Tin Matulja, Ph. D.
University of Rijeka
Faculty of Engineering
Department of Naval Architecture and Ocean Engineering
Vukovarska ulica 58
51000 Rijeka

Miroslav Bogdanović, mag. ing.
STX OSV Design Liburna d.o.o
Fiorella la Guardie 13
51000 Rijeka

Nickol Udovičić, mag. ing.
University of Rijeka
Faculty of Engineering
Department of Naval Architecture and Ocean Engineering
Vukovarska ulica 58
51000 Rijeka

Croatia

Preliminary Communication

Received: 31st July 2013
Accepted: 29th November 2013

SELECTION OF THE RACING MULTIHULL SAILING BOAT EQUIPMENT BY THE AHP METHOD – A CASE STUDY

SUMMARY

The paper aims at presenting the optimal selection of the deck equipment for the racing multihull sailing boat using a novel methodology based on the modified wind loads design and the AHP method. The determination of the modified wind load design due to the mass of the crew on the side hull is essential because of possible greater stability moments. The load obtained in such a way has been compared with the load prescribed by the standard. This modified load resulted to be greater and, therefore, has been used as an authoritative when dimensioning the deck equipment. Furthermore, an optimal selection of the construction and of the materials of the required sailing equipment among a large number of the proposed equipment on the market has been made through an expert approach by using the AHP method to solve such a multi criteria decision making problem.

Key words: racing multihull sailing boat, preliminary design, deck equipment, wind loads, AHP method

1 INTRODUCTION

The amount and type of the built-in deck equipment depends on the requirements of the owner or on the size and type of the boat. Regarding design constraints, the selected equipment weight should be as lower as possible. Nevertheless, the installed equipment must be selected according to the maximum designed forces that are expected in the race. Deck design and equipment selection is related to the determination of the designed loads sailing against the wind in a race. It is therefore of great importance to accurately determine the specified load. This is even more pronounced in the design of a racing yacht where the minimum weight of the boat and its equipment is desired, and which can be achieved with lower safety factors when determining the design loads. After selecting the equipment, it is necessary to determine the optimal position of the installation. Parts of the deck, on which the installation of the equipment is planned, must be of an adequate construction.

2 TECHNICAL CHARACTERISTIC OF THE DESIGNED SAILING BOAT

The basic data of the analyzed preliminary designed racing multihull sailing boat [1] are shown in table 1, while the preview of such a design is given on figure 1.

Table 1 Technical characteristics of the designed racing multihull sailing boat

	Value	Description
L_{OA}	8.65 m	Length overall
L_H	6.99 m	Length of hull
L_{WL}	6.48 m	Waterline length
B_{MAX}	5.6 m	Breadth of hull
B_{MIN}	2.5 m	Breadth of hull (folded)
T_{MAX}	1.4 m	Maximal draught
T_{MIN}	0.35 m	Minimal draught
m_{LDC}	900 kg	Fully loaded mass
N	4	Crew
CE	C	Design category

3 SAIL PLAN AND SAILS SELECTION BY USING THE *AHP* METHOD AND MODIFIED WIND LOADS

The *AHP* method, as one of the multi-attribute decision making, is a structured technique for dealing with complex decisions. Rather than prescribing a ”correct” decision, the *AHP* helps the decision makers find the one that best suits the given constraints and limitations (criteria). Based on mathematics and psychology, it has been developed by Thomas L. Saaty, [2].

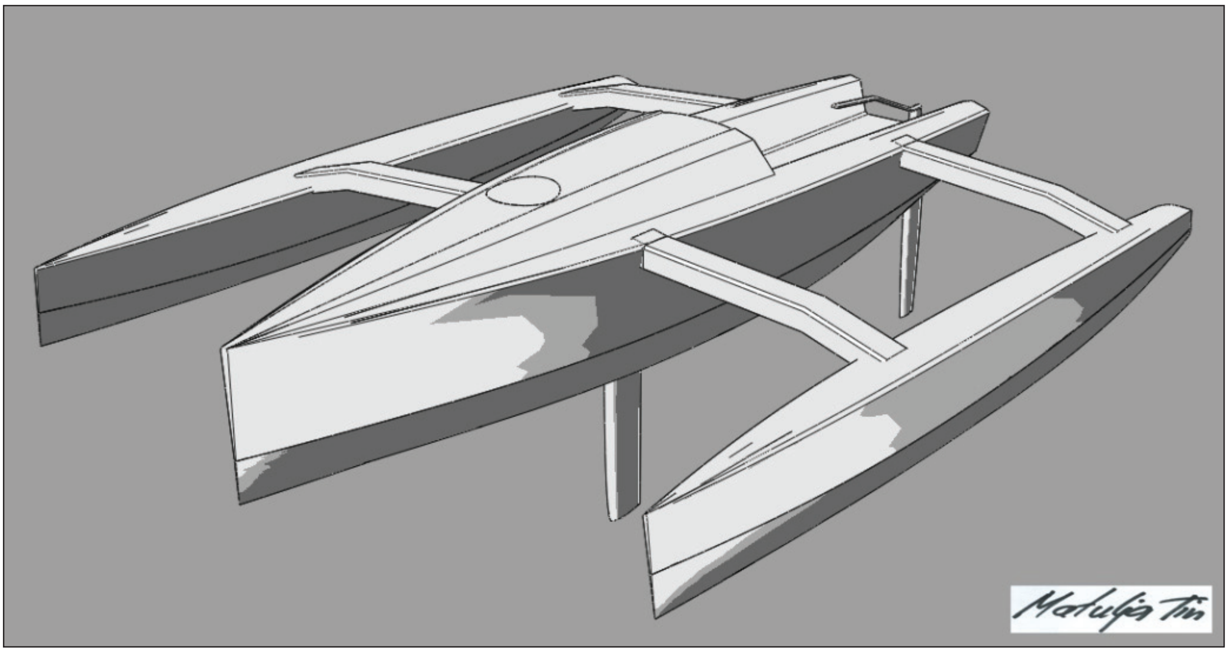

Figure 1 Designed racing multihull sport boat, [1]

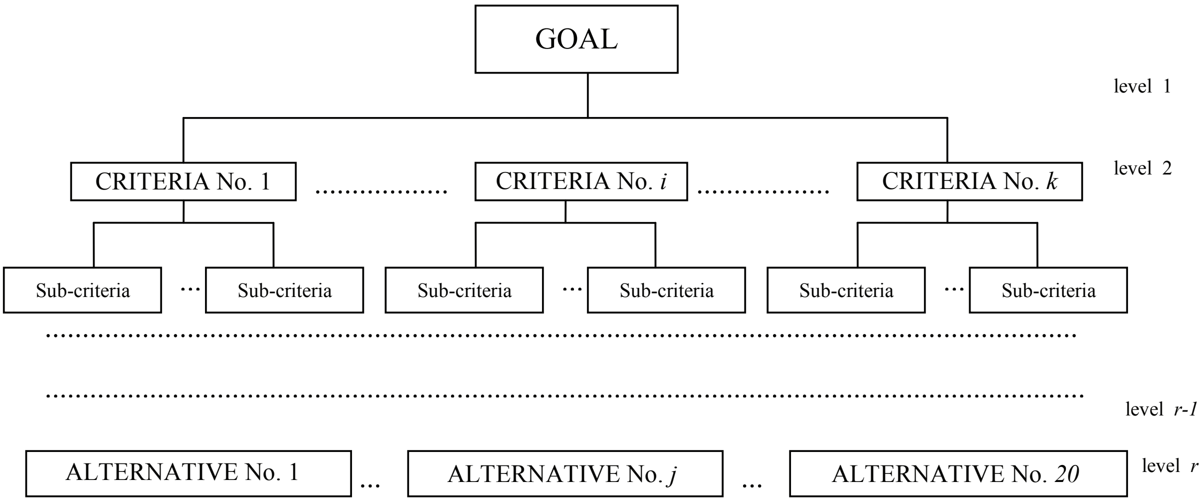

Figure 2 The AHP hierarchical hodel

Table 2 Saaty's scale of relative importance [2]

Intensity of relative importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong	Experience and judgment strongly favour one activity over another
7	Very strong importance	An activity is strongly favoured and its dominance is shown in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is needed between two judgments

The hierarchical model structurally consists of a goal, criteria, sub-criteria and alternatives (solutions), as shown in figure 2.

The goal is placed at the highest hierarchical level and is not compared to any other element of the hierarchical structure. At the first level there are k criteria which are compared to each other in pairs regarding the directly superior element – goal. The $k(k-1)/2$ of comparisons is required. The same procedure is repeated at the next hierarchical level, all the way down to the last r level, whiles all comparisons of all the solutions regarding the superior criteria, down to $r-1$ level, have been completed.

Each comparison of the two elements of the hierarchical model has been made by the Saaty's scale of relative importance, table 2.

The results of the element comparison at the observed hierarchical level are organized in matrix as follows:

If n elements are compared to each other related to the superior corresponding element at a higher hierarchical level, then, when comprising i element to j element by using the Saaty's scale of relative importance, the numerical coefficient a_{ij} is determined and placed in its adequate position in matrix M:

$$M = \begin{bmatrix} a_1 & a_2 & \cdot & \cdot & a_{1n} \\ a_2 & a_2 & \cdot & \cdot & a_{2n} \\ \cdot & \cdot & & & \cdot \\ \cdot & \cdot & & & \cdot \\ a_{n1} & a_{n2} & \cdot & \cdot & a_n \end{bmatrix} \quad (1)$$

The inverse result value is placed on position a_{ji} as to maintain consistency of the decision making. A detailed description of the *AHP* method procedure can be found in [2]. The sail area is determined in the preliminary design of the sailing boat and depends on the size and purpose of the same. Often the ratio of the sail area and the displacement displays performance of the sailing boat. This ratio is slightly higher for racing boats, but a compromise must be found. When building a racing yacht, the goal is to get as lighter a hull as possible and to install only the necessary equipment. Less weight of the multihull sailing boat will allow a relatively greater mass influence of the crew in sailing. The sail area shall be such as to allow sailing with a certain hull heel at a certain wind speed. A too much sail area will be favourable at lower wind speeds, but can demand reefing at higher speeds. In multihull sailing boat sailing, these problems are even more prominent because of the specific lateral stability. Multihull sailing boats have greater moments of stability, comparing them with mono hull sailing boats of equal length, which allows them to sail at higher wind speeds, and thus achieve higher speeds, but also higher loads in the deck equipment.

The table 3 shows that the highest sail area and displacement ratio belongs to multihull yachts, due to their high stability moments.

Table 3 Typical Sailing Area Displacement Volume Ratio [3]

Type of the boat	**Sailing area and displacement volume ratio S_AD**
Sailing boat	16-18
Sport sailing boat	20-22
Racing sailing boat	22-28
Multihull racing sailing boat	28-

Using such a table and when a mass of the yacht is known i.e. the displacement volume, it is possible to preliminarily determine the sail area S_A (main and the jib) from the following equation:

$$S_AD = \frac{S_A}{\bar{\nabla}^{\frac{2}{3}}} \tag{2}$$

where S_A is the sail area in m^2 and V the displacement volume in m^3.

$$S_A = \bar{\nabla}^{\frac{2}{3}} \cdot S_AD \tag{3}$$

For a more precise determination of the sail area, it is necessary to develop the stability curve moments, figure 3. The curve has been made for the total mass of an 800 kg yacht with two crew members. In the first case the crew was located in the centreline, while in the other case it was located at the side hull. It is evident that there is a difference between the maximum

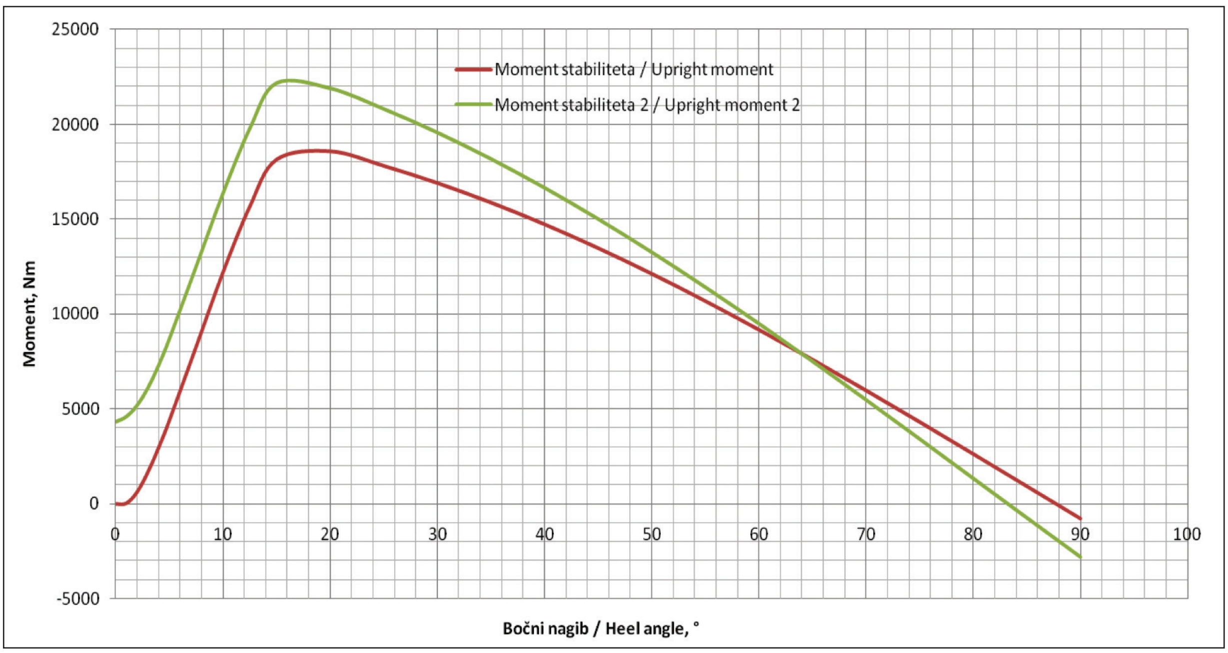

Figure 3 Static stability moment curves

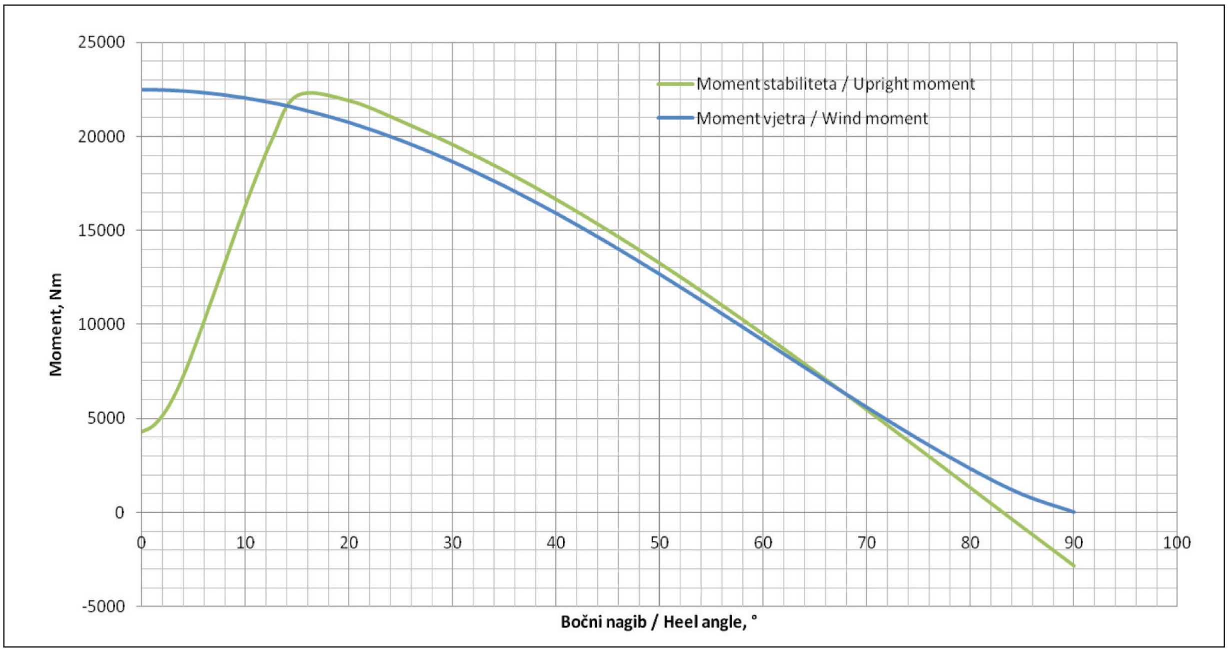

Figure 4 Static stability and wind moment curves

stability moments for these two cases, approximately 20 %. These differences must be taken into account in dimensioning the deck equipment, i.e. a greater moment is taken as a relevant one.

The next step is to preliminarily determine the overturning moment curve of the wind, M_W, in Nm, [4]:

$$MW = 0{,}75 \cdot v^2_W \cdot A'_S \cdot (h_{CE} + h_{LP}) \cdot (\cos\Phi)^{1,3} \quad (4)$$

where v_W is the wind speed in m/s, A'_S is the projected sail area in m², h_{CE} is the centre of gravity of the sail area above the waterline in metres, h_{LP} is the centre of the surface area below the waterline in metres, and Φ is the lateral heel angle in degrees.

It is evident that for the determination of the overturning moment of the wind, it is necessary to know the area and shape of the sails. To determine the actual wind speed at which the normal sailing is possible, a sailing experience is desirable, because the former term does not include the sea state and the wave height. The determination of the sail area is an iterative process that continues even after the installation and sailing. After testing in real conditions by rotating the mast longitudinally, the centre of the sail area and the position of the wind force centre are changed. Figure 4 shows the selected stability moment together with the wind moment blowing at a speed of 11 ms^{-1} (22 kt, 40 kmh^{-1}). A static equilibrium is at approximately 14° angle. The goal is to sail multihull boats at angles as close to that on which the greatest moment of stability is.

It is clear that in case of exceeding the maximum stability moment the wind moment remains always higher and a sailing boat without the intervention of the helmsman can easily rollover. The moments shown are without dynamic effects that occur at sea. Moments that are shown are to be increased for a certain value which is larger for a lighter and faster boat, [4]:

$$RM_D = k_{VS} \cdot RM_{MAX} \quad (5)$$

where k_{VS} is the dynamic coefficient, that should not be greater than 2.

$$RM_D = k_{VS} \cdot RM_{MAX} = 1{,}3 \cdot 24500 = 31850 \text{ N} \quad (6)$$

$$k_{VS} = \frac{2{,}65 \cdot L^2_{WL}}{\sqrt[3]{m^2_{LDC}}} = \frac{2{,}65 \cdot 6{,}48^2}{\sqrt[3]{800^2}} = 1{,}3 \quad (7)$$

The mass of 800 kg was taken with the intent to obtain a higher dynamic coefficient which is more realistic for the racing yacht. Based on the conducted calculations and analysis the sail plan is selected as shown on figure 5, with characteristics given in table 4.

Table 4 Selected sail area

Symbol	Area, m^2	Sail type
A_{MS}	22	Main sail
A_{FT}	11	Jib front sail
A_S	33	Spinnaker front sail

Selected sails are tailored to the desired dimensions. Sails should be made of a small areal mass material, especially because the sails positions are high on the boat, thus significantly affecting the centre of gravity of the system. The material must be resistant to UV rays, must not easily puncture and abrade, must be resilient and have a specific tensile strength and cannot absorb certain amount of water. The selected sail material is usually a compromise of the required characteristics. For an optimal sailcloth selection, the Expert approach has been implemented by the AHP method, [2], through the specialized software ExpertChoice11, [7]. The mentioned characteristics of the sailcloth are used as the wanted criteria, while the optimal material for the sailcloth has been claimed between the offered one on the market.

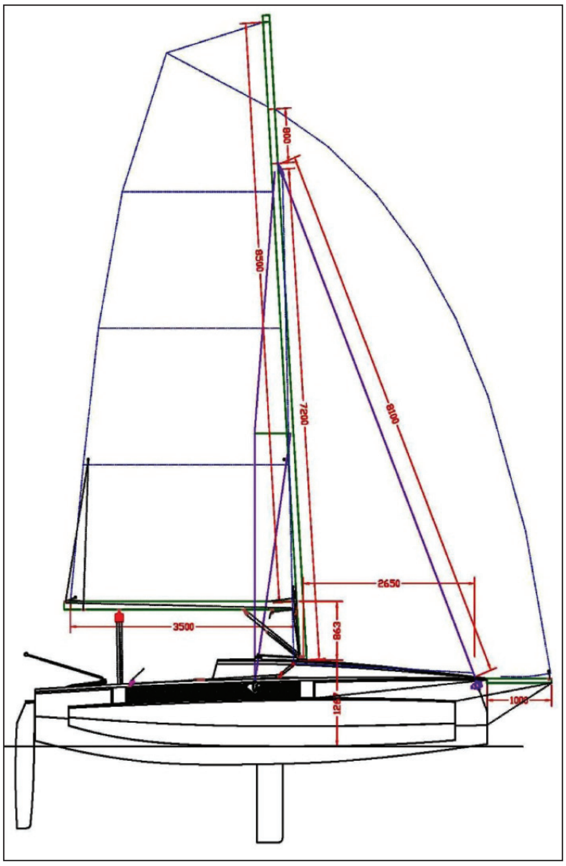

Figure 5 Sail plan, [1]

The results of the applied AHP method are given on figure 6 where the "Carbon" fibered sailcloth is selected as an optimal one for a racing multihull sailing boat. The conducted Sensitivity analysis is justifying even the usage of "PBO" and "Spectra" materials shown as second and third ranked in figure 6. The area specific mass for the selected material is selected due to the desired characteristics of the race, which is in the domain of a professional sail maker. The strength of the sails must be such as to withstand wind speeds before and after the

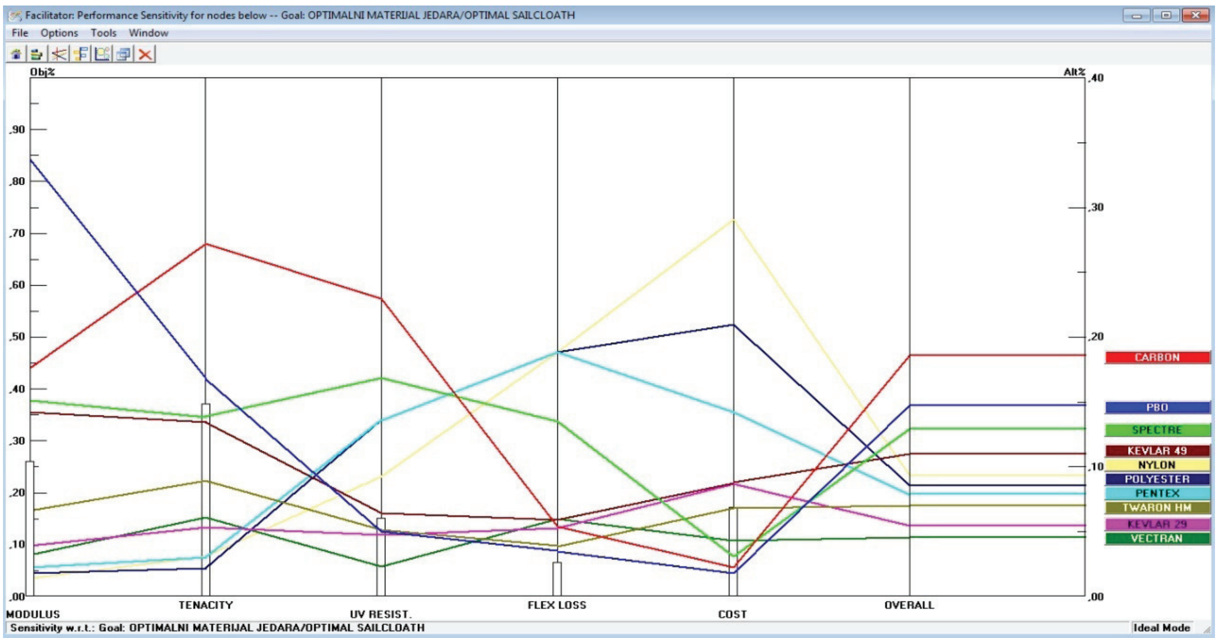

Figure 6 Optimal selected sailcloth using the AHP method, [7]

reefing. The boat has scheduled one mainsail reef, while the jib is wounded around the head stay. Reefing and reducing the sail area allows sailing at higher wind speeds.

4 WIND LOADS

A force that occurs when air flows around a sail spreads around with them on the boom, mast, stays, beams and finally to the hulls. The size of these forces depends on the direction and wind speed and surface of the sails raised. Yachts are designed to transform the force of the wind in the thrust, which is feasible in certain wind speed, after which the boat is too much heeled or becomes too difficult to helm. The main wind forces acting on multihull sailing boats are given in figure 7.

To select the side stays, it is necessary to know the force that can occur in sailing. A force that occurs at stays depends on the size of the overturning moment and the width between the hulls and is determined from the following expression [5]:

$$T_{US} = \frac{2 \cdot RM_D}{B_{CP}} = \frac{2 \cdot 31850}{4{,}91} = 12974 \text{ N} \tag{8}$$

where the project RM_D is the overturning moment and B_{CP} is the width between the side stays. When selecting a side stay, it is necessary to know exactly the size of the expected overturning and the stability moment with all the additional factors of influence. With the knowledge of the load left is the coefficient of safety selection, as prescribed by the rules which sailing boats are built according to. The maximum force on the side stays on the hull is determined by the following formula, [5]:

$$F_{CPW} = T_{US} \cdot \cos\beta + 0{,}5 \cdot T_{HS} \cdot \cos\alpha_1 + \\ + 0{,}5 \cdot T_{MS} + 0{,}5 \cdot T_{JH} \cdot \cos\alpha_1 \tag{9}$$

where the T_{US} is force at upper shroud, T_{HS} force at head stay, T_{MS} force at the mainsail shroud, T_{JH} force stays in the jib halyard. With knowledge of the geometry of the sails and project sta-

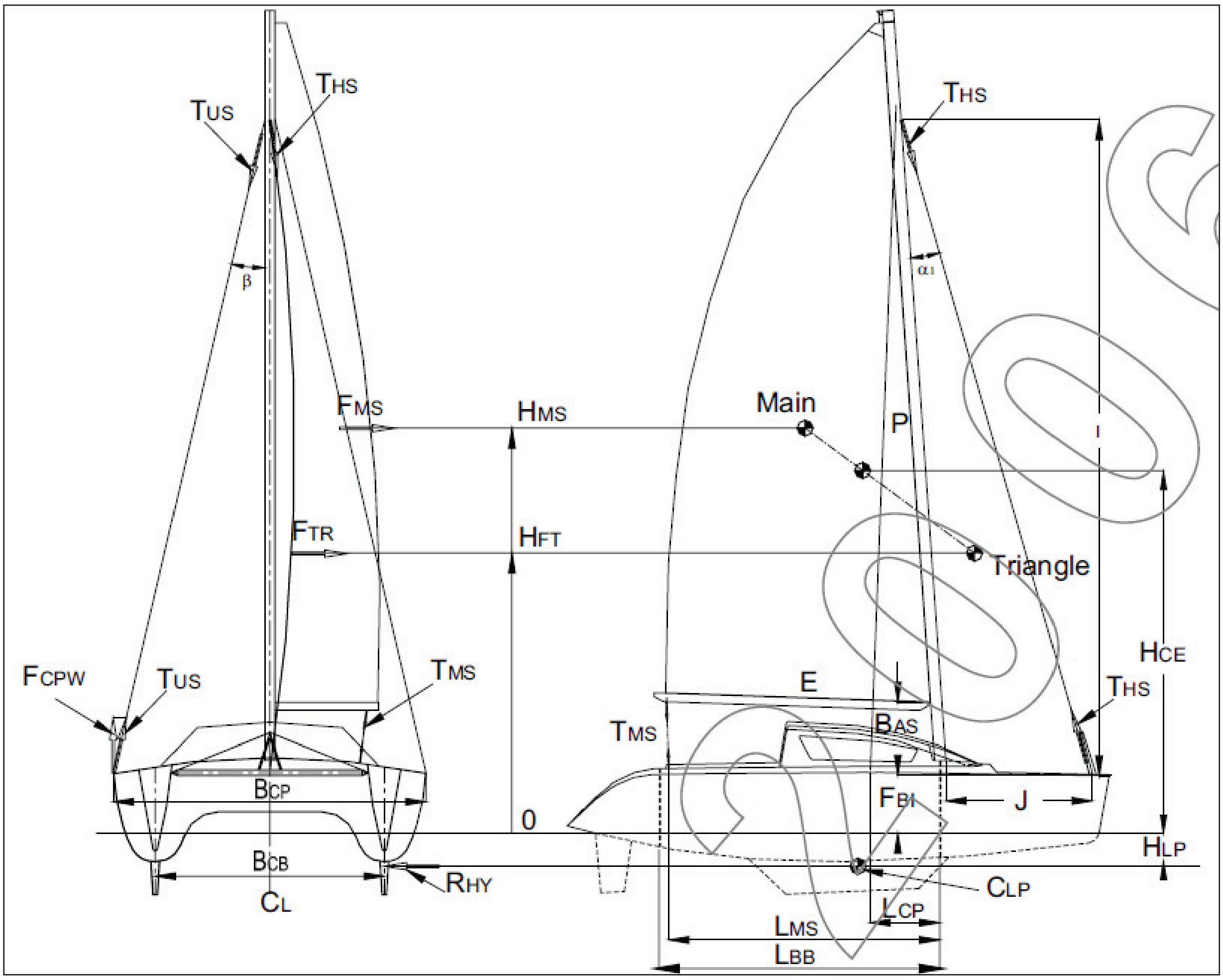

Figure 7 Multihull sailing boat wind forces, [5]

Table 5 Multihull sport boat stays deflections

head stay		jib halyard		mainsail shroud	
deflection, s	T_{HS}/F_{FT}	deflection, s	T_{JH}/F_{FT}	deflection, s	T_{MS}/F_{MS}
0.02	6.25	0.05	2.5	0.08	1.56

Table 6 Shroud selection safety coefficients

	Nitronic 50 Rod	Polymer or carbon ropes
Side shrouds	≥ 2.5	≥ 4.5*
Longitudinal shrouds	≥ 2.0	≥ 3.6*

bility moment M_{HD} the forces can be determined on each sail.

Mainsail force, [5]:

$$F_{MS}=\frac{M_{HD}}{H_{MS}+H_{LP}+(H_{FT}+H_{LP})\cdot\frac{A_{FT}}{A_{MS}}}= \quad (10)$$

$$=\frac{31850}{5,53+0,32+(4,15+0,32)\cdot\frac{11}{22}}=3939\ \text{N}$$

Force at jib, [5]:

$$F_{FT}=F_{FT}\cdot\frac{A_{FT}}{A_{MS}}=3939\cdot\frac{11}{22}=1970\ \text{N} \quad (11)$$

The force at head stay is a function of wind force causing the deflection, i.e. the head stay can be analyzed as a continuous loaded catenaries. The ratio of tensile forces in the stays T and lateral forces from wind F is determined by the following expression, [5]:

$$\frac{T}{F}=\frac{0,125}{s} \quad (12)$$

From these deflections the stays and halyard forces can be determined:

Headstay: $T_{HS}=6,25\cdot F_{FT}$

Jib halyard: $T_{JH}=2,5\cdot F_{FT}$

Main shroud: $T_{MS}=1,56\cdot F_{MS}$

$$F_{CPW}=T_{US}\cdot\cos\beta+0,5\cdot T_{HS}\cdot\cos\alpha_1+ \\ +0,5\cdot T_{MS}+0,5\cdot T_{JH}\cdot\cos\alpha_1 \quad (13)$$

The force at the mast base C_M is determined by the following expression:

$$C_M=T_{US}\cdot\cos\beta+T_{HS}\cdot\cos\alpha_1+T_{MS}+ \\ +T_{MS}+T_{JH}\cdot\cos\alpha_1 \quad (14)$$

When loads which may occur at sailing are known, it is necessary to choose a safety factor for certain parts of the structure. Safety factors that are presented in table 5 show the amount of force multiplication before selecting a particular rope breaking strength, [5].

For more accurate wind loads forces the wind tunnel testing should be performed, [6].

5 SHROUDS SELECTION BY USING THE *AHP* METHOD

In the previously explained way, the Expert approach in combination with the *AHP* method has been used through specialized software ExpertChoice 11 for an optimal rigging selection. When selecting the material the shrouds are made of, the main criteria are the extension, breaking strength and mass, as shown in figure 8. The shroud price is often a neglected factor in the racing sailing boat and, therefore, it is not taken into consideration in the *AHP* calculation. An excessive prolongation of the loaded shrouds leads to changes in the angle of inclination of the mast and thus the inflow of wind, which affects the size of the force created. The goal is to select materials with as higher tensile strength as possible due to the minimization of the shroud diameter which affects the resistance force. For the analyzed racing multihull sailing boat, the selected materials as shown on figure 8 have been analyzed.

The results of the applied *AHP* method are given on figure 9 where the shrouds made of material commercially named “PBO” have been selected as an optimal one for a racing multihull sailing boat. Such a material optimally meets the required criteria and is ranked as first with 37.1 %.

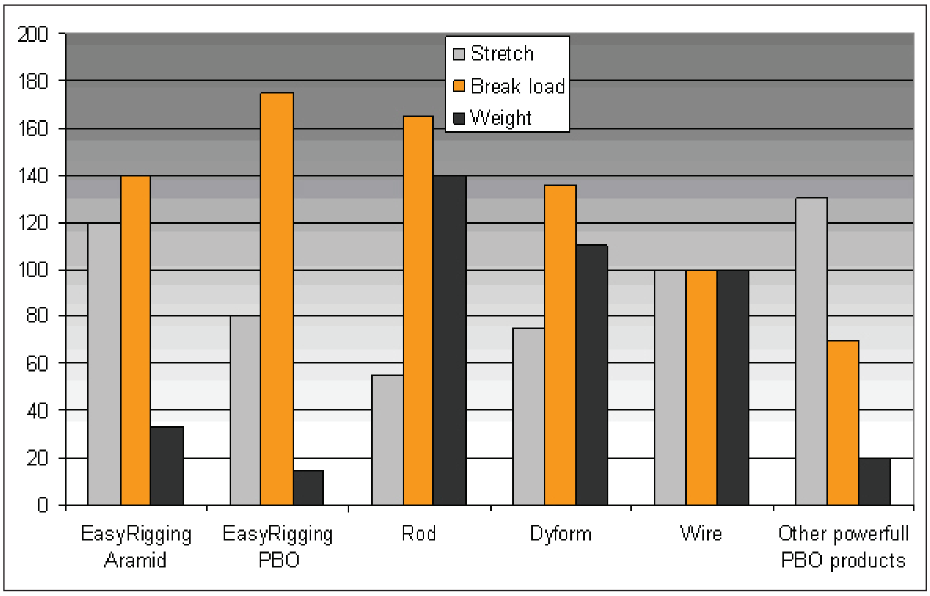

Figure 8 Various shroud materials characteristics [8]

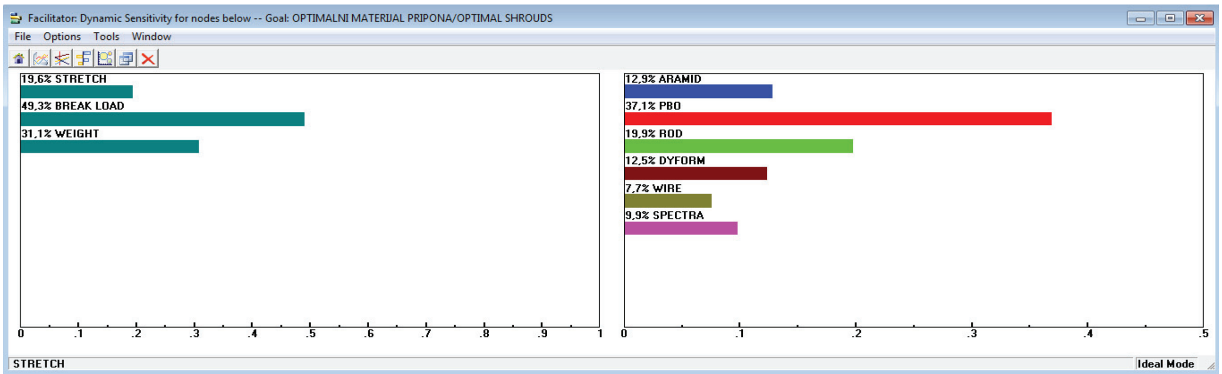

Figure 9 Optimal selected shrouds by using the AHP method, [7]

6 DECK EQUIPMENT SELECTION

Sails manipulation is done by the deck equipment. While selecting such equipment, the suggested Expert approach is essential. The ergonomic position of the equipment is very important. The main sailing equipment of a multihull sailing boat is shown on figure 10.

The sailing boat deck equipment must be selected according to the calculated loads. The equipment manufacturers stipulate a maximum load up to which smooth functioning is possible.

The front sail system is designed to wrap the front sail around the front stay so the fuller is selected, position 1 on figure 10. When choosing fullers, the mass and dimensions for installation are considered. All parts must be dimensioned according to the expected maximum force. The working load that occurs in the fuller's rope depends on the force that occurs at the jib halyard. The ratio of these forces is proportional to the ratio of the drum diameter and winding diameter of the head stay.

To allow trimming of the jib regarding the incoming wind angle and wind force, the jib halyard rope, position 5 on figure 10, is connected with its slider on the deck. By moving the slider on the rail, the trimming can be obtained, figure 11.

Since the working load in the jib halyard is too high for a direct hand manipulation, it is necessary to install a winch, figure 12. The winch is a system of gears with a specific gear ratio appropriate to overcome the working load. With a gear ratio, it is necessary to take into account the ratio of the diameters of lever

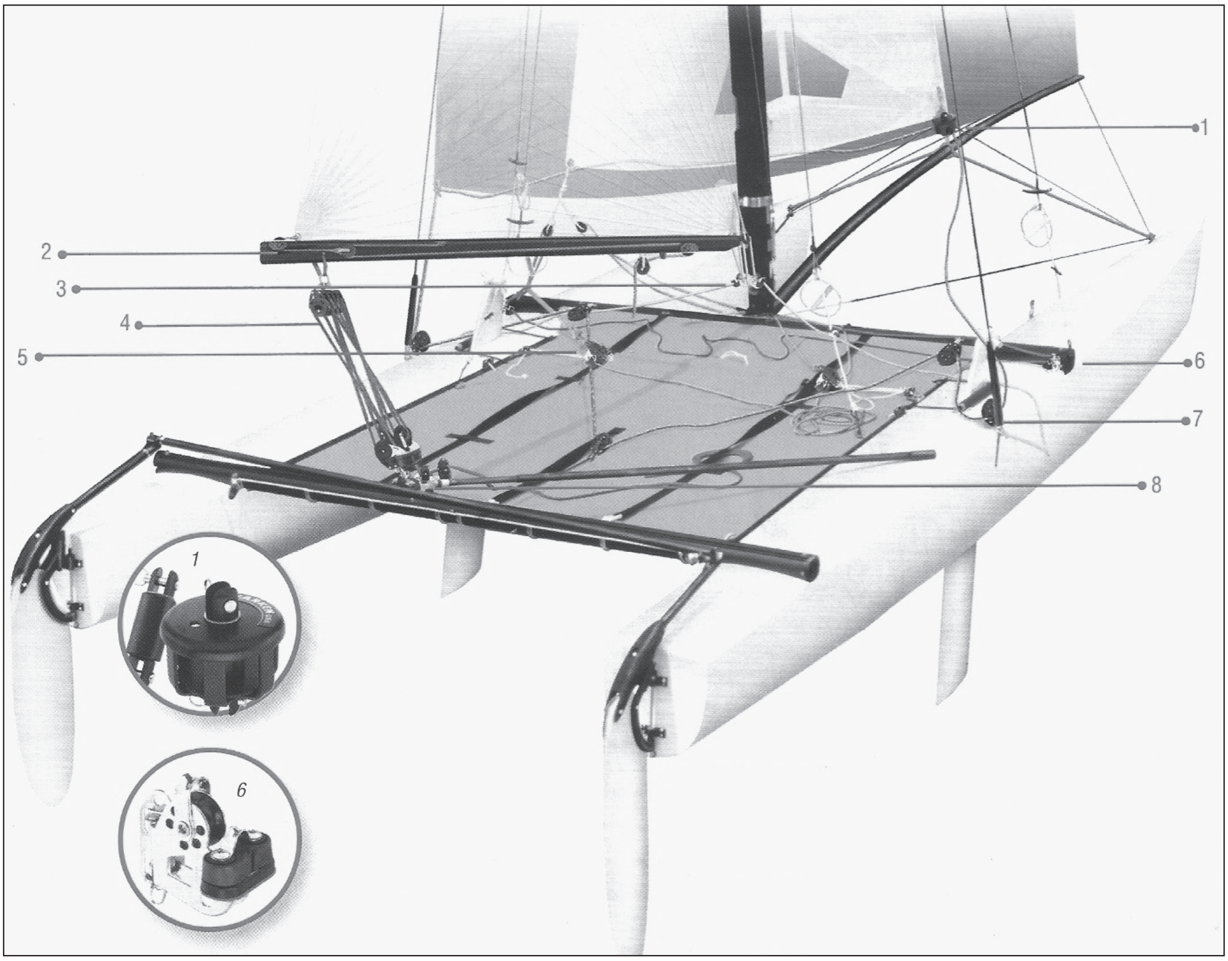

Figure 10 Multihull sailing boat characteristic deck equipment, [10]

and winch drum. Thus it is possible to calculate the overall ratio and the force that must be used for manipulating the jib [5]:

$$F_L = \frac{T_{JH}}{n_1 \cdot n_2} \quad (15)$$

$$n_2 = \frac{2 \cdot l}{d_D} \quad (16)$$

where F_L is the force at lever, T_{JH} the jib halyard force, n_1 the winch gear ratio, n_2 the winch lever ratio, l the length of the lever and d_D the drum diameter. If the selected winch gear ratio is 2.76, the drum diameter 73 mm and the lever length of 254 mm, the required force at the lever would be, [5]:

$$F_L = \frac{T_{JH}}{n_1 \cdot n_2} = \frac{T_{JH}}{n_1 \cdot \frac{2 \cdot l}{d_D}} = 256\ N \quad (17)$$

The resulting size of the force is not negligible, but it should be held in mind that this is the maximum working force that can occur at moments in a regatta sailing.

To adjust the mainsail regarding the intensity and the angle of the wind, the boom can be rotated into the desired position. The boom front end is pivotally connected with the mast and at the rear through the pulley system, position 4 on figure 10, to the slider to the deck, position 8 on figure 10. The main sail form regarding its base can be trimmed by using an Outhaul rope system shown as position 2 on figure 10. Furthermore, the trimming of the main sail along the mast can be done by the Cunningham system of roper shown as position 3 on figure 10.

In the present case, without the winch, the maximum working force that the crew must overcome to correct the boom position is about 219 N. The force by which the stopper on the deck and the rope are selected is 7 i.e. 2 times smaller than the calculated force stays in the mainsail.

Furthermore, a special front sail for downwind sailing, the Asymmetric Spinnaker, also requires adequate deck equipment for an efficient regatta sailing. Besides the sail halyard at-

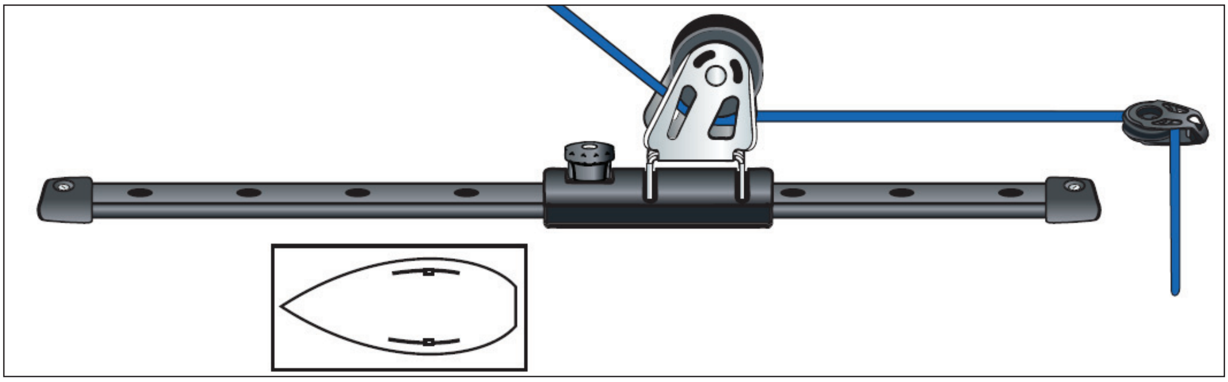

Figure 11 Jib halyard slider, [10]

Figure 12 Winch, [10]

tached on the head of the sail, the front, clew end of the sail is fixed on the so called bowsprit. The bowsprit system can be made with an elastic rope for pulling after the other rope is released on the stopper, figure 13. The final, third end of the sail, tack end, is fixed on the rope used for trimming such a sail passing through two blocks, position 6 and 7 on figure 10.

When selecting the equipment, we took into account its mass and dimensions. The built-in positions on the deck must be ergonomic. On smaller multihull boats generally on the side hull is the steering system only. The sail deck equipment is mounted on the main hull.

7 CONCLUSION

An optimal equipment selection requires a detailed analysis of all the multihull sailing boat specifics, different equipment types on the market i.e. its technical characteristics and pricing as well asd taking into account wind and other loads. The problem is even more pronounced in racing sailing boats equipment selection where the professional crew is pushing such a boat to the limits. Such multi criteria decision making problem requires the usage of certain methodologies based on tools and techniques of the selected Operational research methods. In the first place, the authors have recommended taking the mass of the crew placed on the side of the hull into account when determining

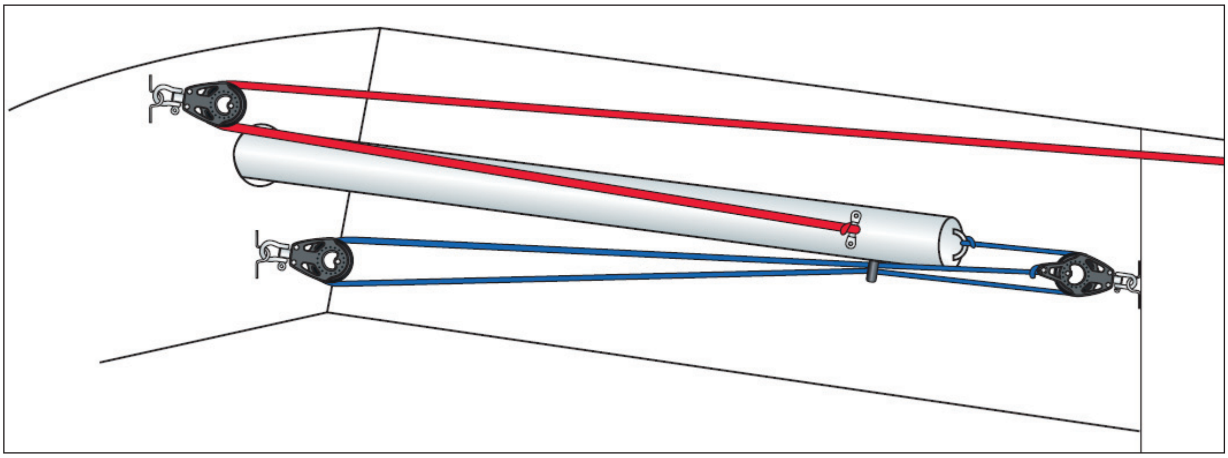

Figure 13 Self-retracting bowsprit system, [10]

the stability moment. Calculations of the working forces need to be carried out with the most likely maximum stability moment at which the sailing is expected. In real life, the equipment manufacturers are recommending the dimensioning and selection of the equipment based on the empirical approach in the function of the sail area. Such approach could be possibly satisfactory for mono hull sailing boats but certainly not for multihull sailing boats where the loads are greater for the same sail area. It is a practice that should be avoided in the design of sport multihull boats. In this sense the authors have presented a novel methodology based on the calculated load values, needed for dimensioning the equipment, followed by an optimal selection of the construction and of the materials of the required equipment based on the expert approach in combination with the *AHP* method for solving the multi criteria decision making problem. Such methodology has been used within the presented case study and the obtained results have been considered to be more accurate.

List of symbols

L_{OA}	m	Length overall
L_H	m	Length of hull
L_{WL}	m	Waterline length
B_{MAX}	m	Breadth of hull
B_{MIN}	m	Breadth of hull (folded)
T_{MAX}	m	Maximal draught
T_{MIN}	m	Minimal draught
m_{LDC}	kg	Fully loaded mass
N		Crew number
CE		Design category
V	m^3	Displacement volume
S_AD		Sail area displacement volume ratio
M_W		Wind overturning moment
v_W	m/s	wind speed
A'_S	m^2	projected sail area
h_{CE}	m	center of gravity of sail area above the waterline
h_{LP}	m	center of area of the surface below the waterline
Φ	°	lateral heel angle
RM_D	Nm	Design overturning moment
k_{vs}		Dynamic coefficient
RM_{MAX}	Nm	Maximum stability moment
A_{MS}	m^2	Mainsail area
A_{FT}	m^2	Jib area
A_S	m^2	Spinnaker area
T_{US}	N	Upper shroud force
B_{CP}	m	Breadth between chain plates
F_{CPW}	N	Windward chain plate force
T_{HS}	N	Headstay force
T_{JH}	N	Jib halyard force
F_{MS}	N	Force at mainsail
F_{FT}	N	Force at jib
C_M	N	Force at mast foot
F_L	N	Winch lever force
n_1		winch gear ratio
n_2		lever / winch ratio
l	mm	winch lever length
d_D	mm	winch drum diameter
AHP		Analytic Hierarchy Process
M		*AHP* matrix
a	°	Head stay angle
b	°	Side stay angle
s		Stay deflection

REFERENCES

[1] Matulja, T.: *Concept design of race multihull sport boat*, Faculty of Engineering, University of Rijeka, 2008.

[2] Saaty, T. L.,: *The Analytic Hierarchy Process*, ISBN: 0-9620317-2-0. RWS Publications, Pittsburg, PA, 1996.

[3] Larsson, L., Eliasson, R. E.: *Principles of Yacht Design,* ISBN: 0-07-135393-3. McGraw-Hill, 2007.

[4] ISO 12215-7 *Small craft – Hull construction and scantlings*, Part 7: *Scantling determination of multihulls*, Draft, 2006.

[5] Germanischer Lloyd,: *Design and Construction of Large Modern Yacht Rigs*, 2009.

[6] Fossati, F.: *Aero-Hydrodynamics and the Performance of Sailing Yachts*, McGraw-Hill, 2009.

[7] Expert Choice, Inc., *Expert Choice software 11*, Arlington, VA, USA, 2004.

[8] http://www.vspars.com

[9] http://www.allspars.co.uk

[10] http://www.harken.co.uk/