Propulsion Aspects of Large Sailing Yachts

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Abstract

The present work forms part of a broader study into the performance of large sailing yachts. The study is driven by developments in commercial shipping projects and environmental conservation projects. The vessels of these projects require a (high) continuous speed, large operating range, low crew numbers and of course low fuel consumption. In many situations sails and engines are used simultaneously. In addition to this the sheer size of the rigs is increasing although it is required that these can be handled by a minimum of crew. Due to these factors, the optimal main dimensions and rig type differ from conventional designs. In order to be able to compare the designs mutually, an Excel-based computer program has been developed in which the performance of these vessels can be evaluated.

Performance calculation is split into a velocity prediction while sailing and a thrust prediction while sailing engine assisted. Velocity prediction is done in the conventional way; force and moment equilibrium are solved for specific wind circumstances. Thrust prediction while sailing on engine and sails is done by an adjustment in the VPP; force equilibrium is calculated at constant speed. Needed engine power and fuel rate can then be computed, based on the propeller and engine properties.

With the aid of this program and a routing sheet, four different rigs are compared: Aerorig, Dynarig, 3-mast schooner and a sloop. The criteria are minimal fuel consumption and minimal voyage time.

The described program makes it possible to evaluate various designs in an earlier design stage and to get a better insight into aspects of the sail assisted mode. It is suitable for a broad range of designs and by its flexible structure, the user can easily adjust several aspects to his own requirements without being a programmer.

1 Introduction

In the past years, the trend in big sailing yachts led to other design requirements. The vessels often use sails and engines simultaneously. In addition to this the sheer size of the rigs is increasing although it is required that these can be handled by a minimum of crew. Therefore, the optimal main dimensions and rig type differ from conventional designs. The consequence is that requirements sometimes exceed the designer's experience and knowledge-based sense for dimensions and that the optimization of main dimensions is more and more a topic of the earlier designs stages.

Until now only rather simple calculations were done on propulsion by engine and sails together. Hansen (1996) gives an overview of wind ship activities and research over the past 30 years. These past researches aimed most of the time on big cargo vessels rather than sailing vessels that are designed in the first place to be propelled by sails. There was no systematic tool that could deal with a whole wind range and that could easily compare different rigs or hulls. Furthermore with respect to velocity prediction while sailing, it was desirable to have a more flexible calculation method in which for example measured resistance and propulsion data or deviating resistance parts could be added by the user himself. To meet these demands, an Excel-based program has been developed at Gerard Dijkstra & Partners.

The main purpose of this paper is to describe this Excel-based calculation method for performance comparison of a vessel that makes use of sails or sails and engine together. Performance is defined as a velocity prediction while sailing and a thrust prediction while sailing engine assisted at a constant speed. It will be explained how performance of different designs can be computed and how these designs could be compared. Furthermore, to show the possibilities of the program, four different rig types suitable for large yachts are compared.

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One of the starting points of the developed program is that resistance is calculated according the Delft Polynomials, although hull ratios exceed the DSYHS (Delft Systematic Yacht Hull Series) dimensions. Some attention will be paid to this in the description of the VPP (Velocity Prediction Program). Furthermore, added resistance due to waves (R_{aw}) is not included yet. Calculation of R_{aw} with the polynomials results in an overestimation of this resistance part and is therefore omitted. Which, at this time, is not of major importance because the main goal of the program is to use it for comparative purposes and not to produce absolute numbers.

The first part of this paper describes both the VPP and TPP (Thrust Prediction Program). Attention is paid to the solved equilibrium, the build up of the program and to the validation of the results. The second part gives a short description of the calculation example with the VPP-TPP. The four different rigs are placed on one and the same hull and are compared for one specific route. Passage time and fuel consumption are computed where average speed is kept to a required minimum. Finally, some conclusions and recommendations are made on the program and the rigs comparison.

2 Build up of the calculation tool

The VPP-TPP has been developed on a normal PC in an Excel-Visual Basics environment. This combination lends itself excellently for a visual check of the calculations and intermediate steps. It is simple to use and also flexible, allowing for user input of for example deviating resistance polynomials or other relations in the equilibrium equations (see also Martin, 2001). During the development of the program, more people have been working on it, one after each other. It was a must that the structure of the program would not be too complicated and that new applications could be easily added. The present structure of the program makes that possible.

The program exists of a VBA (Visual Basic for Applications) part and an Excel part. The latter is used as the interface with the user; it contains input and output sheets. The actual velocity prediction and thrust prediction calculations are done by the VBA part. Velocity and thrust prediction are separated and can be run independently.

Main features of the velocity prediction

The VPP is based on force and moment equilibrium in x direction. The formulation is based on the equations used in WinDesign (see Wolfson Unit, 1995). Figure 1 outlines this equilibrium. The rudder balance of the yacht is not taken into account.

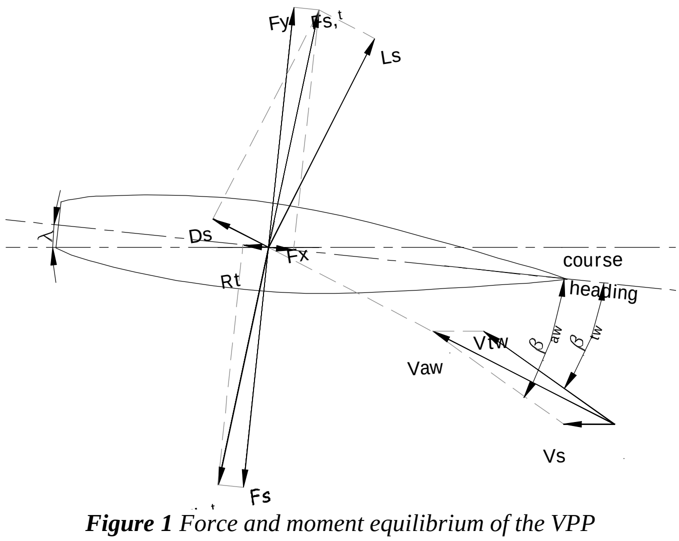

Figure 1 *Force and moment equilibrium of the VPP*

Equilibrium can by simply formulated as:

$$\overline{F}_{H,t} = \overline{F}_{S,t}$$

$$M_{righting} = M_{heeling}$$

With:

$$F_{H,t} = \overline{F_s} + \overline{R_t}$$

$$\overline{F_{S,t}} = \overline{D_s} + \overline{L_s}$$

$$M_{righting} = \overline{\nabla \cdot r \cdot g} \cdot GZ$$

$$M_{heeling} = \overline{F_{S,t}} \cdot (Z_{ce} + Z_{clr})$$

With:

$F_{H,t}$	Total force on the hull
F_s	Side force on the hull
R_t	Total resistance of the hull
$F_{S,t}$	Total force on the sails (windage of hull and rig included)
L_s	Lift force of the sails
D_s	Drag force of the sails
Z_{ce}	Vertical center of effort of the sail plan
Z_{clr}	Vertical center of lateral resistance

A schematic flow chart of the program can be found in the appendix, figure 1. The program is built up in such a way that all resistance calculations are done in the Excel part, so there can be easily checked whether the various resistance parts show a normal trend. The VBA part of the program loads all data from the input sheets into the computer memory and then solves the equilibrium of hydrodynamic and aerodynamic forces and moments. It varies reef and flat to find the best boat speed. The program solves the equilibrium by means of a simple iteration module in which boat speed and heel are varied. The aerodynamic model in the program is based on the same as used in the Windesign VPP (Wolfson Unit, 1995), the hydrodynamic model is based on the DSYHS (Keuning, 1998). The found optimum values for reef, flat, boat speed and heel at the concerned wind speed and wind angle are plotted in the Excel output sheet.

<u>Validation of the VPP</u>

Three parts should be validated to check whether the program is usable for comparative studies. These are the aerodynamic module, the hydrodynamic module and the “solver” module. The aerodynamic module is based on simple equations derived from aerodynamics and are commonly used in yacht design, see also Wolfson Unit (1995). No close validation exists for this part.

As already stated, the concerned hull dimensions and ratios exceed the range of hull parameters tested in the DSYHS, so it is questionable whether the polynomials can be applied. In Nijsten (2002), there is done a comparison for the various resistance parts (frictional, residual etc.) with model tests of the "Athena hull" (3 mast topsail schooner, L_{hull} = 80 m). From this, it became clear that the calculation according the polynomials give a good fit with respect to the upright resistance without leeway (see figure 2). As for the heeled and yawed cases, the tested and computed values show a good match. The mean difference is about 3 %.

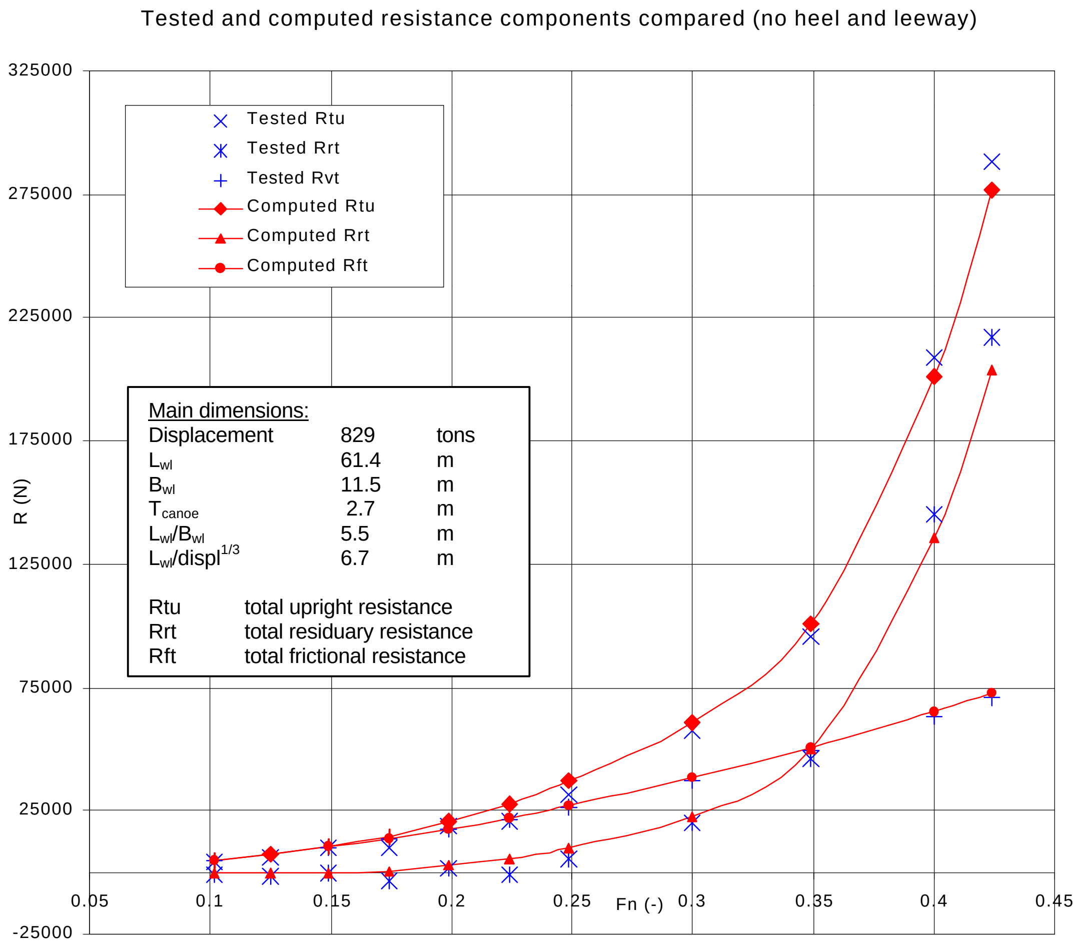

Figure 2 *Upright resistance comparison of a hull that exceeds the range of hull parameters tested in the DSYHS*

To validate the method of solving the equilibrium, the velocity prediction with the TPP-VPP is compared with a prediction according the Windesign VPP. This program is chosen because it uses the same aerodynamic module and has got various hydrodynamic modules, including the DSYHS polynomials. Furthermore, it is commonly used and application of it showed already that the program is suitable for comparative studies, which is also the goal of the VPP-TPP. A detailed explanation can be found in Nijsten (2002). There is concluded that, in spite of a few differences, the velocity prediction according the Excel-VPP is suitable for comparative purposes. It must be emphasized that any agreement with another VPP does not imply that the program yields accurate absolute prediction of the performance. No comparison has yet been made with actual boat data.

Main features of the thrust prediction

The build up of the thrust prediction part of the program is similar to the VPP. Figure 3 shows the forces in x and y direction. Total driving force Fx is now a summation of sail driving force and engine force. The TPP calculates the needed "engine force" for a required constant speed. There is assumed that the added engine thrust only affects this total driving force in x direction and that no differences occur in the moment equation. So:

$$R_t = F_{x,sails} + F_{engine}$$

With:

$F_{x\ sails}$	Sail force in x direction
$F_{engines}$	engine force, assumed to be in x direction only
R_t	Total resistance of the hull

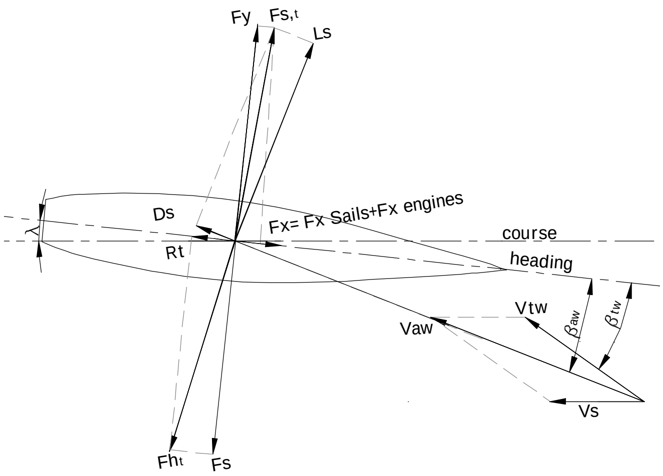

Figure 3 *Force and moment equilibrium of the TPP*

A schematic flow chart of the TPP is included in the appendix, figure 2. It is required to adopt desired Vs in the input sheet. During the calculation, this speed is kept constant and iteration is done with heel only. The output is a minimal needed thrust for the concerned wind speed and wind angle. A negative equilibrium thrust, which means that driving force by sails is bigger then the resistance at the required speed, results in zero engine thrust. In this case, equilibrium speed lies above the required boat speed, which is calculated in the VPP. In some cases, a minimum thrust is calculated at less then the minimum flat and reef values, for example in case of a really small true wind angles. Consequently, the program sets sail power to zero (the sails are down) and the total thrust is equal to the total resistance.

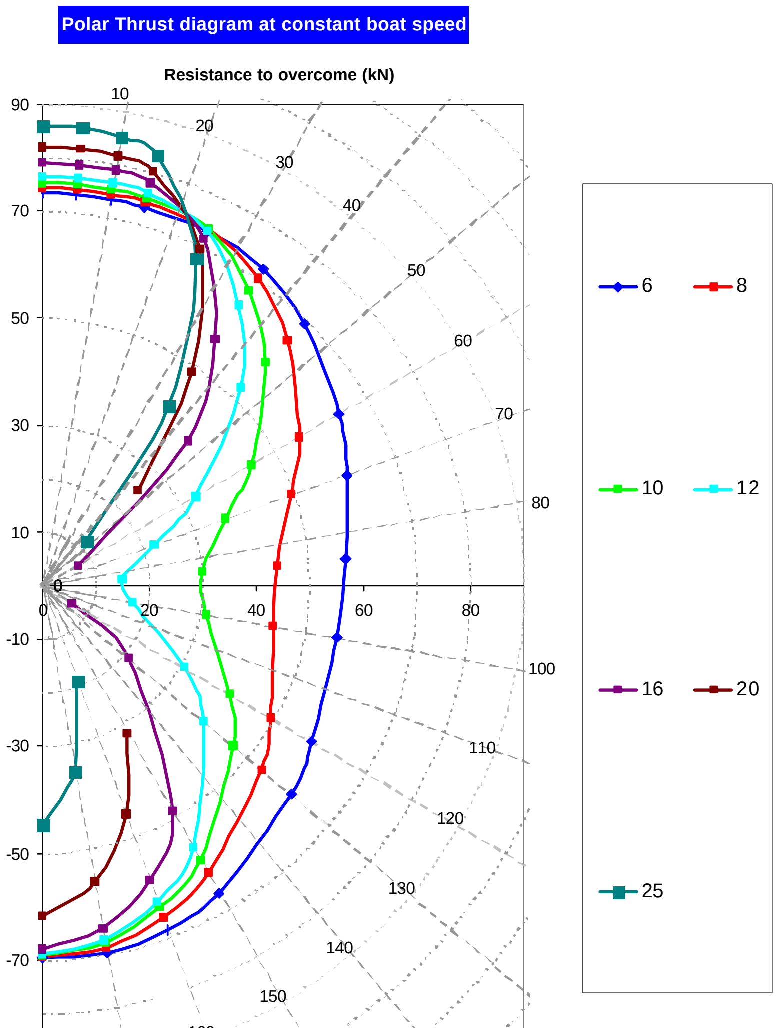

Figure 4 *Example of a polar thrust diagram at constant boat speed of 15 kts.*

The figure above shows a typical thrust diagram, required boat speed is 15 kts. Because the TPP is based on the same calculations and modules as the VPP, it can be assumed that the calculated thrusts are of the same size as the forces in the VPP, and thus should be useable for comparative purposes. It must be emphasized that this does not imply that the program yields accurate absolute prediction of the performance. No comparison has been made with actual boat data. The structure of the program is such that TPP and VPP run totally independent of each other, so they could be run separately and calculation time could be kept to a minimum.

The calculated engine thrust can be expressed in a fuel rate per hour by means of simple relations. For one specific engine and propeller, a relation between needed thrust (T) and propeller efficiency (η_e) is derived (Nijsten, 2002). Here, the propeller characteristics of the controllable pitch propeller are approximated with a propeller diagram of a B series propeller. For every wind circumstance (thus needed thrust), the pitch of the propeller is adjusted so that the working point of the engine lies on the p-curve of the engine. This results in a linear relation that is used to express the force (to be delivered by the engine) in a braking power (P_B) at the shaft and a fuel consumption rate (ϕ_{mb}).

Route calculation

The route sheet is based on a Trans-Atlantic crossing, New York to Landsend. The sheet is used to eventually quantify the performance of the rigs in terms of crossing time and total amount of fuel consumption. The beneath calculation is based on the study on an action vessel for Greenpeace. In this study, a minimum boat speeds was required during a certain crossing and fuel consumption should be kept to a minimum. Fuel consumption consists of fuel used for propulsion only and is an indicator for the performance of a certain rig.

In the route calculation, data from Pilot Charts is put into a spreadsheet. For a certain month, the course time percentage for a range of wind speed and wind angle combinations is calculated (see table 1). With this matrix and a calculation according the VPP-TPP, crossing time and total fuel consumption can be calculated. For every wind speed - wind angle range, an average maximum boat speed and fuel rate is computed.

	Vtw										Total
Btw	2 to 6	7 to 8	9 to 10	11 to 12	13 to 14	15 to 17	18 to 21	22 to 26	27 to 31	32 to 36	%
0 to 40	0	0	0	0	0	0	0	0	0	0	0.0
40 - 44	0	0	0	0	0	0	0	0	0	0	0.0
44 - 48	0	0	0	0	0	0	0	0	0.11	0.26	0.4
48 - 55	1.26	0	0	0	0	0	1.34	1.52	0.93	0.04	5.1
55 - 65	1.67	2.97	2.45	2.75	2.56	3.68	2.08	0.63	0.19	0.11	19.1
65 - 75	0.52	0.63	0.56	0.56	0.63	0.82	0.85	0.33	0.33	0.11	5.3
75 - 85	0.37	0.74	0.41	0.22	0.56	0.56	0.37	0.45	0.30	0.11	4.1
85 - 95	1.04	0.33	0.74	0.48	0.71	0.59	0.93	0.74	0.48	0.15	6.2
95 - 105	0.71	0.41	0.48	0.89	0.82	0.74	1.19	0.45	0.52	0.07	6.3
105 - 115	0.33	0.56	0.78	0.48	0.74	0.78	0.97	0.82	0.33	0.19	6.0
115 - 125	1.04	0.63	0.78	0.45	0.74	0.74	0.63	0.74	0.15	0.15	6.1
125 - 135	0.82	0.30	0.59	0.71	0.52	1.08	1.15	0.85	0.52	0.19	6.7
135 - 145	0.82	0.30	0.67	0.63	0.74	1.30	1.23	0.67	0.82	0.26	7.4
145 - 155	3.01	2.23	2.82	2.30	2.64	3.60	1.93	1.19	0.33	0.26	20.3
155 - 165	0	0	0	0	0	0	2.27	2.71	1.45	0.59	7.0
165 - 180	0	0	0	0	0	0	0	0	0	0	0.0
	11.6	9.1	10.3	9.5	10.7	13.9	14.9	11.1	6.5	2.5	100.0

Table 1 *Course time percentage during a Trans-Atlantic crossing (2765 nm), New York –Landsend*

3 Application of the calculation tool

With the aid of the VPP-TPP and the routing data, a calculation example is done on several rigs. In this example, four different rigs are placed on one and the same hull and performance during a transatlantic passage is calculated. Main goal is to show the possibilities of a program such as the VPP-TPP and to illustrate the broadness of its application.

To find out which rig is most suitable for the given route, two parameters are adopted as a performance indicator: voyage time and amount of fuel consumption. Hereby is assumed that a minimum boat speed of 15 kts is sustained. So sails and engines are used simultaneously at lower wind speeds.

Description of the hull and rigs

The hull is derived from a preliminary study on an 85 m action vessel for Greenpeace. The main dimensions are stated in the following table.

Canoe body:		
Volume	941.53	m3
Displacement, total	1054726	kg
Tmax (T total)	6.57	m
Lwl	82.301	m
Bwl	12.290	m
Cb	0.384	-
Cp	0.528	-
Cm	0.727	-
LCB	45.256	m
LCF	48.304	m
waterplane area	682.571	m2
wetted surface	780.239	m3

Keel:		
Volume	84.53	m3
Span	4.15	m
Croot	24.29	m
Ctip	21.02	m
Cmean	22.65	m
thickness	1.54	m
Vertical center of buoyancy	1.94	m
wetted surface	197.40	m2

Rudder:		
Volume	2.95	m3
Span	4.73	m
Croot	3.80	m
Ctip	2.78	m
Cmean	3.29	m
thickness	0.36	m

Table 2 *Hull dimensions of the 85 m vessel*

The rigs, see figure 5, are still in development or already applied: sloop rig, 3-mast schooner rig, 3-mast Dynarig and 2-mast Aerorig. The 3-mast schooner rig is derived from for the Athena design. The Dynarig was developed in the 60ties by Mr. W. Prölls. It was in the oil crisis that he believed the Dynarig could be used as additional propulsion. The Dynarig is actually a square rig. It has a freestanding mast with yards directly fixed to the mast. The yards already have camber in them unlike the traditional straight yards. The sails are furled onto a mandrill inside the mast. Trimming is done by rotating the entire mast. The Dynarig does not have the disadvantages of a traditional square rig; no limits in bracing angle because there isn't any rigging, sails have better shape due to the curved yards and higher efficiency because there are no gaps between the sails so that they work as one. More on the Aerorig can be found in McDonald (1996).

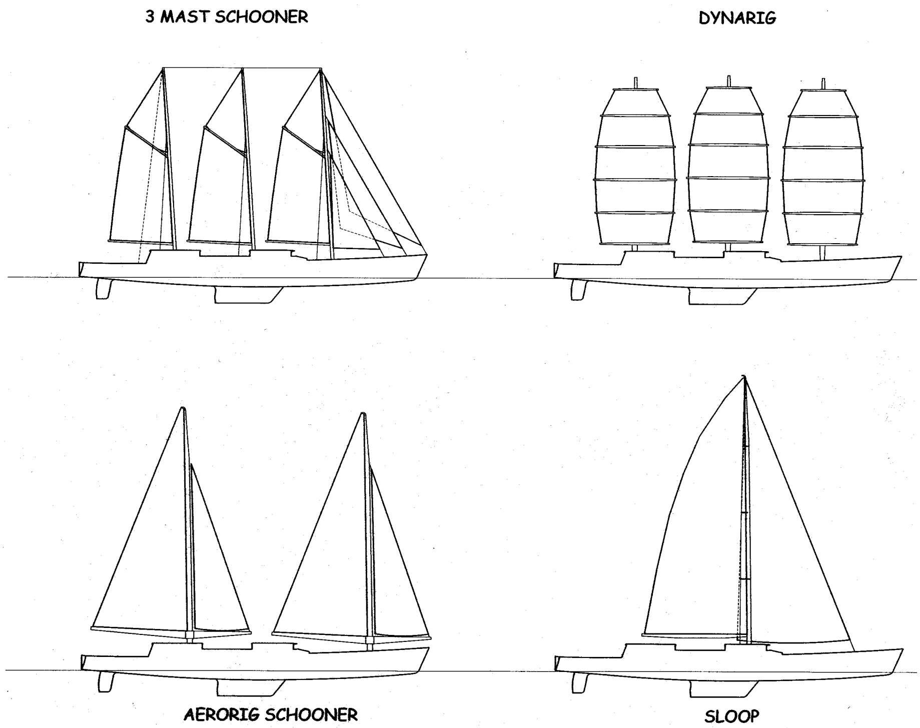

Figure 5 *Schematic sail plans , equal sail area = 2000 m^2*

For simplicity, all the rigs are scaled to the same sail area, 2000 m^2. The total displacement (thus the draught) of the vessel is kept constant by reducing ballast for the heavier rigs. The stability of the vessel is also adjusted according to the weight and center of gravity of the rig. This means that for example the stability of the sloop rig drops due to reduction of the ballast and also due to the high VCG of the rig.

Calculation results

Table 3 sums the total crossing time and fuel consumption for the four rigs. Figure 3 and 4 in the appendix show the polar boat speed and polar fuel rate diagram for 8 and 19 kts true wind speed. It is clear that the Aerorig performances the best for the given route. Both crossing time and fuel consumption are lower then with the other rigs. Striking is that with the sloop, the optimal thrust is always achieved with a combination of sails and engine together (resulting in 0 % of the time on engine alone), although the other rigs show a percentage around 7 % on engine alone. This is caused by the wind speed- wind angle distribution and the fact that the sloop performs best on sails and engine together. Only at really small wind speed-high wind angle combinations it is optimal to sail on engine alone. The high fuel consumption of the 3-mast schooner is mainly caused by the huge amount of windage and also by its low up wind performance. Because the Dynarig and Aerorig produce less side force and have a low center of effort, they are characterized by a big sail carrying capacity when reaching, which suites the given crossing weather profile.

Again there must be emphasized that added resistance in wave is not included in the calculations.

Transatlantic crossing	Rig	3 mast sch. 2000 m2	Dyna rig 2000 m2	Aero rig 2000 m2	Sloop 2000 m2
average time	hrs	175.36	172.94	170.28	176.62
	days	7.31	7.21	7.09	7.36
average distance	nm	2765.00	2765.00	2765.00	2765.00
total fuel consumption	tons	17.52	15.12	12.05	15.51
minimal sustained boatspeed	kts	15.00	15.00	15.00	15.00
percentage of time:					
sails:	%	26	32	39	26
engine and sails:	%	65	61	55	74
engine	%	8	7	6	0

Table 3 *Total crossing time and fuel consumption during the transatlantic crossing*

4 Discussion

Although figure 2 shows a match for a hull that exceeds the Delft-series, more model tests should be done on yachts with higher length-beam and length-displacement ratios. Until now only few test data is available and uncertainties exists between the calculated values and actual boat data. Future research should furthermore aim on a polynomial description of the added resistance in waves for bigger yachts. This could be done in the same way as is done for the present DSYHS; a polynomial is derived from added resistance as calculated with the strip theory program “Seaway”.
A further optimization of the program could lay in the use in a standard Excel solver as in Martin (2001). This could reduce calculation time further. This solver could also be used for the build in of an optimization tool, which could optimize the main dimensions of the rig and hull.

With respect to the example, results depend totally on the choice of weather profile. The example is not meant to quantify the rigs but purely meant to show the possibilities of the program.

For the sail-assisted mode, the used linear relation between propeller efficiency and propeller load is only valid in the circumstances as given. This means only valid for the adoptions with respect to the propeller diagram, interaction coefficients and efficiencies of the propulsion installation. A broader derivation and a better insight into the adoptions could make the program more flexible.

With this in mind, a program like the VPP-TPP could eventually be used for prediction of the actual boat performance instead of for comparative studies only.

5 Conclusions

The described program makes it possible to evaluate various designs in an earlier design stage and to get a better insight into aspects of the sail-assisted mode. Although the concerned hull ratios exceed the present DSYHS, relatively good similarity exists between measured and calculated resistance of a hull that exceeds the series. This, and the match with an existing VPP, makes the Excel-VPP TPP suitable for comparative studies.

The program is suitable for a broad range of designs and by its flexible structure, the user can easily adjust several aspect to his own requirements without being a programmer. The calculation example with the four different rigs shows that, together with routing data, a good quantification can be made of the performance of a (engine-assisted) sailing yacht.

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Appendix

Schematic flow chart, velocity prediction

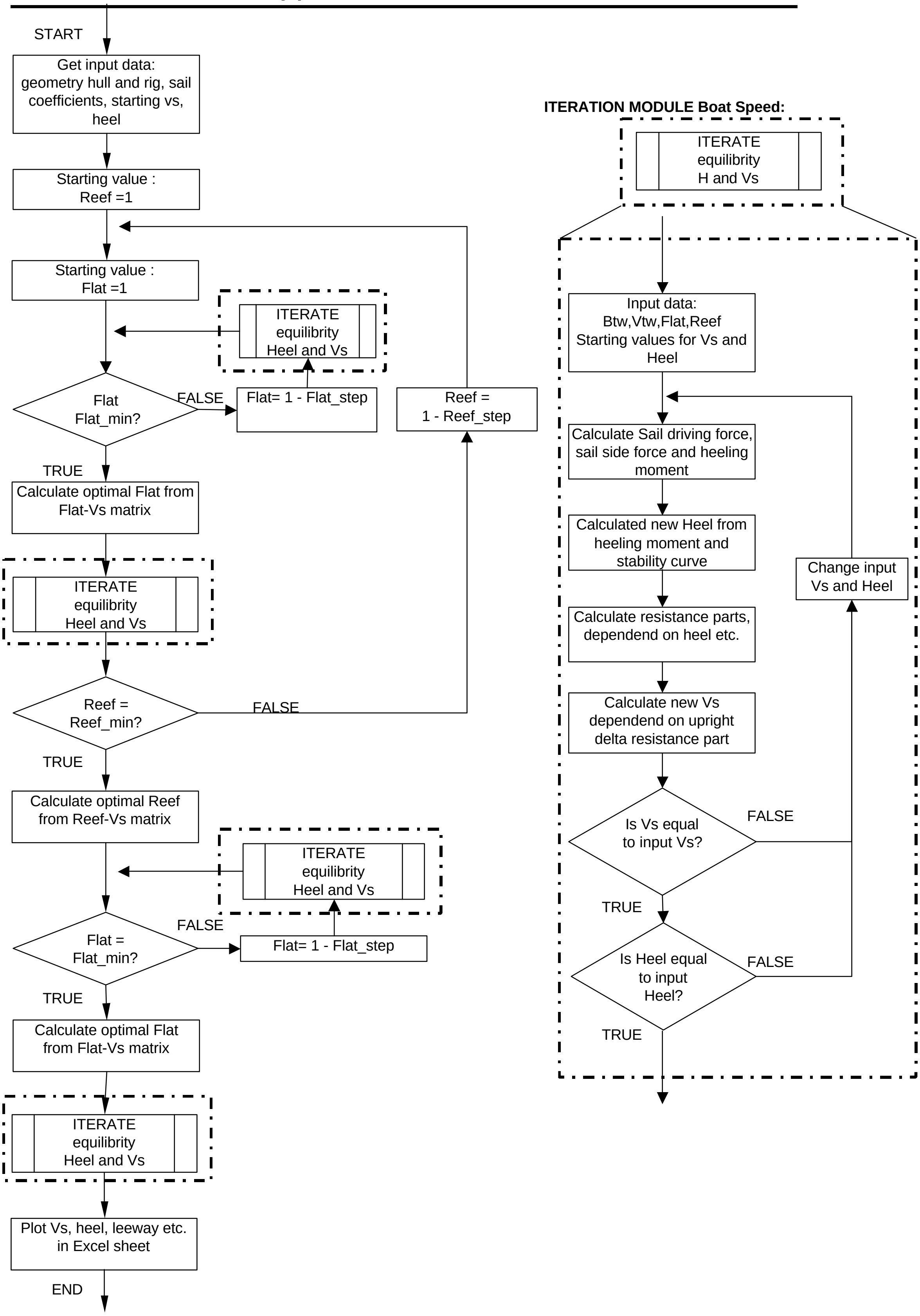

Figure 1 *Schematic flow chart of the VPP*

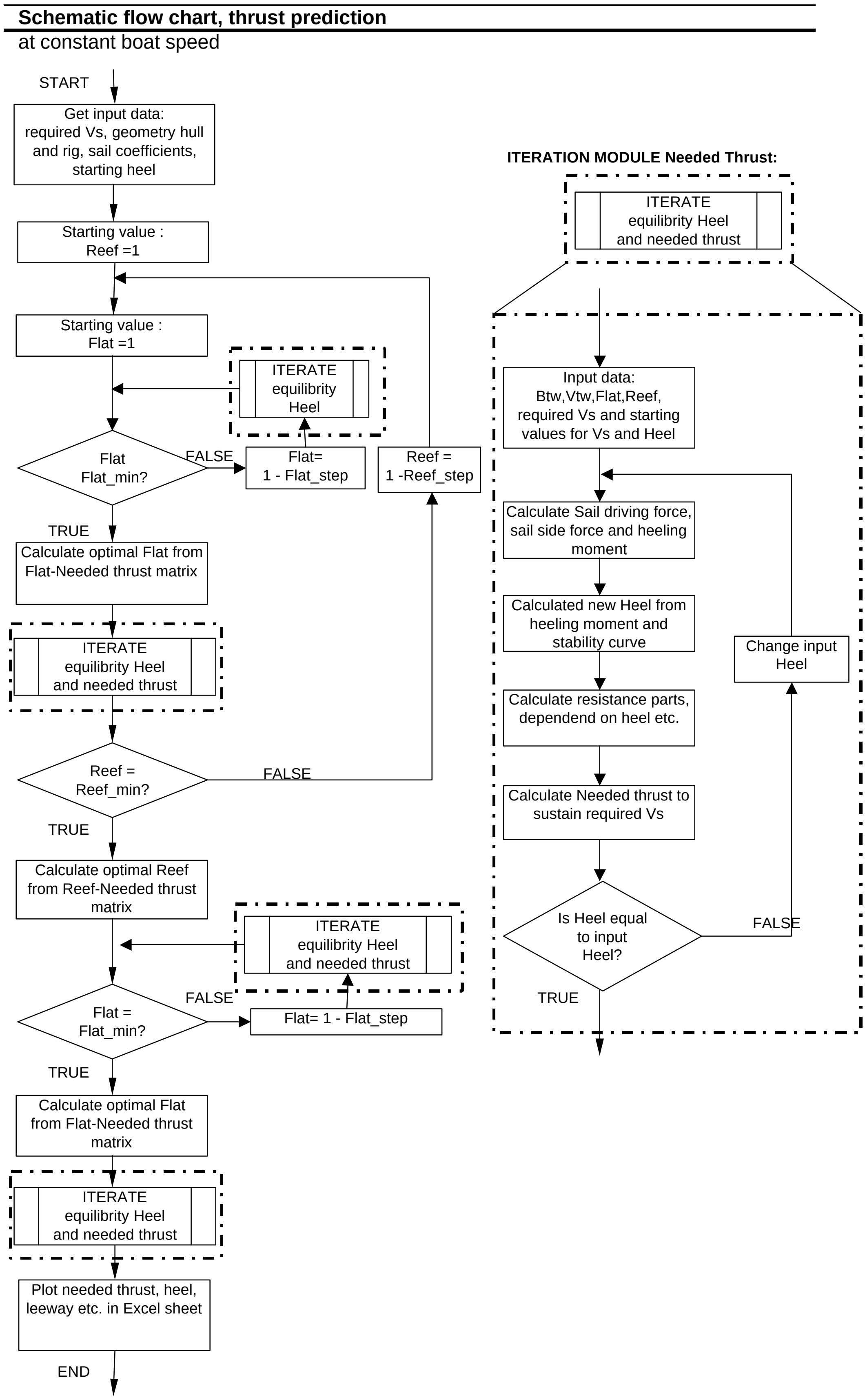

Figure 2 *Schematic flow chart of the TPP*

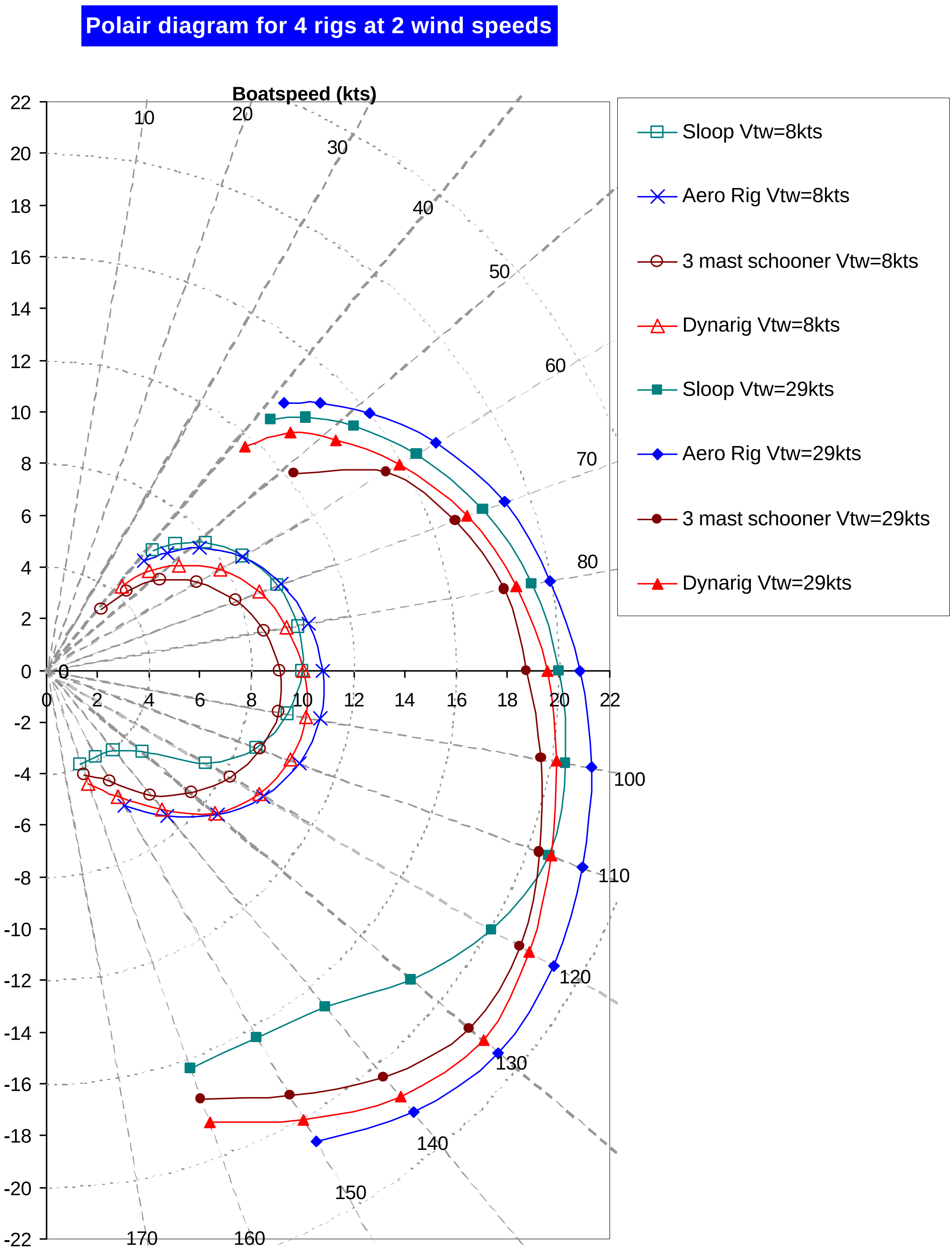

Figure 3 *Polar diagram of the rigs, 2 true wind speeds*

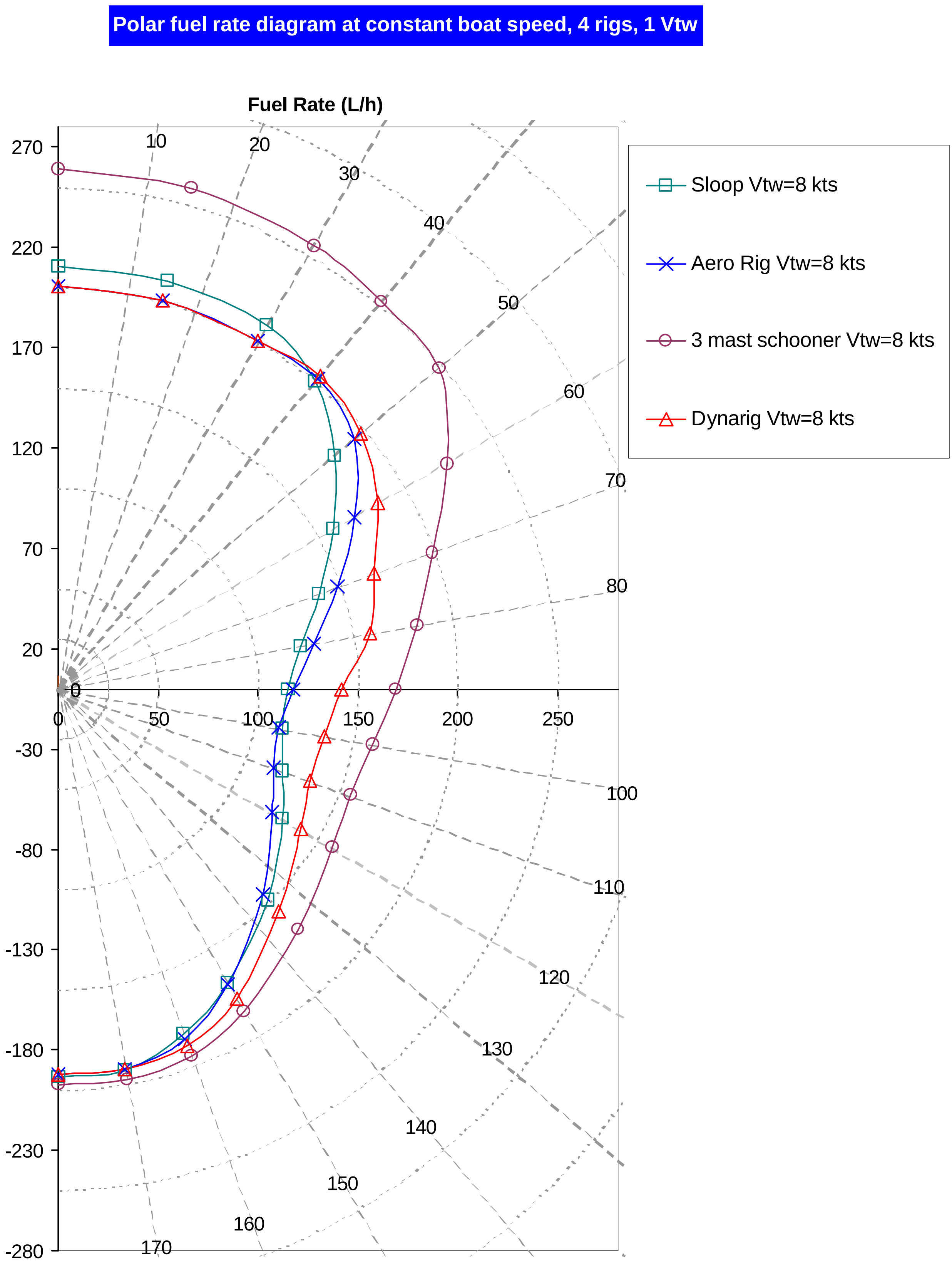

Figure 4 *Polar fuel rate diagram of the rigs, 1 true wind speeds, Vs = 15 kts*