AE)}\right)}{DWT\cdot\left(V_{s,l}w_l + V_{s,h}w_h\right)}. \quad (5.4)$$

Table 5.3 – Summary of fast feeder container ship performance compared to typical existing vessels over fortnightly period

			Singapore Comparison (two ships)	Caribbean Comparison (two ships)	Fast Feeder
fuel emissions and cost	FC	tonnes	593.3	618.5	398.2
		% reduction	32.9	35.6	-
	CO_2	tonnes	2100.3	2190.5	1266.5
		% reduction	39.7	42.2	-
	NO_x	tonnes	38.3	40.0	4.1
		% reduction	89.2	89.7	-
	cost	kUSD	381.5	397.7	185
		% reduction	51.5	53.4	-
efficiency indices	TEI	TEU·knots / kW	6.88	7.12	4.48
	$modified\ TEI$		3.44	3.56	5.61
		% increase	63	58	-
	$EEDI$	grams CO_2 / t·nm	24.15	22.63	14.82
	$modified\ EEDI$		27.05	31.41	11.84
		% increase	56.0	62.0	-
cost	daily capital charge	USD / day	18016	19332	18623
	manning		2226	2396	1588
	repair and maintenance		976	1048	696
	insurance		582	626	416
	admin/other		890	956	635
	fuel		27250	28407	13214
	total cost		49940	52765	35172

However, applying the modified criteria to the 'fleets' presented here, a larger, faster vessel fuelled by LNG offers considerable cost savings and reduced emissions on typical existing ships. Whilst comparison has been made within the operational assumptions followed throughout this work, even on a ship-for-ship basis the fast feeder has a lower power requirement at 15 knots (4880 kW) than the comparative South East Asian vessel (7272 kW) despite an increase in carrying capacity of 43%. This highlights the inefficiency of typical vessels operating on transshipment routes in these regions. A large cost reduction is attributed to the low cost of LNG fuel, however it is recognised that the benefits presented are highly dependent on future trends in fuel price rises.

6. CONCLUSIONS

Comprehensive market analysis has shown that there are a significant number of old and inefficient vessels operated on container transshipment routes, with an estimated 47% of the fleet due for replacement in 2020.

An alternative fast feeder container ship concept has been proposed to improve efficiency of transshipment operations, offering approximately 40% reduction in carbon emissions and 50% reduction in operating costs in the selected operating regions.

The key features of the design approach are:

- a 'hub-and-spoke' network to significantly reduce the total number of transshipment voyages;
- a larger, faster vessel has higher efficiency under the 'economies of scale' principle;
- the use of fewer, highly manoeuvrable ships with ship-board cranes reduces waiting and cargo handling times in port;
- rigid wing sails offer thrust benefit, and additional resistance reduction through motion damping;
- LNG is used as fuel to lower costs and reduce emissions compared to more widely used marine diesel oil.

The simplistic nature of performance indices was also highlighted when applied on a ship for ship basis. Development of these comparison measurements may be required as further innovative low-carbon concepts emerge.

Although not discussed here this novel concept is not covered under 'standard' stability and structural codes, thus close cooperation with legislative and classification bodies is required in the development of sail assisted ships.

7. FUTURE WORK

The main suggestions for the future development of the fast sail assisted feeder container ship are:

- comprehensive evaluation of the motion damping benefits of rigid wing sails, and its incorporation into voyage simulation;
- detailed design and feasibility assessment relating to LNG and cargo handling systems;
- more accurate cost estimation, particularly capital cost relating to installation of LNG and sail systems;

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APPENDICES

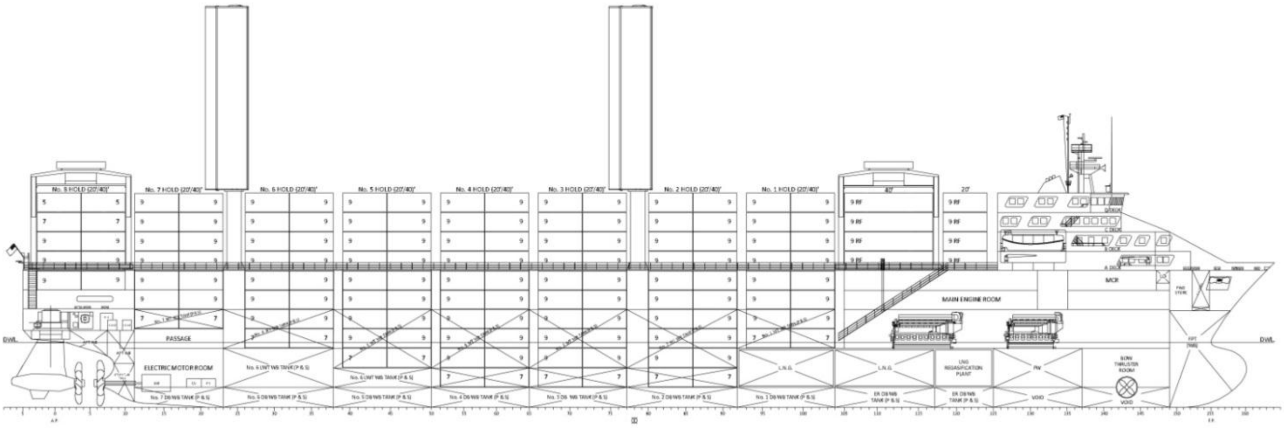

Figure A.1 – General arrangement profile view of fast sail assisted feeder container ship

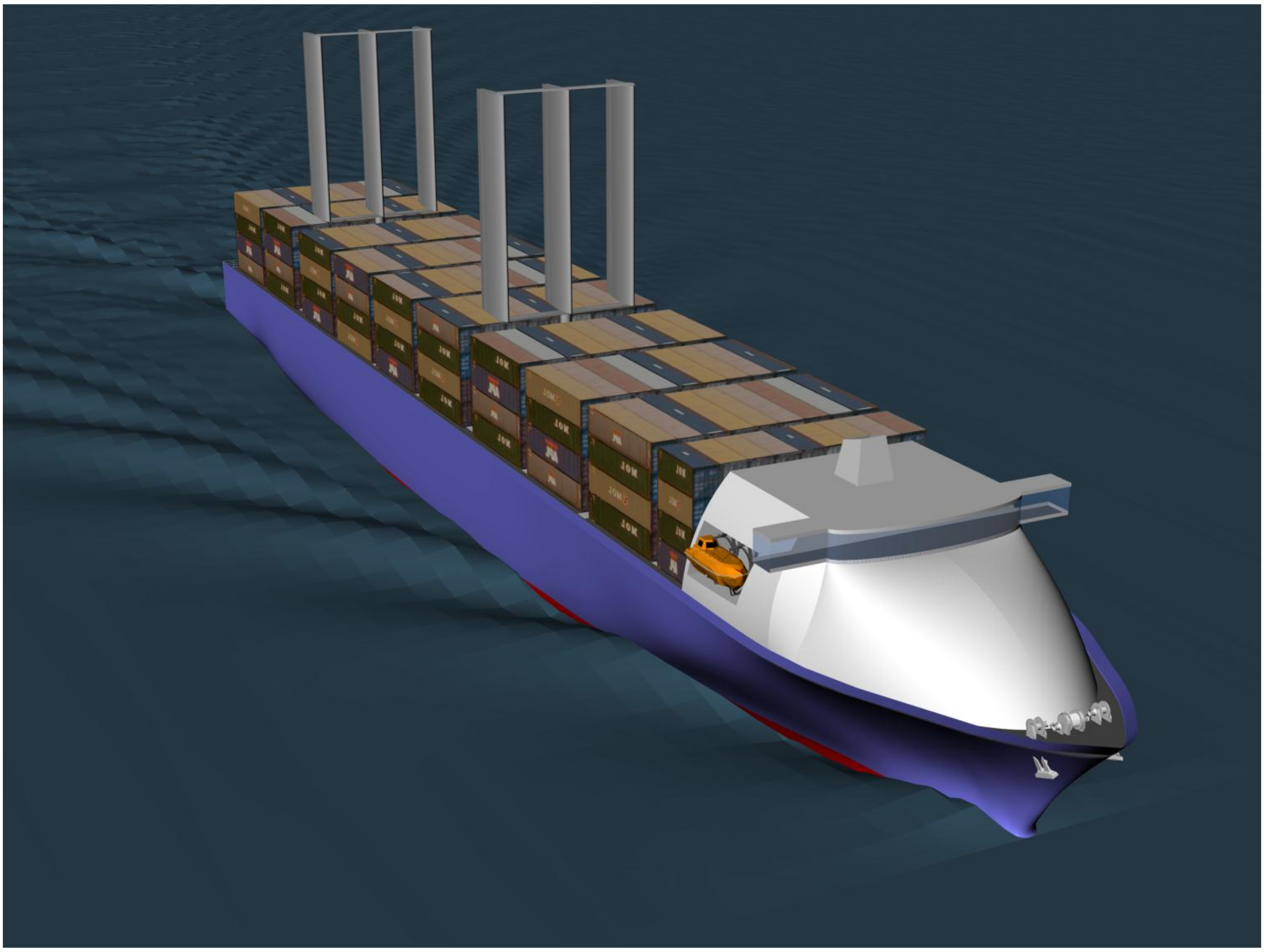

Figure A.2 – Artist’s impression of fast sail assisted feeder container ship