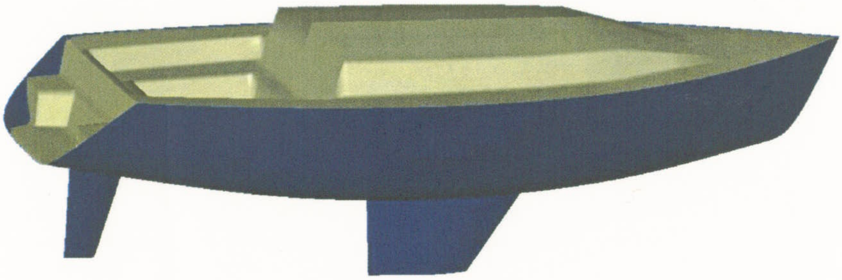
Massachusetts Institute of Technology
DEPARTMENT OF OCEAN ENGINEERING
Cambridge, MA 02139

FINAL PROJECT
PDS39 Cruising Sailboat



13.734
November 21, 2003
Pete Small

Good Evaluation - most accurate [illegible] by another Student

110

13.734 Design Review
December 1, 2003

Design By: George Gougoulidis
Review By: Pete Small

Review Summary

While discussion of the design philosophy was minimal and no comparative design parameters were presented, George's design is intended to be a heavy and comfortable luxury cruiser. And while the design is mostly complete and thorough, the somewhat cursory report does little to convey the design process and decision-making that occurred. The aspect of the design that seems to dominate all others is the boxy and stable hull form.

George has drawn a hull with a wide, flat bottom and firm bilges. I think he intended this for interior volume and perhaps performance, but I believe that the result is a fast but stiff and uncomfortable boat in a seaway. The considerable form stability of the hull has affected other aspects of the design in that a large sailplan with beefy rigging is required. No non-dimensional parameters were presented in the report, but I calculate a DLR of 168, SA/DISP of 21.3, SA/WS of 2.6, and a Dellenbaugh angle of 9.62. These numbers are more indicative of a fast, light, and stiff racer than of a heavy, luxury cruiser. This is not to say he has done a poor job, indeed, the interior as drawn looks luxurious and the SPAN data indicate a fast boat. I just question how "comfortable" the motion of this boat will be. A summary of the specific design review points by category follows.

1. Preliminary Design
    - Only one design goal: a comfortable and luxurious cruiser for six people.
    - No comparative data or non-dimensional design goals presented.
2. Hull Design
    - Fair lines, with boxy sections and flat waterlines.
    - Lots of form stability built in, but I believe it will have a stiff and quick motion.
    - No grid lines or scale presented on lines drawings.
    - No non-dimensional hull data presented (I get DLR=168, SA/D=21.3, SA/WS=2.6).
    - Nice sectional area curve.

3. Appendage Design
    - NACA 64 section is good choice for the keel (which operates at low angles of attack), but its fine leading edge may facilitate stall in the rudder at high angles of attack. A NACA 0010 series foil might be better for the rudder.
    - There is no mention of rudder or keel area and if they provide sufficient lift to reduce leeway and provide adequate steerage. Both the foils look a little small to me.
4. Sailplan and Rig Design
    - Hard to follow the rig structural calculations, but they appear to be complete.
    - I believe the sailplan is so large because the hull was drawn so stable.
    - The hull stability results in large rigging loads and beefy rigging (14mm shrouds).
5. Structural Analysis
    - No stiffener sizing calculations are shown, but stiffener areas were included in the weight calculation.
    - No rudder stock sizing calculations.
    - The plating thickness calculations are complete and thorough. Round up the final numbers instead of specifying a hull thickness of 9.993mm (for example).
6. Weight Table
    - Weight table looks comprehensive.
    - The upright hydrostatic data presented in the report do not reflect the VCG calculated in the weight table. (This might have helped some with the stability problem).
7. Interior and Deck Layout
    - Deckhouse looks very low and narrow. I am not sure if this provides adequate headroom in critical places such as the galley.
    - There might be a problem with space in and access to the aft cabins. It looks low back there.
8. Stability Analysis
    - Hull is extremely stable. Indicators are: GMt=2.2m, RM (1 deg)=535 kgm, Dellenbaugh angle (as calculated by me)=9.6 deg.
    - No hull characteristics when heeled. (Although I don't believe it was clear that this was required. I didn't put this in my report either.)
9. Performance Analysis
    - SPAN results indicate a very fast boat.
    - No real analysis or comparison of results.
10. Overall Design
    - Aside from discussion of length, beam, and weight, not much attention is paid to achieving design goals.
    - While the interior is luxurious, I don't think the impact of the hull stability on comfort was adequately considered.
11. Final Report
    - Report is somewhat cursory.
    - See attached sheet for grades assigned to each category.

Student name	**Comments**	**Grade**
Georgios Gougoulidis		
Sandeep Dave Pete Small		
Preliminary Design Design phylosophy, choice of initial parameters, comparison with existing designs.	[illegible] comparison data - comfort - priority #1	5 / 10
Hull Design Line drawings, sectional area curve, maximum area section, canoe body specifications.	very boxy lines - form stability ⇑ - comfort ↓ ~~No [illegible]~~ [illegible] no scale, grid lines	9 / 12
Appendage Design Planform design, profile choice, location.	Rudder NACA 641 - high angle of attack? No [illegible] (leeway) keel looks small	6 / 7
Sailplan and Rig Design Sailplan choice, sailplan dimensions, rig dimensions, rig structural design.	Hard to follow rig structural calcs. ~~No [illegible] of spreader length/sail list~~. Form stability → thick rigging	8 / 10
Structural Analysis Construction method choice, deck and hull structural design, including internals, keel attachment, and rudder stock.	- no stiffener sizing calcs (but areas incl. for weight) - no [illegible] calc. good [illegible] but round up instead of having 9.9mm or 8.1mm	7 / 10
Weight Table Weight and center of gravity estimates of different components, final LCG and VCG.	Seems Good - upright hydrostatic data do not reflect [illegible]	6 / 6
Interior and Deck Layout Interior arrangements, and deck layout.	[illegible] [illegible] headroom [illegible] [illegible]	4 / 5
Stability Analysis Large angle stability analysis performed with Hydromax, including angle of positive stability nad hull characteristics when heeled.	No [illegible] [illegible] not sure he gets [illegible] boat?	5 / 7
Performance Analysis Polar graph from Span, comparison with existing designs.	Boat is fast, not much analysis of results.	5 / 5
Overall Design Achievement of initial goals.	Not much discussion [illegible] goal (comfort), other than 'larger' beam and weight - I say boat is not really comfortable as was goal	3 / 5
Final Report Presentation, organization, completeness.	Somewhat cursory write up	10 / 15
Final Grade		71 / 92

DLR = 165
SA/D = 21.3
SA/WS = 2.62
Dellenbaugh = 9.62
GM1 = 2.2
LOA/B = 3.3

Student name SMALL	**Comments**	**Grade**
Oral Presentation Given to the 13.734 class.		8 / 8
Preliminary Design Design phylosophy, choice of initial parameters, comparison with existing designs.		10 / 10
Hull Design Line drawings, sectional area curve, maximum area section, canoe body specifications.		12 / 12
Appendage Design Planform design, profile choice, location.		7 / 7
Sailplan and Rig Design Sailplan choice, sailplan dimensions, rig dimensions, rig structural design.		9 / 10
Structural Analysis Construction method choice, deck and hull structural design, including internals, keel attachment, and rudder stock.		10 / 10
Weight Table Weight and center of gravity estimates of different components, final LCG and VCG.		6 / 6
Interior and Deck Layout Interior arrangements, and deck layout.		5 / 5
Stability Analysis Large angle stability analysis performed with Hydromax, including angle of positive stability nad hull characteristics when heeled.		7 / 7
Performance Analysis Polar graph from Span, comparison with existing designs.		5 / 5
Overall Design Achievement of initial goals.		4 / 5
Final Report Presentation, organization, completeness.		15 / 15
Final Grade		98 / 100

hull & interior too heavy

Small

Very thorough study of existing available designs.

Very balanced waterlines fore and aft. Good for nice sailing boat although added resistance from sea waves more then minimum.

Appendages logically designed for the draft limitation goal.

Good analysis (quantitative and qualitative) for chainplate width.

Sail area seems a little too small, both from calculation to heel 25 degrees and the Dellenbaugh angle. A slightly taller mast is recommended.

With the 135% genoa, and figuring for three jibs total and two spinnakers, the space under the forward berths will probably not hold not all the sails as presumed in the report. Not much can be done about this except to have some sails in the interior.

12 mm keelbolts seem very small in diameter. The ABS RULE probably permits this because the keel is thick, but the safety and greater nut bearing surface of larger diameter bolts is recommended. They can easily fit in the large keel.

Nicely, this is one of the few cases where the "designer" added the wind speeds to the polar speed curves.

The sail area/wetted area and sail area/displacement$^{2/3}$ are in the middle of the statistical ranges of older boats. They should be slightly larger for this modern boat that is oriented to light wind performance.

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References

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Gerr, Dave. The Nature of Boats. Camden, ME. International Marine, 1992.

"Guide For Building and Classing Offshore Racing Yachts." American Bureau of Shipping. Notice 3, 1 January, 2001.

Killing, Steve, and Hunter, Douglas. Yacht Design Explained. New York, NY. W.W. Norton & Company, Inc, 1998.

Larsson, Lars, and Eliasson, Rolf E. Principles of Yacht Design. Camden, ME. International Marine, 2000.

1.0 Design Philosophy

The PDS39 is primarily an inshore cruising boat that will have limited offshore capabilities. The accommodations are simple but adequate for a small family or two couples for a long weekend. As such, the weight is on the lighter side in an attempt to increase cruising performance. The length overall (LOA) is 12m to minimize construction, maintenance, and operation costs. The largest limitation on the performance of the boat is a six-foot (1.83m) overall draft. The market for the PDS39 is primarily the Mid-Atlantic region of the United States, and the boat is expected to cruise the waters from North Carolina to Long Island Sound. A draft of more than six feet can seriously limit the cruising grounds in these waters. The boat must perform well in light wind, as these conditions prevail in the late summer of much of the intended cruising realm such as the Chesapeake Bay. The sail plan is generous yet simple, with two sets of spreaders and no running backstays. The spars are aluminum with stainless steel wire rigging. Construction methods and materials are simple to reduce cost and extend the useful life of the boat. The hull is solid glass-reinforced plastic (GRP) with vinylester resin for ease of construction, durability, and strength. Headroom of six feet, six inches was required below, and a sloop rig was specified.

2.0 Parametric Design Study

An internet search was conducted and data were collected for similarly-sized boats. Only data for new cruising or cruising/racing boats were obtained. Many of the boats such as the J120 and Swan 45 tended more toward lightweight racing boats than true cruising vessels. On the other end of the spectrum were the heavy, ocean-capable boats from Island Packet Yachts. Other mass produced boats such as those from Beneteau, Catalina, and Jeanneau better represented the design space of this project.

Hull and sail plan data as available were collected in a spreadsheet, and many design parameters such as sail area to displacement ratio (SA/D), displacement to length ratio (DLR), and length to beam ratio (LOA/B) were calculated. The boats were sorted by ascending DLR, with the lightweight racers on the left and the heavyweight cruisers on the right. Mean, median, minimum, and maximum values for all the data and the design parameters were calculated. In addition, running averages for the design parameters were kept from left to right to better understand the parameter transition from left to right and boat to boat. The parametric design spreadsheet is included as Appendix A.

This small collection is not necessarily a representative sample of the yachts in production today, but was simply assembled from class recommendations and the author's own experience with boat builders. Nor does it represent the long and rich history of cruising yachts that are no longer in production. Acknowledging these limitations, one trend was clearly seen. The DLR of most of the boats is significantly lower than what has been the generally accepted value for cruising boats (around 200). The average and median DLR for the sampled boats were 183 and 171, respectively. Correspondingly, the length to displacement ratios (L/D) were considerably higher than those put out in class and the text, Principles of Yacht Design, by Lars Larsson and Rolf Eliasson. The mean and median values were 5.4 and 5.5 respectively. In general, the parametric data provided valuable insight into many useful hull and rig design parameters.

3.0 Initial Design Parameters

As mentioned above, the length overall (LOA) was limited to 12m. The parametric data indicated a typical LOA to waterline length (LWL) ratio of 1.14 which is in the range presented in the text (1.23 +/- 0.15). Using 1.14 gave a LWL for the PDS39 of 10.53m. The mean DLR from the parametric data was 183, but this still seemed on the light side for a cruising boat of solid GRP construction, so a DLR of 190 was chosen for the PDS39. This gave a displacement of 7951kg. The average parametric value of LOA/B (3.15) was chosen which gives a beam of 3.81m. This corresponds nicely with the hull statistics provided in the text. The average freeboard selected (1.35m) was somewhat higher than the limited data available based on the six-foot, six-inch headroom requirement for the boat. The prismatic coefficient (C_p) was set at 0.57 in accordance with the optimization presented in the text.

The canoe body draft (T_c) was set at 0.55m. The text recommended LWL/T_c ratio of 18 gave a T_c of .585m and a midship area coefficient (C_m) of 0.63. Reducing the T_c to 0.55 gave a more reasonable C_m of 0.67. Since the overall draft of the boat is limited to 6 feet (1.829m), the resulting keel span is 1.279m. The initial design parameters are summarized in Table 1 below.

Table 1. Initial Design Parameters

LOA (m)	12
LWL (m)	10.53
DLR	190
Displ. (kg)	7951
L/D	5.27
B (m)	3.81
BWL (m)	3.21
C_p	0.57
T (m)	1.83
T_c (m)	0.55
SA/D	20
LCB frac	0.535
LCF frac	0.57
Ballast ratio	0.45

The waterline beam (BWL) was initially set at 3.51m to give six inches (15 cm) of flare on each side of the hull. This was later changed to 3.21m after the initial stability was calculated and the velocity prediction program (VPP) analysis was completed. This gives one foot (30 cm) of flare on each side, which is quite reasonable. The ballast ratio (BR) was set at 0.45. This corresponds to the data in the text, but is somewhat higher than the averages seen in the parametric data. The increased ballast will help to offset the relatively shallow draft of the boat.

At this point the hull of the PDS39 was pretty well defined. Additional design parameters were required, however, in order to conduct the VPP analysis. The mast diameter was based on the 221 aluminum mast section for typical 40-footers listed on the Sailnet.com web site. Mast span (16m), sail area to displacement ratio (SA/D=20), and fore triangle distance (J=4.7m) were selected from parametric data and corresponded well with the text. Longitudinal center of buoyancy (LCB) fraction (0.535) and longitudinal center of flotation (LCF) fraction (0.57) were selected from recommendations presented in class.

Sizing the keel and rudder size was not as simple. A spreadsheet was built to calculate the size of a simple trapezoidal keel and rudder. Given overall draft (T), T_c, thickness fraction (t/c), and taper ratio, the spreadsheet could be used to size the keel to fit the volume of lead required (based on ballast ratio) or area required (based on percentage of sail area as described by Larsson and Eliasson). An example of the spreadsheet is included as Appendix B.

3.1 Velocity Prediction Program Analysis

A simple DOS-based VPP was used in an attempt to predict the performance of the PDS39. It turns out that the program will only run properly with deep keels. Realizing that the PDS39 is limited in draft to six feet, some utility was extracted from the VPP model by attaching a deep keel to the boat and varying waterline beam and mast span. Table 2 below provides a sample of the VPP output. The optimal upwind and downwind sailing conditions in ten knots of breeze are presented for two values of BWL and mast span. The narrow waterline and tall mast combination maximized VMG both upwind and downwind. The details of the rig design were finalized later, but the narrower waterline was incorporated into the initial design.

Table 2. Sample VPP Output.

10kts of Wind	UPWIND		DOWNWIND	
Variant:	V	VMG	V	VMG
16m Mast, 3.2m Bwl	5.945	4.108	6.292	-5.834
16m Mast, 3.5m Bwl	5.8	4.005	6.197	-5.746
17m Mast, 3.5m Bwl	5.934	4.133	6.229	-5.775
17m Mast, 3.2m Bwl	6.085	4.258	6.323	-5.863

4.0 Initial Design of Hull, Appendages and Rig

4.1 Hull Design

The DLR was increased to 200 prior to starting the actual design of the hull. Further reading indicated that this was more realistic for a dedicated cruiser (not necessarily cruiser/racer) and that the data in the parametric study was heavily weighted towards the light side of the spectrum. The waterline length was decreased to 10.0 m to give a more graceful bow overhang. This gives a LOA/LWL ratio of 1.20 which is still reasonable and within the range given by Larsson and Eliasson. It is interesting to note that even though DLR was increased, the displacement of the boat still decreased because of the reduction in waterline length. The prismatic coefficient was reduced to 0.56 to give the PDS39 a slight edge in light wind. Canoe body draft was reduced slightly to

0.52 to increase the keel span and improve upwind importance. The new hull design parameters can be seen in Table 3.

Table 3. Revised Hull Design Parameters

Parameter	Initial	Revised
LOA (m)	12.00	12.00
LWL (m)	10.53	10.00
DLR	190	200
Displ. (kg)	7951	7176
L/D	5.27	5.18
B (m)	3.81	3.81
BWL (m)	3.21	3.2
C_p	0.57	0.56
T (m)	1.83	1.83
T_c (m)	0.55	0.52
SA/D	20	20
LCB frac	0.535	0.535
LCF frac	0.57	0.57
Ballast ratio	0.45	0.45

The appendage design spreadsheets were used to estimate the displacement of the foils and the hull was drawn in MAXSURF. The lines drawings can be seen in Appendix C. The final hull data as drawn is presented in Section 4.4 below.

4.2 Keel Design

NACA section foils were selected for the keel and rudder. For the keel, a NACA 64 series section with thickness ratio (t/c) of 12 percent at the root and 15 percent at the tip was chosen. The smaller t/c at the root was chosen to reduce drag from wavemaking and interference at the hull/keel intersection (Larsson and Eliasson, 131). The larger t/c at the tip increases stability by allowing more lead to be placed low in the keel. The 64 series section gives a relatively low drag coefficient at low angles of attack and is commonly selected for sailboat keels (Killing, 74).

The keel design spreadsheet mentioned above (Appendix B) was used to size the keel for area and volume. The thumbrule for required keel area based on sail area given by Larsson and Eliasson (keel area~3.5% of sail area) was used to size the keel. A taper ratio of 0.6 was chosen to allow for ballast in the short span of the keel. The penalty in induced drag because of the high taper ratio is slight because the keel has relatively low aspect ratio. The keel volume was calculated by integrating the NACA section shape

(Abbott and von Doenhoff, 385) to get section area and then integrating along the span of the keel. The volume was checked to see that it was large enough to enclose the required lead ballast. This spreadsheet allowed various keel sizes to be investigated quickly and accurately.

After the keel was drawn in MAXSURF, it became apparent that it was very thick because of the long chordlength. The root and tip thickness ratios were reduced to 10 and 12 percent, respectively, in order to give more realistic thicknesses. This still provided enough volume for the required ballast. The root thickness is still 0.25 m (10 inches) which should allow enough room for keelbolts. The final keel design is shown in Appendix B in the spreadsheet and in Appendix C in the lines drawings.

4.3 Rudder Design

A skeg hung rudder was considered for the PDS39 for strength and safety, but a spade rudder was chosen for simplicity of design. A NACA 0012 section was chosen for the rudder. This section should provide good lift characteristics at higher angles of attack and maximum side force (Killing, 114). The rudder span was set at 80 percent of the keel draft and a near optimal taper ratio of 0.5 was selected. The area was set using the thumbrules from Larsson and Eliasson (rudder area~1.4% of sail area) and checked with a spreadsheet just like the keel. When it was drawn in MAXSURF, it looked too large. So the rudder area was reduced to 1% of the sail area. This rudder looked more reasonable and the area is still in the range indicated. Both rudders were kept in separate files and validated using VPP as described in the next section.

4.4 Appendage Validation

There was still a large amount of uncertainty in the size and performance of the appendages. An attempt was made to compare and validate the foil sizes using the updated DOS-based VPP, but the code still would not run successfully with the data for this particular boat. Instead, a preliminary rig was input to SPAN and the two boats (same keel, different rudders) were run through the VPP. The data for the two rudders were nearly identical, and while SPAN does not give a leeway angle, the keel appeared to provide adequate side force for good performance.

The rudder was changed slightly after the validation step above just to get it to look better. In the end, a compromise was struck between the large and small rudders described above. The final rudder was designed to have 1.2% of the design sail area and a taper ratio of 0.55. Appendix B contains the spreadsheet with the final rudder data. The final hull and appendage data from MAXSURF are presented in Tables 4 and 5 below. Upright hydrostatic and large angle stability data from MAXSURF and HYDROMAX are included in Appendix D.

Table 4. Hull Data

	Bare Hull	Appended Hull
Displacement (kg)	6756	7143
Volume (m^3)	6.59	6.99
Draft to Baseline (m)	0.52	0.52
Immersed depth (m)	0.52	1.83
Lwl (m)	10.11	10.61
Beam wl (m)	3.20	3.20
Wetted Area (m^2)	25.09	32.21
Max cross sect area (m^2)	1.17	1.42
Waterplane area (m^2)	23.16	23.25
Cp	0.56	0.46
Cb	0.40	0.11
Cm	0.72	0.25
Cwp	0.72	0.69
LCB from zero pt (m)	-0.36	-0.38
LCF from zero pt (m)	-0.61	-0.63

Table 5. Appendage Data

	Keel	Rudder
Displacement (kg)	359	57
Volume (m^3)	0.35	0.06
WSA (m^2)	5.41	1.71
Span (m)	1.31	1.35

4.5 Rig Design

A masthead, two spreader rig with an aluminum, keel-stepped mast was specified for the PDS39 for simplicity and durability. A 135 percent genoa was chosen to provide good performance over a range of cruising conditions. Again the parametric data were used to provide a starting point for rig dimensions. A SA/D of 20 (based on the initial design parameters) gave a required 100% sail area of 73.8 m^2. In order to get the sail area to wetted surface ratio (SA/WS) in the range of 2.2-2.4 (Gerr, The Nature of Boats), a sail area of 71-78 m^2 was required. I, J, P, E were then chosen to give the required sail area with adequate boom clearance above the deck. The aspect ratios of the main and jib were kept relatively high in order to minimize induced drag and maximize performance.

A scale drawing of the rig was used to see if the rig looked "right" and to initially place the spreaders. A rig design spreadsheet was used to specify the spreader location and size and standing rigging and mast sections. The procedure presented in Larsson and Eliasson was used for the basis of the calculations with one exception. The shroud loads were calculated using the simpler procedure outlined by Henry and Miller. The basis for the calculations was the righting moment at 30 degrees from a HYDROMAX large angle stability analysis.

In addition to calculating the geometry and structural requirements of the rig, the spreadsheet was used to calculate the minimum chainplate width and to verify that the jib did not contact the spreaders while sailing upwind. In a nominal breeze of 15 knots, boat performance data from SPAN were used to calculate the local apparent wind angle at each spreader. The apparent wind angle at the deck was adjusted for height above the deck, jib downwash, main upwash, and the jib ideal angle of attack. Then the minimum spreader length could be calculated. As expected, the jib leech position at the upper spreader was the limiting parameter. Upper spreader height and length were adjusted to ensure the jib leech did not contact the spreader while trying to keep the third diagonal angle as large as possible. The final rig design has a third diagonal angle of 10.7 degrees which is on the low end, but acceptable. The chainplate width was extended 6 cm past the minimum in order to allow the chainplates to be connected to the structural bulkheads and frames on either side of the mast without disrupting the interior arrangement too much. This will sacrifice a tiny bit of upwind performance for more interior comfort, but also results in a tight squeeze on deck between the shrouds and the lifelines (7 inches).

Two rigs with similar sail areas were investigated. The original rig had a larger J and shorter I dimension. When the rig was drawn on the boat, however, the keel-stepped mast was too far aft in the saloon and the cabintop traveler location placed the mainsheet too far forward on the boom. So a second rig was designed with a smaller J and larger I. The two rigs were run through SPAN to compare the performance. As expected (and predicted by the earlier VPP analysis), the higher aspect ratio rig was slightly faster (a few hundredths of a knot). So the taller rig with the optimal spreader and chainplate locations was kept as the final design. All of the rig calculations and drawings are enclosed as Appendix E. The final rig dimensions are summarized in Table 6 below.

Table 6. Rig Dimensions

% of foretriangle area	135.00	Main SA (m^2)	39.67
I (m)	16.00	Jib SA (m^2)	45.36
J (m)	4.20	100% Jib area (m^2)	33.60
E (m)	5.10	100% Sail Area (m^2)	73.27
P (m)	14.00	Upwind Sail area (m^2)	85.03
P/E	2.75	SA/Disp Ratio	19.70
Main AR	5.49	SA/Wetted Surface	2.28
100 % Jib AR	7.62		

4.6 Balance

The method presented in Larsson and Eliasson was used to estimate the center of effort of the sailplan and the center of lateral resistance of the underbody. The center of effort was placed on the line between the geometric centers of the main and foretriangle. The distance along this line was determined using the given relation between the main sail area and foretriangle area. The center of lateral resistance was estimated to be at 45% of the draft down from the design waterline on the one quarter chord line of the keel. The "lead" was then set at 70 cm or approximately 7% of the design waterline in accordance with the thumbrules provided. The rudder shaft is placed two inches forward of the quarter chord line of the rudder to ensure adequate balance and a good "feel" when steering the boat.

The rig design spreadsheet was also used to check the transverse balance of the boat. The heeling arm of the boat was calculated using the estimates of center of effort and center of lateral resistance from above. Twenty five degrees was chosen as the balance point beyond which any further heel (or windspeed) would require shortening sail. The righting moment at 25 degrees of heel was obtained from HYDROMAX and the heeling force was calculated using an average lift coefficient of 1.0, the sail area, and the density and speed of the wind. The wind speed was varied until the heeling moment balanced with the righting moment at 25 degrees of heel. This wind speed was just under 20 knots, which is quite reasonable with a 135% genoa. Any further increase in wind speed would require reefing the main or partially rolling the genoa or both. The Dellenbaugh angle was calculated to be 13.8 using the 100% sail area. This also indicates that the boat is sufficiently stable even with the relatively shallow keel. The large angle stability results and righting arm curve are enclosed in Appendix D.

5.0 Arrangements

5.1 Interior

The overall design philosophy for the interior of the PDS39 was, "simple, spacious, and comfortable accommodation for two couples for a long weekend." Since this boat is not intended for extended offshore cruising or the charter market, there was no attempt to cram the boat full of amenities. Because of this, the boat has large and useful common areas with plenty of berthing and stowage. The interior arrangement can be seen in Appendix F.

In the forepeak a chain locker (with optional windlass mount) is forward of a watertight collision bulkhead. Access to the locker is from above. The forward cabin has a huge V-berth and hanging lockers port and starboard. Sail storage is underneath the V-berth mattress. The main saloon is aft of a structural bulkhead separating the saloon and forward cabin. Two 7 ft (212 cm) straight settees will comfortably sleep two or seat eight. Plenty of storage is available underneath and outboard of the settees. A pipe berth above the starboard settee will sleep another person or offer more storage space. Both the starboard settee and pipe berth can be used as sea berths with lee-cloths if required for overnight passages.

The galley to port is large with double sinks, a two burner propane stove, a refrigerated icebox and large preparation surfaces. The navigation station to starboard has a large desk surface with chart storage below and plenty of bulkhead space for instruments. The single head is just to starboard of the companionway, offering full headroom and access to a wet locker under the starboard cockpit seat. Access to the aft cabin is via the galley to port. A large hanging locker is immediately to port where there is still headroom to stand and change clothes. Another large double berth is situated fore and aft under the port cockpit seats. Almost 360 degree access to the engine is achieved via removable companionway steps and removable, insulated access panels in the aft cabin.

5.2 Deck Arrangements

The cambered cabintop is designed to give 6.5 ft standing headroom on centerline, allowing for deck support beams and cabin sole height. It extends athwartships far enough to give good standing headroom in the galley and above the settees, while allowing for wide side decks above for access forward and aft. Two large opening hatches (one in the forward cabin and one in the saloon) and dorade vents provide ventilation below. An opening port in the cockpit (above the sole, below the seat) provides additional ventilation to the aft cabin.

The cockpit seats are almost eight feet long, providing ample room for relaxing while sailing or entertaining at anchor. The cockpit seats and seat backs are sloped to provide a comfortable seating position at various degrees of heel. Not shown in the MAXSURF drawings are molded cockpit coamings that simultaneously keep water out of the cockpit, extend the backrest of the cockpit seats, and provide a comfortable seat for the helmsman sitting to windward or leeward. The cockpit sole is deep enough to provide a comfortable seating position without compromising too much space in the aft cabin. A deep cockpit locker under the starboard cockpit seat provides storage for fenders, lines, deflated dinghy, and cleaning supplies. A vented propane locker is aft and to starboard of the cockpit. Opposite this is a small lazarette for more storage. In between is a void for the rudder post and steering quadrant.

All lines are run aft on the cabintop through rope clutches to the cockpit. Two Lewmar 40ST winches port and starboard of the companionway hatch accommodate the mainsheet, halyards, and other sail control lines led aft. Two Lewmar 54ST primaries are mounted on the coaming just outboard of the cockpit seats for the genoa or asymmetric cruising spinnaker sheets. The mainsheet is not within reach of the helmsman, but most cruising boats of this size will have an autopilot if singlehanded sailing is desired. This setup guarantees easy shorthanded sailing.

6.0 Structure

The hull and stiffeners are made of solid E-glass fiberglass mat and roving set in vinylester resin. While sandwich laminate or cold molded wood can provide a stiffer, lighter hull, solid laminate was chosen for simplicity of construction and maintenance and for increased durability. The laminate density was calculated using the densities of E-glass and vinylester resin found online. A fiber to resin ratio of 0.35 was assumed. Other material properties were taken from Larsson and Eliasson for a woven roving E-glass laminate. Where material properties from multiple sources (ISO, ABS, other) were available, average values were used. All skin thicknesses and stiffener dimensions were designed to comply with the ABS rule for offshore yachts.

A spreadsheet was used to calculate minimum hull and stiffener dimensions. These calculations and drawings of the stiffener locations are included in Appendix G. All bottom plating of the hull was conservatively set at 13mm in order to meet all ABS requirements and have extra strength forward for slamming and aft for grounding loads from the keel. The shell plating forward is 8mm and the aft shell plating is 7mm. The minimum keel bolt thickness was calculated according to the ABS rules as well. Five pairs of 12mm steel keel bolts with steel backing plates are used to secure the keel to the hull. The plating around the keel is thick enough to comply with the ABS rules to accommodate the keel bolt loads.

Two major longitudinal stiffeners run under the cabin sole with seven transverse floors between them. Two smaller longitudinal stringers under the engine box are provided for mounting points for the Yanmar 4JH3E diesel engine and to help distribute the thrust bearing loads on the hull. Two more pairs of tapered longitudinal stringers are installed to support the bottom and side plating.

7.0 Weights

A spreadsheet was used to estimate the weight and center of gravity of the boat. Hull weight was calculated using the skin thicknesses and stiffener areas calculated above. The weight of the standing rigging, mast and boom were based on the mast and boom sections and wire rigging selected in the rigging analysis. A few major components such as engine and deck hardware were selected to provide better weight estimates. Additional information on these components is included in Appendix J. Water and fuel tankage were selected based on the parametric data collected in the beginning of the project. Other weights such as those of the galley and cabins were based on the values presented in the appendix of Principles of Yacht Design for the YD40 (which coincidentally is very similar in size and layout to the PDS39). The weight spreadsheet is included as Appendix H.

After the initial weight calculation, the weight of the boat was considerably more than the design displacement. This is somewhat due to the conservative construction of the hull, but is largely due to the reduction in LWL that occurred in the original stages of the design. Even with an increased DLR, when the LWL was reduced the displacement went down but the LOA stayed the same. In other words, the design displacement went down, but the boat size stayed the same (because the DLR is based on LWL and not LOA). While the boat could easily settle to a new DWL with the added weight (because of the graceful overhangs), the excess weight was removed from the margins and the keel to preserve the validity of the previous analysis based on the existing DWL. So the final boat weight matches the design displacement of 7140 kg. The design displacement was not increased in order to preserve all of the analysis that occurred previously.

Two hundred kilograms of moveable ballast was used to match the longitudinal center of gravity with the longitudinal center of buoyancy and to correct the slight transverse moment the boat had. The vertical center of gravity was found to be only slightly higher than zero (7 cm), indicating that the impact of the reduced keel ballast on upwind performance will be slight. The final ballast ratio is 0.38 which is certainly reasonable, but considerably lower than the design value of 0.45.

8.0 Performance

The final hull and rig data were run through SPAN to validate the performance of the boat. The polar plot and raw data are included in Appendix I. The results indicate that the goals of achieving good light air and overall cruising performance were achieved. The PDS39 makes seven knots of boatspeed upwind in 14 knots of true wind and exceeds nine knots on a broad spinnaker reach in 20 knots of wind. This last case is not for the lighthearted cruiser! While these numbers seem very good, they may be somewhat optimistic. The SPAN results also show the boat making more than 4 knots of boatspeed upwind with only 6 knots of wind, which seems a little too good to be true.

9.0 Summary

The PDS39 is a relatively simple coastal cruiser with a good turn of speed. The hull and rig have been designed for ease of operation and maintenance, and the shoal draft keel ensures access to cruising grounds along the entire east coast of the United States. The open and spacious interior and large cockpit will allow for entertaining guests at the raft-up, and for comfortable accommodation for a small family or two couples.