Cost and Energy Assessment of a High Speed Ship

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A comparison in total life cycle costs and energy consumption for one high speed ship design with three different structural materials have been performed. The investigation considers a high speed ferry with a steel hull and an aluminium superstructure, an all aluminium concept and a ship built in sandwich material with carbon fibre faces. The different materials will affect several cost elements during the design, the production and the operation of the ship until and including its disposal. Furthermore, the material selection has an impact on the energy consumption within all stages of the ships life cycle. The assessment is made in a comparative manner. Hence, identical out fitting components, e.g. interior, instrumentation, and ventilation are left out.

It is shown that the steel version causes the highest costs and energy consumption. The sandwich construction has the lowest life cycle costs while the aluminium version has the lowest energy consumption. The break-even point between the steel and the composite versions appears after 4 years (only 2 years of operation!), the break-even point between the aluminium and the composite ferry is after 12 years (10 years of operation).

A sensitivity analysis with different possible scenarios, e.g. change in interest, petrol cost, maintenance cost, has been performed. All of the investigated scenarios identify the composite version to have the lowest life cycle costs. This paper summarises an original work carried out as a master of science work as given in [1-2].

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1. Introduction

The aim of this work is an assessment of costs and energy consumption of a ship made of three different materials concepts, steel, aluminium, and carbon fibre sandwich. To make a correct comparison between different materials due to economy and environmental effects, it is necessary to analyse its entire life cycle. The investigated type of ship is a high speed ferry used for transporting passengers, cars and trucks. The steel version of this type of ship already exists. For the aluminium and carbon fibre versions detailed preliminary designs were used [2].

Aker Finnyards (Finland) produce high speed ferries in mainly steel and aluminium. Several monohull and twinhull vessels (catamaran) have been developed. Aker Finnyards has constructed the largest aluminium ship in the world, the HSS 1500, a High Speed Car/Passenger Ferry

Kockums, Karlskronavarvet (Sweden) has a vast experience in designing and producing commercial and naval ships using steel, aluminium, and composites. Recent production has been focused on the 72-meter all carbon fibre sandwich Visby stealth-corvette for the Swedish navy.

2. Background

In a life cycle cost analysis (LCCA) the accumulated costs of a product or a system is studied over its entire life. This considers costs for engineering and development, production, operation, maintenance and disposal, figure 1. The analysis is based on estimated and/or calculated costs of a product. The LCCA can help to evaluate different alternatives of a project.

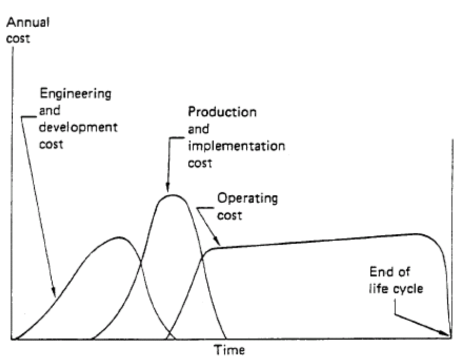

Figure 1 Example of cost categorisation (stages of life cycle costs) [3]

By manufacturing ship structures in aluminium or composite materials, the structural weight can be decreased. This may be used for: fuel savings according to smaller engine power, higher payload, bigger fuel tanks, increase of service speed, or longer range.
From a pure manufacturing point of view, steel is the most economical material when producing large ships and cruising vessels. However, a ship will continue to cause costs for operation and maintenance during its usage. Therefore, the costs in a life cycle perspective is of interest.

Since only costs and no operational revenues are taken into consideration during the LCCA, the same service in terms of payload, range and speed is chosen to enable a comparison. This means that the engine power can be reduced for the lightweight structure ship and the fuel consumption can be decreased.

As input for the LCCA for the steel version the existing ship's data and also the data from its operation are partly used. For the investigation of the aluminium craft, an existing preliminary design of Aker Finnyards is used. The composite preliminary design is based on the existing concept of the aluminium ship. The costs during all life cycle including design, production, operation, maintenance and disposal are mainly based on the experience of the two shipyards.

3. Theory

Current trends show that, in general, the complexity of systems and products is increasing while the time to market needs to be reduced. At the same time, technology in almost every industrial sector is changing rapidly. This reasons for cost growth combined with inflation makes it essential to optimise the value for money. Herein, optimising does not mean minimise the acquisition costs as a short-term objective but rather to focus on the overall cost in the meaning of a long-term strategy. A life cycle cost analysis aims to uncover any "hidden" costs of the entire life cycle of a system or product, and as a consequence minimise them. Naturally, there exists more than a single definition for life cycle cost analysis,but Kumaran provides one that suits well [5]:

> Life cycle cost analysis may be defined as a systematic analytical process for evaluating various designs or alternative courses of actions with the objective of choosing the best way to employ scarce resources.

The accomplishment of an LCCA includes all costs of an item from the first consideration of its acquisition until the end of its disposal. Therefore, costs of all producer, supplier, customer (user), maintainer and related costs need to be regarded.

Several different models of LCCA have been worked out and successfully implemented. As the underlying motivation of their development differs, their objectives vary from each other. It is not feasible to develop a unique LCCA model, which will suit all requirements. A review of some of the more common ones are described in [1] and referced here [3-10].

The LCCA model used herein is based on the principles suggested by Woodward [4]. The model of Woodward is intended to be implemented for the planning of investments rather than a recurring evaluation at divers stages of a product's life cycle.

The methodology is formulated in the following eight steps:

1. Establish the operation profile
2. Establish the utilisation factors
3. Identify all the cost elements
4. Determine the critical cost parameters
5. Calculate all costs at current prices
6. Escalate current prices at assumed inflation rates
7. Discount all costs to the base period
8. Sum discounted costs to establish the net present value

This model enables us to evaluate investment options on a more accurate cost calculation rather than only on the initial capital costs.

In addition, Woodward suggests the LCC procedure to be followed by an analysis of different cost areas and examining trade-offs between them. As a consequence thereof, total costs of products or systems may be optimised. The figure below illustrates the convenience of the identification of trade-offs. The example shows how the trade-off between purchase and acquisition cost and operating cost results in the lowest life cycle cost.

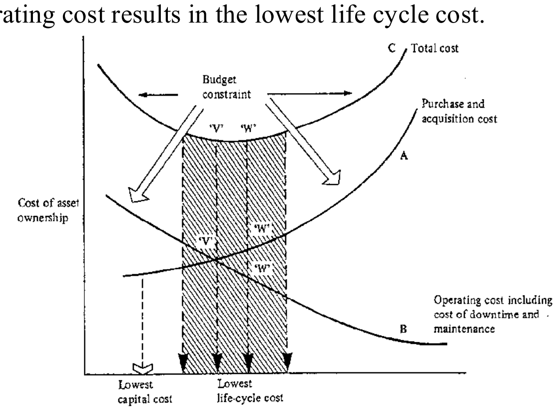

Figure 2. Trade-off between purchase and acquisition cost and operating cost

4. Vessel characteristics and system definition

The vessel used as an example herein is a high speed ferry designed using three different material concepts:

- The <u>steel version</u> consists of a steel hull and an aluminium superstructure.
- The <u>aluminium version</u> is an all aluminium version.
- The <u>composite version</u> is a sandwich construction with faces made of multiaxial carbon fibre reinforcement and vinyl-ester matrix, and structural foam core material (Divinycell)

Table 1 Main characteristics, identical for all three vessel concepts

Length overall	128.00 m
Breadth, maximum	19.00 m
Draught, maximum	3.33 m
Passengers	1000
Operating range	300 nm
Speed	42 kn
Cargo capacity	Case A: 250 cars / 35 motorbikes Case B: 102 cars / 220 trailers

The main physical difference between the different versions is their weight. The actual weights for the various components of both steel and aluminium version are based on the data sheets from Aker Finnyards [1]. For the composite version the weight of hull and superstructure has been derived from the preliminary design study. As the structural weight of the aluminium and composite version are similar, it is assumed that the same type of engine can be used for the two versions. Furthermore, the weight of painting, hull and deck outfitting, interior and panelling, electrical power distribution and lighting are assumed to be the same for both lightweight structures. However, weight savings due to the unnecessary thermal insulation in the composite version are taken into account.

Table 2: Weight split-up

	Steel version	Aluminium version	Composite version
	(tons)	(tons)	(tons)
Hull	940	470	607
Superstructure	120	110	
Painting	12	10	10
Hull and deck outfitting	250	230	230
Interior and paneling	133	130	130
Thermal insulation	35	40	0
Fire insulation			27
Machinery	485	380	380

Electrical power distribution and lighting	55	55	55
Total	**2030**	**1425**	**1439**

To reach the strived speed of 42 knots, the machinery types listed in table 3 are used. Due to the lighter weight of the aluminium and composite version, the two diesel engines are omitted.

Table 3: Machinery, *two additional diesel engines are required on the steel ship

Number	Type	Specification	Power in kW at 100 %
2	Gas turbine	GE LM2500	22000
2	Diesel engine*	MTU 20V1163	6500

In order to gain a fair comparison of costs and energy requirements, the following assumptions are stated:

- No investment costs in additional infrastructure due to technology adaptation of a manufacturer is considered.
- The life span of all three versions is set to 25 years, although the technical life spans are expected to differ one from each other. However, a calculation of LCC using varied life spans would distort the result of this study.
- For the hourly rate of manufacturing and engineering average values are taken. This is because the data from the collaborating companies differ due to their locations and may not be published.
- All cost and energy elements, which are identical or similar, are not taken into account; Outfitting, Painting, Electrical power supply and distribution, Crew wages, Harbour and channel dues, Loading and discharging, Classification, Insurance and administration.

The operation is split up into three modes: operation in summer, operation in winter, and maintenance.

Summer (May – Sept)	18 h/day
Winter (Oct – April)	12 h/day
January	Maintenance, yearly docking

During summer and winter operation, the ferry is running its machinery at the following time and power proportions:

Table 4: Time and power proportions, only applicable for the steel version

Time proportion	Gas turbine	Diesel engine
3 %	100 %	100 %
82 %	95 %	90 %
15 %	20 %	20 %

5. Life cycle cost analysis

An LCC model of Woodward [3] has been chosen to analyse the costs of the three different ship concepts. This model is simple but covers all aspects of importance for the cost comparison at this stage. The adjusted flow chart in figure 3 presents the steps that lead to the LCC of the vessel. The energy assessment included in this chart will not be presented here in detail and interested readers are referred to [1].

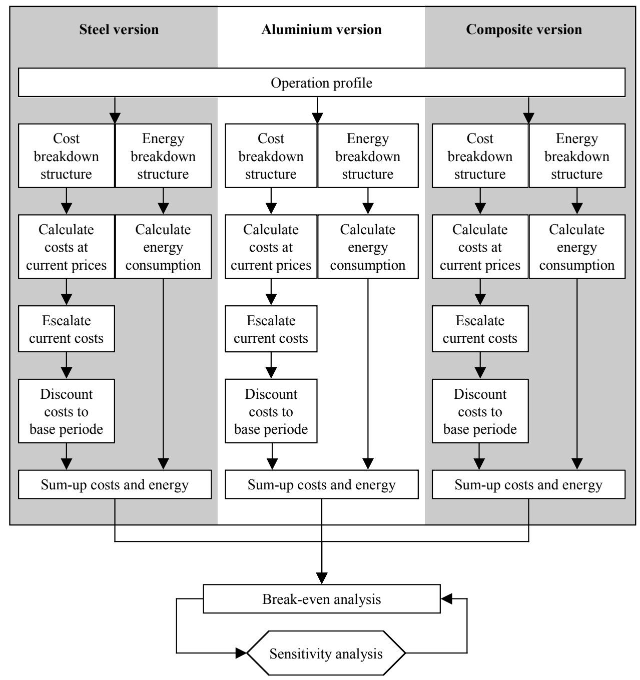

Figure 3. LCCA and energy assessment process, followed by a break-even and sensitivity analysis

Traditionally, the cost breakdown comprises all cost elements of a product. Since the presented study is of a comparative nature, identical or similar costs are not considered.

The cost elements are grouped according to their appearance in the different periods of life. The terminology of these four periods have been partly adopted from the model of Woodward, and partly adjusted according to the considered cost elements in shipbuilding and operation:

- Planning, design and production costs
- Operation and maintenance costs
- Disposal costs

For input data in labour hours the following rates are used; Production hours 45.00 €/h, Design/Engineering hours 50.00 €/h

5. Planning, design, and production

In the **planning** costs, market analysis and feasibility studies are included. The design phase is split up in three elements, according to the terminology of Aker Finnyards. In the detailed **design**, workshop drawings, review, tests and documentation are included. In the **engineering** during the production phase, production control and support are included. **Material** – The data source for the steel and aluminium version is based on Aker Finnyards experience. For the composite version the weight and costs are calculated in the preliminary design study [2]. The outfitting and waste cost is based on Kockums experience. The insulation (fire) is: material 0.065 M€ and labour 700 h · 45 €/h. The cost for the machinery and electrical for the composite version is taken as the same as for aluminium version. As mentioned earlier no investment costs in additional infrastructure due to technology adaptation of a manufacturer is considered in this study. The cost break down is presented in table 5.

Table 5: Planning, design, and production cost breakdown

Cost element	Steel	Aluminium	Composite
	(M€)	(M€)	(M€)
Planning, total	**0.10**	**0.10**	**0.13**
Conceptual design	0.15	0.15	0.15
Basic design	1.50	1.55	1.50
Detailed design	4.55	4.60	4.25
Design, total	**6.20**	**6.30**	**5.90**
Engineering, total	**0.25**	**0.35**	**0.30**
Structure	2.35	3.05	11.20
Structure, waste	0.60	1.05	1.68
Outfitting	5.80	6.30	5.70
Interior	7.80	8.10	6.00
Insulation			0.10
Machinery and electrical	32.60	27.40	27.40
Material, total	**49.15**	**45.90**	**52.08**
Tooling	0.14	0.45	0.29
Fabrication, structure	6.39	9.00	11.93
Outfitting	12.60	12.74	9.00
Energy costs for manufacturing	0.50	0.62	0.63
Manufacturing, total	**19.63**	**22.81**	**21.85**
Planning, design, and production, total	**75.33**	**75.43**	**80.26**

6. Operation and maintenance costs

The operation costs consist of the fuel costs only, when other running costs are expected to be identical for the three concepts. The specific fuel consumption is given in table 6..

Table 6 Specific fuel consumption of gas turbine[6] and diesel engine

	Power of GT [kW]	Fuel consump. GT [g/kWh]	Power of diesel [kW]	Fuel consump. diesel [g/kWh]
100 %	22000	232	6500	210
95 %	20900	234	5850	215
20 %	4400	394	1300	340

The above figures combined with the operation profile presented earlier result in the annual fuel consumption presented in table 7.

Table 7 Annual fuel consumption per gas turbine and diesel enging

Operation profile			Gas turbine		Diesel engine	
Time	Annual running hours	% of max. power	(kW)	Annual (tons/ year)	(kW)	Annual (tons/ year)
3 %	133	100 %	22000	680	6500	182
82 %	3641	95 %	20900	17806	5850	4580
15 %	666	20 %	4400	1155	1300	294
Total	**4440**			**19641**		**5056**

The used fuel is Marine Gas Oil (MGO), ISO 8217-F-DMA. The fuel price differs much, depending on the actual market situation, political issues, port of refuelling and other circumstances. The cost assumed for this study is 207 US$/ton, or 233 €/ton[7].

Table 8 Total annual operation costs

Cost element	Steel	Aluminium	Composite
	(M€)	(M€)	(M€)
Operation of two gas turbines	9.14	9.14	9.14
Operation of two diesel engines	2.35		

[6] Information from General Electric Aircraft Engines, http://www.geae.com
[7] Published on the website of Bunkerworld in 2002, http://www.bunkerworld.com

Annual operation, total	**11.49**	**9.14**	**9.14**
Operation, 25 years of operation, at current prices total	**287.19**	**228.40**	**228.40**

7. Maintenance

In the course of this study only maintenance costs of the machinery and the hull structure are considered. Maintenance costs for the outfitting are irrelevant for this comparative investigation, since they differ within marginal borders only. Since the maintenance costs are spread over the operating lifetime, they need to be discounted back to the base period. This is fully described in [1] Herein, the annual costs are listed and summations thereof are based on current prices.

The maintenance costs of the machinery are estimated to be 100 US$ per running hour for each gas turbine and diesel engine[8].

An estimation of annual maintenance costs of the hull structure is a more difficult issue. The presented mathematical formulation is of course a crucial simplification, but it might be the only way to compare the three versions in this perspective. All estimations are based on the experience of various national and international ferry operators. For confidence reasons the companies as well as the names of their ferries have to stay unnoticed in this report.

For the steel hull, the annual maintenance costs are 0.6 M€ in the first years of operation. The aluminium hull with costs of 0.7 M€ per year is said to be slightly more expensive. The composite hull is less expensive; its maintenance costs are approximately 15 %, i.e. 0.10 M€ of that of the steel hull. Additionally, maintenance costs of a metallic structure will increase with the years of operation. The estimated simplification for this purpose is a constant cost for the first 15 years of operation, and a linear increase of the cost for the following 10 years. At year 25 the costs will reach the doubled amount of the initial costs. This increase does affect both the steel and aluminium hull, but not the composite one.

Table 9 Total maintenance costs

Cost element	Steel	Aluminium	Composite
	(M€)	(M€)	(M€)
Machinery, total (4440 running hours/year)	47.89	23.95	23.95
Hull structure, total	17.70	20.65	2.40
Maintenance, total	**65.59**	**44.60**	**26.35**

[8] Experience of Aker Finnyards

The estimation of the annual maintenance costs is a crucial issue, as mentioned earlier. It affects the total LCC of the versions in a deciding way, why extra attention is paid on its uncertainty as fully discussed in [1].

8. Disposal costs

The disposal of large structures are a very complex process. Its main steps are dismantling, cutting and crushing. Figure 4 illustrates the steps in the preparation semicircle for plastic materials but is valid for metals too.

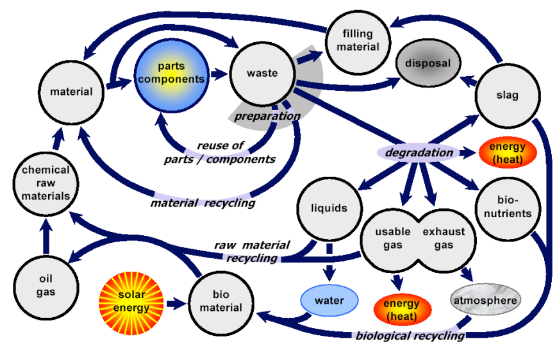

Figure 4 Possible material cycles for recycling and ways of disposal of plastics [11]

After the preparation, the crushed pieces of the metallic versions are sold to be reused. These revenues are taken into account for the LCC, since they are not operational revenues.

For sandwich materials the recycling process is more complex, as many different scenarios may be chosen. To keep this study manageable, the crushed sandwich waste is incinerated. In doing this, extra costs for incineration and landfill occur.

Since costs for dismantling and cutting of the structure are assumed to be similar, they are left out in the LCCA.

The structural weight used to calculate the costs in this chapter include the production waste, table 10. This results in a small error of the total cost, because costs and revenues of the production waste are considered 25 years too late, table 11. Furthermore, the quality of production waste material is better than of the structural material that has been in use for 25 years. Average scrap prices are taken to get an adequate result.

Table 10 Total material weights, including waste and machinery

Material	Steel version	Aluminium version	Composite version
	(tons)	(tons)	(tons)
Steel	940		
Production waste, steel (25%)	235		
Total steel	**1175**		
Aluminium	120	580	
Production waste, aluminium (35%)	42	203	
Total aluminium	**162**	**783**	
Composite			607
Production waste, composite (15%)			91
Total composite			**698**
Machinery	485	380	380

Table 11 Total disposal costs

Cost element	Steel	Aluminium	Composite
	(M€)	(M€)	(M€)
Crushing	0.06	0.04	0.03
Incineration and landfill			0.04
Revenues for scrap, steel	-0.13		
Revenues for scrap, aluminium	-0.18	-0.88	
Revenues for scrap, machinery	-0.05	-0.04	-0.04
Disposal, total	**-0.31**	**-0.88**	**0.03**

Data source:

- Crushing[9]
  - o Steel: 300 SEK/t · (1175 t + 162 t + 485 t)
  - o Aluminium: 300 SEK/t · (783 t + 380 t)
  - o Composite: 250 SEK/t · 698 t + 300 SEK/t · 380 t
- Incineration and landfill[1]
  - o Composite: 550 SEK/t · 698 t
- Revenues for scrap[10]
  - o Steel: - 100 US$/t · (1175 t + 485 t) - 1000 US$/t · 162 t
  - o Aluminium: - 100 US$/t · 380 t - 1000 US$/t · 783 t
  - o Composite: - 100 US$/t · 380 t

9. Summation of costs at current prices

The relevant comparison of all cost elements is presented above, where the time value of money is taken into account. Here, a first overview of the cost split-up into the three life cycle phases is given, using costs at their current prices.

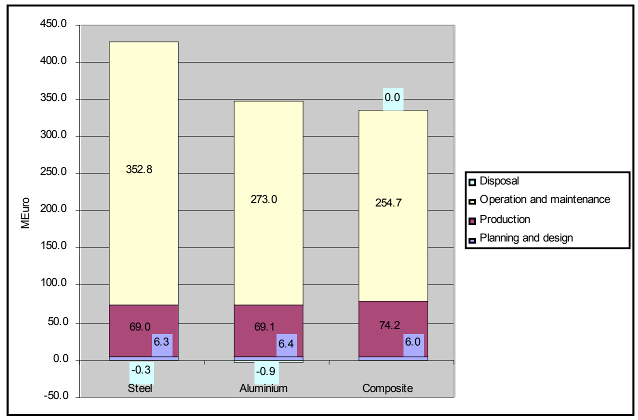

Figure 5. Accumulation of costs, at current prices

All cost calculations are based on current prices. According to the time value of money, all future costs (considering inflation) need to be discounted back to a base period using the interest rate. Naturally, the first costs to appear are the planning and design costs. These are said to be spread over the first year. Next, the production costs will follow during the second year. After these two years all initial costs are spent and the annual costs for the following 25 years are operation and maintenance costs. While the operation is assumed to be steady the necessary expenditures for maintenance are a function of time. They increase linearly from year 17 until year 27 (year 15 until year 25 of operation). Since maintenance takes place yearly in January, it is left out in the first year of operation. With the termination of the operational life of the ship, disposal costs will appear, again within one year. The base period is set to the beginning of the first year. This schematic distribution of costs is illustrated in the following figure 6.

For simplification reasons, costs that appear during any year are said to be paid by the end of that year. Therefore, the costs of planning and design will need to be discounted too, although they are the first costs to appear.

[9] Information from Stefan Jonsson, Stena Gotthard AB, Sweden

[10] Average prices for scrap, published on the website of Metalbulletin.com, http://www.metalbulletin.com

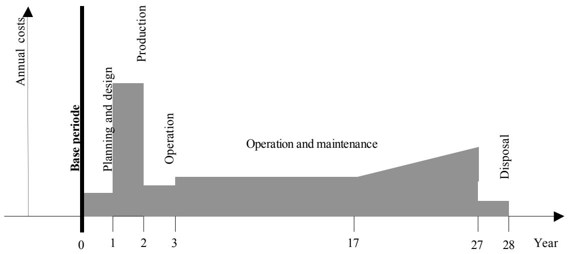

Figure 6. Schematic distribution of LCC

10. Summation of costs and break-even analysis

The accumulated costs over the entire life of the ferry are presented in the following chart. The break-even points between steel and composite (4 years) and between aluminium and composite (12 years) are marked in figure 7.

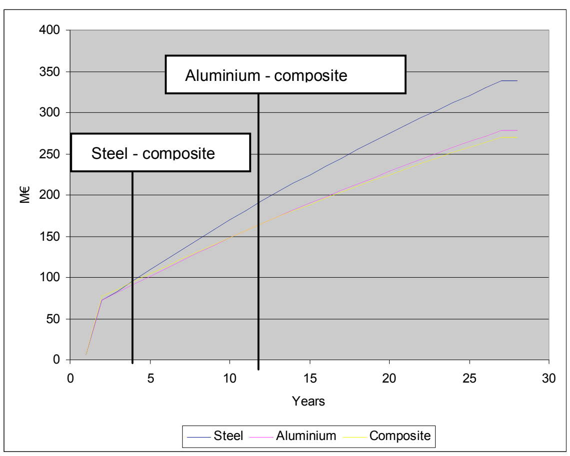

Figure 7. Accumulation of costs

The break-even between steel and aluminium is reached right after the beginning of the operation, as the costs for planning, design and production of the steel vessel are only slightly smaller than those of the aluminium vessel.

11. Conclusion

The planning and design costs show quite an evened picture for the three versions with a slight advantage for the composite craft. The expectation of the conceptual formulation, that steel is the most economical material from a pure manufacturing point of view, is confirmed within this study. However, the inclusion of the machinery balances the production costs of the investigated steel and aluminium ship nearly. Due to the high material prices the composite ship is the most expensive alternative in the production phase, which contains engineering, material and manufacturing costs. The major part of the entire life cycle costs stem from the operation and maintenance. The steel version needs owing to its heavier weight additional machinery, what raises both fuel consumption and the maintenance costs. The major advantage of the composite version is the lower maintenance costs for the hull structure. Revenues and costs of the scrap do not significantly affect the life cycle costs of a ship.

The calculation indicates that the composite version is definitely the most economical option. The accumulated costs of the steel version exceed those of the composite version after only 4 years (2 years of operation). In the same perspective, the aluminium version tops to composite version after 12 years (10 years of operation).

The distribution of energy consumption onto the three ferries shows the highest energy consumption for the steel version, as expected. More than 99.5 % of the consumed energy over the entire life span of all versions comes from the operational fuel consumption. The investigated aluminium version possesses slightly smaller energy consumption compared to the composite version. This difference stems from the energy consumption of material production, where carbon fibre has the highest energy rate per unit.

The well-optimised aluminium version possesses slightly smaller energy consumption than the composite ship. This is due to the carbon fibre production, which is high energy consuming. A structural optimisation of the composite version can change this order.

However, more than 99.5 % of the consumed energy over the entire life span of all versions comes from the operational fuel consumption as illustrated in figure 8.

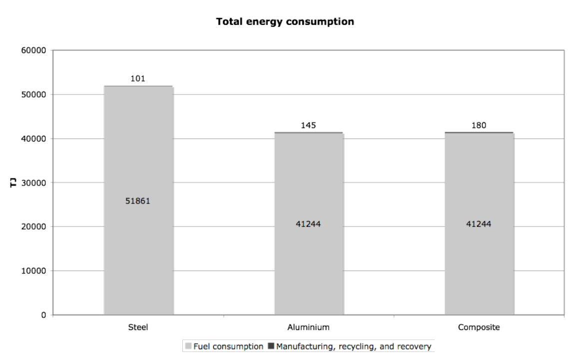

Figure 8. Energy consumption

12. Sensitivity analysis

Varying certain parameters during a sensitivity analysis [1] affects the break-even points of the different ships.

The additional weight savings on the composite version are not a farfetched scenario, they are by all means passable.

This will lead to less fuel consumption and minimises the costs thereby incurred. The energy consumption of this optimised composite vessel is below the one of the aluminium version.

A further decrease of the carbon fibre price, which can be expected in the future, will obviously be advantageous for a composite ship.

Maintenance costs have the most interesting influence on the break-even points, since they appear repeatedly. The accomplished analysis shows, that increasing the maintenance costs of the hull structure of the composite vessel shifts the break-even point towards the end of the vessel's life. However, the composite version still becomes more profitable after less than twenty years of operation.

A variation of the inflation and interest rates can lead to both, an earlier or a later break-even point of the composite version compared to the others. The result changes are small and all reasonable assumptions for inflation and interest rates cannot affect the general statement of this study.

The life span of the different version must be taken into consideration too. To get comparable numbers it is set to 25 years. The composite ship is estimated to be in service up to 30 or even 35 years, while calculating with 25 years might be rather optimistic for an aluminium ship of that size, since fatigue is expected to become an inconvenience towards the end of its operational life. However, at the time there are attempts in Europe to limit metal vessels' life span, which may emphasise advantages of a ship built of fibre reinforced sandwich structures.

As with any life cycle cost analysis or energy assessment, the figures presented in this paper are to be handled with care. The results heavily depend on the input data, which is frequently based on assumptions and estimated figures of complex processes.

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