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“Does it pay to play with the construction material of a sailing yacht?”

by

Hunyadi Balasz and Jan Alexander Keuning

1. Introduction.

Nowadays when one is looking around the boat market to see what kind of materials are being used for hull construction, a wide spectrum can be observed, ranging from traditional boat building materials to space age composite structures. One of the first decisions to be made at the beginning of any new yacht design is to determine the materials of the hull construction. To make the right decision brings many different aspects of the inquiry together: i.e. the cost of the alternative materials that will greatly influence the price of the vessel; the designer’s and builder’s experience with the construction method; the service cost of the vessel, etc. Of course this will be the customers’ choice but the designer’s and builder’s have to guide the owners with useful and practical information to be able to make the right decision.

To make the right choice the purpose or mission of the vessel should be clear. This will have an important effect on the materials used for the construction. For instance, the weight of a racing yacht hull has to be as low as possible, and the cost of it is not as important a question as the performance. A lighter hull requires less power to drive it, which means the efficiency of a lighter vessel with the same power or sail area will be better than of a heavier one. For vessels which are designed to operate at semi planing or planing speeds, a low weight is also beneficial. Racing yachts are commonly “one-off” projects and therefore made of high tech composite materials. (i.e. America’s CUP, Volvo Ocean Race, The Race, etc.) In the case of the cruiser category boats, which are usually more or less standardized production boats, the comfort and the final cost of the yacht have a much greater importance in the decision process and the performance has less than is the case with the racing vessels. In our days these cruising yachts are mostly made of glass FRP in combinations with sandwich construction.

Looking at the “performance cruiser” (as an increasing segment of the yacht market) one sees the selection of the right hull construction to be not so clear and evident. The flavours of this yacht can be described as a “High Performance Sailing Yacht”, which means that it has a luxurious inside with all the facilities that one wants onboard. Beside this luxury the yacht requires good sailing performance and must be able to compete in races with her “colleague yachts”. Of course the main “driver” in the design again is the light weight of the vessel, but fashion and hypes take this problem sometimes a bit out of hand. Because of the fact that high performance composite materials become nowadays more and more affordable we can see new trends in the construction of these yachts. But most of the time these come from the “owners’ fashion” and sometimes these don’t know or care about the disadvantages of the chosen materials. Nowadays the trend of these yachts is to be made of light weight high tech composite materials.

The logical task is to formulate the expected advantages when using these high tech hull materials for your next boat. Well, the lightweight is a good choice, and if you se the length-displacement ratio separately -as one index number of the boat performance- you will think this is the best solution. But it is not the only indicator of the yacht’s speed prediction.

The aim of the present study was to determine: ***”what are the differences in a sailing yacht performance in different sailing conditions if the building material is changed for the same hull shape, while some selected speed factors are kept the same”?***
Or: ***“how significant is the advantage of weight on the yacht’s performance?”***
And: in particular **“*at which cost”***?

2. *The approach.*

For the present study one particular yacht will be used. This “base yacht” will be the Standfast 64’. It is a design from Frans Maas and was built in 2002 at the Standfast Yachts yard in Breskens, the Netherlands. It is a carbon epoxy sandwich hull construction.
Based on this design three other versions of the same boat have been engineered with different materials for the hull construction. These new designs have been used for a weight estimate based on the new hull construction. With this data a performance analysis has been made at different wind conditions using a state of the art Velocity Prediction Program. (VPP)

The following procedure for the derivation of the new versions of the base design and in agreement with the designer Frans Maas the following “boundary conditions” were considered:

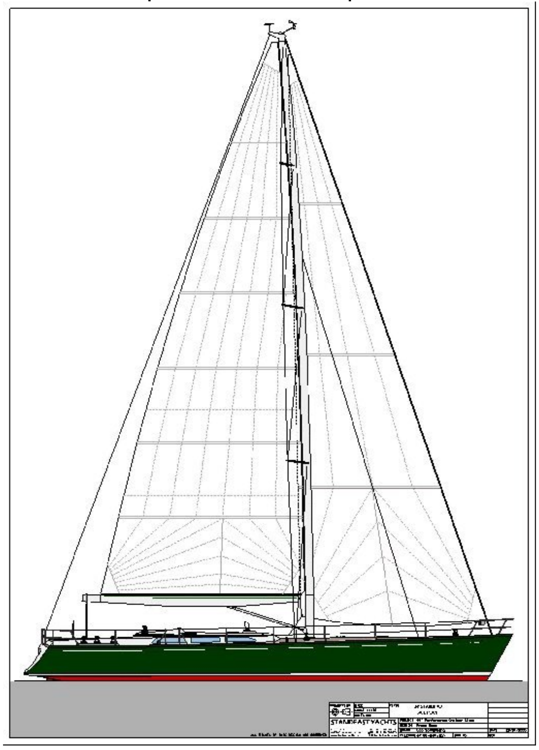
1. The base yacht the Standfast 64 is classed according to Germanischer Lloyd (GL). To make an equal comparison for the alternative versions they also have to comply with the regulations according to GL.
2. At all times the hull geometry of the base yacht will be used for the weight assessments and the following VPP calculations.
3. The main distinction between the different versions of the yacht is the choice of building materials of the hull such as the frames and stiffeners. The considered alternative building constructions are:
   - Carbon fibre reinforced sandwich with foam core (Carbon),
   - Aluminium construction (Aluminium),
   - Glass fibre reinforced sandwich with foam core (Glass),
   - Glass fibre reinforced sandwich with wood core (Wood).
4. For each construction material the weight and the height of the Centre of Gravity of the hull and deck construction has been calculated based on a construction according to GL.
5. For maintaining the sailing performance of the alternative designs the sail area-displacement ratio ($SA/\Delta^{2/3}$) of the various design variations has been maintained
6. For maintaining the sailing performance of the alternative designs also the heeling angle at a given wind speed (Dellenbaugh angle) has been kept the same.
7. This implied for the different building materials used that different amounts of sail area and ballast have been determined in order to yield the required stability moment
8. The VPP calculations have been carried out for light, moderate and heavy air conditions. To take account of the influence of the waves due to wind the typical North Sea wave spectrum has been used.
9. The yachts that are considered are all assumed to be built as a one-off project. This is a boundary condition used, because the original yacht is a one-off product and the continuous produced yachts are really in a different market segment especially concerning moulds costs.

To keep the amount of work within the present study within certain limits some of the items in the design have been kept the same for all versions of the design: i.e. the rudder remains the same, the interior remains the same and the technical installation remains the same. No specific engineering has been put in the design of mast and rigging but instead specific generic design data for these items have been used. This does not imply that at these items no weight benefits may be obtained.

3. The base boat

As base boat the Standfast 64’ yacht will be used throughout this study. The yacht has been designed by Frans Maas in 2002 and has been built at the yard Standf Standfast Yachts at Breskens, the Netherlands.

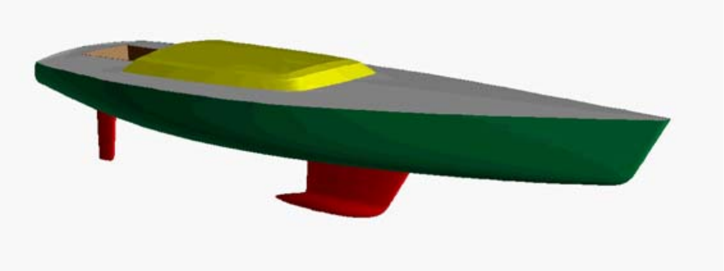
The yacht can be best described as a “High Performance Sailing Yacht”, which means that it has a luxurious accommodation with all the necessary facilities. Beside this luxury the yacht possesses a very good sailing performance and has proven to be quite able to compete in races with her “colleague yachts”. The main particulars are depicted in the Table.



L_{oa}	19.70	[m]
L_{wl}	17.00	[m]
B_{oa}	5.20	[m]
B_{wl}	3.34	[m]
T	2.50	[m]
∇	23.0	[m^3]
Bulb	9240	[kg]

I	24.8	[m]
J	7.1	[m]
P	22.8	[m]
E	8.3	[m]
SF	88	[m^2]
SM	106	[m^2]
SA	194	[m^2]

The yacht has been designed as a sandwich hull with epoxy resin and carbon fibre reinforcement. All construction laminates consist of twill woven carbon (12k T700 600 g/m^2) in epoxy resin (SP Prime 20). The foam core (Core Cell A550 90 kg/m^3) has 25 mm thickness. All interior parts were constructed of fibre/epoxy foam core panels and are glued together with fillet technique, to further minimise the weight. After the hull is turned these interior parts are mounted in.
Thanks to “post curing” construction technique of the complete hull with deck bonded at 55°C for 16 hours, a very strong and stiff but light hull was created. This carbon fibre with epoxy prepreg laminate composition and production method results in an efficient ratio of matrix material (resin) with fibres and extremely low levels of enclosed moist and air in the laminate. The same technique was applied to the fabrication of the Hall Spars mast and “Park Avenue” boom.



4. The construction and weight assessment.

For engineering the new constructions in the various versions of this design using the four building methods described use has been made of the 3D CAD program DELFTSHIP as developed by the Design Department of Maritime Technology Faculty of the Delft University of Technology. DELFTSHIP is an entirely 3D CAD Design tool for application in the marine industry, best characterized by its ability to create any kind of hull form with high flexibility. A short description will be given here.
At present DELFTSHIP consist of two fully integrated modules: i.e.
1) Using the hull form module, a model of the ship can be modelled either from scratch, by transforming a previous design or by importing it from another program. The hull form is accurately described using the latest surface-modelling techniques. After the body has been made various calculations and transformations can then be performed, such as volumes, centre of buoyancy and mass, moment of inertia around a specific axis etc. Contrary to most other ship design tools, DELFTSHIP does not use stations for the calculation of hydrostatics. Instead the panels obtained by the subdivision surfaces are used. This way more accuracy is obtained in areas such as gondolas and bulbs.
2) Once the shape of the (initial) hull is created the construction-module is used to add all the internal structures in a parametric way. This means that variations in hull form or construction can be explored without having to redefine the construction or hull. The 3D construction model is entirely parametric. This means that after a change of hull form the construction model will be updated to the new state. Also, when for example the tank top height is altered, all plate floors and girders are adapted to the new situation. Further repetitive construction items can be copied to different locations. This reduces the amount of required user input strongly. All parent-descendant relations thus created are maintained and updated by DELFTSHIP and can be disconnected or reconnected when required.

5. Global description of the Germanische Lloyd (GL) method

GL has special regulation for pleasure crafts in general. The regulations which have been used in the present study are: “Rules for Classification and Construction, I – Ship Technology, Part 3 – Special Craft, Chapter 3 – Yachts and Boats up to 24 m, edition 2004”. These regulations are generally applicable for recreational motor and sailing crafts with a scantling length **L**[1] between 6 and 24 meters made out of wood, metal and composites.

The hull of a yacht is divided in two areas: a horizontal line separates these areas at 150 mm above the CWL of the yacht. The main dimensions of the yacht, will determine the working loads for the areas of the different hull parts, which are mostly a function of the scantling length, waterline length, operating categories and the expected maximum speed. These loads on the areas are the points of departure for further calculations.

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[1] $L= ((L_{WL}+L_{OA})/2)$

5.1 Aluminium configuration

The formulae used for the calculation of the component scantlings embody the mechanical characteristics of ordinary hull structural steel. For the use of different metals a simple formula is present to calculate the material factor ‘k’:

$$k = \frac{635}{R_{p02} + R_m} \quad [\,\text{-}\,] \quad \text{, where:}$$

$R_{p0,2}$ = 0,2 % yield strength of the aluminium alloy in [N/mm^2]
R_m = Ultimate tensile strength of the aluminium alloy in [N/mm^2]

This factor will become k = 1.6 due to the aluminium, which will be used linear with the determination of the required section modulus (W) and with the square root for the minimum plate thickness.

The scantlings of the shell (bottom and side) and deck will be determined for various alternatives of the stiffener spacing. These stiffeners may be arranged either on the transverse frame principle or the longitudinal frame principle, or on a mixture of the two. After this the scantling of the bulkheads, the structural members and finally the scantlings of the floor beams will be determined. These contain the required minimum plate thickness and stiffeners section modulus.

Description		Plate [mm]	Frames	
			Transverse	Longitudinal
Shell	Bottom	8	HP 80x6	FB 120x50
	Side	6	HP 80x6	FB 120x50
	Stern	17	-	HP 80x6
Deck	Deck	5	HP 80x5	T 100x11
	Superstructure	5	HP 80x5	T 80x9
	Cockpit	5	HP 80x5	-
Bulkheads	Fore	5	-	HP 80x7
	Midship	5	-	HP 80x7
	Aft	5	-	HP 80x7

Properties of the aluminum construction

The results of the scantlings determination for the aluminium yacht are shown in the Table above. According to the rules the aluminium components do not need any allowances for corrosion. It is assumed that these components will be adequately protected against corrosion by a coating. Non seawater resistant components or coated seawater resistant alloys below water shall be protected against corrosion by zinc galvanic anodes. [GL, 2004]

6. Composite configurations

For the sandwich construction the regulations of GL, as they were in 2004, start with the minimum requirements for the thickness of the solid laminate [Chapter I-3-3, Section 1, B]. The minimum outer skin thickness of a sandwich panel is determined by multiplying with a factor of 0.8 the calculated glass weight per square meter of the solid laminate. Hereafter the calculation, which shall be based on the classic beam/plate and laminate theory, is required for the total sandwich structure with the various design pressures and laminate layers. For the total sandwich structure the following factors of safety (*FoS*) are required for the lay-up and stiffener:

The laminate lay-up has to contain the strain of each individual FRP layer, the shear stress of the core in the case of a sandwich construction and the deflection of the panel. The required *FoS*

between the ultimate strain and the calculated strain of each FRP layer according to the ply analysis must be at least 4.0 In the case of a sandwich construction the *FoS* against core shear failure must be at least 2.0. The standard value taken for the maximum panel deflection is 1% in the case of a sandwich panel.
For stiffeners the factor of safety between the ultimate calculated strain of each FRP layer due to stiffener's bending must be at least 4.0. This holds true also for the ultimate shear stress in stiffener webs and the default value for maximum deflection of stiffeners is 0.5% of their unsupported length.

The Table shows the results of the scantling calculations for the sandwich construction. The properties of the foam used in the shell are: 25mm thickness and 90 kg/m^3 average density, while the red cedar used as core in the wood-core construction is 35mm thick and the mean density is 350 kg/m^3. In the calculations of the deck construction 25mm foam thickness and 110 kg/m^3 average density has been used.
According to the boundary conditions the weight of the keel bolts, rudder and rudder construction, engine, mast and rigging are considered as a given weight on board. The reason for this simplification is found in the assumption that the changes in the weights of these items are considered not to be significant compared to the hull weight. It does not mean that the scantling of these parts is negligible but from in the scope of the present project these do not play a significant role.

Description		Glass Weight [g/m^2]	Thickness [mm]	Section Modulus [cm^3]
Shell	Keel	6800	16	-
	Bottom	3000	7	-
	Side	2300	5,5	-
	Stern	2300	5,5	-
Deck	Deck	1600	4	-
	House	1500	3,5	-
	House side	2200	5	-
Frames	Transverse	1800	-	61
	Longitudinal	2700	-	91
Bulkheads		2400	6	-

Properties of the sandwich laminate

7. Results of the weight calculation

For the weight calculation the previously (Chapter 2.4) presented *DelftShip* CAD program has been used. After the hull shape has been made the internal structure is added to this model. Using the results of the scantling and the structural mass database of this program the weight of the various yachts was determined. The results of the weight calculations based on the scantling calculations as described above are presented below.

Using the structural arrangement of the control yacht the following mass groups have been assumed:

- Construction;
    - Hull
    - Deck
    - Structure (frames, interior walls, keel)
- Insulation;
- Bulb;
- Unchanged mass (wood work, technical installation, deck equipment, rig and sail, electric installation, painting, instruments, inventory, etc.)

The Table shows the calculated mass of the four different constructions:

Yacht	Hull	Deck	Structure	Construction
Carbon	1550	910	1140	3600
Aluminium	3730	1720	3150	8600
Glass	2670	1230	1400	5300
Wood Core	3670	1230	1400	6300

Construction mass in [kg] of the various designs

What is eminent from these results is that the aluminum hull construction leads to an excessive construction weight. This will lead to the introduction of some design alternatives, which will be discussed in more detail further in this report.

So in close consultation with the designer of the Standfast 64, i.e. Frans Maas, it was decided to design also an alternative design for the aluminum construction. First the possibility of a new hull shape was considered. But this would lead to an increased draft over the imposed limit of 2.5 meters. This option therefore was rejected. So the basic yacht hull shape was now “stretched” in the athwart direction in such a way that, by keeping the overall length and the waterline length within the imposed limits, the draft of the canoe body did not change.

Also for the aluminium, the glass and the wood-core versions the “not-watertight” bulkheads are assumed to be constructed from 25.0 mm foam core (ρ=230 kg/m^3) with a 2.5 mm mahogany (ρ=600 kg/m^3) laminate at both sides. The deck sandwich construction of the wood-core yacht is the same as the glass one. This is a commonly used technology for weight saving.

8. Determination of Sail Area and Stability.

Using the results as derived above for the weight of the hull, deck and structure a choice has to be made for the sail area and the ballast, or actually the bulb weight, to go with it.
According to the boundary conditions for the design variations the performance of the yacht using different construction materials should be kept the same as much as feasible.
In consultation with the designer Frans Maas it was decided to focus on the following two design parameters:

- The Sail Area versus Displacement ratio, since this is an important parameter for the performance of the yacht in light air
- The Sail Area versus Wetted Area ratio, since this is an important parameter at higher wind speeds
- The Sail Carrying Ability , the so called Dellenbaugh angle is used, which relates the heeling forces of the sails to the stability moment of the yacht and is an important parameter for the upwind and beam wind conditions.

Through the project the following definition for the relation between sail area and displacement has been used: $10*\frac{\sqrt[3]{\nabla}}{\sqrt{SA}}$

The sail area used in the expression is the full main sail area and the so called 100% fore triangle in [m^2] and the displacement of the yacht represented in [m^3].
After consultation with the designer, the recommended range for this type of performance cruiser is the sail area displacement ratio to be between 2.0 and 1.9, where the lower value means a better performance ability. However, in the subsequent calculations for the base yacht it turned out to be:

$$10*\frac{\sqrt[3]{\nabla}}{\sqrt{SA}}=2{,}04$$

This value was used as the starting point of the further calculations. The relation between the fore and main sails was assumed to be the same so the 'J' and 'E' dimensions had to be considered constant. The results of these calculations are shown in the Table below:

Yacht	SA [m^2]	SF [m^2]	SM [m^2]	I [m]	J [m]	P [m]	E [m]
Carbon	194	88	106	24.8	7.1	22.8	8.3
Aluminium	254	114	140	32.4	7.1	30.4	8.3
Glass	204	93	111	26.2	7.1	24.2	8.3
Wood Core	210	96	114	27	7.1	25	8.3
A5	219	100	119	28	7.1	26	8.3

Sail area and sail dimensions of the various designs

From the results in this Table we may observe that the sail area of the Aluminium yacht has been considerably increased when compared with the other designs due to this applied design rule. It results also in value for *'I'* and so mast height, which is considered highly undesirable. Although this result is in agreement with the imposed boundary conditions it was felt that the feasibility of such a design is doubtful. Therefore, in agreement with the designer Frans Maas, the fifth design variation, nominated A5, was introduced. The basic of this A5 design is the same aluminium construction as the first one with the same shape and calculated weight but the mast height is limited to an *'I'* value of 28m. Thereby the sail area/displacement ratio of her is 2.11 what means the power capacity is slightly worse than with the other four designs.

With the sail area determined the sail carrying capacity may be determined also.
Basis of this assessment is the criterion that all variations should under similar wind condition, i.e. 22 knots of wind in a close hauled condition, have the same heeling angle. This implies that:

$$HM_{\varphi}=RM_{\varphi}$$ Heeling Moment = Righting Moment

or in formula form:

$$FH_{\varphi}*a=W*GZ_{\varphi},$$

where :
'a' = the vertical distance between the centre of effort of the sails and the centre of lateral pressure on the underwater body,
'W' = the weight of the yacht and
'GZ' = the righting arm of the stability moment.

So we may write the following:

$$\frac{FH_{\varphi} * a}{W} = GZ_{\varphi}$$

The left side in this equation can be seen as the heeling arm (*HA*).

To determine the heeling sail force from 5° to 35° heel angles the following experimental expression has been used:

$$FH = \frac{\rho}{2} * C_H * S_A * V_a^2 ,$$

where

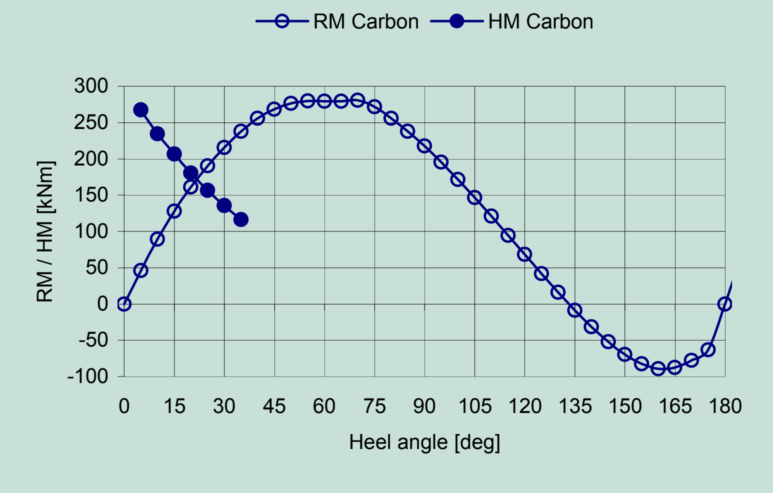
ρ	density ofthe air [kg/m^3]
C_H	heeling coefficient [-]
S_A	the sail area of the main and 100 % fore triangle in [m^2]
V_a	apparent wind speed [m/s]

The values of Ch are derived from the so called *Gimcrack* sail coefficients based on a full-scale trials of the *Gimcrack*, a 6-Metre type yacht, supplemented by towing tank model tests to predict yacht performance.[2] The Table below presents these values at different heel angles ranging from 5° to 35°.

Angle of heel (φ)	5°	10°	15°	20°	25°	30°	35°
Heeling coefficient (C_H)	1,54	1,345	1,195	1,045	0,902	0,778	0,666

The Gimcrack sail coefficients

For the *FH* calculation the assumed apparent wind speed is 22 knots. The intersection of the *RM* curve and *HM* curves will determine the heeling angle at which equilibrium is obtained at the used wind speed. The plot of the stability curves of the various designs again was generated using the *DelftShip* program. The result of such an exercise for the base yacht, the carbon Standfast 64, is depicted in the figure below.



The calculated heel angle of the carbon base yacht is 21.8°. According to the boundary conditions the other versions have to keep the same properties. This requirement is solvable by the systematic changing of the mass and vertical centre of gravity of the ballast (bulb).

The result of this procedure applied to all the other design variations in the project is depicted in the Table below:

Yacht	Mtot [kg]	Zg [m]	Mbulb [kg]	Zg bulb [m]	Heel [deg]
Carbon	23000	-0.23	9240	-2.13	21.8
Aluminium	34500	-0.36	12740	-2.35	22.1
Glass	24700	-0.24	9240	-2.25	22.1
Wood	25700	-0.25	9240	-2.31	22.2
A5	30500	-0.06	8740	-2.18	22.1

Heeling angles at equilibrium of the different yachts

The total mass of the yachts may now be calculated and the results are then presented in the following Table.

Ship	Construction	Insulation	Bulb	Unchanged	Total
Carbon	3600	-	9240	10160	23000
Aluminium	8600	3000	12740	10160	34500
Glass	5300	-	9240	10160	24700
Wood Core	6300	-	9240	10160	25700
A5	8600	3000	8740	10160	30500

Total mass of the different yachts in [kg]

The 5th yacht design variation in the Table above (A5) is an aluminium construction with the same hull as the other ones but with a smaller sail area than the other aluminium yacht. The rationale behind this design variation will be explained in the section about sailing performance. This design variation results in a lower ballast weight, as will also be explained in the section about performance.

9. The Building Cost Assessment.

Comparing costs for alternative materials is rather difficult, since they largely depend on the starting point. A yard specialising in aluminium alloy may find the cost of retooling/retraining to build in composites to be prohibitive. Design costs may also be an issue. Designing an aluminium alloy hull to class rules may be a fraction of the cost of a fully engineered advanced composites solution, albeit that the latter results in a 'better' structure. Alternatively an independent designer/specialist structural design bureau may be able to approach a range of yards and so this issue may not arise. It is generally accepted that comparisons based on raw material cost have limited value. For production craft, it is the overall cost per unit that matters. For racing yachts, cost may be virtually irrelevant in the drive towards the minimum weight solution in order to maximise ballast ratio and hence sail area capacity.

The building cost of a one-off sailing yacht is something that many builders keep as a company secret because the up front costs of the yacht cannot be easily predicted. The determination of the actual cost afterwards, when the yacht is delivered to the customer, is often not fully carried out. However, the aim of this project is to make a comparison of the building costs involved with

the various building materials used. Therefore in the next paragraph the main outline of the cost calculations and the result of this comparison will be introduced.
For the sake of simplicity the expense can be separated in two main groups, namely the costs involved with *building* and the cost involved with *equipment and installation*.

The first part contains the *building* price of the:

- positive mould;
- hull;
- deck construction;
- bulkheads and walls;

the *equipment* part contains the costs of the:

- engines and propulsion line;
- rig and sails (shrouds, mast, etc.);
- deck gear;
- keel (ballast).

Building price:

At the preliminary design stage it is possible to use the following estimation[3] of the building cost:

$$F_c = O_F * H_W(1+S) * [M_R + L_P * W_R + T_C + M$$

F_c = fabrication cost;
O_F = overhead factor;
H_W = hull weight in kg;
S = proportional of scrap material;
M_R = material rate in Euro/kg;
L_P = labour productivity in man-hours/kg;
W_R = wage rate in Euro/kg;
T_C = tooling cost per kg worked;
M = margin.

It is assumed that the composite yachts are all being built at the same yard. Hereby the productivity, the wage rate and the other workshop factors such us the technology will have the same value and by comparing the fabrication costs with each other we can assume that knowledge about the hull weight and material rate is sufficient. The applied technology during the building process will also affect the cost and therefore throughout this project the Vacuum Resin Infusion method was assumed. This method was also used for building the base yacht. The following average material cost values have been used in the calculations:

Carbon	30 € / kg
Glass	6 € / kg

Foam Core	20 € / kg
Red Cedar	6 € / kg
Ayous	2.50 € / kg

The ayous is generally used to positive mould for the hull and the deck. For the wood core construction the assumed core material is the Red Cedar. From a building cost point of view the main advantage of the wood core construction is that you don't have to build complete mould for the hull. This means that the man-hours can be significantly decreased. It remains necessary however to build the frames to plank the hull on.

The following table shows the result of this comparison where the base of the comparative is the carbon yacht.

Description	Carbon		Glass		Wood	
	work hours	material price	work hours	material price	work hours	material Price
Hull mould	1.00	1.00	1.00	1.00	1.00	0.20
Deck mould	1.00	1.00	1.00	1.00	1.00	1.00
Hull	1.00	1.00	0.90	0.34	0.20	0.14
Deck	1.00	1.00	0.90	0.28	0.30	0.28
Constructions	1.00	1.00	1.00	0.24	1.00	0.24
Summa	1.00	1.00	0.97	0.36	0.78	0.27
Total	1		0.64		0.50	

Comparison of the building cost of the yachts

The comparison of the composite and the aluminium construction remains rather difficult due to the considerably dissimilar construction technology. Hereto ample consultation with builders and designers amongst others with Standfast Yachts (Breskens) and Gerard Dijkstra and Partners (Amsterdam) who are well established in the composite and aluminium yacht construction lead to the following assumptions used: the determination of the building costs for the aluminium yacht largely depends on the number of bulkheads, tanks, complexity of the cockpit and keel, incorporated deck fittings, foundations etc. Nevertheless it is possible to use a range of €/kg value for the estimation of the building cost including the price of the material and working hours.

For the aluminium building price the following items have to be taken in consideration:

- Hull and deck construction
- Insulation
- Bulkheads and walls

The following table shows the comparison between the carbon and aluminium yachts.

Description	Carbon price	Aluminium price
Building	1.00	0.76

Equipment price:

The comparison of these groups is a little easier than the previous because we can use the same man-hours and the price of the equipments can be estimated as a function of the weight or the sail area. The next table shows the comparison of the equipment prices for the five yachts:

Description	Carbon	Aluminium	Glass	Wood Core	A5
Main engine + Propulsion line	1	1.5	1.08	1.12	1.33
Rigging (carbon)	1	1.3	1.05	1.08	1.13
Sails	1	1.3	1.05	1.08	1.13
Deck gear	1	1.3	1.05	1.08	1.13
Keel (ballast)	1	1.5	1	1	0.95
Total	1.00	1.32	1.05	1.08	1.14

Equipment cost relation

The rate of the final results is shown in the following figure where the basic of the comparison is the Carbon yacht.

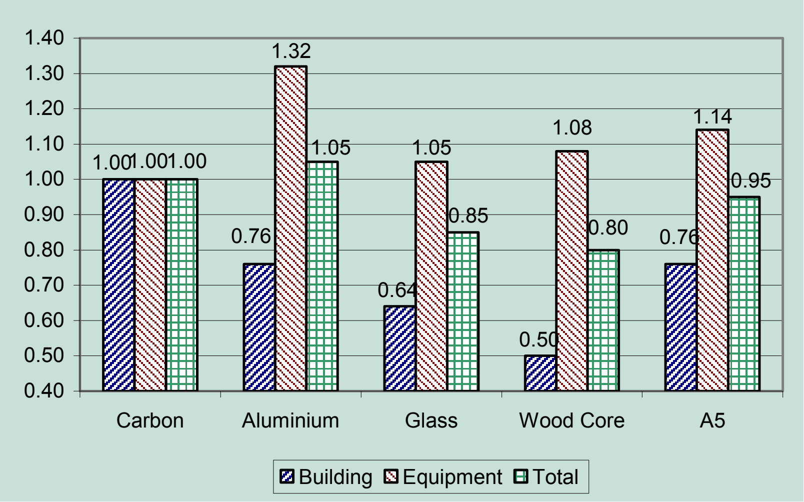


Figure: Overall cost relation of the yachts

The results in this figure clearly shows that although the material rate for example the glass to the carbon is about 20% the building cost changing to about 64% and finally the total cost of the yacht is about 85%. So comparing only the prices of the materials separately is rather inaccurate and the change of the equipment prices due to the increasing loads have to be taken in to account also in the yacht overall price comparison.

10. The Performance Assessment

In order to assess the performance differences between the various realizations of the same design (the base boat) build in different materials use has been made of a Velocity Prediction Program, i.e. “Windesign”. The formulations used for the assessment of the hydrodynamic and aerodynamic forces involved use has been made of those expressions derived from the results of the Delft Systematic Yacht Hull Series (DSYHS).
The performance of these boats has been compared in different environmental conditions, i.e.:

Light air	5 knots true wind
Moderate air	10 & 14 knots true wind
Heavy air	20 & 25 knots true wind

To calculate the influence of wind-waves on the performances the North Sea conditions have been taken into consideration. The Table below shows the characteristics of the wave spectra used at the different wind speeds.

Wind speed [kn]	Wave height [m]	Period time [s]
1,6	0,50	3,25
3,9	0,65	3,65
7,4	0,80	3,90
12,0	1,10	4,30
17,5	1,65	4,75
22,0	2,50	5,30
25,0	3,50	6,00

North Sea wind-wave conditions

In the calculations for the sake of comparison the following sail sets have been applied:
Sail set with the true wind direction between 0 – 130 degrees: Main and Jib and with the true wind direction from 80 to180 degrees: Main and Spinakker.
The sail dimensions used in the VPP calculations are depicted in the table below:

Yacht	Main			Fore				Spin				
	P	E	BAD	IG	J	LP	HBI	ISP	SPL	SMW	SLU	SLE
	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]	[m]
Carbon	22,8	8,3	1,98	24,8	7,1	7,9	1,650	24,8	7,1	12,78	25,80	25,80
Aluminium	30,7	8,3	1,98	32,4	7,1	7,9	1,623	32,4	7,1	12,78	33,17	33,17
Glass	24,2	8,3	1,98	26,2	7,1	7,9	1,618	26,2	7,1	12,78	27,14	27,14
Wood	25,0	8,3	1,98	27,0	7,1	7,9	1,599	27,0	7,1	12,78	27,92	27,92
A5	26,0	8,3	1,98	28,0	7,1	7,9	1,575	28,0	7,1	12,78	28,87	28,87

Sail dimensions of the various designs as used in the VPP

The following Table shows the mast dimensions which were used to determine the mast and rigging drag. These were the same at every version.

MDT1 [m]	MDL1 [m]	MDT2 [m]	MDL2 [m]	TL [m]
0,22	0,35	0,22	0,25	5,13

Mast dimensions

The following Table depicts the flotation data of the various designs as used in the VPP calculations:

Yacht	Dsplt	Dsplc	Lwl	Bwl	Tc	Tmax	Awp	Cp	LCB	LCF	Mlong
	[kg]	[kg]	[m]	[m]	[m]	[m]	[m^2]	[-]	[%]	[%]	[m]
Carbon	23081	21775	16,901	4,350	0,740	2,500	51,16	0,564	-5,18	-7,09	34,581
Alu	34520	33320	17,106	4,838	0,951	2,527	58,24	0,563	-4,40	-7,41	27,315
Glass	24739	23432	17,094	4,399	0,772	2,532	52,39	0,565	-4,70	-6,80	33,810
Wood	25742	24434	17,208	4,427	0,791	2,551	53,10	0,566	-4,43	-6,63	33,360
A5	30518	29330	16,729	4,756	0,881	2,457	55,85	0,560	-5,25	-7,95	28,017

Flotation data as used in the VPP calculations.

For the ease of assessment only the optimal performances of the various designs are listed. First the results for the upwind conditions will be presented.

Yacht	Wind speed (Vt) in knots				
	5	10	14	20	25
Carbon	2,882	5,101	5,788	5,847	5,688
Aluminium	3,360	5,491	6,013	6,126	5,928
Glass	2,992	5,192	5,833	5,895	5,727
Wood	3,052	5,241	5,859	5,961	5,750
A5	2,982	5,151	5,595	5,629	5,395

Optimal upwind performance in Speed made good (knots)

The differences in delta's and percentages with the carbon base boat are presented in the Table below:

Wind speed (Vt) in knots				
5	10	14	20	25
0,00	0,00	0,00	0,00	0,00
0,48 16.59%	0,39 7.65%	0,23 3.89%	0,28 4.77%	0,24 4.22%
0,11 3.82%	0,09 1.78%	0,04 0.78%	0,05 0.82%	0,04 0.69%
0,17 5.90%	0,14 2.74%	0,07 1.23%	0,11 1.95%	0,06 1.09%
0,10 3.47%	0,05 0.98%	-0,19 3.33%	-0,22 3.73%	-0,29 5.15%

Delta Vmg in knots and in %

When considering the different performances of the various designs it should be noted first that only those characteristics of the boats are visible in the results that are actually accounted for in the VPP. This implies amongst others that performance improvements associated by boat stiffness are not found in these results. This is one of the reasons for designers to choose for a carbon construction.

What becomes obvious from these results is that in the light conditions the advantage of the wood core boat over the carbon boat is close to 6%, while in heavy air this is about 1%. Something similar is seen with the modified aluminium boat A5 which performs circa 3.5% better in light air when compared with the base boat but 5% worse in heavy air.
To a large content these differences may be attributed to the differences in sail area versus wetted surface ratio, as demonstrated in the table below:

Yacht	Sail Area [m^2]	Wetted surface [m^2]	SA / Ws [-]
Carbon	194	56,01	3,464
Aluminium	254	66,38	3,826
Glass	204	57,78	3,531
Wood	210	58,80	3,571
A5	219	62,68	3,494

Sail area versus wetted area ratio's

The last table shows the heeling angle of the boats at their optimal performance upwind. It clearly demonstrates the validity of the design rules used as all the heeling angles are close. The carbon boat is the stiffest after the A5 variant, which has less sail then it should have.

Yacht	Wind speed (Vt) in knots				
	5	10	14	20	25
Carbon	3,3	12,8	19,1	20,3	21,0
Aluminium	4,6	16,2	21,4	22,0	22,2
Glass	3,6	13,7	19,7	20,5	21,3
Wood	3,7	14,2	20,0	21,4	21,5
A5	3,7	15,2	18,9	19,3	20,4

Heeling angles at optimal speed made good

Another possibility to compare the different performances is by sailing different course types with the boats and compare their average time needed over one mile of such a course. This procedure is similar to the standard course types used in the International Measurement System handicap options.
The course types used are:

- Windward – Leeward consist of one track upwind and one track downwind of the same length(WL)
- Olympic Triangle consist of the classical Olympic track two windward tracks, one down wind track and two reaching tracks (OLY)
- Linear Random which is a straight track with systematically varying wind direction over the entire length (LR)

The results for these tracks are:

Yacht	Wind speed (Vt) in knots				
	5	10	14	20	25
Carbon	1116	629	529	485	473
Aluminium	989	594	515	472	465
Glass	1085	620	526	482	471
Wood	1068	615	524	479	470
A5	1086	626	543	501	496

WL course times in seconds per mile

Yacht	Wind speed (Vt) in knots				
	5	10	14	20	25
Carbon	1057	600	516	484	477
Aluminium	929	567	503	472	470
Glass	1025	591	513	481	475
Wood	1008	587	511	478	474
A5	1026	597	531	503	504

OLY course times in seconds per mile

Yacht	Wind speed (Vt) in knots				
	5	10	14	20	25
Carbon	748	455	396	356	335
Aluminium	678	443	395	361	345
Glass	732	451	395	357	336
Wood	723	449	394	356	336
A5	729	458	408	373	356

LR course times in seconds per mile

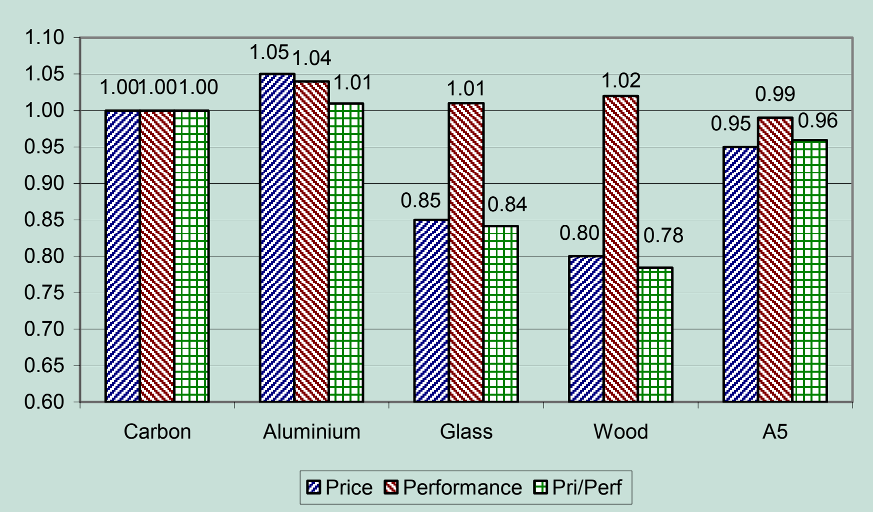
The general conclusion that may be drawn from these results can be summarized as follows

- At light wind conditions the yachts with bigger sail area has better performance due to the better SA/Ws ratio.
- At medium and heavy air conditions the effect of the L_{wl} is determine the performance because the SA/∇ ratio are equal.
- At the angel of stability the yachts have the same property.
- Differences between the comparable performances at light wind are not bigger than 6%. At moderate wind this gap is decreasing to 3% while at heavy weather this is more or less balanced (1%).
- Although the first aluminium version is matching with the precept it can be seen that her performance is incomparable due to the disproportionate huge sail area.

11. Conclusions

In this study the Standfast 64' yacht has been used as a base boat for comparising the building price and performance differences that arise when the same yacht is build in different materials.
The base yacht was designed as a carbon epoxy sandwich construction and the considered other building materials are aluminium, glass epoxy sandwich and wood-core.
The main boundary conditions used are that the hull shape remains the same, an equal SA/∇ ratio and the same stability at a given wind speed. It was necessary however to make another hull shape for the aluminium version, because when the design rules were strictly applied the weight and the draught increased too much. Due to this large weight difference the sail area of this yacht became impractical when the SA/∇ ratio had to be kept constant. This yacht does not seem to be feasible and therefore the fifth yacht A5 was presented in to this study. This design has the same hull and construction weight as the aluminium one but the sail area is limited by the value of the mast height.

As an overall result the following table which contains the condensed differences between the various designs is presented. The data in the figure are derived from the building cost, the overall cost relation and the average speed prediction. The last column is the price-performance ratio relative to the carbon yacht.



Price-Performance comparison

From this figure we can see the yacht's performances are close to each other therefore the price-performance relation is mostly depends on the building cost discrepancy in this situation. While the performance difference is about 5% the building cost diverge to 20%. Seen like this the cheaper building construction seems to be a profitable choice. On the other hand, the rate of the design attributes for a performance cruiser such us safety, cost, comfort, beauty, etc. are usually have major angle than the cruising speed but this is mostly the owner's task to determine this weighted rating.

List of symbols

Basic

L_{oa}	[m]	Length over all		I, IG	[m]	Vertical dimension of fore triangle
L_{wl}	[m]	Waterline length		J	[m]	Longitudinal dimension of fore triangle
B_{oa}	[m]	Beam over all		P	[m]	Vertical dimension of main triangle
B_{wl}	[m]	Waterline beam		E	[m]	Longitudinal dimension of main triangle
T	[m]	Draught		SM	[m^2]	Main sail area
Disp, ∇	[m^3]	Volume displacement		SF	[m^2]	Fore sail area
Bulb	[kg]	Mass of the ballast		SA	[m^2]	Total Sail area

Symbols used in the VPP

Rig parameters

BAD	[m]	Vertical distance from HBI to bottom of P		MDT1	[m]	Mast Section Transverse Dimension
HBI	[m]	Height of base if I above sailing water plane		MDL1	[m]	Mast Section Longitudinal Dimension
SPL	[m]	Spinnaker pole length		MDT2	[m]	Topmast Section Transverse Dimension
SMW	[m]	Spinnaker mid width		MDL2	[m]	Topmast Section Longitudinal Dimension
SLU	[m]	Spinnaker luff length		TL	[m]	Length of mast Taper
SLE	[m]	Spinnaker leach length				
ISP	[m]	Vertical height of spinnaker halyard sheave				

Hull parameters

Dsplt	[kg]	Total Displacement		Awp	[m^2]	Water plane area
Dsplc	[kg]	Canoe Body displacement		Cp	[-]	Prismatic Coefficient of canoe body
Lwl	[m]	Waterline length		LCB[1]	[%]	Longitudinal centre of buoyancy
Bwl	[m]	Waterline beam		LCF[1]	[%]	Longitudinal centre of flotation
Tc	[m]	Canoe body draft		Mlong	[m]	Something
Tmax	[m]	Maximum draft of keel				

[1] - % of Lwl - relative to Lwl/2 - aft is negative

[2] - for 0,2,10,25 & 40° heel

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