Design of Autonomous Surface Vessels

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Resumo Alargado

O objectivo da dissertação é efectuar um estudo sobre os navios autónomos de superfície e dimensionar um navio autónomo (navio sem presença humana a bordo) capaz de efectuar diversos tipos de missões, típicas para estes robôs.

Através da informação reunida relativamente aos navios autónomos existentes, decidiu-se efectuar o dimensionamento de três navios, que pudessem ser adaptados para diversos tipos de meios e com um pensamento num possível desenvolvimento futuro.

Os navios autónomos de superfície foram pensados já há mais de meio século, durante a segunda grande guerra e desde aí foram seguindo a evolução tecnológica e começaram a ser utilizados para fins científicos e não apenas militares. Hoje em dia qualquer pessoa pode adquirir um navio autónomo e até ao momento ainda não foram instituídas qualquer tipo de regras em relação à utilização destes aparelhos. Os cientistas utilizam estes robôs para efectuar estudos sobre as qualidades da água, suporte em construção marítima e na previsão de sismos, batimetria, etc. Dependendo do meio onde irão operar e do tipo de missão, é escolhido um tipo e forma de casco e todo o equipamento a bordo terá de ser baseado nas características desse casco.

Nesta dissertação efectuou-se o dimensionamento de três tipos de embarcações: um catamaran, um monocasco e um catamaran-SWATH, sendo que os dois primeiros foram baseados em navios autónomos existentes e o terceiro foi dimensionado com um pensamento nas aplicações futuras destes navios.

O navio catamaran foi dimensionado para actuar em águas calmas, como rios, estuários e barragens, sendo que é de pequena dimensão (comprimento 2 metros, largura 1.5 metros e altura 0.50 metros) em que o objectivo foi o manter um calado reduzido, mas ao mesmo tempo proporcionar uma boa capacidade de carga para que possam ser instalados diferentes tipos de aparelhos electrónicos.

O monocasco foi dimensionado para operar em ambientes mais hostis, onde existam correntes e ondas (comprimento 5 metros, largura 1.5 metros e altura 0.70 metros), além disso neste navio foi incluído um painel solar para que a sua autonomia fosse optimizada.

Por fim, o catamaran-SWATH é um tipo de navio que, para os dias de hoje pode parecer impensável tendo em conta os riscos que podem estar envolvidos na sua utilização. Este navio possui um comprimento de 16 metros, uma largura de 7 metros e uma altura de 9 metros. O dimensionamento foi efectuado da mesma forma que para um navio tripulado, mas o arranjo geral e a divisão dos compartimentos foi pensada para um navio não tripulado. Apesar de parecer ser uma ideia utópica, será apenas uma questão de tempo até a grande maioria dos navios serem deste género, autónomos.

Palavras chave: **Navio autónomo de superfície (ASV), materiais compósitos, catamaran, monocasco, SWATH.**

Abstract with Key Words

The aim of this dissertation is a study about autonomous surface vessels (ASV) and the design of an autonomous craft (with no human presence onboard) capable to perform different type of missions, typical to these robots.

Using the gathered information regarding these type of ships, it was concluded that not only one, but three different vessels should be designed and that could be adapted to operate in different environments, always with a though in the future.

The idea of an autonomous surface vessel started nearly half a century ago during the WWII and since then this vessels have been following the technology evolution and started to be used not only for military purposes but also for scientific. Nowadays anyone can have an ASV and until now there are no mandatory rules regarding the usage of these drones. Scientists use them to perform studies on the water quality, offshore support, seism prediction, bathymetry, etc. Depending on where they will operate and the mission requirements, a hull type and form are chosen and all onboard equipment is depending on that.

In the dissertation three vessels were designed: one catamaran, one monohull and one catamaran-SWATH, where the first two were based on existence autonomous ships and the third was designed thinking in the future application of these vessels.

The catamaran has been designed to operate in calm waters, like rivers, estuaries and dams, because it is small sized (length 2 meters, width 1.5 meters and height 0.50 meters), where the main goal was to keep a low draft and at the same time a good payload capacity for installing diverse electrical devices.

The monohull was designed for more rough environments than the catamaran, where currents and waves can be existent (length 5 meters, width 1.5 meter and height 0.70 meters), besides that, a solar panel was included on this ship to increase its autonomy.

Finally, the catamaran-SWATH is a type of ship that seems to be unthinkable for nowadays, because of the risks associated to its operation. This ship has a length of 16 meters and a width of 7 meters, with a total height of 9 meters. Its design was performed in the same way as a manned ship, but the general arrangement and the existing compartments were designed for a unmanned vessel. Although it seems an utopic idea, it is just a question of time until majority of ships are adapted to be autonomous.

Key words: **Autonomous Surface Vessel (ASV), composite materials, catamaran, monohull, SWATH.**

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Nomenclature

AUV	Autonomous Underwater Vessel
UUV	Unmanned Underwater Vessel
ASV	Autonomous Surface Vessel
USV	Unmanned Surface Vessel
GPS	Global Positioning System
DGPS	Aft Perpendicular
LOA	Length Over All
LPP	Length Between Perpendiculars
B	Breath
D	Depth
T	Draft
CFD	Computer Fluid Dynamics
rpm	rotations per minute
APP	Aft Perpendicular
FPP	Forward Perpendicular
LW	Light Weight
DW	Dead Weight
Lcg	Longitudinal center of gravity
Tcg	Transverse center of gravity
Vcg	Vertical center of gravity
PS	Portside
SB	Starboard
AP	Aft perpendicular
FP	Forward perpendicular
SWATH	Small Waterplane Area Twin Hull
Cat-SWATH	Catamaran-SWATH

Chapter 1. INTRODUCTION

Vessels follow both human and technology evolution, according to their needs and capabilities. A new generation of crafts is starting to get more attention because of its multi-functionality, providing safety and comfort to users, and it can be achieved with low-cost investment. This new generation belongs to the robotic family, where technology allows the operation of a floating machine without human presence on board. This kind of vehicle is named autonomous/unmanned vessel and can operate underwater or on surface. These autonomous craft have revolutionized the way to explore the seas. With them it is already possible to explore, with 100% safety, waters that could bring severe health problems to humans and, since these ships are machines they will not need to rest or refuse to do their jobs. The major impulsion given to the development of autonomous vessels was due to the military applications, where safety is the biggest concern, then scientist adopt these vessels to explore waters taking the advantages of technology advances (Romano & Duranti, 2012).

Autonomous Underwater Vessels (AUVs) or Unmanned Underwater Vessels (UUVs) actuate underwater and are controlled by someone at the surface, but sometimes it may not be the best solution due to high investment and large restrictions in the control distance and communications, caused by the water above the vehicle (Leonessa et al., 2003).

An Autonomous Surface Vessel (ASV) or Unmanned Surface Vessel (USV) is a floating type of platform that has revolutionized the exploitations of waters. The vast versatility of ASVs allows them to operate in a large variety of missions, like oceanographic measurements - bathymetry, water monitoring, salinity, currents, chemistry, earthquake prediction, hydrographic data, ship wreck survey and structure inspection, air and atmosphere measurements - surface winds, air temperature and humidity, sea surface temperature, hurricane path prediction and weather forecasting , military missions - coastal/port surveillance, mine detection and reconnaissance, military training and security , or simply follow an AUV in order to provide support communications as well as precision location and navigation (Eve et al., 2012).

ASVs are an ecological solution for water survey and monitoring, and nowadays that is really important characteristics, due to all the pollution issues and the greenhouse effect problems. The fact that the costs associated to these kinds of vessels are relatively small makes them a good investment. ASVs are generally smaller than usual ships because they need to be flexible for transport due to the constant change of operation area.

Scientific purposes are the major cause of an exponential growth in the production of this kind of vessels. Since scientific studies are made in estuaries or lakes, deep water or shallow water conditions, oceans or in a pool, there is a large variety of vessels' sizes and forms - they can be monohull, catamaran, small waterplane area twin hull - SWATH, hydrofoils, trimaran and so on, and it's up to the designer to choose what is the best arrangement for the required mission. The conditions in which the ASV will operate must always be defined; conditions like the maximum draft, required speed, existence of high currents or high waves, the total reach area and the probability of traffic must always be taken into consideration.

With technology development, electric devices are becoming smaller and more sophisticated, for instance, computers - important component onboard - are becoming lighter, much faster and smaller, which is important because it reduces the required space in ASVs. These robots are all made of electric parts that control the vehicle, so it is necessary to have space and enough payload capacity to carry all of these equipment on board. Batteries, electronic and measurement devices are part of the payload capacity and sometimes they can be very heavy.

When talking about a sophisticated drone that requires no human presence onboard and has the ability to perform almost any task, it is important to know its autonomy and capacity.

Nowadays ASVs are trending to become one hundred percent ecologic avoiding diesel engines and adopting fully electric thrusters(Higinbotham et al, 2006). These electric propulsion motors require power supply, done by batteries that need to be recharged once in a while, making designers trying to adopt self-recharging and economic systems like solar panels and oscillatory platforms to transform natural energy sources (Byrne et al., 2012).

Other important parameters like the transport, deployment and recovery of the ASV represent more design variables. Deployment and recovery are two really important factors because of the need to easily deploy and remove the vehicle in/off the water without damaging it. Recovery becomes essential when the batteries need to be recharged and when the mission ends. In this process, safety removal is the key to a successful mission, guaranteeing no damage to the electric parts and measuring samples. The weight of the vehicle is directly influencing deployment and recovering, and it is the key factor that states if it is necessary to use lifting equipment, or only a few pair of human arms, to perform both deployment and recovery actions. In order to keep ASVs light weighted, composite materials are the most common used for construction. Composites like fiberglass or carbon fiber have excellent mechanical properties and are completely compatibles with small vehicles like ASVs.

ASVs are small ships and at the same time robots, built from electric components, controllers and navigation devices, connecting two sides of engineering: the Marine Engineering and the Electrical Engineering. These controllers may be small but they are very complex and the vehicle will only operate if they are well designed, therefore an experienced electrical engineer is needed, but when talking about the ship behavior and which hull form is the better for some specific conditions, the hand of the naval engineer is essential.

The objective of the dissertation is to study and design the applications and the types of autonomous surface vessels, including only the naval architecture and the marine engineering role in the design of these kinds of systems, by excluding the controllers and electrical design. Two generic small hulls will be designed for the major applications of these vessels, and a third ship will be bigger, more complex and more sophisticated than the typical ASVs, thinking about future development of robotic vessels.

The idea of having a significantly bigger unmanned ship must not be considered as utopic, because machines are always overlapping the human hand. Maybe, for now it is unthinkable, due to all the danger that comes with it, but who knows that in the future, not only the scientific vessels become unmanned, but also all the other types of ships.

In the State of the Art (Chapter 2) a global evaluation of what has been developed and what are the future ideas for the applications of these kinds of vessels, were studied.

After the study of the typical purposes of ASVs, a set of Mission Requirements (Chapter 3) were imposed. These requirements have influenced the shape, form and general arrangements of the designed vessels (Chapter 4, 5 and 6). Chapter 4, 5 and 6 are divided in subchapters, each one representing one step of the design of the vesssels.

Chapter 2. STATE OF THE ART

Autonomous Surface Vessel is a concept introduced in World War II (WWII), where a small group of remote control vessels were designed for gunnery and missile target systems (Roberts & Sutton, 2006). These vessels were developed only for military purposes and had simple algorithms associated to their functions. Other vessels were built by that time for mine and obstacle clearance (Bertram, 2008), being called by “Demolition Rocket Craft”. It was possible to see that ASVs were a good way to save human lives and could bring many advantages to military applications. From WWII to the 90’s a large number of autonomous crafts were built for military purposes with United States Navy as the major producer. Despite belonging to military institutions, some vessels were already performing measurements in some places where no human could go, without endangering anyone’s health, like radioactive waters after atomic bomb blasts. In Europe the big step on the development of unmanned marine vessels began in the 80’s when nations like Germany and Denmark started to develop a new generation of mine countermeasure (MCM) systems (Roberts & Sutton, 2006).

With the *Global Position System* (GPS) and long range bandwidth wireless data systems evolving and becoming more affordable and efficient, ASVs were given new missions and were quickly inserted in the scientific field, helping scientists to perform their studies (Manley, 2008), reducing the costs related to oceanographic research.

One of the first developers of scientific purpose ASVs was the *Massachusetts Institute of Technology* (MIT) *Sea Grant College Program* (Manley, 1997), where two autonomous crafts were developed, the *ARTEMIS* and *ACES*. *ARTEMIS* was the first platform designed by MIT in 1993 and it was a testing platform, where navigation and control systems were tested. It was built from a 1/17 scale replica of a fishing trawler, but since it was small sized, it was not suitable for coastal or ocean research because it had limited seakeeping and endurance (Manley, 1997 ; Manley, 2008). *ARTEMIS* was equipped with rudimentary navigation and control systems and was operated in Charles River, having a total length of 1.37 meters with 0.38 meters width. It was a monohull with a draft of 0.2 meters and a total autonomy of 4 hours reaching a maximum speed of 2.25 knots with its diesel engine. This resulted in a maximum displacement of 29 kg but, for the MIT, this vessel needed to be improved in three main aspects; increase the payload capacity, the autonomy and the speed. The goal was to achieve 10 hours endurance with 5-7 knots of speed.

In order to provide better roll stability and a greater payload capacity, a catamaran hull form was the best solution. *ACES* was the ASV designed in 1996, to fulfill all goals that *ARTEMIS* couldn’t achieve, and the final result was a catamaran vessel with a total length of 1.9 meters, 1.3 meters breath and 0.45 meters draft. This new craft could reach a maximum displacement of 158 kg and a speed between 5 to 10 Knots. Despite having a gasoline engine, the vessel could operate for 12 to 18 hours and the navigation and control devices were also replaced by better quality ones. Both *ARTEMIS* and *ACES* had devices that allowed them to perform bathymetric measurements (Caccia, 2006).

Even with this new vessel, MIT wanted better. The next step was to construct one hull from lighter materials and dismiss gasoline engines. The result was a new ASV built from fiberglass composite material and electric thrusters. *AutoCat* was the name of the vessel and it was constructed in 1999 (Manley et al, 2000). It was a bit smaller than *ACES* with only 1.8 meters length and 1 meter breath, but since it was built from composites it was much lighter, weighting only 100 kg. This vessel had to carry batteries to provide power to the electric motor and it could only sail for 4 hours with a maximum speed of 8 Knots. *AutoCat*, *ACES* and *ARTEMIS* had inspired other scientist of the world because of their simplicity, vast applications, low-cost investment and safety.

Europe also tried to impose its name in the development of ASVs, therefore in Germany during the period of 1998-2000 a program had started, the *MESSIN* project (Roberts & Sutton, 2006 ; Caccia, 2006), sponsored by the *German Federal Ministry of Education, Research and Technology* (BMBF). This project consisted on the design of a fully autonomous surface vessel capable of high accuracy of positioning and track guidance and, as a carrier of measuring devices in shallow waters. The project was named *Measuring Dolphin* and the hull had 3.3 meters length, 1.8 meters width with a total weight of 250 kg. *Dolphin* could carry up to 100 kg of payload and achieve a maximum draft of 0.4 meters which is great for shallow water navigation. Once again, the catamaran hull was the best choice to use and the materials used in the construction were fiberglass composites. The propulsion was given by two counter rotating propellers, powered by hybrid energy supply generated from a gasoline generator and lead-acid accumulator batteries, which could run for 13 hours and achieve a maximum speed of 3.85 knots.

In the same period of time (1997-2000), *Europe Union* founded the project named *Advanced System Integration for Managing the Coordinated Operation of Robotic Ocean Vehicles* (ASIMOV) (Caccia, 2006 ; Oliveira et al., 2000), where the objective was to develop a number of ASVs that could supply direct acoustic communication link with AUVs, improving the navigation and positioning of the vehicle. In this project the Portuguese institution from Universidade de Lisboa - *Instituto Superior Técnico* (IST) had developed an ASV named *DELFIM* to support the AUV *INFANTE*, ensuring fast data communication between both vehicles (Alves et al., 2006). *DELFIM* operated near Azores islands in the Atlantic Ocean, so the vessel had to be robust to navigate in ocean waters without endangering its stability and availability, resulting in a bigger craft with better seakeeping properties. The designers choose the catamaran hull type for better roll and pitch motion. The ASV had some more innovations onboard, like a new methodology for guidance and control by using Petri-net based software named *CORAL*. Equipped with a *Differential Global Position System* (DGPS) and a *Doppler unit* for transmissions the ASV had a total communication range of 80 km. Other components like sonars and scanning devices allowed the ASV to perform bathymetric measurements and communications with the submerged ASV. Reaching a total weight of 350 kg, *DELFIM* was a 3.5 meter long and 2.0 meters width, capable of a maximum speed of 5 Knots. The vessel also adopted a full electric system, avoiding gasoline engines or generators onboard. Propulsion was done by two bladed propellers, one in each floater.

On the other side of the globe, in Japan, *Yamaha Motor Co*., *Ltd* designed and built one autonomous vessel, at the request of the *Japan Science Foundation*. The boat was named *Kan-Chan* and it was the first ASV to measure colloidal particles (aerosol) in the air over the oceans (Desa et al., 2007). *Kan-Chan* was an adopted sailing cruiser vessel with propulsion provided by diesel engine and wind turbines generator. In calm water it could reach a cruising speed of 4 knots with a maximum autonomy for 700 hours. The total length of the ship was 8 meters with 2.8 meters width and a displacement of 3500 kg. The ship was going to operate in open ocean water so it had to be robust enough to perform its mission.

Back in Europe, another country that entered in the history book on the development of ASVs was Italy, by developing the *Sea Surface Autonomous Modular Unit* (*SESAMO*) ASV (Caccia, 2006 ; Caccia & Bono, 2005). The work was done by the robotics group of *CNR-ISSIA* with cooperation of the *National Program of Research in Antarctica* (*PNRA*), between 2002 and 2004, and the main objective was sea surface micro layer sampling in Antarctica. The vessel was designed to be able to achieve high cruise speeds to go and come back from the sampling area, and needed to have the ability to collect up to 35 liters of sea water. It was equipped with devices that would perform onboard measurements of the water samples, in order to evaluate if it was a good or a bad sampling. This vessel was going to operate in open waters and therefore good stability was needed. Once again the catamaran hull type was the final choice and the total weight of the vehicle was 360 kg. The catamaran was 2.4 meters length, 1.8 meters width and 0.9 meters height with a total payload capacity of 55 kg plus 60 kg destined only for water samples. Propulsion was provided by two propellers powered by two electrical thrusters, and steering was based on differential propeller revolution rates with a total autonomy of 4 to 6 hours without need to recharge. Composite materials were used to build the catamaran. The vessel was always followed by a manned vessel to prevent any problem, and communications between both vessels could be done up to a distance of 550 meters. The main problems faced in this project were the obstacles in the water, where a new obstacle detection and avoidance system was needed. The lack of autonomy was also a problem to be solved.

In 2004, the *MIT* developed a new concept for the usage of ASVs, with the project *Surface Craft for Oceanographic and Undersea Testing* (*SCOUT*) program (Curcio, 2005), consisting in the fabrication of four vessels. The design objectives were simplicity, robustness, versatility and improved utility. Easiness in deployment and recovery were one of the main constrains of the project, bringing the simplicity of the design. *SCOUTs* were programmed to work together in their research tests for a period of time of 8 hours at a maximum working speed of 3 knots. Kayak hulls were adopted to become the floating platform of the robots, built from high density polyethylene material they were a perfect structure to perform the mission. Some modifications were made on the kayak in order to allow propulsion and autonomous control which were all powered by electrical batteries. Inside the hull was a watertight box, containing the main vehicle computer and the associated cooling system. With all electrical components and batteries, *SCOUTs*' weight was only a mere 81.64 kg, fulfilling one of the objectives of the project and allowing fast deployment and recovery of the vessel. The total length of one kayak was 3.05 meters and its top speed was of 5 knots (greater than the working speed). The transport of the vessels was done by a supply ship, while deployment and recovery was done by hand (Manley, 2008). Later, the *SCOUT* project was also adopted to work with direct interaction with AUVs, providing any necessary help to navigation and communication between AUVs and the operators.

From 2004 to nowadays, the ASVs suffered a big jump in their production. Scientists yielded to these robots and with the growth on the production and technology, new systems were developed and better crafts were constructed.

In the end of 2004 a new revolutionary vessel was developed, in the USA, by the *National Oceanic and Atmosphere Administration* (*NOAA*) in cooperation with *National Aeronautics and Space Administration* (*NASA*) (Higinbotham et al., 2006). This vessel was called *Ocean Atmosphere Sensor Integration System* (*OASIS*) and its main task was to collect in-situ, ocean and atmosphere measurements. *OASIS* was designed to be a low-cost, low-speed, reusable and long duration platform to operate in open ocean waters. Equipped with sensors to obtain biogeochemical and air-sea measurements, it could quantify the air-sea CO_2 fluxes and gas transfer velocity. *OASIS* may also be used for mapping dynamic features like oil spills and harmful algal blooms, but the major innovation was on the power domain. This platform was equipped with solar panels to automatically recharge its batteries. Six solar panels were mounted on the fiberglass vehicle with internal aluminum stiffeners and a mast. It was a 5.5 meters length, 1.52 meters width and 1.83 height monohull. The draft was around 0.66 m with a displacement of 1361 kg and a payload capacity of 226.8 kg. With the solar panels installed, it was a really long duration vessel with autonomy between 36 to 72 days (2160 – 4320 hours). The maximum speed was 2.5 knots and since it was a bigger vessel, it needed rudder for steering. Propulsion was done by a single propeller located on the stern. *OASIS* transport could be done using a boat trailer attached to a car. One of the major concerns was the obstacle avoidance and collision, because of the size of the ship. To prevent any collision, the designers decided to implant lights on the mast in order to maintain the vessel visible to others, obeying the *COLREGS* rules for manned ships.

More and more ASVs were being developed to perform scientific explorations, and universities were also developing their own vessel for academic purposes. In the year of 2006 some projects stood out in relation to others, but they all belong to university researches and applications. In UK, the *University of Plymouth* developed an unmanned vessel named *Springer* for environmental monitoring (Naeem et al, 2006). The vessel was designed to carry out pollutant tracking and hydrographic and environmental surveys, sailing mainly in shallow waters, like rivers, reservoirs and inland waterways. Designed as a catamaran the vessel was 4 meters long and 2.3 meters wide with a total displacement of 600 kg. Each hull was divided in three watertight components and the vessel carried 350 kg of batteries which provided electrical power to the propulsion system. Two propellers were mounted on the ASV, one in each hull, and one electrical thruster was connected to each propeller. The ship was also equipped with leak sensor who would alert if any water was entering the hull. A mast was also installed to carry the GPS and the communication antennas.

Another innovative ASV that appeared in 2006 was a vessel designed in the *Autonomous System and Control Lab* (*ASCL*) at *Virginia Tech*, USA (Subramanian et al, 2006). This vessel used an Omni-directional camera for several applications, but the most interesting one was shoreline mapping. This camera had the ability to photograph a 360º image, showing everything around the vessel. Using simple algorithms, the shoreline distance was calculated and a map was created. In order to take a 360º photo, the camera had to be in a high point and the designers decided to put it on the stern of the craft. The ASV was a catamaran hull with rigid pontoons connected by aluminum bars with a length of 2.7 meters, width of 1.5 meters and a total height of 0.5 meters. The mechanisms and electrical parts were inserted in watertight boxes, to be protected. This vessel was powered by a gasoline engine that could run between 3 our 4 days without need of refuel. The weight of the ship was 125 kg with a capacity for 57 kg payload and could be deployed and recovered without any help of mechanic components. It was a slow ship with, operating at 3 knots with two propellers and no rudder, steering was done by differential revolution of the propellers. The omni-directional camera system proved to be a very useful tool to map the shoreline.

In Portugal two new ASVs were being developed by *Instituto Superior de Engenharia do Porto* (*ISEP*). Both ASVs were designed to support an AUV in its missions. The first ASV produced was named *ROAZ* and it could not only support the AUV but also perform bathymetry of riverbeds, estuaries, dam basins and harbors (Ferreira et al, 2006). *ROAZ* was designed to operate only in shallow water conditions where the handling of the vessels is quite simple. Having a catamaran hull type, the vessel was 1.5 meters length, 1 meter wide and 0.52 meter height. Built from fiberglass composite material, the ASV could carry a maximum payload of 50 kg and had a flat surface where solar panels have been inserted. The vehicle had the ability to be reconfigured, if necessary, where a communications mast or a camera tripod could be mounted. The propulsion system consisted on two propellers, one at the stern of each hull, and the movement was created by two electric thrusters powered by batteries. With the solar panels onboard the vessel was a long range, long duration ASV and was suit to follow an AUV in any operation.

The second project, made by *ISEP* was an open ocean waters ASV, named the *Swordfish* et al, 2007). Similarly to the *ROAZ*, this vessel had the mission to follow an AUV, providing communications and navigation support. Despite having the same mission, the *Swordfish* would operate in open waters and the platform needed to be stable, robust and efficient to succeed in its mission. The hull was built from high density polyethylene and it was a catamaran type, with aluminum bars connecting both floaters. Stainless steel central platform were also mounted on the craft to support the payload. The devices were transport on watertight cases that would be placed on top of the steel platform. Red and green signal lights as well as a horn were installed on the vessel to increase safety in navigation. *Swordfish* had not the ability to carry solar power panels, so its endurance was a mere 6 hour maximum. The vessel was way bigger than *ROAZ* with a length of 4.5 meters, a width of 2.2 meters and a height of 0.5 meters. Its total weight was about 190 kg with the batteries and the maximum speed was 3.88 knots. The power was provided by four batteries and the propulsion was done by two electrical thrusters connected to two propellers. The vessel was trimmed for buoyancy and weight distribution and also proved to be helpful tool to control the AUV.

In Italy another ASV have been built, in 2010 by *Scuola Superiore Sant'Anna* (Ferri et al., 2011), with the main mission of monitoring heavy metals in coastal waters. With the *wifi* technology advancing, the vessels could already provide real-time measurements of the waters. Since this ASV would operate in shallow waters, special attention was given to maintain a low draft design and protected propellers to avoid any breakdown. For the hull type, the catamaran was the best choice and the main dimensions were 2 meters length and 1.15 meters wide. The vessel propulsion system was constituted by two electrical thrusters that could operate at a maximum of 24 hours without fail. The hull was built from carbon-fiber material, because it is lighter than fiberglass composite, with hull thickness of 2 millimeters, keeping a low draft of 0.179 meters. The total weight of the model was a mere 80 kg and it would operate at a cruise speed of 2 knots.

Another Italian project was named *CatOne* and was designed in 2012 (Romano & Duranti, 2012). The project consisted in the construction of various ASVs with the same characteristics to be used in shallow waters, requiring very low draft with no propeller and no rudder. The vessel should have low noise level and zero pollution emissions. In order to fulfill all mission requirements, a catamaran hull built from composites was chosen. Propulsion was made by two fans mounted on top of the platform, connected to an electric motor, avoiding any component bellow hulls. *CatOne* main mission was hydrographic measurements, mainly bathymetry and environmental monitoring in shallow and calm water. Two vessels were built in the project, one with 1.6 meters length and 1 meter wide, with a light weight of 12 kg. The other vessel was a bit bigger with a total length of 1.9 meters and width of 1.2 meters, reaching a light weight of 20 kg. Both vessels were capable of reaching 3.7 knots and operate autonomously for 8 hours.

In Germany another interesting project was developed, in 2011, for monitoring blooms of the hazard and noxious cyanobacteria in the Lake Zurich (Eve et al., 2012). The vessel designed for the mission was called *Lizbeth* and it was a catamaran with 2.5 meters length and 1,8 meters wide. The design of the vessel was especially interesting because they needed to carry a custom winch that could reach a maximum depth of 130 meters. With the catamaran hull type they could place the winch in the middle of the vessel supported by steel bars. Each hull had one propeller at the center, protected by aluminum sheets to avoid any contact with the winch wire. The total light weight of the vessel was 120 kg, and the maximum weight supported was 320 kg. A person could be standing in the boat without endangering its stability. It was built from fiberglass with a foam core layer to provide light weight and strength, and it could reach a maximum speed of 3 knots. The thrusters were electrical ones and they were powered by two lead batteries.

Later, in 2013 the *MIT* developed a new kind of ASVs for high speed purposes and called them as the second generation of ASVs (Brizzolara & Chryssostomidis, 2013). The project consisted in the design of two high speed vessels, one respecting the conventional SWATH hull type and the other with a hybrid Hydrofoil-SWATH hull type, both designed to minimize the advance resistance and obtain favorable propulsive power at relatively high speeds. In the first project, the vessel was 6 meters length and the main mission was to quickly launch, recover and recharge AUVs, reaching a top speed of 12 knots. The ASV was also equipped with sensors allowing autonomous environmental measurements. The propulsion system consisted on two diesel-electric engines, connected to two propellers.

The second project was the development the super-fast hybrid hydrofoil-SWATH where the objective was the design of an ASV that could reach a top speed of 120 knots. The vessel must be able to operate in displacement mode and in foilborn mode, where in the first case the hydrofoils are folded against the structure, becoming a conventional SWATH vessel and in the second case turbo-jet engines are started and two pairs of surface-piercing hydrofoils are folded down. In the second case the weight of the vessel is sustained by the four hydrofoils. This vessel was designed with 20 meters length and 16 meters wide and 5.5 meters height, with a total weight of 42 tons. This second project is in the design phase, but MIT believes that this high-speed design may revolutionize the ASV production.

All ASVs referred before were designed for research and scientific purposes, either for testing or in-situ measurements. On the other hand, military ASVs were also developed, built and used, but only a few are fully described and known. Military ASVs are usually built from existing craft like jet skis and semi-planning hulls, where electrical components and controllers are inserted onboard to transform the ship into an autonomous one (Roberts & Sutton, 2006). Normally these vessels are bigger and faster than research vessels and they usually operate in ocean open waters, performing missions like port vigilance and surveillance, counter terrorism and anti-submarine warfare, (Yan et al., 2010). Once again, USA was the biggest developer in the field of ASVs production and the major projects were (Bertram, 2008); the *Owl* and *Roboski*, both built from existing Jet Ski hulls; the *SPARTAN* ASV was designed to protect troops against naval threats and was a 7 meters rigid inflatable hull.

Summarizing, despite being recent, ASVs have changed a lot since the beginning of 1990, with new hull shapes and types, new propulsion systems, new applications and missions, new operation scenarios, new measuring devices and so on. In these years of evolution some characteristics and design solutions presented themselves as better choices for a specific mission. Choosing the hull type is only possible after knowing the mission requirements, in which are stated the operation conditions. In case of a shallow water operation, with a maximum tabled draft, a catamaran hull type is the best choice, giving good payload capacity and stability. Catamarans can be larger than monohulls and yet, maintain reduced draft values. Stability is also a strong point of catamarans, and since shallow waters are generally calm, like estuaries, lakes, or rivers, an increase of safety and control is guaranteed. Catamarans are also a very good choice to operate in open ocean waters, but in these cases, the main dimensions are generally higher than shallow water dimensions. For ocean operations robustness and good seakeeping conditions are important design parameters, but a catamaran is a low speed choice. For missions where the speed is important, the best choice is a monohull or a SWATH. Monohulls are cheaper and easier to design but SWATH guarantee very good seakeeping conditions and stability. In general, missions where speed is required are the transport and recovering of AUVs.

The hull construction material is also very important to define the total weight and draft. In the beginning of the 90's the material used in the manufacture of ASVs was steel, which was not very easy to handle in these small types of constructions. Nowadays all these vessels are built from composite materials, for being cheaper, easier and lighter than steel. During the manufacture, no welding is needed and the whole craft is molded.

The propulsion system was also affected by the growth and evolution of ASVs. In the beginning of the 90's, ASVs were equipped with gasoline engines and needed fuel onboard to have sufficient autonomy to perform their missions. As technology advanced, gasoline engines were quickly replaced by electrical ones, which were lighter, more reliable and had controllable rotational speeds, but the only problem was the need of heavy batteries onboard and only few hours of endurance. Once again, with the development of new technological devices, some ASVs designers choose to remove some batteries by placing renewable energy devices onboard, like solar panels, increasing the autonomy of the vessel. Renewable energy devices allowed self-recharging and therefore less stops. Other important aspect of the propulsion system is the propeller design, which also depends on the hull type. For a catamaran hull, the typical choice is to use more than one propeller and use no rudder, applying differential revolution rates for steering. For a bigger vessel, it is best to use rudders aft the propellers but, for small vessels operating in very shallow waters, the best choice is probably to remove the propellers and place fans on top of the hull. In high speed vessels it is better to use gasoline or hybrid engines, for greater power and torque.

New hull shapes and concepts are always being developed, not only because the improvement of the ship efficiency, but also in the demand of the safety onboard. New hull concepts like the catamaran-SWATH are starting to show themselves as really good solutions, when a single vessel needs either speed or static behavior in the water. This concept has to be really well studied and designed, because the ship must be provided with really large ballast tanks that can submerge the pontoons to a draft where the ship enters in SWATH mode. Nowadays SWATHs are starting to become a more used concept for passenger ships, because of the extreme comfort they provide. A SWATH has a small waterplane area and because of that, they are less subjected to waves, giving them a stable position even if there is a harsh sea state. In scientific applications this can be really useful because it will give a more accurate and precise conditions for any measuring, mapping or even bathymetric research of a vessel.

In terms of navigation, GPS, DGPS and compasses are always present. Each vessel is equipped with its own navigation system and algorithms, controlled and observed by an operation center, even if they are fully autonomous, guaranteeing safety and mission success.

In Annex 1. it can be found the list of the main ASVs used for this dissertation.

Chapter 3. MISSION REQUIREMENTS

ASVs are programmed to accomplish certain mission(s). Since there are a lot of applications in which autonomous vessels are useful, it's up to the ASV user to choose the main goal(s) of the vessel, according to his needs. Mission requirements state the restrictions of the project according to the owner's requirements. The hull form, shape and layout are entirely dependent on these restrictions.

By designing a generic hull for generic missions, it is assumed that the vessel is completely capable of performing multiple tasks; therefore, the main objectives are hydrodynamic performance, stability, payload volume, weight, robustness and aspects related to mechanical performance.

Studying the applications already attributed to ASVs, it is possible to divide them into two main groups, the military and the scientific. It was decided to keep military ASVs aside because of the lack of information about their usage and applications. Scientific ASVs are being more used and since the majority of their missions are known, this work will be based on them. Scientific ASVs are typically developed to operate between the first six levels of the Beaufort scale. Lakes, rivers, estuaries and dams are typically associated with lower Beaufort levels, going from 0 to 3 which can be considered as lower sea states. Higher levels correspond to higher sea states, and there are ASVs capable to operate at a Beaufort level 5 (Elkaim & Cruz, 2008). In these cases seakeeping conditions, like roll, pitch and yaw, must specified in order to avoid excessive vibration that could cause the devices malfunction, and to maintain a reliable operation condition of the vessel.

In order to achieve most of the required ASV competences, it was decided to design not only one, but three different types of vessels: one to operate in lower sea states and the other two, able to operate in higher sea states.

The vessel designed to operate in calm waters must have as mission requirements stability to allow good measurements, enough cargo volume, for equipment transportation, system reliability, and low draft as an important requirement, to avoid any grounding or risk of get stuck at algal. The propeller should be protected from ground plants and any water pollution, and the vessel must be small sized, taking into consideration that two persons can transport, deploy and remove it from the water. The vessel should be designed to operate with electric propulsion only, powered by batteries that are carried onboard. The hull will be built from composite materials, maintaining the low weight, yet high strength. Cargo capacity is an important requirement, in order to allow the carriage of all electric equipment and the measuring samples and devices. Considering the existing ASVs, it was chosen a catamaran hull form to operate in calm waters. The objective is to prepare the vessel to perform hydrographic and environmental measurements, bathymetry and shoreline mapping, by providing enough space in the hull for any necessary equipment.

Harsh sea states require larger vessels with improved seakeeping characteristics, resulting in a more complex design. In a way to study the different types of hulls that are mostly used on ASVs, a monohull and a catamaran-SWATH were chosen for the design of the two vessels. The monohull vessel will be smaller and slower, than the SWATH, with enough cargo space to carry several electrical devices, to perform any necessary measurement. In this case, the objective is to maintain all boarded devices, electrical powered, excluding any combustion component. The hull shall be built from composite materials and shall have means to be lifted, in order to facilitate deployment and recovery. The speed is not a requirement, but must be sufficient to allow AUV following missions.

On the other hand, the catamaran-SWATH vessel will be the biggest and the fastest one. Following the idea of (Brizzolara & Chryssostomidis, 2013), this vessel is to become a part of the new generation of ASVs, where the speed is one of the most relevant requirements. The vessel must be large enough to carry at least one AUV, for transport, deployment and recovery and must be able to recharge on site a USV, enlarging its autonomy. The ASV will also be capable of performing oceanographic measurements, like bathymetry and wreck spotting, leading to extra cargo capacity. Propulsion system will consist of two diesel engines and two waterjets. One emergency diesel generator will be provided to ensure that the vessel can operate in critical conditions. The ship will be designed according to International Maritime Organization (IMO) rules, to make it as similar as possible to any ship design. Some rules do not need to be applied to this ship because it has no persons onboard. On the other side, since it is not a manned vessel and it is fast, it can represent a real danger to any other ship, and because of that, the ship must be provided with proper equipment to make it safe, like radars, masts and antennas, signal and navigation lights and emergency systems to guarantee the control of the ship is never lost.

Having a catamaran-SWATH design, the vessel can perform really accurate measurements, by flooding the ballast compartments and enter into the SWATH mode. In the SWATH mode the ship is less subjected to waves, decreasing the roll and becoming almost still in the water.

In both monohull and catamaran-SWATH vessels, good stability and seakeeping are very important.

Chapter 4. CATAMARAN

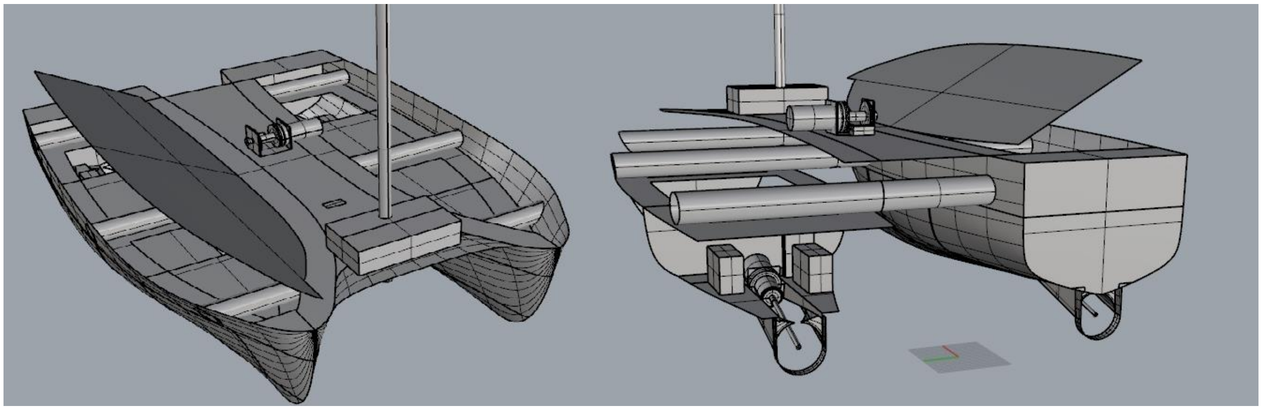

Figure 4.1. Catamaran model.

Chapter 4.1. Hull type and form

A catamaran hull is a really good solution when payload and stability are required, due to the presence of two hulls. By designing a catamaran vessel, low draft was achieved and since this hull was designed to operate in shallow waters, there was the objective of maintaining the design draft as low as possible.

In order to design a vessel of this kind, some assumptions were made, related to size, weight and speed. The size was to be kept small, with a maximum length of 2 meters, and there should be enough space for equipment and cargo. The max breadth of the ship was assumed to be 1.5 meters and the total lightship weight should be low enough so that two persons could lift it, but never forgetting that robustness and endurance should be present. Therefore, a composite material should be used for hull construction, and since there are a lot of possible fiber choices, the one used was E-Glass polyester woven roving, which is the most used in shipbuilding (Greene, 1997), ensuring good mechanical properties to the hull (Table 4.1).

Table 4.1. E-Glass Polyester Woven Rovin material proprieties.

E-Glass Polyester (WR)		
Fiber Volume Fraction	0.34	[-]
Density	1700	[kg/m^3]
Young's Modulus [E]	15	[GPa]
Shear Modulus	3.5	[GPa]
Tensile Strength [σvr]	250	[MPa]
Compressive Strength	210	[MPa]
Shear Strength	100	[MPa]

A new hull form had to be developed, and after some attempts on designing a good smooth surface and a proper hull shape, it was decided to use an existing hull series for the hull shape. This was a choice derived from the complexity of designing a very small hull shape, which is really different from the conventional hull curves. Other motive also influencing this choice was the fact that the series were already tested and adopted in ship design.

The series adopted for the hull design were the NPL High Speed Round Bilge Displacement Hull Series (Bailey & M.R.I.N.A, 1976), consisting in the development of catamarans. Despite being used for ships with 35 meters and above, this hull series was a good choice because the models used for resistance and propulsion predictions had similar sizes (Radojcic et al., 1997) to the one pretended for the design. One of the models was 2.45 meters long and its offset table is available for consulting. Using a scale factor for dimensions transformation, it was possible to build the new hull. By performing this step it was necessary to reform the position of some points, which were misplaced and incorrect. Rearranging the offset table and applying the transformation factor, the new catamaran was defined.

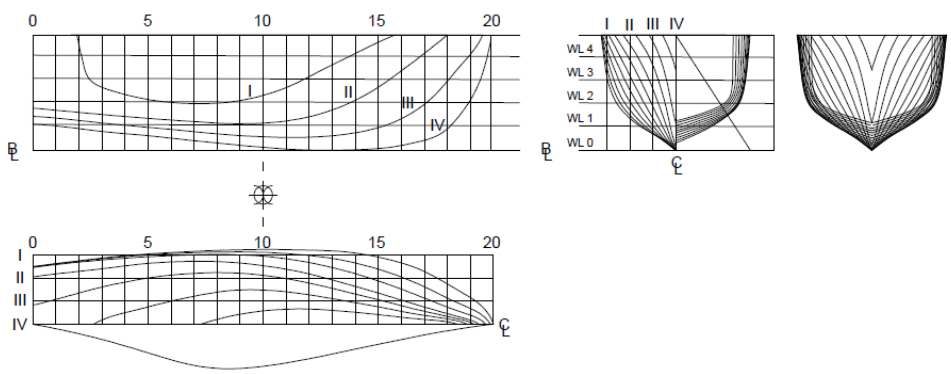

Figure 4.2. Catamaran lines plan (See Annex 2 for offsets)

Using the CAD software *Rhinoceros* and *Excel spreadsheet*, it was possible to build the 3D model of the hull, based on the new offset table. Connecting all the points resulted in a new hull, where some changes had to be done in order to achieve a nice and clean hull form, without edges or openings. The defined max breadth and length were achieved and hull spacing was assumed (Table 4.2).

Table 4.2. Catamaran main design dimensions.

Catamaran designed dimensions		
LOA	2.00	[m]
LPP	1.96	[m]
B_{Total}	1.50	[m]
B_{demi}	0.50	[m]
D	0.50	[m]
T	0.26	[m]

Both hulls are symmetric, connected by three aluminum bars and a composite platform. Both the shaft and the propeller are protected by a composite duct.

Since the hull is to be built from composite materials, construction is to be done by using a female mold. The hull was designed to be a single skin laminate, which is the most appropriate for small vessels (Greene, 1999), resulting in a very light weight structure. Single skinned laminates can suffer structural damages due to the lack of thickness if big forces are applied to the structure, which is why only small vessels are usually built with this type of laminates. In order to reinforce the hull, two transverse bulkheads and one stringer deck were designed (Table 4.3). Both bulkheads are to be watertight and also single skinned. By introducing these components to the hull, dry spaces were created either for payload or for any necessary equipment. Other connecting element is the aluminum structure, consisting in three aluminum bars, to be bolted to both hulls.

Table 4.3. Position of the structural elements of the catamaran.

Component	Number	Location		
Aluminum Bars	3	0.167-1.00-1.667	[m]	fwd APP
		0.470	[m]	above base line
Watertight bulkheads	2	0.500-1.300	[m]	fwd APP
Stringer deck	1	0.357	[m]	above base line

After completing the 3D model of the catamaran it was possible to calculate the main form coefficients corresponding to the designed draft. In this step, it was used the software *Model Maker* and *Autohydro* to calculate the preliminary hydrostatics of the vessel, for further resistance and propulsion prediction. Other information like the trim, draft and displacement were also obtained from *Autohydro*.

Since the design of the vessel followed the design spiral, modifications on the hull and layout had to occur during the design process, in order to satisfy the floating conditions and to optimize the vessel.

Regarding the hull, the catamaran is divided in three main areas:

- The Shell – Designed based on the NPL series; the hull does not have any flat of bottom or flat of side. At the bow, a really sharp ending is possible to identify and the transom is flat. The development of the hull lines makes the breath at midship higher than on other areas.
- Watertight deck – On this deck it is possible to find the watertight doors that separate the cargo area from the outside, where waterproof is guaranteed by adding a rubber gasket between the doors and the shell. Between these doors exists the deck platform, where the winch, the mast and the doors' joints are attached.
- Inside structure – The structure inside the ship is constituted by the transverse bulkheads, which separate the cargo spaces. The longitudinal reinforcement, made by a thin layer of composite materials. Six doors that provide access to the cargo areas. The bottom deck is constituted by flat panels to support the cargo and the equipment onboard.

Chapter 4.2. Hull Resistance and Propulsion

The hull hydrostatics were analyzed in order to evaluate which would be the displacement of the ship for the different drafts. The longitudinal and vertical centers of buoyancy, as well as the transverse and longitudinal metacentric height, were obtained. To calculate these parameters, *Autohydro* was used.

The ship model used in *Autohydro* was built using Model Maker and was based on the 3D model designed with *Rhinoceros*.

In the calculation of these hydrostatics, it was assumed that the ship would be in even keel

Table 4.4. Calculation of the hydrostatics of the catamaran, assuming even keel.

Draft [m]	Displacement [kg]	LCB [m]	VCB [m]	LCF [m]	TPcm [kg/cm]	MTcm [kg.m/deg]	KML [m]	KMT [m]
0.200	132	0.897f	0.144	0.796f	15.210	5.331	2.641	2.448
0.250	213	0.860f	0.175	0.807f	17.080	6.215	1.993	1.804
0.300	301	0.848f	0.204	0.829f	18.228	6.891	1.630	1.443
0.350	395	0.846f	0.233	0.853f	19.020	7.571	1.418	1.232

The hydrostatics of one demi hull were also calculated (Table 4.5) in order to compare the effect of a twin hull in the catamaran. Comparing both results, changes were easily seen, mainly in the transversal metacentric height (KMT), which was expected to be bigger in the catamaran case (Table 4.4).

Table 4.5. Demi hull, hydrostatics.

Draft [m]	Displacement [kg]	LCB [m]	VCB [m]	LCF [m]	TPcm [kg/cm]	MTcm [kg.m/deg]	KML [m]	KMT [m]
0.200	67	0.897f	0.144	0.796f	7.510	2.515	2.640	0.351
0.250	109	0.860f	0.175	0.807f	8.964	3.012	1.993	0.349
0.300	154	0.848f	0.204	0.829f	9.648	3.451	1.629	0.346
0.350	202	0.846f	0.233	0.853f	10.023	5.145	1.417	0.353

Analyzing the hydrostatics of the catamaran (Table 4.4), it was clear that the initial design draft of 0.3 meters was unacceptable, due to the high value required for displacement. Although the design draft would probably be changed, its values were used for resistance prediction. Prismatic, block, midship and waterplane coefficients were obtained, as well as waterplane area and wetted surface area (Table 4.6). Catamarans have two different block coefficients (Moraes et al., 2007) the demi hull block coefficient, regarding to only one floater, and the ship's block coefficient, which is related to both hulls. In this case, the block coefficient used in resistance prediction was regarding both hulls.

Table 4.6. Catamaran, hull coefficients and areas.

Coefficients	[-]	Areas	[m^2]
Block - Cb	0.617		
Prismatic - Cp	0.668	Waterplane - Awl	1.721
Midship - Cm	0.923	Wetted Surface - S	2.522
Waterplane - Cw	0.602		

The resistance of the vessel was obtained using the *NavCad* software. The initial idea was to use the provided data already studied by the NPL series, the difference on the hull sizes had an effect on some parameters due to the scale factor. NPL series use the Length/Displacement ratio ($L/V^{1/3}$) parameter to predict the resistance and since the studied catamaran $L/V^{1/3}$ was not equal to any of the studied cases, applying NPL values would have been an error.

It was important to define the water proprieties in which the vessel was going to operate, therefore the standard fresh water proprieties from *NavCad* were used (999.01 kg/m^3)

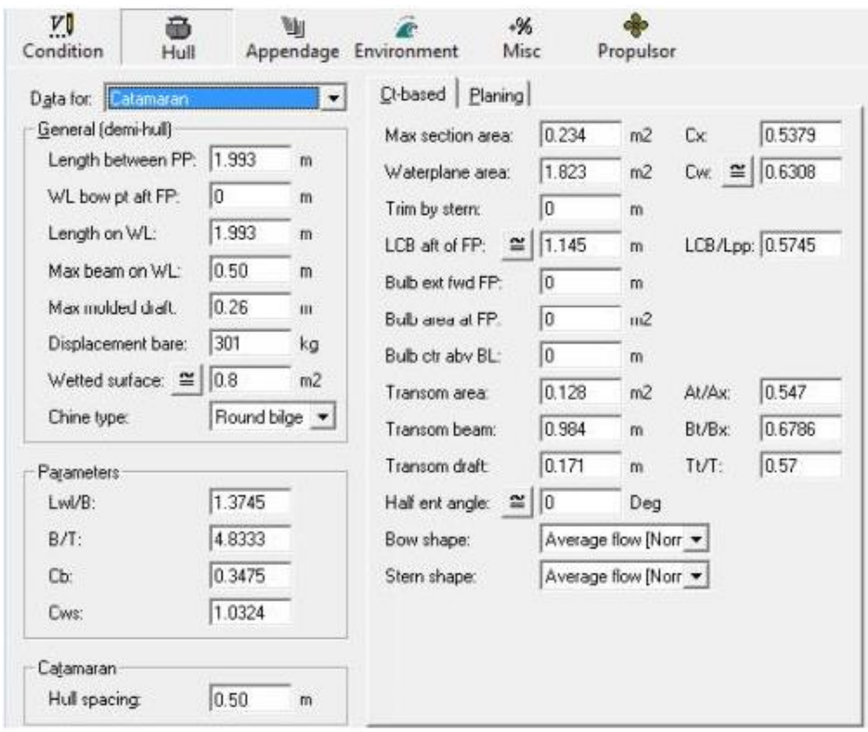

Figure 4.3. *NavCad* input data file.

NavCad has a lot of different methods to predict the resistance of the hull, like the classic Holtrop (Holtrop & Mennen, 1982), Oortmerssen (Oortmessen, 1964) and much more. One of the possible methods that the software is able to use is the NPL. The requirements which are demanded by NPL resistance prediction (certain Froude and form coefficient intervals) were fulfilled, therefore the method was acceptable and possible to use (Table 4.7).

Although this method was appropriate, there was a problem in the prediction of the resistance at lower speeds. Since the working speeds of the catamaran are low, some errors could appear on the values of the resistance.

After running the program, the resistance values, even for low speeds were calculated and with that the effective power could be determined. This value would stablish the amount of energy required by the motors.

Table 4.7. Resistance values, predicted using *NavCad* software.

Vel [knt]	Fn	Cf	Cr	Ct	Rbare [Kn]	Rtotal/W	Petotal [Kn]
1.0	0.116	0.0048	0.0092	0.0140	0.003	0.001	0.002
1.5	0.175	0.0044	0.0156	0.0200	0.010	0.002	0.007
2.0	0.233	0.0041	0.0205	0.0246	0.021	0.004	0.021
2.5	0.291	0.0040	0.0242	0.0281	0.037	0.006	0.048
3.0	0.349	0.0038	0.0261	0.0299	0.057	0.010	0.088
3.5	0.407	0.0037	0.0273	0.0310	0.080	0.014	0.145
4.0	0.465	0.0036	0.0304	0.0340	0.115	0.019	0.237
4.5	0.524	0.0035	0.0303	0.0338	0.145	0.025	0.335
5.0	0.582	0.0035	0.0274	0.0309	0.163	0.028	0.420
5.5	0.640	0.0034	0.0240	0.0274	0.175	0.030	0.496

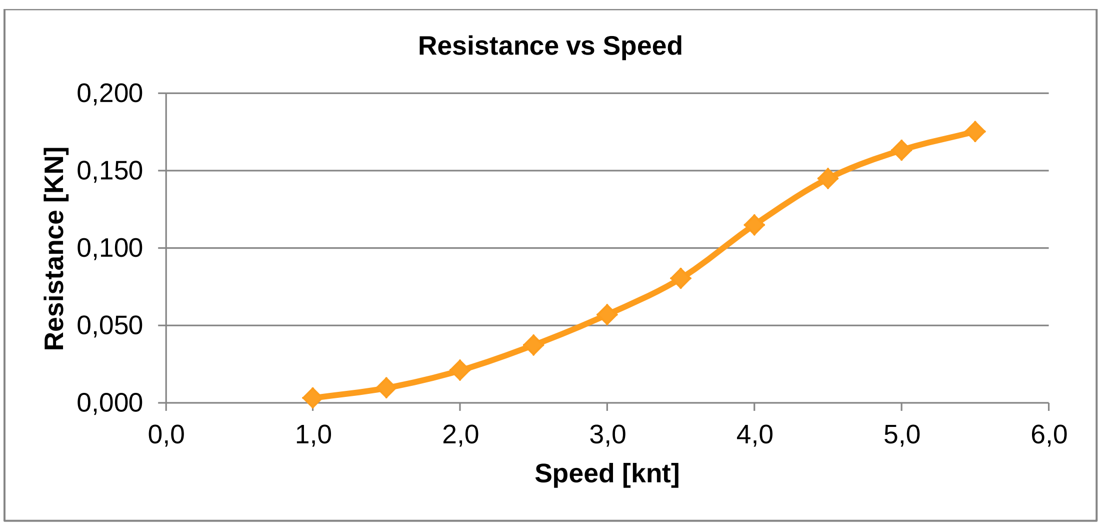

Figure 4.4. Catamaran resistance evolution, due to the effect of the speed.

Chapter 4.3. Hull equipment and ship light weight

The propulsion system should be constituted by electrical devices only. There are a vast number of companies that are specialized in small electrical motors for marine application and since the catamaran is really similar to a small model vessel, it was not very hard to find an appropriated motor. Two M644E-2530 motors, fabricated by the company Mclennan Servo Supplies Ltd., were installed on the catamaran, one in each demi-hull, providing a more stable thrust, and facilitating the hull layout. By introducing one electric motor in each floater, it was assumed that no steering gear was needed, since maneuver could be done by applying differential propeller revolution. Attached to each motor, is installed a gearbox to reduce the motor's rotation speed. The HPE70 gearbox is also produced by Mclennan Servo Supplies Ltd., and is connected to the shaft line. Other component connected to the motor is the drive system, which is responsible for the interaction between the onboard computer and the motor, in order to regulate either the speed, heading course or maneuvers. It is an IPM240 Drive, also fabricated by the same company. The last components attached to the motor are the batteries, responsible for the autonomy of the vessel. To choose the batteries it was necessary to verify in which voltage and amperage the motor would work. Then, according to the discharge rate of the batteries, the autonomy could be calculated. The batteries used for the catamaran are distributed by RLK Company and the model is the sealed lead-acid battery RLK-1280, with a nominal voltage of 12 V and a rated capacity at 8 Ah of 20 hours. Each motor is connected to two batteries, where one battery is in standby mode and only to be used in case of raising autonomy, operation speed or failure of the twin battery. Assuming that the motor should consume the energy of one battery only, autonomy was guaranteed, at least, for 20 hours.

The shaft line was designed according to the hull characteristics and the position of the gearbox. Small shaft lines are also produced by model boat companies and the one chosen for the catamaran is a stainless steel tube, with 6 millimeters of diameter, built by Cornwall Model Boats Company. The shaft line, gearbox and motor are not parallel to the base line, having a 15 degree trim, in order to align the prime mover and the propeller in the same referential.

The vessel is also equipped with a winch and a mast, to increase its versatility and allow, even more applications. The winch can be used either for trawling or for operation, and it is located at midship. The position of the winch was influenced by the position of the center of buoyancy, in order to prevent big variations to the trim. The mast is made of aluminum and was bolted to the forward aluminum bar. Attached to the mast is a watertight box where the electronic cables and devices, can be connected to the mast.

After defining all necessary equipment for propulsion a new calculation of the vessel's hydrostatics was performed. This time, in the hydrostatic measurement was inserted all the weights and the respective position inside the vessel. All the weights, used in this new measurement, belong to the lightship weight and the objective of the new *Autohydro* .run file was to verify the new draft, trim and position of the center of buoyancy. The weights can be divided in three categories: the composite structure weight, aluminum weight and the equipment weight.

The composite structure weight was calculated according to the density of the E-Glass polyester woven roving (Table 4.1) and the defined thickness of the material. Based on some of the already developed works (Ferri et al., 2011), a thickness of 3 millimeters, for the composite elements, was assumed. In order to know the total weight of the composite, it was necessary to verify the total area of the composite plates, using the 3D model (Table 4.8). Knowing the areas and applying equation (1) it was possible to know the total weight of the designed composite material. Once again, using the 3D model it was also possible to define the position of the longitudinal, transversal and vertical center of gravity of the selected components.

Table 4.8. Composite elements constituting the catamaran.

Name	**Area [m^2]**	**Thickness [m]**	**Weight [kg]**
Upper deck doors	1.661	0.003	8.47
Watertight doors	0.924	0.003	4.72
Inner structure	1.016	0.003	5.18
Watertight bulkheads	0.548	0.003	2.79
Connecting platform	0.941	0.003	4.80
Outer Shell	5.125	0.003	26.14
Propellers duct	0.094	0.003	0.48
Composite Density	1700 kg/m^3		

$$Weight = Area * Thickness * Material\_Density \text{ (kg)} \qquad (1)$$

The previous method was also adopted to calculate the weight of the aluminum components (the three structural bars and the mast), where a 3 millimeter thickness was also assumed. The information of the center of gravity was divided in two - the weight of the mast and its center of gravity, and the weight of the three aluminum bars and the respective center of gravity (Table 4.9).

Table 4.9. Area, position and weight of the aluminum components.

	Aluminum bars	**Mast**	
Area	1.026	0.145	[m^2]
thickness	0.003	0.003	[m]
Weight	8.62	1.21	[kg]
Lcg	1.667	0.882	[m]
Vcg	0	0	[m]
Tcg	0.882	0.408	[m]

The equipment weight is specified by the building companies, so it was only necessary to note the location of each one. With all weights and respective center of gravity defined (

Table 4**.10** & Table 4.11), the lightship weight of the vessel was calculated.

Table 4.10. Light ship weight components.

	Component	Location	Weigth [kg]	Lcg [m]	Tcg [m]	Vcg [m]
1	**Composite structure**	-	52.58	0.904	0	**0.339**
	add panel	-	1.34	1.745	0	**0.549**
2	**Mast**	-	1.21	1.667	0	**0.882**
	Aluminum Structure	-	8.62	0.913	0	**0.406**
3	**Electric Motor**	Portside	1.9	0.345	0.425	**0.154**
		Starboard	1.9	0.345	-0.425	**0.154**
4	**GearBox**	Portside	2	0.302	0.425	**0.136**
		Starboard	2	0.302	-0.425	**0.136**
5	**Shaft Line**	Portside	0.207	0.135	0.424	**0.095**
		Starboard	0.207	0.135	-0.424	**0.095**
6	**Lead Batteries**	Portside Demi, Portside	2.5	0.329	0.537	**0.205**
		Portside Demi, starboard	2.5	0.263	0.314	**0.205**
		Starboard Demi, Portside	2.5	0.263	-0.314	**0.205**
		Starboard Demi, Starboard	2.5	0.329	-0.537	**0.205**
7	**Support Structure**	Portside	0.767	0.302	0.425	**0.149**
		Starboard	0.767	0.302	-0.425	**0.149**
8	**Drive**	Portside	0.6	0.391	0.314	**0.222**
		Starboard	0.6	0.391	-0.314	**0.222**
9	**Winch**	-	8.5	1.441	0.000	**0.536**

$$Xcg = \frac{\sum_{n=0}^{n}(Weight_n * xcg_n)}{\sum Weight}\ (m) \quad (2)$$

$$Ycg = \frac{\sum_{n=0}^{n}(Weight_n * ycg_n)}{\sum Weight}\ (m) \quad (3)$$

$$Zcg = \frac{\sum_{n=0}^{n}(Weight_n * zcg_n)}{\sum Weight}\ (m) \quad (4)$$

Table 4.11. Catamaran Light weight

	weigth [kg]	Lcg [m]	Tcg [m]	Vcg [m]
Light weight	93.20	0.842	0.000	0.337

Applying equations (2), (3) and (4), it was possible to determine the ship light weight (Table 4.11).

In *Autohydro*, a new .run file was developed. The weights of the structure and the equipment were defined as local forces instead of distributed loads, where the location of each force was positioned at the center of gravity of the corresponding component. After defining the weights and positions, the trim of the light weight vessel was calculated.

Six compartments were defined as cargo holds, with the possibility of adapting the bottom void space for water sample tank. The numbers of compartments allow several divided spaces for different equipment. The main cargo space was located forward of the propulsion division, as near as possible from the center of buoyancy. Each hull has three compartments for payload, the space available in each compartment is measured in volume, but its capacity is measured in kg, due to the weight of the equipment (Figure 4.5).

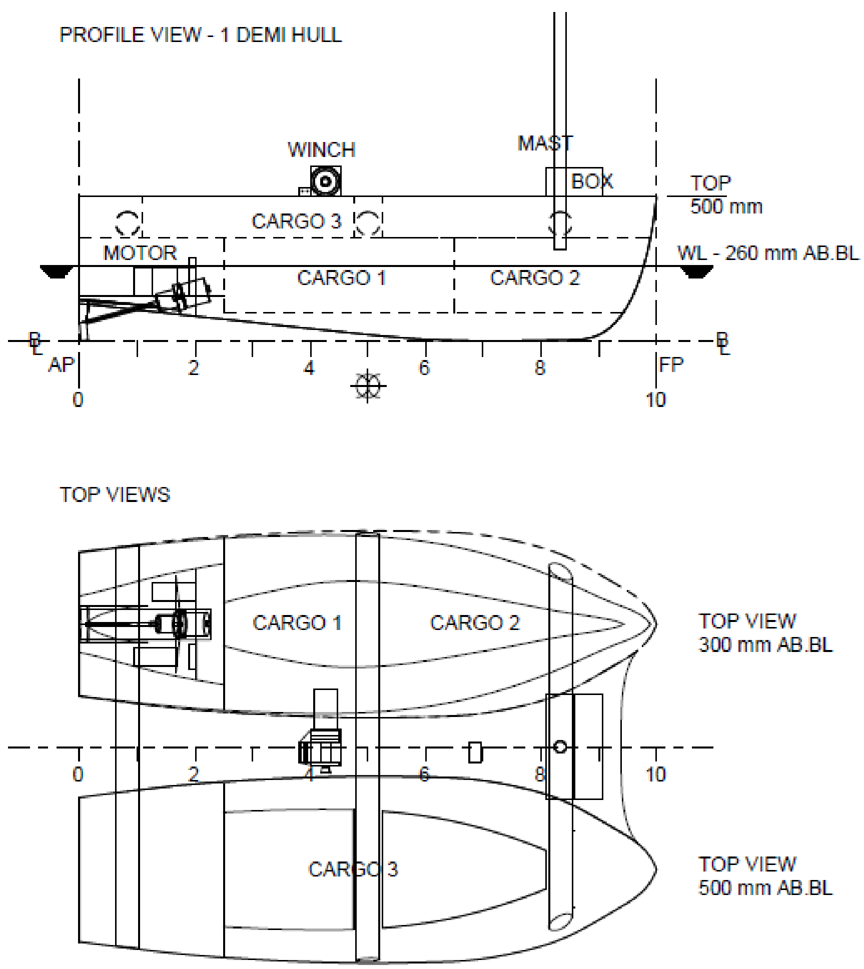

Figure 4.5. Catamaran general arrangement. (see Annex 4 for detail)

$$\Delta = 2 * L_{wl} * T * b\_demi_{wl} * C_b \text{ (kg)} \tag{5}$$

$$DW = \Delta - LW \text{ (kg)} \tag{6}$$

L_{wl} = Length at design waterline (m);

B_demi_{wl} = demi hull beam at design waterline (m);

T = Design draft (m);

C_b = block coefficient;

LW = Light Weight (kg);

DW = Dead Weight (kg);

With a deadweight of 130 kg (equation 6.), the total catamaran displacement is of 223.2 kg, with a draught of 0.26 meters.

After calculating the designed deadweight, it was necessary to distribute it the vessel. The total amount of cargo was divided by the designed cargo compartments, where near the center of buoyancy more weight was going to be inserted and, near the bow only a small amount of weight was to be boarded, due to the compartments sizes and trim problems. There are a lot of possible combinations of weights to achieve a trim near to zero, but one suggestion was calculated and validated.

Chapter 5. MONOHULL

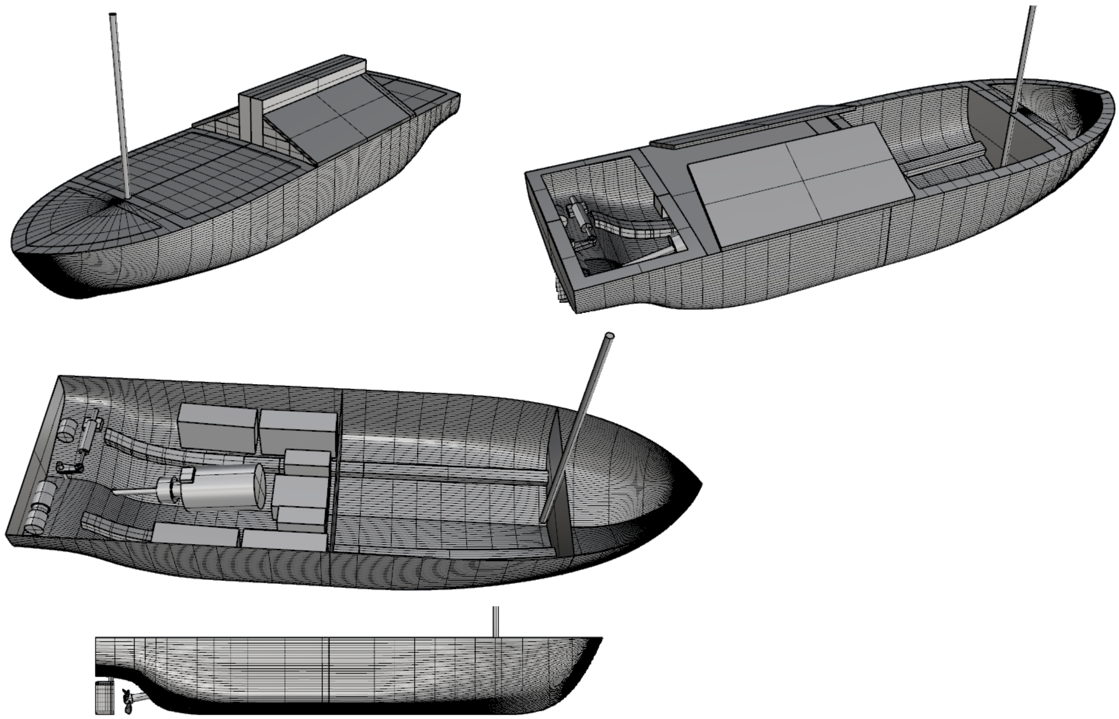

Figure 5.1. Monohull model.

Chapter 5.1. Hull type and form

The monohull is a vessel designed to operate in open waters and therefore it must have enough stability to guarantee the safety of the equipment. At the beginning, the idea was to design a vessel similar to a recreational vessel, like a kayak or even a jet ski, because of their low weight and good flexibility, but with a disadvantage of low cargo capacity, which lead to the exclusion of such hull types.

A barge hull form was also assumed, which would give much cargo volume, and it would be simple to design. In this case a bigger problem would appear, regarding the ship maneuvering and ship behavior at the sea, because such structure would be have very rough hydrodynamics and would be hard to control the sailing direction when facing waves and currents.

Other possibility was to create a planning hull form, which would give very good behavior at high Froude numbers and could be designed according to planning hull series like hard chine hull series 62 or 65 (Clement & Blount, 1963 ; Holling & Huble, 1974). Hard chine series are very common in pleasure crafts, providing good behavior at high speeds, but the hull form is not always the most adequate when payload is a requirement.

It was important to balance the vessel in order to have good behavior at relatively high Froude numbers and also have good cargo volume, therefore it was chosen a semi-planning hull type, which possesses a little of the planning hull characteristics and a common displacement hull, balancing the most important requirements (Codega & Blount, 1992). This type of hull form has a flat area with a certain degree of inclination located at the keel, which provides enough lifting capability to reduce wave resistance and the development of the outer shell doesn't creates any visible edge, instead a round bilge provides a development of the hull which allows a very good flat of side area, increasing the cargo space.

Some initial dimensions like the length, maximum breath and design draft were assumed, based on the environment in which the vessel should operate and based on former designs, most of them for military applications (Desa et al., 2007; Bertram, 2008). The initial dimensions (Table 5.1), followed by the form of the semi-displacement hull, result in a vessel with the coefficients of Table 5.1. According to some changes that had to be done when the resistance and propulsion was being calculated (explained in Resistance and propulsion), the initial design draft of 0.3 m could not be used. Instead, it was assumed a draft of 0.4m and a new hull shape resulted in new coefficient values (Table 5.1). The changes on the hull were done at the stern, with a new development of the stern panel, necessary to allow the installation of the propeller and the steering gear, according to the new draft and to the propulsion requirements. The importance of the changes was not only to provide the vessel with a better seakeeping behavior, but also to improve the vessel's agility, by installing a bigger rudder.

Table 5.1. Monohull design parameters.

initial design draft 0.3 m			**final design draft 0.4 m**		
LOA	5	[m]	LOA	5	[m]
Lpp	4.42	[m]	Lpp	4.833	[m]
B	1.5	[m]	B	1.5	[m]
D	0.7	[m]	D	0.7	[m]
T	0.3	[m]	T	0.4	[m]
Lwl	4.42	[m]	Lwl	4.833	[m]
Bwl	1.497	[m]	Bwl	1.5	[m]
V	1.212	[m^3]	V	1.816	[m3]
Displacement	1243	[kg]	Displacement	1862	[kg]
Cp	0.761	[-]	Cp	0.736	[-]
Cb	0.611	[-]	Cb	0.627	[-]
Cm	0.803	[-]	Cm	0.852	[-]
Cwp	0.873	[-]	Cwp	0.881	[-]
Awp	5.779	[m^2]	Awp	6.378	[m^2]
S	6.756	[m^2]	S	8.146	[m^2]
Lcb	2.415	[m]	Lcb	2.404	[m]
Vcb	0.184	[m]	Vcb	0.24	[m]

Having the hull form defined, it was necessary to choose the best material to build it, and since low weight was to be kept, the composite E-Glass Polyester Woven Rovin was once again used, but this time it should not be a single layered vessel, but a sandwich laminate composite hull, for higher structural strength and, for that it was necessary to perform some scantlings using the ISO rules for composite vessel.

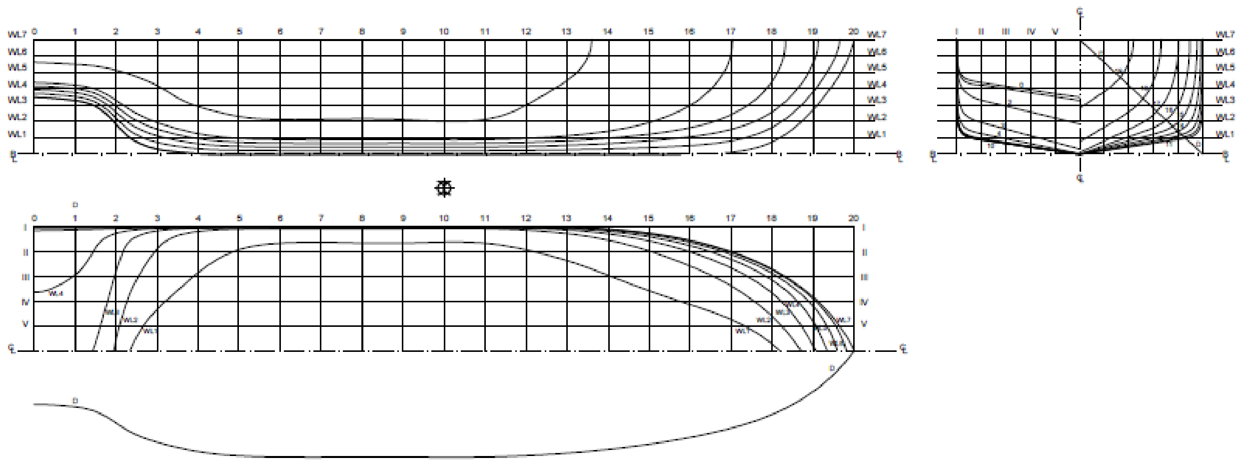

Figure 5.2. Monohull Lines plan (See annex 2 for offsets)

As in the catamaran's demi-hulls, there are two watertight bulkheads, dividing the hull in three main compartments. In the aft compartment it is possible to find the engine, batteries, and all equipment necessary to the propulsion and maneuvering of the vessel. The other two areas of the hull were designed for cargo. It is also possible to find structural composite reinforcements, also designed according to ISO rules. Flat deck panels were positioned for equipment support. These panels were designed as single skin laminates.

Table 5.2. Area and position of the monohull's bulkheads.

Watertight Bulkheads		
Bulkhead	Area [m^2]	x [m]
Transom	0.435	0
Fwd Engine Area	0.956	2300
Fwd Bulkhead	0.740	4000

Another characteristic of the vessel is the capability of ballasting the small sampling tanks, located forward. There are a total of six small water sampling compartments, divided by single skin composite lamination, for different types of measures. The flat area above them, allows the installation of any necessary equipment to the water measurement procedure.

The vessel is to be 100 % electrical, and since it is to have a good autonomy it was decided to install solar panels, that would be connected to the batteries of the main engine. In order to do that, it was necessary to develop a support structure for them, which would be located at the top deck. This support structure had to be big and strong enough to hold two solar panels, and at the same time provide dry spaces for the electrical wires that would be connected to the batteries. The structure was designed to be built from single skin laminates, providing good stiffness and low weight. The dry volume obtained from the structure can also be used to install or carry more equipment. The structure was designed according a standard solar panel size. The vessel is also equipped with a mast, and since it is to operate in open water, the mast will have not only the role of support a GPS or antennas, but also lights to maintain the vessel visible even at night. The mast is to be bolted to the forward bulkhead and to the bottom plate.

The top deck is equipped with six watertight doors, designed to give different accesses to the interior compartments. The vessel also presents a small camber to allow water flow, avoiding the existence of puddles at the top deck.

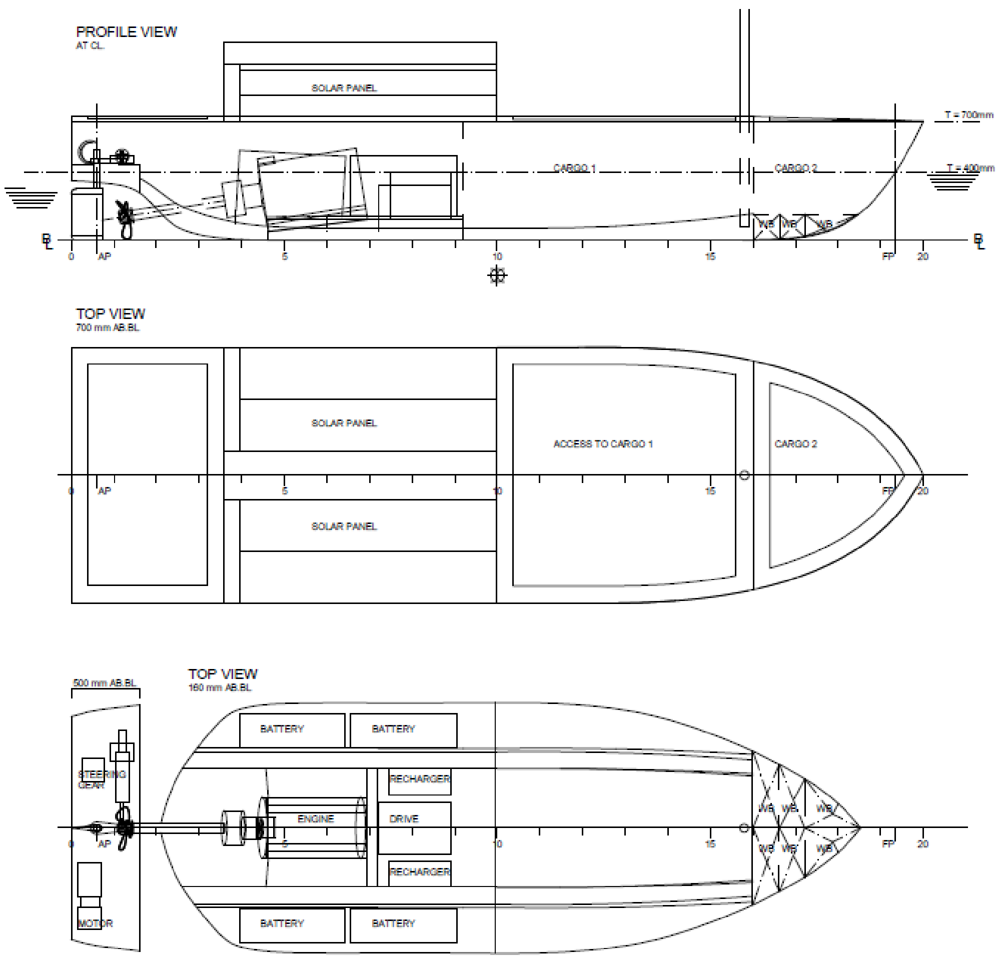

Figure 5.3. Monohull general arrangement. (See Annex 4 detail)

Chapter 5.2. Scantlings for hull and reinforcements

The scantlings were based on the Draft International Standard ISO/DIS 12215 (International Organization for Standardization, 2004) for small crafts. According to the rules, for crafts with length between 2.5 m and 12m, that fulfill the requirements of the design category C, a simple design method can be applied. This method is for vessels that operate in seas with significant wave heights of 2 m and a wind force up to Beaufort Force 6.

In this method, the vessel is named as a motor craft or a sailing craft, according to the type of propulsion and hull characteristics. Since this vessel was not designed to be equipped with sails and not propelled by wind means, it was classified as a motor craft (category C) and the respective rules were followed.

A formula was given to calculate the required thickness of the laminate. All the coefficients that must be used for the calculations are provided in the graphics which relate the speed and the length of the vessel, and it is according to the obtained value that the calculations shall be done.

$$panel\ laminate\ thickness\ (t_r) = c_t * b\ (mm) \quad (7)$$

c_t= value obtained by [ref graph]

b= 400 + 10 * L_{WL} (mm)

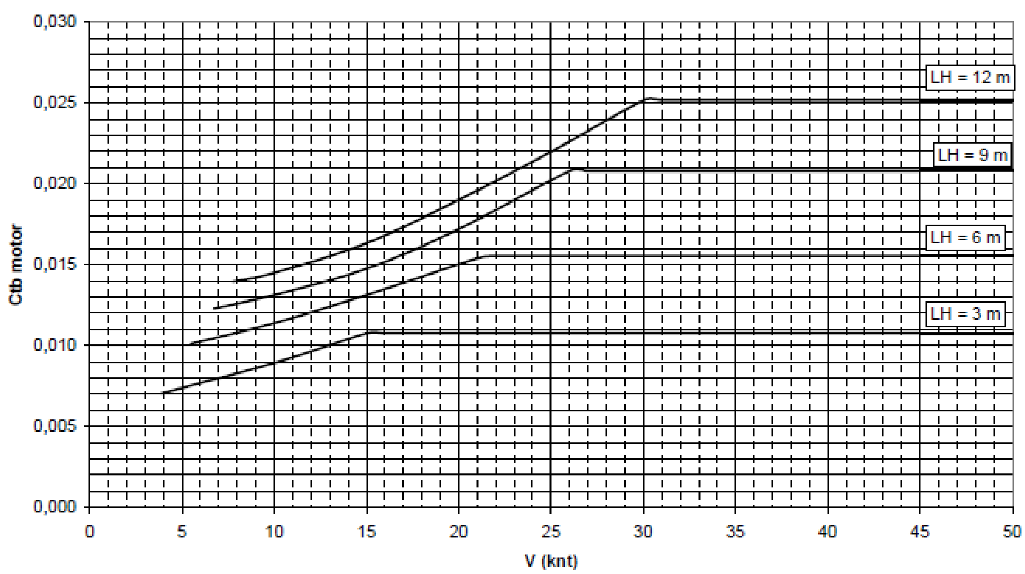

Figure 5.4. Ctb values for motor craft vessel type (International Organization for Standardization, 2004)

Ctb factor was obtained from the graphics, given by the ISO rules. With the Ctb value calculated, the minimum thickness for the hull panels was obtained, as also the total fiber weight of the outer shell. The performed scantling was only regarding the minimum thickness of the laminate, so it was necessary to calculate the thickness of the foam and the section modulus of the reinforcements.

The section modulus of the reinforcements (SMr) was obtained by a similar way as the minimum thickness, but this time it was necessary to input the spacing between reinforcements and their total length. In order to proceed with the scantlings, a position and span were assumed and represented at the 3D model.

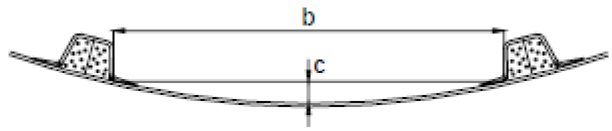

Figure 5.5. Representation of the span and distance of reinforcements. (International Organization for Standardization, 2004)

Table 5.3. Span and curvature for reinforcement scantlings.

b	663	mm
c	50.66	mm

Once again, the value for the Csm was obtained from the graphic, regarding the motor craft, and the minimum section modulus was calculated. Having the section modulus it was possible to define the size and type of reinforcement, by checking the standard tables from the rules, and then update the 3D model in order to know the total reinforcement volume of the vessel.

$$min\ stiffener\ thickness\_st_r = 0.5 * \Delta^{0.33} * \frac{b}{400} * k_{loc} * k_r * f_k\ \ (mm) \qquad (8)$$

$k_{loc} = 1.0$

$$k_r = 0.54 + 0.23 * \frac{l}{b}$$

$$f_k = 1.1 - 3.3 * \frac{c}{b}$$

Table 5.4. Scantlings of the reinforcements.

Min stiffener thickness	8.43	[mm]
b	663	[mm]
kr	1	
length	2500	[mm]
kloc	1	
fk	0.847	
c	50.66	[mm]
Displacement	1861.932	[kg]

According to the rules, it was necessary to perform a thickness correction for a sandwich laminate, where core material and its thickness were chosen. The criterion of selection of the core material was according to its density, where it was decided to use a light core, to maintain lighter weight. The equation used for the minimum thickness of the core material was:

$$\min core\ depht\ (dc) = \frac{4400 * t_r^3}{b^2}\ \ (mm) \tag{9}$$

Table 5.5. Total laminate panel thickness.

Foam thickness	2.0	mm
Fiber thickness	4.0	mm
Composite thickness	6.0	mm

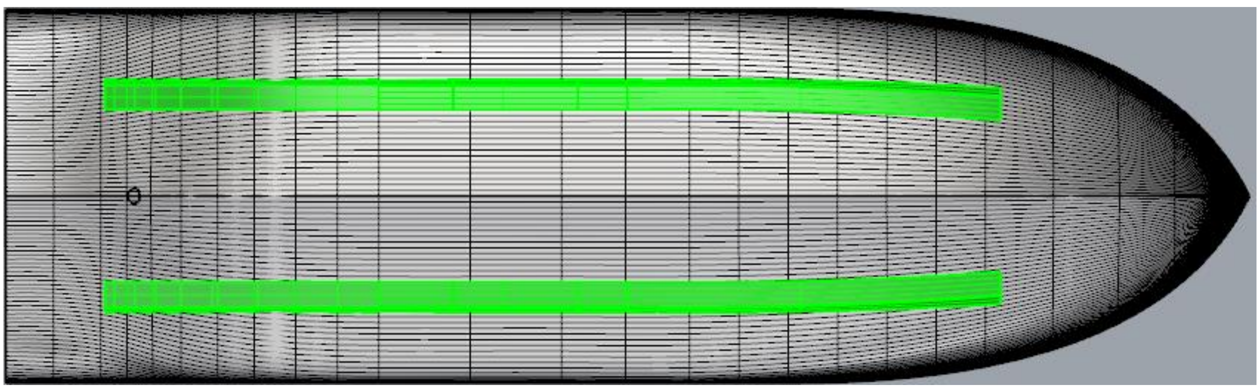

Figure 5.6.Top view of the monohull composite reinforcements (represented with green color).

Chapter 5.3. Resistance and propulsion

Following the procedure once done at the catamaran, resistance and propulsion were calculated right after the initial dimensions and the hull form were defined.

Model Maker and Autohydro were used again, to calculate the hull hydrostatics in even keel (**Table 5.6**).

Table 5.6. Monohull hydrostatics.

LCF Draft (m)	Displ (kg)	LCB (m)	VCB (m)	LCF (m)	TPcm (kg/cm)	MTcm (kg-m /deg)	KML (m)	KMT (m)
0.250	953	2.412f	0.156	2.430f	56.578	117.452	7.434	1.118
0.300	1243	2.415f	0.184	2.415f	59.234	133.340	6.520	0.963
0.350	1544	2.415f	0.212	2.393f	61.664	149.975	5.939	0.867
0.400	1862	2.404f	0.240	2.315f	65.365	178.572	5.868	0.816
0.450	2197	2.386f	0.268	2.268f	68.132	200.244	5.596	0.796

According to Table 5.6 the total displacement for the initial design draft was 1243 kg. Before using *NavCad*, it was attempted to input the hull data at *Autopower*, in order to evaluate if the resistance calculation methods, used by the software, were enough to predict the monohull resistance, but, the fact of being a small vessel, excluded that possibility.

The first attempt to calculate the resistance of the monohull was made for the initial design draft of 0.3 m, where the input that for the *NavCad* was obtained at *Autohydro*. In this case, the vessel fulfilled the requirements to apply the NPL resistance, because the block coefficient and the location of the center of buoyancy were between the intervals of the NPL series. The resistance was predicted and it was possible to perform the propulsion calculations, where the propeller was going to be dimensioned. One engine was chosen, according to the necessary amount of power to achieve the maximum speed of 10 knots, but when the propeller was being dimensioned a new problem appeared, cavitation (Paik et al, 2008). Since the draft was too small, and the distance between the center of rotation of the propeller was too close to the sea surface, the necessary amount of rotations per minute (rpm) of the propeller would create cavitation, which would result in severe damages of the propeller blades and the lack of bollard thrust applied to the craft. Therefore it was necessary to perform some changes at the hull. Firstly the design draft was raised, and secondly the stern shape was changed in order to allow the installation of a bigger propeller, by providing a bigger distance between the base line and the sea surface.

With the new hull shape and parameters related to the new draft, a new iteration of the resistance was performed. The new attempt brought other kind of problems, because the NPL method was no longer suitable to predict the new resistance. The *NavCad* database is equipped with a large number of resistance methods, for different types of hulls and forms. Some of them were possible methods for the monohull, but there was one which was the most indicated, the NTUA method (Tzabiras & Kontogiannis, 2010), which is a method based on Computed Fluid Dynamics (CFD) tests, in models.

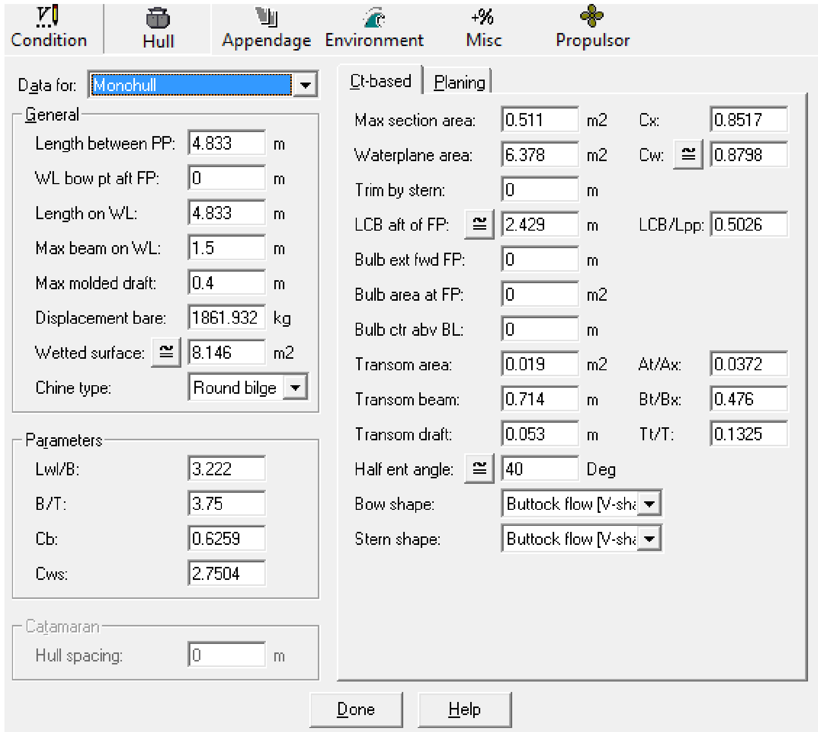

Figure 5.7. Monohull input data at NavCad.

Table 5.7. Calculation of the resistance of the monohull.

speed [knt]	Fn	Rn	Cf	Cr	Ct	Rbare [kN]	Rtotal [kN]	Rbare /W	PE total [kW]	P_D total [kW]
2	0.149	4.18E+06	0.004	0.006	0.009	0.042	0.042	0.002	0.043	0.044
3	0.224	6.28E+06	0.003	0.014	0.017	0.168	0.168	0.009	0.259	0.270
4	0.299	8.37E+06	0.003	0.019	0.022	0.388	0.388	0.021	0.798	0.831
5	0.374	1.05E+07	0.003	0.022	0.025	0.680	0.680	0.037	1.750	1.823
6	0.448	1.26E+07	0.003	0.022	0.025	1.004	1.004	0.055	3.100	3.230
7	0.523	1.46E+07	0.003	0.021	0.024	1.314	1.314	0.072	4.731	4.928
8	0.598	1.67E+07	0.003	0.019	0.022	1.574	1.574	0.086	6.479	6.749
9	0.673	1.88E+07	0.003	0.017	0.020	1.778	1.778	0.097	8.231	8.574
10	0.747	2.09E+07	0.003	0.015	0.018	1.950	1.950	0.107	10.033	10.451

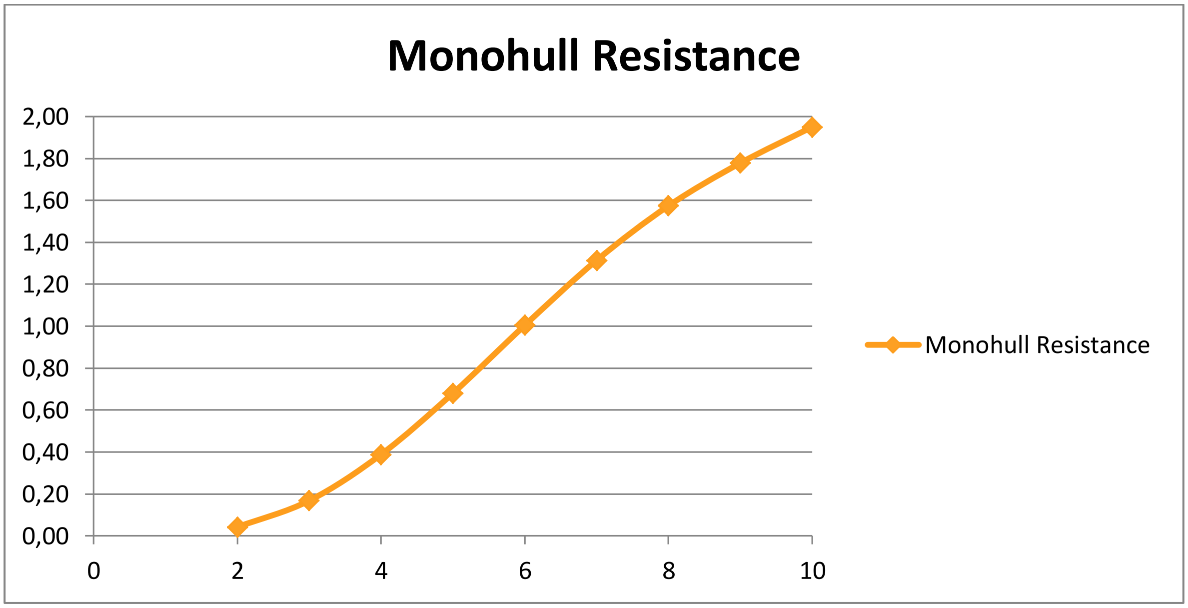

Figure 5.8. Resistance curve of the monohull.

After calculating the resistance of the hull, it was necessary to choose an engine, which could produce the amount of power necessary to reach the max speed of 10 knots. This engine was to be an electric one, but much more bigger and heavier than the one chosen for the catamaran. There were several possibilities for the engine arrangement; the first one adopted was an external engine, which could be placed at the transom, with an external shaft line, but these engines could not produce the required amount of power. If an external engine arrangement was to be adopted, then it was necessary to have a diesel engine. Therefore and internal engine arrangement was chosen.

The engine chosen is produced by the *MasterVolt Marine Company*, and is named Drive Master Ultra 20. The arrangement of the motor was done in order to give a certain angle to the shaft line, increasing the distance of the center of the shaft-line to the bottom of the stern panel. This increase would allow an installation of a bigger propeller. The angle of the shaft was directly influencing the maximum diameter of the propeller. The biggest concerns were the base line of the vessel, the draft line and the stern panel.

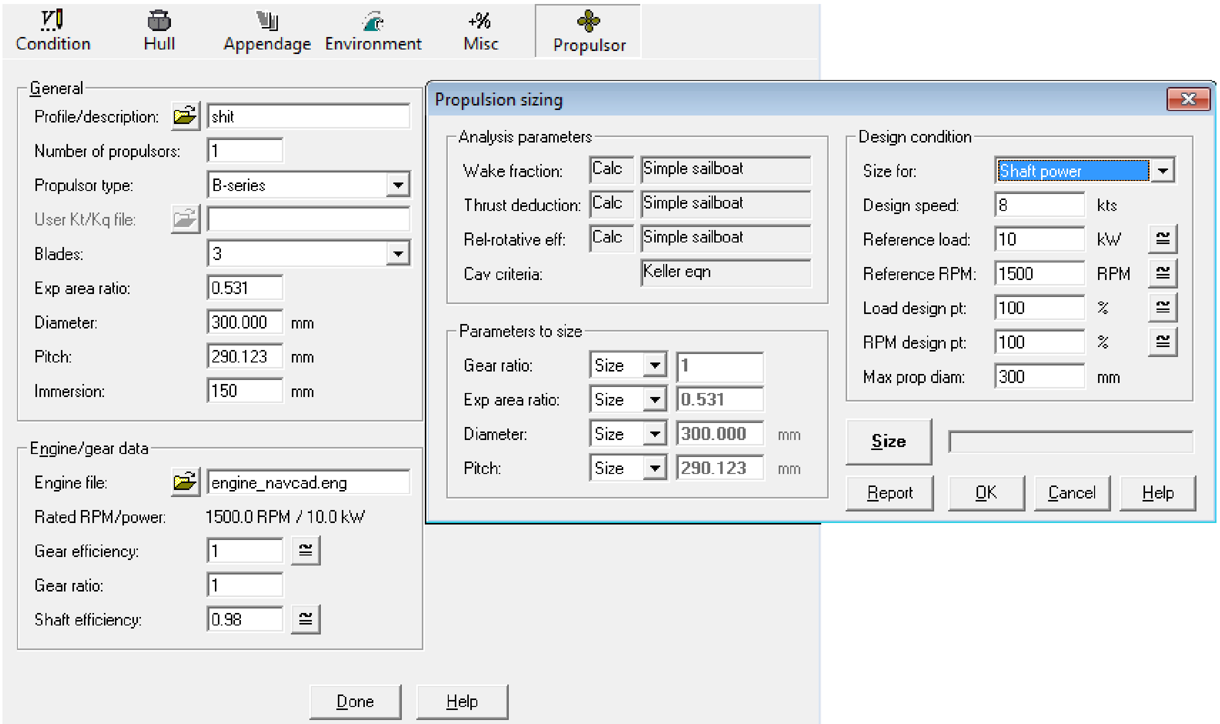

Figure 5.9. Input data for propeller dimensioning (NavCad)

Using *NavCad* software for the propulsion prediction and inserting the engine data, plus the restrictions for the propeller, the propulsion properties were calculated. Similarly to the resistance prediction, a calculation method was necessary for the propulsion, and this time, the Holtrop and Mennen (Holtrop & Mennen, 1982) was a good choice.

Table 5.8. Propeller caracteristics for the monohull.

speed	Fn	Per[kW]	WakeFr	Eng rev [rpm]	Prop rev [rpm]	Propeff	thrust	PD [kW]
2	0.149	0.043	0.11	323.7	323.7	0.570	0.05	0.08
3	0.224	0.259	0.11	582.2	582.2	0.488	0.19	0.535
4	0.299	0.798	0.11	842.7	842.7	0.454	0.423	1.704
5	0.374	1.75	0.11	1116	1116	0.430	0.768	4.08
6	0.448	3.1	0.11	1339.3	1339.3	0.430	1.106	7.052
7	0.523	4.731	0.11	1539.5	1539.5	0.436	1.449	10.631
8	0.598	6.479	0.11	1704.1	1704.1	0.449	1.74	14.179
9	0.673	8.231	0.11	1844.1	1844.1	0.465	1.986	17.571
10	0.747	10.033	0.11	1954.5	1954.5	0.486	2.158	20.318

Running the software and applying the method resulted in the propeller dimensioning (**Table 5.8**).

Chapter 5.4. Steering Gear and Arrangement

A steering system was necessary for the vessel, because, differently from the catamaran, there was only one propeller, and differential propeller revolution was impossible to be applied.

A rudder, combined with a proper steering electrical system had to be designed, according to the vessel's speed and propeller size. The electrical system would consist in a motor connected to a hydraulic electrical valve. The valve is controlling an arm that performs a forward or a backward movement to a tiller arm, and it is this last item that performs the rotation of the rudder shaft, with a maximum degree of 35º either to portside and starboard. This system is known as ram rudder system.

In order to allow the installation of such kind of system it was necessary to insert a platform at the aft part of the vessel. The weights and position of the main components, such as the motor, the hydraulic valve, the hydraulic arm and the tiller arm were carefully placed onboard, because it is not a symmetric system, and therefore it could create trim to one side of the vessel. (Figure 5.10 & Table 5.9).

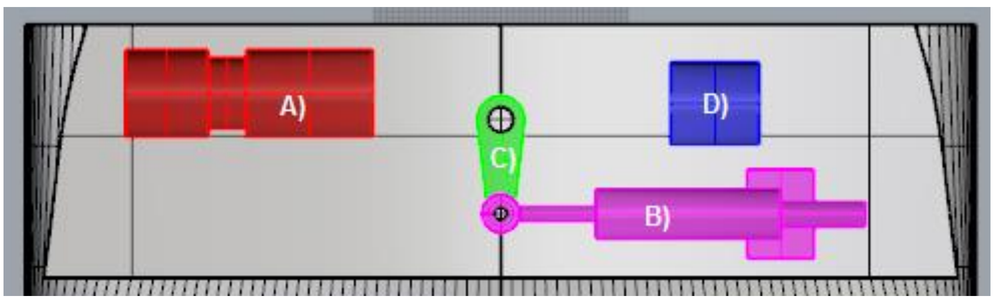

Figure 5.10. Top view of the steering equipment

Table 5.9. Description of the steering equipment.

Equipment	Model	Company	Function	Weight [kg]
A) Rudder engine	24V power pack	LECOMBLE & SCHMITT	Maneuvering engine	9.50
B) Rudder controller	VHM 50 DTP	LECOMBLE & SCHMITT	Arm for rudder shaft rotation	5.00
C) Rudder bearing			bearing connecting rudder arm and shaft	2.35
D) Rudder valve	LS50	LECOMBLE & SCHMITT	Hydraulic valve	4.00

The rudder was designed to be built from aluminum material. Despite being heavier, it provides more reliability than a composite rudder, while the rudder's shaft line is to be built from steel, to guaranty high strength.

The entire steering system must be connected to vessel controller, or computer, to perform the desired maneuvers.

The steering motor was designed according to the maximum torque that the rudder could be exposed. The calculation is based on the total area of the rudder, coefficients, speed and maximum angle.

Chapter 5.5. Hull Equipment and Light Weight

In order to be completely autonomous, the vessel must have a proper propulsion system, connected to a control station. The engine has been chosen right after predicting the resistance of the vessel and it was necessary to choose the appropriate batteries to power the engine. Not every battery is compatible with the engine, because the voltage and amperage can vary from engine to engine.

As expected, the batteries used at the monohull are much bigger and heavier than the ones used on the catamaran. Also more batteries had to be installed to supply the right amount of power to the engine (MASTERVOLT, 2011). The batteries are lithium-ion and built by the same company of the engine, *MasterVolt.* These batteries are highly efficient and have a high durability, which represent a higher autonomy of the vessel. The battery model are to be the MLi Ultra 24/5000, because of the voltage and amperage, to be the same as the one at the engine. Each battery has a nominal energy of 5 kW and weights 58 kg.

Table 5.10. Information about the Monohull's batteries.

Batteries		
Voltage	24	V
Nominal capacity	180	Ah
Nominal energy	5	kW
Weight	58	kg
Number of cells	8	

A total of four batteries were installed onboard, with the same working logic of the catamaran, two are working and the other two are at standby mode. These batteries are powering not only the engine, but also the steering gear system. To keep the weight distributed, two batteries were placed at each side of the vessel, at the engine compartment. Due to their size and power, the batteries are really heavy and because of that, it was important to place them on top of a reinforced area, to avoid any damages to the hull. The batteries discharge rate are directly associated with the total autonomy of the vessel. The rate of discharge is influenced by the total amount of energy that the engine needs for consumption. The voltage is not the element that defines the autonomy, but the amperage is and it is according to that factor that the autonomy must be calculated.

In order to control the engine it is necessary to have a controller/driver onboard. This controller is connecting the main computer to the engine, and transmits the information from one to the other. Information like the maneuvering, steering and speed must be directly connected to the controller and to the persons responsible for the vessel’s mission. The controller or driver was positioned at the center line of the vessel, to avoid any transversal asymmetry, avoiding transversal trim at the vessel. It was placed close to the main engine, and it can also be used for support the main computer, reducing the length of the electrical wires that connect the diver with the computer.

Other equipment placed at the engine compartment are the battery rechargers. The rechargers are necessary to convert the energy that is produced by the solar panels, to the energy used by batteries. It was necessary to place this item near to the batteries and near to the solar panel. Two rechargers were placed onboard of the vessel, one at the portside and other at starboard. The system shall work in order to the portside solar panel be connected to the portside recharger and batteries. The recharger is supposed to be always working, as long as the panels can produce energy, and only feeding one battery at the time, reducing energy losses. The recharger is the ChargerMaster 24/60-3 model, produced by the *MasterVolt Company*.

Two solar panels can be found at the main deck, supported by the composite structure already mentioned, built by the *Sunmodule Company*. The module is the SW145 poly R6A, and the criteria used to choose these panels was related to the amperage and working voltage.

The light weight was divided in two categories, the hull and the equipment. Hull weight represents all weights that are part of the structure of the vessel, like the shell, reinforcements, platforms and the solar panel platforms. The weights were obtained by using the same method as the catamaran. According to the scantlings, the thicknesses of the laminates were stablished. Using the 3D model, it was possible to evaluate all the areas and corresponding centers of gravity. Multiplying the areas with the thickness, the volume is obtained, and applying equation (1) the weights are calculated.

Table 5.11. Areas, weights and position of center of gravities of composite materials.

	Area [m^2]	Weight [kg]	Lcg [m]	Vcg [m]
Shell area	11.60	82.5	2.385	0.261
Transom area	0.40	3.0	0.000	0.549
Reinforcement area	2.00	13.3	2.173	0.142
Reinforcement volume (Balsa)	0.06	9.0	2.173	0.142
Aft Bulkhead area	0.95	6.7	2.301	0.378
Fwd Bulkhead area	0.74	5.2	4.001	0.408
Deck fixed structure	3.83	27.1	1.998	0.701
Deck engine doors	0.91	6.4	0.448	0.72
Deck cargo doors	1.67	11.8	3.238	0.72
Deck forward doors	0.55	3.9	4.400	0.711
Solar Panel Support	5.54	37.6	1.673	0.868
Bottom plates	3.08	21.8	2.608	0.140
Engine support structure	0.23	1.6	1.423	0.103
Rudder equipment structure	0.70	4.8	0.244	0.434
Fwd bottom structure	0.41	2.8	4.236	0.136

The density of the grain balsa is 144 kg/m^3 (Greene, 1997)

These weights (Table 5.11) are only regarding the hull and the panels that constitute the hull structure. As to the equipment weight, some of the components were already defined, due to the catalogues provided by the companies, but some items had to be calculated applying the same logic as before. The elements that had to be calculated were the propeller shaft line, the rudder shaft line, the rudder, the propeller, the rudder bearing and the mast.

The rudder, the propeller, and the mast are built from aluminum, with a density of 2800 kg/m^3. As to the bearing and shaft line, the chosen material was stainless steel, to provide durability safety of the vessel, with a total density of 8030 kg/m^3. Once again, applying equation (1) the weights of these components were calculated (Table 5.12).

Table 5.12. Weight calculation of the defined equipment.

Equipment	No	Weight [kg]	Lcg [m]	Tcg [m]	Vcg [m]	Material	Density (kg/m^3)
Rudder	1	3.5	0.097	0	0.2	Al	2800
Propeller	1	5.5	0.32	0	0.1	Al	2800
Rudder bearing	1	2.4	0.209	0	0.5	Steel	8030
Shaftline	1	13.4	0.607	0	0.2	Steel	8030
Mast	1	11.6	3.95	0	1.1	Al	2800

As to the other equipment the weights are known, and the centers of gravity were calculated (Table 5.13)

Table 5.13. Equipment of the monohull.

Equipment	Model	Company	No	Weight [kg]	Lcg [m]	Tcg [m]	Vcg [m]
Electric Motor	DriveMaster Ultra 20	MASTERVOLT	1	178.2	1.336	0	0.308
Motor Controller	DriveMaster Ultra 20 - controller	MASTERVOLT	1	20.6	2.016	0	0.219
Engine support	DriveMaster Ultra 20 - support	MASTERVOLT	1	18.0	1.43	0	0.106
Battery recharger	ChargeMaster 24/60 -3	MASTERVOLT	2	14.0	2.05	0	0.258
Battery	Mli Ultra 24/5000	MASTERVOLT	4	116.0	1.288	0	0.331
Battery	Mli Ultra 24/5001	MASTERVOLT	2	116.0	1.954	0	0.314
Solar Panel	SW 145 poly R6A	Sunmodule	2	23.6	1.742	0	0.863
Rudder controller	VHM 50 DTP	LECOMBLE & SCHMITT	1	5.0	0.298	0.331	0.487
Rudder engine	24V power pack	LECOMBLE & SCHMITT	1	9.5	0.109	-0.398	0.516
Rudder valve	LS50	LECOMBLE & SCHMITT	1	4.0	0.125	0.338	0.512

Table 5.14. Monohull Light Weight.

	Weight [kg]	Lcg [m]	Tcg [m]	Vcg [m]
Light weight	784.4	1.710	-0.001	0.374

The total weight of the equipment was defined (Table 5.14).

The deadweight is to be divided by the cargo compartments. The heavier cargo is supposed to be placed at the aft cargo compartment, for being closer to the center of buoyancy.

Chapter 6. CATAMARAN-SWATH

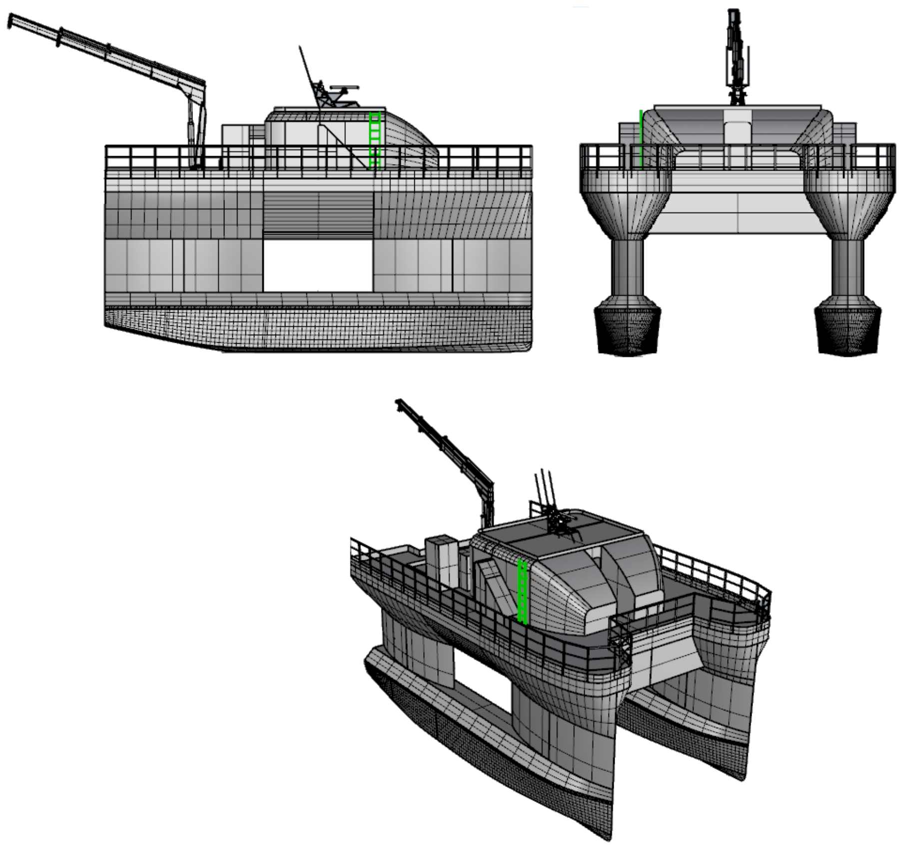

Figure 6.1. Catamaran-SWATH model

This type of ship is now being more and more commonly used for transporting people, they can be from fast ferries to work boats, per example to transport operators and engineers to windmills, but due to the versatility that comes with this design, these ships can become a really good solution for unmanned purposes. The main advantages of this design are the ability to reach high speeds when sailing in the catamaran mode and the ability to stay almost completely steady when it changes to the SWATH mode. However, this type of ships is not recommended for a cargo type vessel, since the deadweight associated to them is never too big.

Normally, catamaran-SWATHs are divided in four main parts (Kennell, 1992):

- The pontoons: With completely watertight arrangement, even on the top, without any sounding or air pipes, ventilation pipes or any other kind openings on the top, because they are supposed to be submerged in the SWATH mode. The propulsion system and the ballast tanks are also located on the pontoons.
- The struts: The struts are the legs of the SWATH, and in the legs it is usually to find the exhaust pipes from the engine and also access ladders that connect the lower rooms to the main deck.

- The haunches: Structural area that connects the top struts to the bottom of upper platform,
- Main platform: Platform where the accommodations, emergency and auxiliary engines, superstructure and bridge are found.

Chapter 6.1. General Arrangement

In the development of the third model of the dissertation, rules and international conventions had to be the base guide lines of the design. The fact that the ship is to be of fast speed and the size is considerable bigger, the ship can be a serious threat to any other vessel. Safety and efficiency had to be always side by side with the development of the ship, leading to several and several changes in its process.

The first step on the design of the catamaran-SWATH was a sketch of the general arrangement, in order to know the amount of space, the equipment and the shape of the ship. The length and the width of the ship were assumed, based on the existence MIT development (Brizzolara & Chryssostomidis, 2013).

The length of the pontoons was assumed as the same length of the main deck and their width and height was chosen in order to be able not only to place a powerful propulsion system, but also to allow any necessary inspections or works in the machinery.

The speed that this vessel should reach was of 20 knots in the catamaran mode, making it really fast for an unmanned 16 meter vessel. In the SWATH it is not intended to have any operation speed, although it should be able to do some minor maneuvering or sailing speed, because the ship will only be in SWATH mode when it is necessary to stay in a completely steady position.

The catamaran draft and the SWATH drafts were also assumed. In a first assumption, these drafts can be really difficult to predict, because of the difference of the displacement in each mode. Flooding both pontoons in a way to make them submerged is a real challenge due to their amount of volume.

In the catamaran mode, a low design draft of 1.5 meters can be achieved only if the vessel is built from light materials. Three main materials were assumed for the design of the cat-SWATH, but only one was chosen. Steel was one of the building materials that could be used, but then the weight of SWATH would have been considerable higher, and because of that, it would be really difficult to achieve the required speed of 20 knots. Aluminum is also a common choice for ships of this size, despite being more expensive than steel, it has also good mechanical properties and it is lighter than steel, but even lighter it would not be possible to achieve a draft of 1.5 m. Therefore it was chosen to use carbon fiber as the building material, giving really good mechanical properties and at the same time, being a light construction. Carbon fiber is a good choice for small ships, but at the same time is much more expensive than steel, aluminum of glass fiber.

With the main dimensions chosen, it was performed a preliminary sketch of the general arrangement and a division of the ship by frames of 500 mm distance. Symmetric pontoons were designed and the span between them was chosen. There a few methods for calculating the optimum spacing between the demi hulls, per example the method of Tuck and Lazauskas (Tuck & Lazauskas, 1998) which calculates the impact on the wave resistance due to the distance between hulls. Although there are some methods to optimize the distance between demi-hulls, the decision for the catamaran-SWATH span was according to existing vessels with similar sizes.

The span of the pontoons is chosen according to the characteristics, purpose and resistance of the vessels and its optimization is very difficult to achieve. In this dissertation, the span was chosen based on similar existing SWATHs. The span is measured from the center line of the pontoons.

The next step was the definition of the position of the collision bulkhead and it was calculated according to the rules. The rules used in the design of the catamaran-SWATH were a mixture of the Danish Maritime Authorities (DMA) and the (DNV, 2014). According to DNV the collision bulkhead must be located not less than:

Min distance from fwd PP: (10)

$$Collision\ Bulkhead = 0.05 \times L \ \ (m)$$

Max distance from fwd PP:

$$Collision\ Bulkhead = 3.0 + 0.05 \times L \ \ (m) \tag{11}$$

Other watertight divisions were designed, in order to give structural and watertight integrity to the ship. By designing the watertight divisions, the location of the engine room and thruster room were defined. It was decided to place the engine room in the aft part of the ship, close to the thrusters, avoiding the existence of long shaft lines.

The main concerns of a catamaran-SWATH are the ballast tanks. In order to change from the catamaran mode to the SWATH mode, the ship must be able to loose buoyancy and at the same time to guarantee that the trim doesn’t change to an angle where the propellers/ thrusters get out of the water. This loss of buoyancy is achieved by means of ballast tanks, where the compartments are flooded to increase the draught to the struts level. The problem of the ballast tanks is the necessary volume they need to have. When comparing the volume of the ship and the necessary volume of the tanks sometimes the tanks are more than one third of the volume of the ship. Since the propulsion system is normally located on the pontoons, there is not much space to properly fit the tanks in a way that when they are flooded, the trim is kept the same. In a first approach, the main ballast tank would be positioned in front of the engine room, close to the midship area, where the center of buoyancy would probably be.

The struts of a SWATH are one of the most important parts of a SWATH. They not only connect the pontoons too the upper deck, but they also decide the efficiency of the SWATH mode. There are several types of struts, and several ways to design them. When designing the struts, parameters like the necessary speed of the SWATH, the resistance, the capacity and the robustness must be taken into consideration and then it must be decided if the SWATH will have a single strut, going from one end to the other of the pontoons, double struts (or tandem struts), where it is possible to find a gap in between the struts, or even a triple strut.

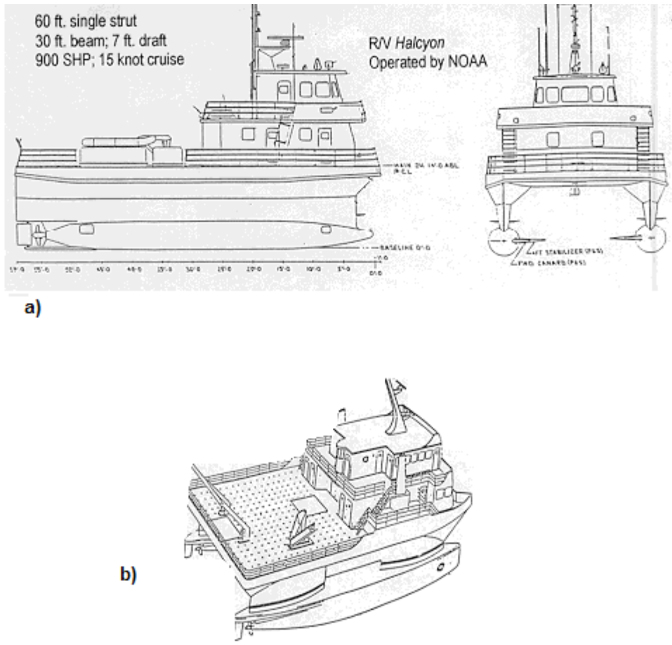

Figure 6.2. a) Single strut SWATH; b) double / tandem strut SWATH. (Kennell, 1985)

In the developed work it was chosen to adopt the double strut configuration, but even inside this group of struts it is possible to find a large variety of forms, from round struts, asymmetric ones or elliptical. Each with advantages and disadvantages, for example, round struts can be very good when it is necessary to have a large area in the strut width, for removing the engines or to have easy and fast access from the upper deck to the inside of the pontoon. Although, this implies that the waterplane area at the SWATH mode is not optimized, and therefore the SWATH will not be as much efficient. On the other hand, having different strut shapes in the aft and in the forward part is a really good solution when trying to avoid some rules, like the ship total length. This happens because the total length of the ship, for the majority of the rules is measured in terms of the waterline. So if the length of the ship in the pontoon area is smaller than the length in the upper platform, for the rules the length that counts is the one of the waterline. This is more common to see in ships which the length is close to 24 meters, because of the differences of the rules for ships with less than 24 meters and for ships longer than that.

For the 16 meter catamaran-SWATH a total of four struts connects the pontoons to the upper platform. The struts have a length of 5.9 m and a maximum width of 1.0 m in the center area. They have an elliptical shape and the distance between the forward and the back struts' centerline it is of 10 m.

Making the struts long and at the same time narrow is a good solution for either having a small waterplane area, but at the same time to give the possibility of access to the pontoons. The space between the pontoons was intended to reduce the waterplane area, making the SWATH mode even more efficient.

The platform above the struts will contain all the electronic cargo, batteries, emergency engine, main switchboards, anchor and mooring system, and all the systems necessary for the operation of the ship. It is divided in two decks, the lower deck and the upper deck. The lower deck is a closed deck, with a total height of 2.2 meters, giving enough space for creating easily access divisions for placing, changing or even working on any necessary equipment. In this deck level it is possible to find the anchor and the towing system, consisting in a number of winches, lines, chocks and fairleads. It is also possible to find the AC unit of the ship and the storages for the equipment needed onboard. A set of corridors, doors and ladders provide the necessary accesses for every part of the deck.

Above, at the upper deck it is possible to find the superstructure. Actually since this ship does not have any bridge, or the necessity of having any wheelhouse, the superstructure was somehow optional, although, it was decided to design it, because it had no sense to create an entire deck for the remaining equipment. In this deck it is also possible to find hatches that give direct access to the lower deck, this are really important for loading the ship with the necessary equipment for the scientific researches. It is also possible to find the emergency generator room, as well as the main switchboard room and the computer room. The battery rooms in the forward part of the superstructure are supposed to be filled with battery supplies for the computers at the computer room and to the switchboard room. The upper deck is surrounded by handrails and bulwarks, in order to make it safe when someone as to go onboard of the cat-SWATH.

A crane is also located at the upper deck. This crane is to be of a telescopic type, and its main purpose is to recover UUVs from the water. The capacity of the crane and its reach must be enough for recovering almost any type of small UUVs, from ROVs to small research submarines.

External access and the casing are also found in the upper deck. There is also a ladder that gives access to the top of the superstructure, where the mast with the radars, DGPS, navigation lights, and other COLREG requirements can be found for the safety of the vessel.

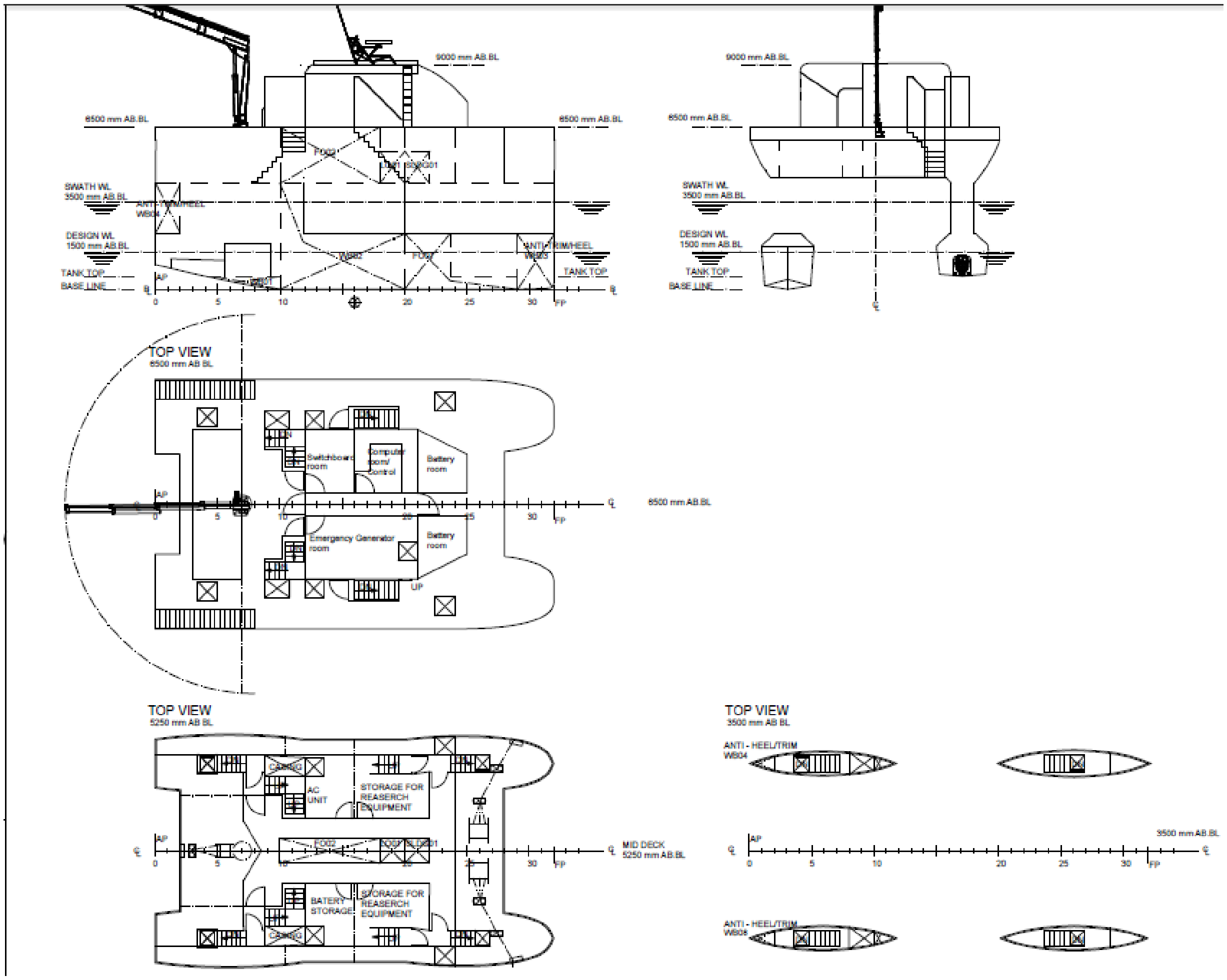

Figure 6.3. Catamaran-SWATH general arrangement. (For detail, see Annex 4)

Chapter 6.2. Hull type and form

The hull had to be designed for both ship modes. In the catamaran mode, the hull should be appropriated for achieving high speeds and in the SWATH mode it should be designed to have a small waterplane area. The changing from one mode to the other is directly related with the displacement of the ship. This was a serious challenge because of the volume of the pontoons.

In the catamaran mode, the pontoons are the only components that are in contact with the water. In order to make the fast and less subjected to the water resistance, the hard chine concept was adopted. (Clement & Blount, 1963) A hard chine hull form is suitable for achieving high speeds and is commonly used in pleasures crafts, yachts and sailing vessels. The hard chine is achieved by having an angled ship bottom and having one or more visible edges in the transition bottom to the ship side. This characteristic gives the ability of the hull planning, reducing the volume inside the water and therefore reducing the resistance.

The bow shape was designed to be really sharp with the intention to make it similar to a bow shape of a wave piercing catamaran (Moraes et al., 2004). A wave piercing bow is a really good solution for high speed craft, because as the name indicates, it cuts through the waves, creating an extreme high pressure water flow in the edge of the bow and by that, the water resistance is lower. Normally, wave piercing catamarans have asymmetric pontoons, because the water flow direction must be controlled and that is why these kinds of ships achieve extraordinary high speeds.

The catamaran-SWATH was designed to have symmetric pontoons, a vertical straight transom with a parallel ship side in the aft body part due to the necessity of space for the engines. This characteristic increased a lot the volume of the pontoons, so a decision had to be taken to reduce this increase of volume. The mid body should not be too sharpened, because there was where the ballast tanks would be and they would require a large amount of volume. The forward body part was sharpened and the top of the pontoons was changed. Instead of having a vertical parallel top, a recess was created in order to reduce the pontoons volume. This recess was done taking into consideration the struts and the necessary area that they would require to be attached.

The design of the struts was based in several factors like the waterplane area, space for the exhaust pipes, accesses and hatches and structural reinforcements. The struts have an elliptical shape with the biggest breath at their mid body. In the mid body the width is of 1 meter. The length of the four struts is the same, 5.9 meters.

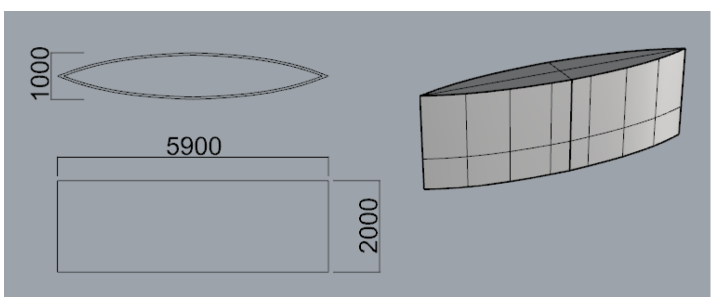

Figure 6.4. Struts dimensions and shape.

With a preliminary hull form designed, the next step consisted in the calculation of the hull proprieties and the hydrostatics of the ship, in order to evaluate the displacement of the ship as well as the longitudinal center of buoyancy, center of floatation and the metacentric heights for both catamaran and SWATH mode.

Table 6.1. Catamaran-SWATH hull design properties

	Catamaran mode	SWATH mode
LOA (m)	16	
LBP (m)	15.985	
D (m)	6.5	
T (m)	1.5	2.7
B (m)	9.20	
b_demi (m)	2.2	1
Span (m)	7	
Displacement (ton)	69.5	116.0
Speed (knt)	20	5

Using the software *Rhinoceros* and its plug-in *Orca*, the hull was designed and the hydrostatics were calculated. Although *Orca* calculated the hydrostatics of the model, the results are not 100% accurate, because it depends from the 3D model from *Rhino*, and despite being good software to create hulls, sometimes it creates strange boundaries on the surfaces, leading to errors in the calculations. Therefore it was also necessary to create the same hull in Model Maker.

Several drafts were taken into consideration in the preliminary hydrostatics calculations, but in *Orca* only one draft at 1.5 meters was calculated and compared with the results from *Autohydro*.

Table 6.2. Comparing *Orca3D* with *Autohydro* hydrostatics for 1.5m draft.

	Orca3D	Autohydro	difference (%)
draft (m)	1.500	1.500	
Displacement (ton)	69.5	69.5	0.03
Lcb (m)	7.633	7.633	0.00
Vcb (m)	0.869	0.869	0.00
Cb	0.312	0.312	0.00
Cwp	0.414	0.414	0.00
Cws	3.957	-	-
Lcf (m)	7.341	7.342	0.01
Vcf (m)	1.500	1.500	0.00
kMt	11.170	12.030	7.15

Although the results from *Orca* and *Autohydro* are really similar, it was decided to use only *Autohydro*'s information, because it is more specialized software, resulting in more accurate calculations.

More drafts were defined and the SWATH hydrostatics were also calculated. In these preliminary calculations it was assumed that the ship would have no trim or heel, in order to find the exact location of the center of buoyancy and the draft for the perfect condition. Later, it was given several trims (forward and aft), in order to evaluate the changes of the values and the proprieties of the hull when the ship was trimming.

Table 6.3. *Autohydro* hydrostatics for the catamaran mode

Draft at 7.993f (m)	Displ (MT)	LCB (m)	VCB (m)	LCF (m)	TPcm (MT/cm)	MTcm (MT-m /cm)	KML (m)	KMT (m)
1.400	63.388	7.662f	0.813	7.308f	0.61	0.72	18.100	12.830
1.500	69.492	7.633f	0.869	7.342f	0.62	0.74	17.055	12.030
1.600	75.702	7.610f	0.924	7.376f	0.63	0.77	16.167	11.354
1.700	81.978	7.593f	0.980	7.375f	0.63	0.77	15.086	10.628
1.800	88.136	7.577f	1.034	7.381f	0.59	0.74	13.392	9.445
1.900	93.730	7.566f	1.082	7.399f	0.53	0.68	11.547	8.142
2.000	98.716	7.558f	1.126	7.422f	0.47	0.62	9.966	7.034

Table 6.4. *Autohydro* hydrostatics for the SWATH mode.

Draft at 7.993f (m)	Displ (MT)	LCB (m)	VCB (m)	LCF (m)	TPcm (MT/cm)	MTcm (MT-m /cm)	KML (m)	KMT (m)
2.240	108.203	7.550f	1.213	7.516f	0.32	0.47	6.879	4.893
2.400	110.921	7.561f	1.240	7.993f	0.17	0.37	5.398	3.110
2.500	112.619	7.567f	1.258	7.993f	0.17	0.38	5.353	3.100
2.600	114.317	7.573f	1.277	7.993f	0.17	0.38	5.311	3.092
2.700	116.016	7.580f	1.297	7.993f	0.17	0.38	5.272	3.085
2.800	117.714	7.586f	1.318	7.993f	0.17	0.39	5.236	3.080
2.900	119.413	7.591f	1.340	7.993f	0.17	0.39	5.202	3.077
3.000	121.111	7.597f	1.363	7.993f	0.17	0.39	5.171	3.075

Comparing both Table 6.3 and Table 6.4 it is possible to evaluate the main differences from both catamaran mode and SWATH mode. In the catamaran mode the kMt is significantly higher, which corresponds to the really good transverse section proprieties of catamarans because of the existence of two hulls. However the position of the Lcb doesn't suffer any major changes, which is good to avoid unexpected trims when changing from one mode to the other. Other important note is the big difference on the moment to change trim (MTc) and the tons per centimeter (TPcm), showing exactly why the SWATH mode is much more unstable against roll, pitch or heave than the catamaran mode. Once again, the SWATH is a really good solution for lowering the wave effects and forces due to the really small waterplane area, but is not more stable than a catamaran because of that same small waterplane area.

The KN curves (stability cross curves) were also calculated. These curves are calculated by assuming a certain center of gravity height (Vcg), but they can also be calculated assuming that the Vcg is located at the base line, and in this case they are called KN curves. KN means the righting lever measured from the keel. For a preliminary stage, these curves give an idea of the righting arm (GZ) of the ship, but the correct value will only be calculated after knowing the exact center of gravity, by using the following formula (Barrass & Derret, 2006)

$$GZ = KN - G * sen\theta \ \ (m) \qquad (12)$$

Table 6.5. Catamaran-SWATH KN curves

Draft (m)	Dipl (MT)	1º	5º	8º	10º	15º	20º	25º	30º	35º	40º	50º	60º
1.5	69.49	0.21	1.03	1.59	1.92	2.48	2.95	3.41	3.77	3.81	3.74	3.18	2.83
1.6	75.70	0.19	0.95	1.44	1.70	2.16	2.63	3.09	3.46	3.47	3.42	3.22	2.88
1.7	81.97	0.18	0.86	1.27	1.45	1.89	2.34	2.8	3.03	3.03	3.00	3.27	2.94
1.8	88.13	0.16	0.76	1.07	1.24	1.66	2.09	2.52	2.64	2.66	2.66	3.36	3.02
1.9	93.73	0.14	0.65	0.90	1.07	1.48	1.90	2.27	2.34	2.37	2.38	3.51	3.17
2	98.71	0.12	0.53	0.77	0.93	1.33	1.75	2.04	2.10	2.14	2.17	3.24	2.97

Table 6.5 shows the KN curves for the even keel condition. The final GZ curve would be calculated after knowing the exact center of gravity.

Chapter 6.3. Tank Plan

The tank plan was another challenging part on the design of the catamaran-SWATH and it could only be done after the prediction of the location of the longitudinal center of buoyancy. The main fluid systems of the ship are the ballast water system, the fuel oil system, the lubricating oil system and the sludge / bilge system. The most important ones were the ballast system and the fuel system because of the amount of volume that they required.

The ballast system was only possible to be designed after knowing the displacement of both the catamaran mode and the SWATH mode, because the ballast tank(s) should be designed to have the volume corresponding to the difference of the displacements. But that was not the only problem, it was also necessary to take into consideration that the center of gravity of the ballast tank(s) should be aligned or aft of the center of buoyancy of the ship, because of the trim that the tank would create. The amount of necessary ballast water would have a significant impact on the buoyancy and on the stability of the ship.

The ballast system of the catamaran-SWATH consists in two groups; the main ballast tanks and the anti-heel/trim tanks.

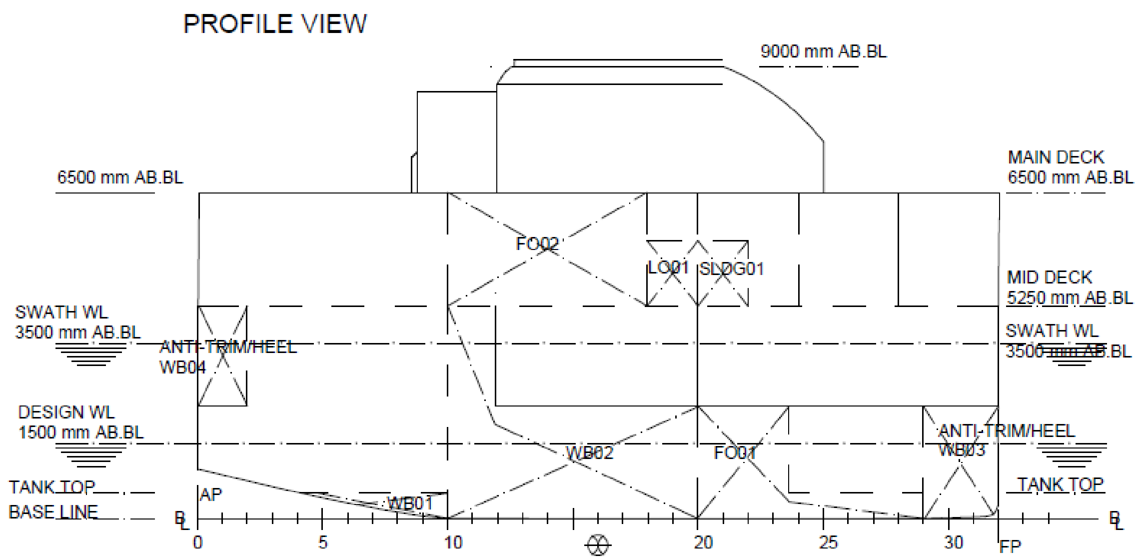

Figure 6.5. Longitudinal section view of the catamaran SWATH: WB01 and WB02 are the main water ballast tanks; WB03 and WB04 are the anti heel/trim tanks. The map is symetric for both of pontoons, resulting in a total of 8 waterballast tanks.

The main ballast tanks are located in each pontoon (Figure 6.5: corresponding to WB01 and WB02) and are responsible for the transition of the catamaran mode to the SWATH mode. There is one tank in each pontoon and the tanks were extended to the forward part of the aft struts to achieve the necessary volume. The tanks are really big and that brings other types of problems, like the flooding time and the big free-surface that is being created during the flooding. This problems could be solved by dividing the tanks and make it with smaller tanks, resulting in a faster flooding, but also in a much more expensive solution, because every tank would have its own pumping and piping systems.

The anti-heel/trim tanks are to be used if any corrections on the ships trimming or heeling need to be done, like per example when the ship is using the crane to lift an UUV or when there is some damaged compartment. These tanks are much smaller than the main ballast tanks and they should always be close to the ship's ends, where the effects of the ballast would be bigger(Figure 6.6).

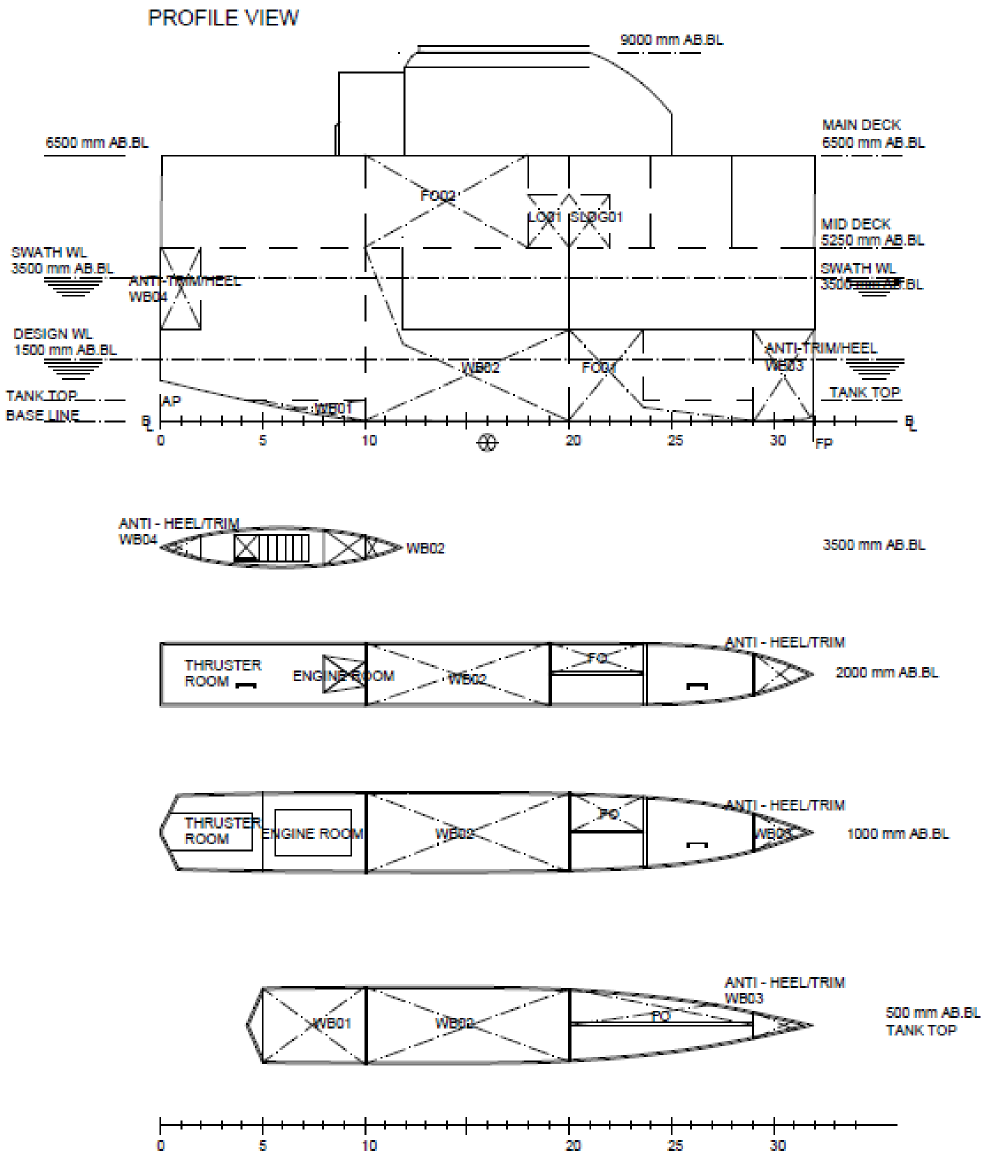

Figure 6.6. Tank plan of the pontoons, looking from different heights of the SB pontoon. The portside pontoon is symmetric.

Regarding the fuel oil tanks, there were several rules that had to be taken into consideration. According to MARPOL (International Convention for the Prevention of Pollution from Ships), the fuel oil tanks in this particular kind of vessels catamaran-SWATH must be located in the inner side of the pontoons, and can never be in contact with the unprotected sides, because of the risk of collisions and spilling. There was the possibility of designing the fuel oil tanks in the mid deck, away from the pontoons, but due to the lack of space and mainly due to the huge negative effect that would bring to the stability, it was decided to make one tank in each pontoon, but due to the lack of space and volume, one third fuel oil tank had to be designed in the mid deck, with a much reduced volume. Figure 6.6 shows the location of the FO tank in the pontoons. The LubOil tank (LO01) and the bilge/sludge tank (SLDG01) are located in the mid deck and at the center line of the ship. Since they have small volume, the impact on stability is not a concern. In Figure 6.7 it is possible to see the location of the mid deck fuel oil tank (FO02) and the location of the LO01 and the SLDG01, close to the midship and centerline.

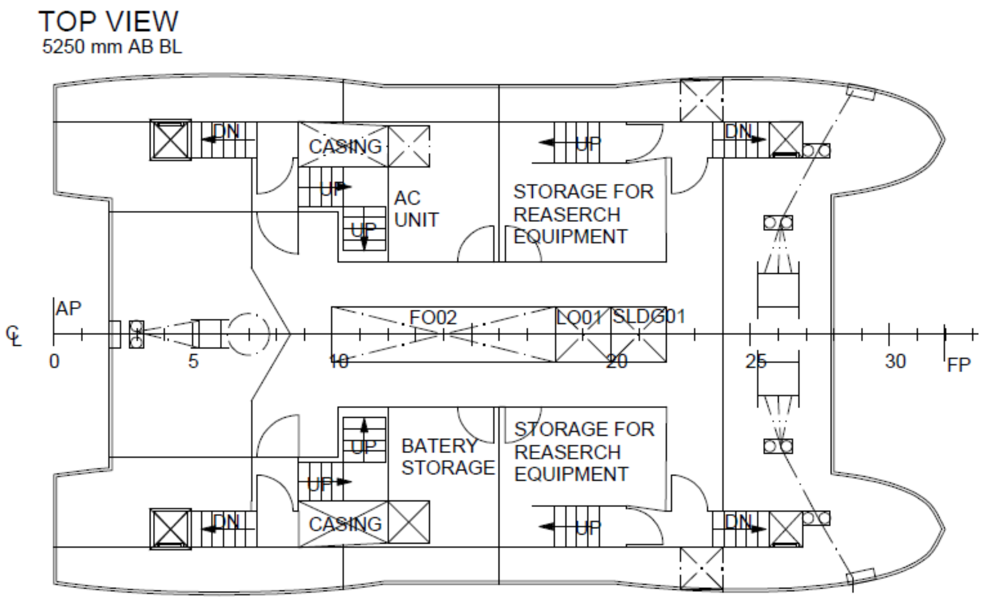

Figure 6.7. General arrangement - mid deck. Showing the location of the FO02 as well as the location of the LO01 and the SLDG01

Table 6.6. Tank capacity and location of the center of gravity of each tank.

Tank	contents	density (m^3)	Frame start	Frame end	Lcg (m)	Vcg (m)	Tcg (m)	volume (m^3)
WB01	SW	1.025	5	10	4.051	-3.503	0.345	1.211
WB02	SW	1.025	10	20	7.432	-3.053	1.191	20.736
WB03	SW	1.025	29	32	15.005	-3.503	1.330	1.578
WB04	SW	1.025	0	2	0.650	-3.503	3.240	0.687
WB05	SW	1.025	5	10	4.051	3.503	0.345	1.211
WB06	SW	1.025	10	20	7.432	3.503	1.191	20.736
WB07	SW	1.025	29	32	15.005	3.503	1.330	1.578
WB08	SW	1.025	0	2	0.650	3.503	3.240	0.687
							total	48.424
FO01	FO	0.86	20	29	11.214	-3.922	1.074	4.234
FO02	FO	0.86	20	29	11.214	3.922	1.074	4.234
FO03	FO	0.86	10	18	7.050	0.000	5.364	8.814
							total	17.282
SLGD01	MISC	1.000	18	20	9.500	0.000	4.887	1.200
							total	1.200
LO01	LUBOIL	0.900	20	22	10.500	0.000	4.887	1.200
							total	1.200

Table 6.6 shows all the tanks of the ship as well as the location of the center of gravity of each tank. It is possible to see that the amount of ballast water is around 48 m^3, which is more than the difference between the volume of the catamaran mode and the SWATH mode from Table 6.1 which is 45.4 m^3, meaning that the ballast volume is sufficient to allow changing from catamaran mode to SWATH mode.

Chapter 6.4. Design Loads

The design loads were calculated according to the DNVGL High Speed, Light Craft and Naval Surface Craft rules, chapter 1 part 3. This calculation would provide the information regarding the maximum allowed bending moments, shear forces and the minimum midship section modulus.

Following the calculation standard, the first calculated propriety was the wave coefficient.

$$Cw = 0.08 \times L \ (m) \text{ for L < 100 m} \tag{13}$$

The vertical and horizontal accelerations at the midship were calculated assuming that the vessel would operate in unrestricted waters.

Design acceleration at vessel center of gravity:

$$a_{cg} = \frac{k_h \, g_0}{1650}\left(\frac{H_s}{B_{WL2}} + 0.084\right)(50 - \beta_{cg})\left(\frac{V}{\sqrt{L}}\right)^2\left(\frac{L\, B_{WL2}^2}{\Delta}\right) \quad (m/s^2) \tag{14}$$

V : Ship speed = 20 knts

L: Ship length

Hs: Significant wave height = 4.0 m

β_{cg}: Deadrise angle at LCG in degrees (min 10º)

k_h: Hull type factor (Catamaran = 1.0)

g_0: Gravitational acceleration (9.81 m/s^2)

B_{WL2}: Waterline breadth at L/2 in m

Δ: Displacement in tonnes

Design vertical acceleration:

Design Vertical acceleration:

$$a_v = a_{cg} \times k_v \quad (m/s^2) \tag{15}$$

k_v: Longitudinal distribution factor (k_v= =1.0 at Midship)

Horizontal accelerations:

$$a_i = 2.5\frac{C_w}{L}\left(0.85 + 0.25\frac{V}{\sqrt{L}}\right)^2 g_0 \quad (m/s^2) \tag{16}$$

Period of forced roll:

$$T_R = \frac{\sqrt{L}}{1.05 + 0.175\frac{V}{\sqrt{L}}} \quad (s) \tag{17}$$

Maximum roll inclination:

$$\theta_r = \frac{\pi h_W}{2L} \quad (rad) \tag{18}$$

h_W: Max wave height in which 70% of max service speed will be maintained - Min = 0.6Cw

Transverse acceleration:

$$a_t = \left(\frac{2\pi}{T_R}\right)^2 \theta_r r_r \quad (m/s^2) \tag{19}$$

r_r : Height above axis roll (at waterline for twin hull craft) = 1.5m

The slamming pressure on the bottom was also calculated according to the ruled equation:

$$P_{sl} = 1.3k_l\left(\frac{\Delta}{nA}\right)^{0.3} T_O^{0.7}\left(\frac{50-\beta_x}{50-\beta_{cg}}\right)a_{cg} \quad (kN/m^2) \tag{20}$$

k_l : Longitudinal distribution factor = 1 for midship

n: Number of hulls = 2 for catamaran

A: Design load area for element $A = 0.002\,\frac{\Delta}{L} \quad (m/s^2)$

T_0: Draught at L/2 in m at normal operation condition = 1.5 m

β_x: deadrise angle in degrees at transverse section (min=10º)

The hull girder loads were also calculated.

Crest landing:

$$A_r = k\Delta\left(\frac{1+0.2\left(\frac{a_{cg}}{g_0}\right)}{T}\right) \quad (m^2) \tag{21}$$

k= 0.7 for crest landing

k= 0.6 for hollow landing

Longitudinal midship bending moment:

$$M_B = \frac{\Delta}{2}\left(g_0 + a_{cg}\right)\left(e_W - \frac{l_s}{4}\right) \quad (kNm) \tag{22}$$

e_W= 0.25 L if not known (0.2 L for hollow landing)

ls= $\frac{A_R}{b_s}$

b_s= breadth of the slamming

The still water, sagging and hogging bending moments:

Still Water bending moment:

$$M_{SW} = 0.11C_W L^2 B C_b \quad (kNm) \tag{23}$$

Twin hull craft – Hogging bending moment:

$$M_{hog} = M_{SW} + 0.19C_W L^2 (B_{WL2} + k_2 B_{tn}) C_b \quad (kNm) \tag{24}$$

Twin hull craft – Sagging bending moment:

$$M_{sag} = M_{SW} + 0.14C_W L^2 (B_{WL2} + k_3 B_{tn})(C_b + 0.7) \quad (kNm) \tag{25}$$

k_2 *and* k_3: empirical factors for the effect of cross structure immersion in hogging and sagging waves

B_{tn}: breadth in m of cross structures (tunnel breadth)

The vertical hull girder shear force, related to the hull girder bending moments:

$$Q_B = \frac{M_B}{0.25L} \quad (kN) \tag{26}$$

It was also necessary to calculate the vertical bending moment (Ms) and shear force (S) at the hull centerline. It was also calculated the hull girder torsional bending moment (Mt) and the pitch connecting bending moment (Mp).

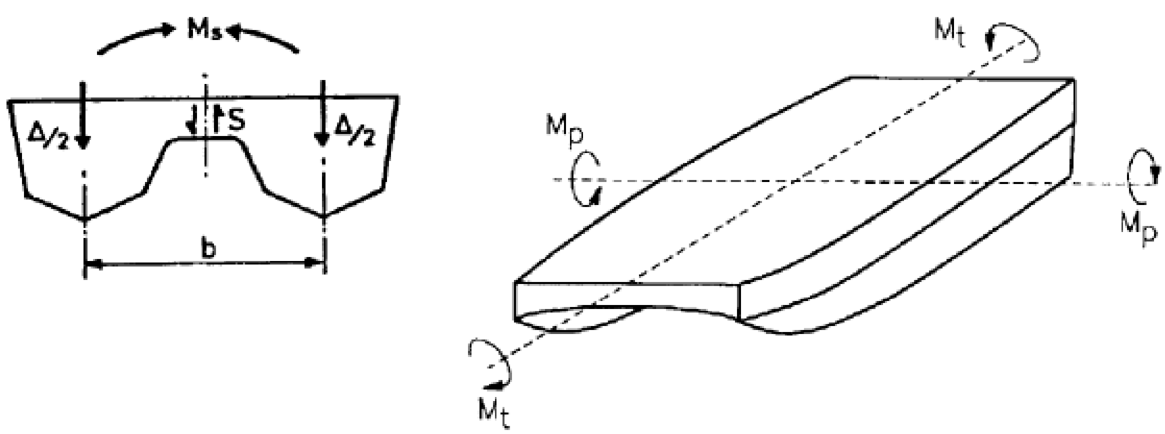

Figure 6.8. Catamaran bending moments - **a)** Twin hull vertical bending moment at centerline (Ms) and vertical shear force at centerline (S). **b)** Pitch connecting bending moment (Mp) and torsional bending moment (Mt)

$$M_S = \frac{\Delta a_{cg} b}{s} \quad (kNm) \tag{27}$$

s: given factor for unrestricted waters = 4.0

b: distance between centerlines of pontoons = 7m

$$S = \frac{\Delta a_{cg}}{q} \quad (kN) \tag{28}$$

q: given factor for unrestricted waters = 3.0

$$M_p = \frac{\Delta a_{cg} L}{8} \quad (kNm) \tag{29}$$

$$M_t = \frac{\Delta a_{cg} b}{4} \quad (kNm) \tag{30}$$

Using the same DNVGL rules for high speed, light craft and naval surface craft, but this time using Part 3 Chapter 4 – “Hull Structural Design, Fibre Composite and Sandwich Construction”, the required hull section modulus was calculated, based on the highest bending moment.

$$Z = \frac{M}{\sigma} 10^3 \quad (cm^3) \tag{31}$$

M: max [still water; sag; hog] bending moment.

σ = 0.3 σ_{nu}

σ_{nu}= Laminate tensile strength - Carbon fiber = 518 N/mm^2 (explained in next chapter)

Table 6.7. Catamaran-SWATH design loads.

Calculated Design Loads			
	[-]	[-]	equation
Cw	1.28	-	(13)
a_{cg}	5.22	m^2/s	(14)
a_v	5.22	m^2/s	(15)
a_h	2.17	m^2/s	(16)
T_r	3.34	s	(17)
θ_r	0.08	rad	(18)
a_t	0.40	m^2/s	(19)
P_{sl}	53.32	kN/m^2	(20)
A_r	35.88	m^2	(21)
M_s	2084.57	kN.m	(22)
M_{sw}	555.41	kN.m	(23)
M_{hog}	926.13	kN.m	(24)
M_{sag}	1505.88	kN.m	(25)
Q_B	521.63	kN	(26)
M_s	634.49	kN.m	(27)
S	120.85	kN	(28)
M_p	724.45	kN.m	(29)
M_t	399.91	kN.m	(30)
Z	13414212.05	cm^3	(31)

Chapter 6.5. Midship Section

After calculating the required midship section modulus, it was necessary to define the panels and the reinforcements that would be part of the midship section. The ship was designed to be built from composite materials, consisting mainly in carbon fiber and foam, in a double layer laminate sandwich.

Carbon fiber is much more expensive than fiber glass, but it has also better mechanical proprieties. These properties are, of course, dependent on the percentage of fiber and resin in the laminate. A proper standard matrix of carbon fiber combined with polyester resin was used, being suitable for the catamaran-SWATH design. The laminate chosen is according to the ISO composite for hull construction and scantlings. (International Organization for Standardization, 2004)

Table 6.8. Material proprieties of the carbon fiber and polyester resin.

Carbon fiber + Polyester/Epoxy	density	Laminate density	% of fiber in the laminate	Laminate young Modulus	Laminate tensile strength
	t/m^3	t/m^3		N/mm^2	N/mm^2
Fiber	1.8	1.44	40%		
Resin	1.2			47800	518

According to Table 6.8 the percentage of carbon fiber on the laminate is 40% and comparing the mechanical proprieties, like the tensile strength, of the carbon fiber and the tensile strength of the fiber glass (Table 4.1) it is possible to see that the fiber used on the catamaran-SWATH has twice the strength of the fiber used on the other two designs.

The laminate was designed to have a thickness of 5 mm, corresponding to 10 mm in a sandwich laminate.

The core material was also chosen according to a standard. The corecell M130 was the one used for the sandwich panels.

Table 6.9. Properties of corecell M130

density	shear strength	tensile strength	compression strength
kg/m^3	MPa	MPa	MPa
130	1.98	2.85	2.31

The total thickness of each composite panel was defined to be of 50 mm, corresponding on 10 mm of laminate plus 40 mm of core material.

Two midship sections were defined, one located at the midship (frame 16) and another one located at the middle of the struts. Both have a lot of differences due to the existence of the haunch. The haunch must have extra reinforcements because it should compensate the stresses of the connection between the struts and the deck platform.

The section in the middle of the ship has two main components: the hull and the platform, and in this section there is no structure connecting them.

Two different types of reinforcements were used for the structural design. The standard “tall” or top hat profiles were used to strengthen the pontoon. Three different sizes of these stiffeners were used: the 100 mm, 150mm and 200mm, each one with its particular proprieties and weight. These stiffeners consist in a layer of laminate glued to the hull panels and in the space between them it is possible to find foam to reinforce the hull. The foam used in between the profiles is the same used in the panels, the corecell M130 for this design.

Table 6.10. Top hat stiffener proprieties.

type	Stiff laminate	SM	A	Ina
	kg/m^2	cm^3	cm^2	cm^4
100	1.8	48.4	8.4	434
150	2.7	126.2	18.9	1496
200	3	289.9	24.5	4102

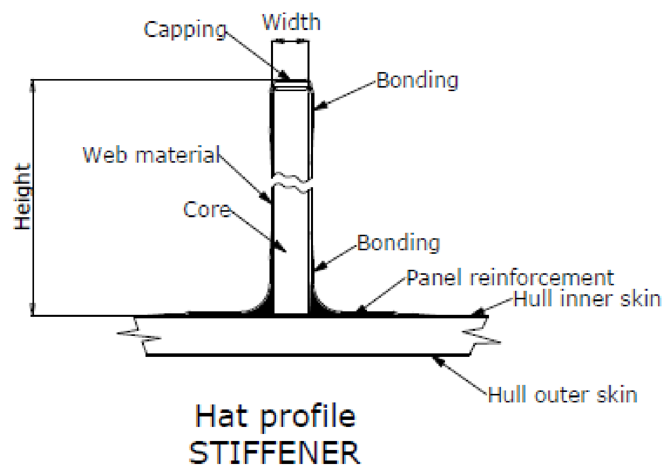

Figure 6.9. Top hat profile stiffener

The other type of stiffeners has no foam, and therefore they are lighter than the previous ones. They are similar to the steel U profiles, but they are made of laminate. In this case the laminate is thicker and is also glued to the hull panel that needs to be reinforced.

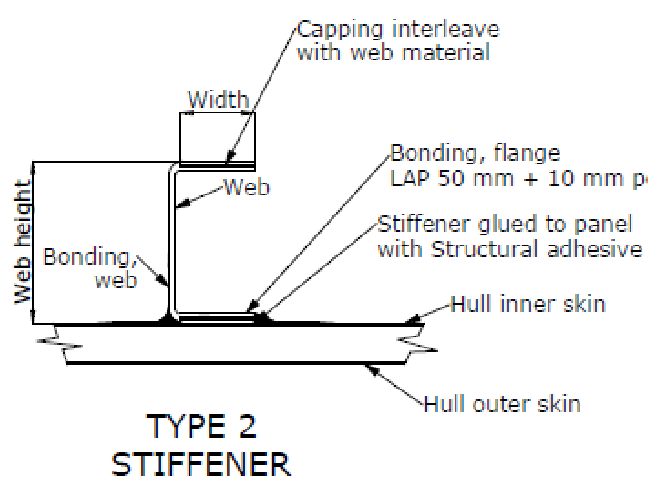

Figure 6.10. Other type of used stiffeners in the catamaran-SWATH midship section.

After defining the panels and the location of the reinforcements it was necessary to calculate the total panel area and stiffener area of the midship section. Then the location of the neutral axis was also calculated in order to evaluate the material proprieties around the center. The first and second moments of inertia were calculated for each component of the midship, and then it was calculated the total midship section inertia. The final section modulus was also calculated and compared with the required section modulus.

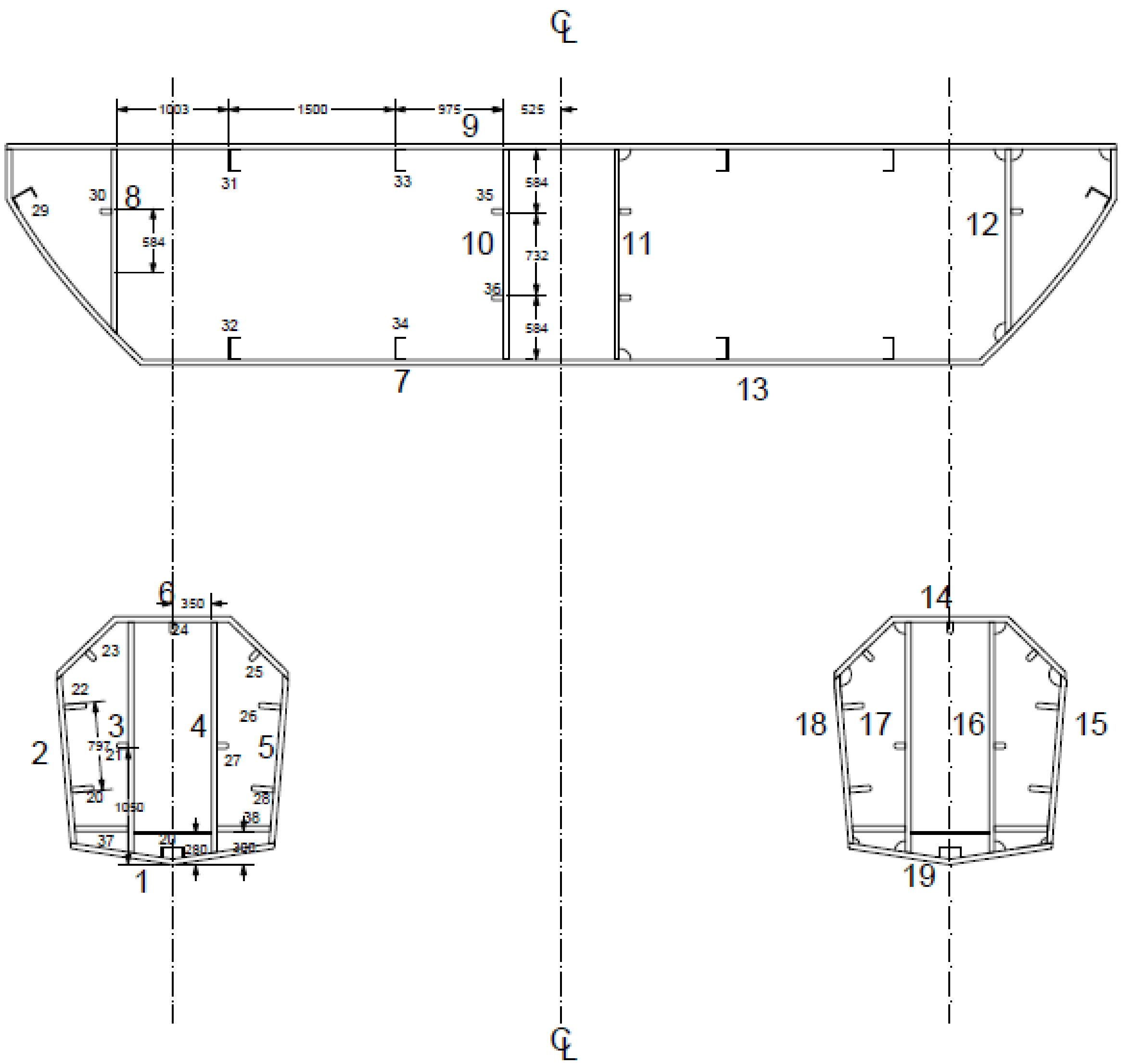

Figure 6.11. Midship section.

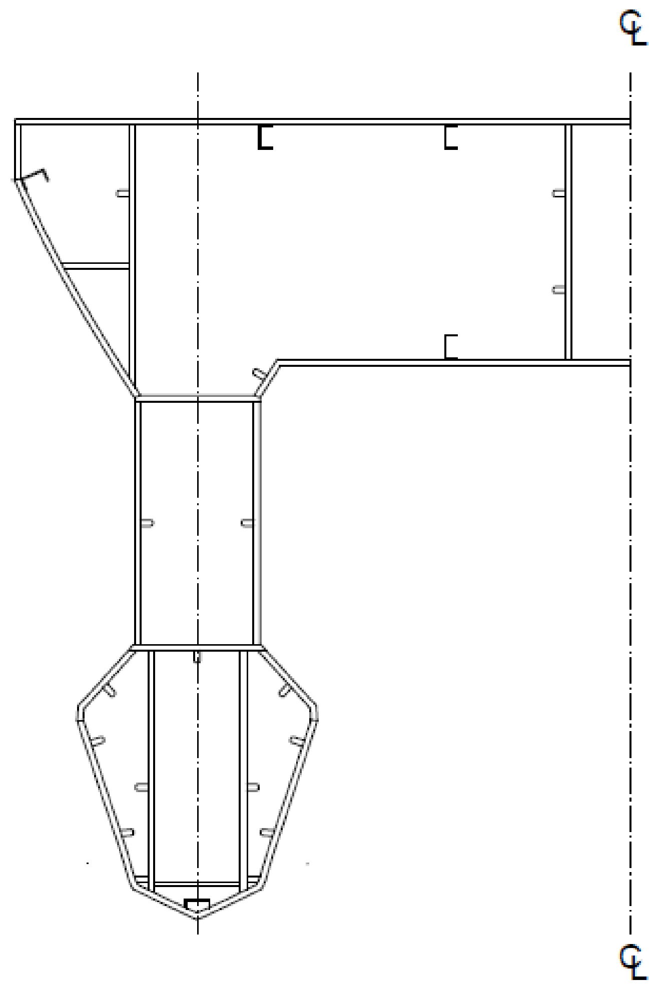

Figure 6.12. Section with the strut and the haunch.

The table with the information of all panels and stiffeners used in the calculation of the midship section mechanical proprieties can be found in Annex 3.

Having the information regarding each component of the midship section, it was possible to calculate the final section proprieties.

Table 6.11. Midship section proprieties.

ycg	0.00	m
zcg	3.759	m
Area_structure	3.403	m^2
Area_Midship	13.203	m^2
Ssection	19.617	m^3
Isection	50.618	m^4
Sbottom	13.467	m^3
Sdeck	18.465	m^3
required section modulus		
Srequired	13.414	m^3

Chapter 6.6. Resistance and Propulsion

The resistance and propulsion of the catamaran-SWATH was made using the software NavCad. The fact that the hull is intended to sail only when it is in catamaran mode, simplified a lot the calculation of the resistance because it was only necessary to take into consideration the shape of the pontoons and the distance between them. Similar to the other two designs, the input in NavCad consisted on the hull dimensions and coefficients, the design speeds and the water density.

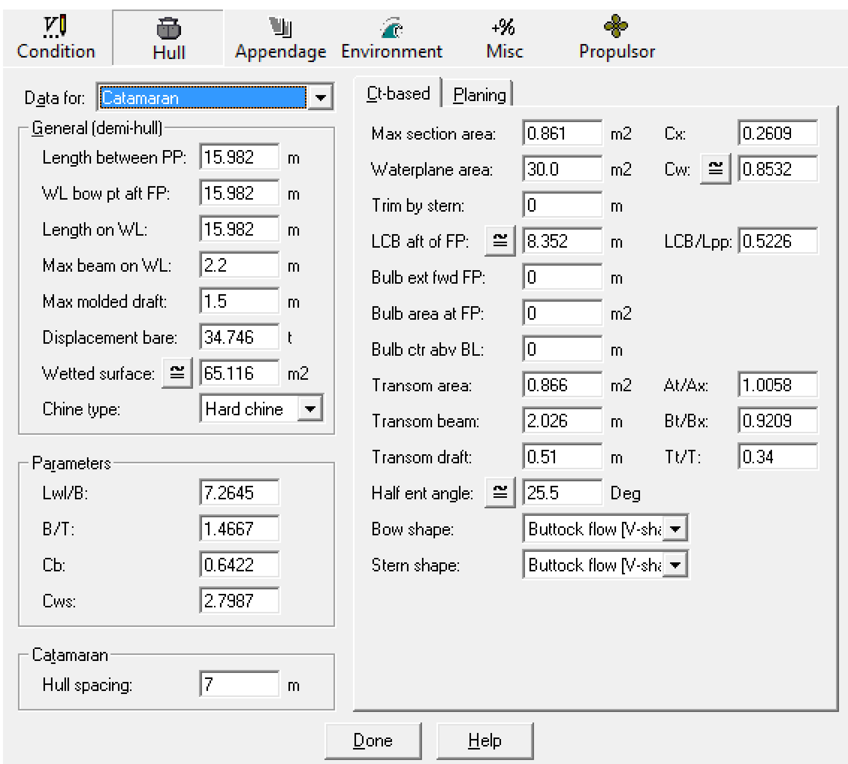

Figure 6.13. NavCad input hull parameters of the catamaran-SWATH.

The method used to calculate the resistance of a single pontoon was the method of DeGroot (DeGroot, 1955). This method is suitable for hard chine hull shapes with a vertical stern transom. In order to calculate the effect of the distance between the pontoons the software used the Insel and Molland interference calculation method (Insel & Molland, 1991). The prediction of the resistance was made for a draft of 1.5 m.

Based on the final result of the resistance prediction, it was possible to choose the necessary power for the main engines.

Table 6.12. Prediction of the resistance of the catamaran-SWATH

speed [knt]	Fn	Rn	Cf	Cr	Ct	Rbare [kN]	Rtotal [kN]	PE total [kW]	P_D total [kW]
5	0.20	3.46E+07	0.002	0.0014	0.0042	2	2	5	5.2
10	0.41	6.92E+07	0.002	0.0156	0.0182	32	32	166	173
15	0.61	1.04E+08	0.002	0.0208	0.0232	93	93	715	744
20	0.82	1.38E+08	0.002	0.0112	0.0136	97	97	994	1035
25	**1.02**	**1.73E+08**	**0.002**	**0.008**	**0.010**	**114**	**114**	**1470**	**1531**
30	1.23	2.08E+08	0.002	0.004	0.007	112	112	1730	1802

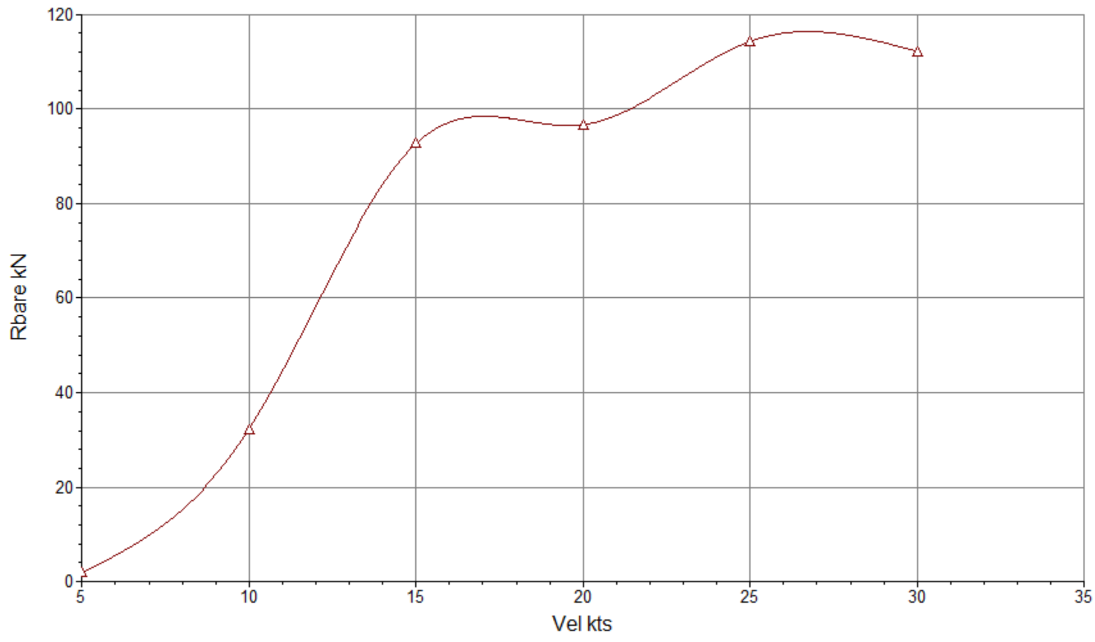

Figure 6.14. Graph of the effect of the speed in the resistance of the catamaran-SWATH.

The propulsion was predicted assuming a propulsive efficiency (η_D) of 0.96.. The propulsion of the catamaran is to be driven by two waterjets. These thrusters were chosen according to the low draft line of the catamaran and its transom shape, which would not allow to install a proper propeller size, capable of producing the necessary bollard power to achieve the 20 knots. The waterjet would be directly connected to the main engine gearbox shaft and therefore it would not be necessary to have a lot of shaft meters inside the hull, making it lighter. Other advantage of using these types of thrusters would be the inexistence of a rudder, and with that, the inexistence of a steering gear system, because maneuvering would be performed by differential thrust of the waterjets.

The main engine is a Caterpillar C18 ACERT.

Chapter 6.7. Light weight – Structure

The calculation of the ship light weight was divided in two main categories, one regarding the structural weight and other regarding the machinery and equipment weight.

The calculation of the structure was based on the midship section, where the areas of each section of the ship (at the frames) were compared in terms of percentage to the area of the midship section, and the difference would be multiplied and added/removed. The percentage difference would be multiplied to the calculated weight of the section corresponding to the midship, and the result was the additional/difference of the required section weight. Meaning that if the midship section has an area of 100 m^2 and weights 1 ton, then an area of 90 m^2 would weight (1ton – (90/100)*1ton) = 0.9 ton.

Since the frame-spacing is 500 mm, the weights calculated correspond to each 500 mm of structure. Each section has its own center of gravity, meaning that in the end all the weights are summed and one only center of gravity will correspond to the actual center of gravity of the structure.

Normally, it would be expected for the midship section to be the heaviest one, and all the other section would have less weight, but since in this vessel there is the existence of the struts, the midship section would not be the heaviest one.

The weights were divided has:

- Panel weights: In these weights it is possible to find the total carbon fiber laminate weight and the total core cell foam weight, corresponding to the panels of the ship.
- Stiffeners weights: Using the proprieties of the standard stiffeners (Table 6.10) and the core cell foam weigth.

The ship has the cylindrical shape between frames 12 to 19, until the struts. The area of the midship section can be found in Table 6.11, and it is 13.203 m^2.

Table 6.13. Catamaran-SWATH midship section weight.

section	Lcg (m)	Vcg (m)	total laminate weigth (t)	total core weigth (t)	total stiff weight (t)	total section weigth (t)
12	6	3.759	0.559	0.202	0.036	0.797
13	6.5	3.759	0.559	0.202	0.036	0.797
14	7	3.759	0.559	0.202	0.036	0.797
15	7.5	3.759	0.559	0.202	0.036	0.797
16	8	3.759	0.559	0.202	0.036	0.797
17	8.5	3.759	0.559	0.202	0.036	0.797
18	9	3.759	0.559	0.202	0.036	0.797
19	9.5	3.759	0.559	0.202	0.036	0.797

All the section between frame 12 and 19 have the same vertical center of gravity (Vcg) and the same transverse center of gravity (Tcg) which is zero because they are symmetric, see Table 6.13.

To the other sections, where it is possible to find the struts, it was used the relation described before and one other regarding the area of the strut.

Table 6.14. Catamaran-SWATH section areas and coefficients

section	Ahull(m^2)	A_strut (m^2)	coefficient (hull)	coefficient strut	Length (m)
0	2.144	0.000	0.162	0	0.500
1	7.047	0.720	0.534	0.351	0.500
2	12.188	1.246	0.923	0.608	0.500
3	12.532	1.598	0.949	0.780	0.500
4	12.804	1.828	0.970	0.892	0.500
5	13.068	1.961	0.990	0.957	0.500
6	13.282	2.050	1.006	1.000	0.500
7	13.468	1.961	1.020	0.957	0.500
8	13.557	1.828	1.027	0.892	0.500
9	13.630	1.598	1.032	0.780	0.500
10	13.554	1.246	1.027	0.608	0.500
11	13.469	0.720	1.020	0.351	0.500
21	13.249	1.246	1.003	0.608	0.500
22	13.301	1.598	1.007	0.780	0.500
23	13.283	1.828	1.006	0.892	0.500
24	13.214	1.961	1.001	0.957	0.500
25	13.070	2.050	0.990	1.000	0.500

26	12.842	1.961	0.973	0.957	0.500
27	12.492	1.828	0.946	0.892	0.500
28	7.164	1.598	0.543	0.780	0.500
29	6.381	1.246	0.483	0.608	0.500
30	5.315	0.720	0.403	0.351	0.500
31	3.868	0	0.293	0.000	0.500

The coefficient (hull) described in Table 6.14 shows the difference of the areas of each section regarding the midship section. The other coefficient (strut) shows the difference of the area of the strut.

Taking into consideration the area of the stiffeners as well as the area of the sections, preliminary light weight estimation was performed.

Table 6.15 shows the weight of each section of the ship, where it is possible to find the weight of 500 mm long section and each position of the center of gravity.

Table 6.15. Catamaran-SWATH section weigths and centers of gravity.

section	section wegith (t)	Lcg (m)	Tcg (m)	Vcg (m)
0	0.136	0.25	0	1.606
1	0.468	0.75	0	3.665
2	0.809	1.25	0	4.117
3	0.841	1.75	0	4.228
4	0.865	2.25	0	4.319
5	0.886	2.75	0	4.252
6	0.902	3.25	0	4.25
7	0.911	3.75	0	4.245
8	0.913	4.25	0	4.23
9	0.911	4.75	0	4.238
10	0.896	5.25	0	4.232
11	0.875	5.75	0	4.227
12	0.797	6.25	0	4.21
13	0.797	6.75	0	4.199
14	0.797	7.25	0	4.196
15	0.797	7.75	0	4.194
16	0.797	8.25	0	4.194
17	0.797	8.75	0	4.195
18	0.797	9.25	0	4.196
19	0.797	9.75	0	4.199
20	0.797	10.25	0	4.28
21	0.877	10.75	0	4.24
22	0.890	11.25	0	4.223
23	0.895	11.75	0	4.217
24	0.895	12.25	0	4.157
25	0.888	12.75	0	4.086
26	0.871	13.25	0	4.005

27	0.845	13.75	0	3.915
28	0.500	14.25	0	4.152
29	0.441	14.75	0	4.229
30	0.358	15.25	0	4.574
31	0.245	15.75	0	6.25

According to Table 6.15 the sections corresponding to the highest weights are the ones where the strut fits the pontoons. In this area, the position of the vertical center of gravity is also higher than the rest, due to the existence of the additional panels above the pontoons.

On the other hand, the ship's structural weight is not only distributed along the ship sections. The superstructure as well as the hull outfitting and the material protection are also part of the structure weight.

In order to make the light weight calculation as more organized as possible, the SFI Coding and Classification System was used. The SFI code classifies the ship components in a certain number of groups, and each group encompasses a specific system of the ship, per instance, the SFI 200 corresponds to everything regarding the structure of the ship, like the midship section, the foundations on the hull, bulkheads, bulwarks, etc. The mast is also included on SFI 200 since it is part of the structure of the ship. It is really important that the mast is able to have all the required navigation lights from COLREGS. These lights will be the first warning to any other ship.

Regarding the requirements of the SFI 200 group applied to catamaran-SWATH, the total structure weight as well as the structural light weight center of gravity was calculated. The tables with the full description of the components that are part of the light weight can be found in Annex 3. These tables were based on existing projects and lightweight estimations.

Table 6.16. Catamaran-SWATH hull structure weights, using SFI code.

Item:		**Weight**	**VCG**	**LCG**	**TCG**
					PS +
SFI no.		(t)	(m)	(m)	(m)
200	Hull	28.183	4.544	7.840	0.000

Chapter 6.8. Light Weight – Machinery and equipment

The second major group of the light weight prediction was the machinery. According to the rules all the required machinery that is necessary to be onboard of the ship in order to make it run and operate for at least 10 seconds is part of the lightship, meaning that all the small equipment like pumps, valves, pipes, fittings and other small mechanical components are integrated in the lightship weight. Then the major components are of course the heavy ones, like the main engines, the thrusters, the emergency generator, the switchboards and in the case of this particular ship, the computers and batteries are also part of the light weight, since they are necessary to make the ship an autonomous one.

The main engines were chosen according to the resistance and propulsion requirements to achieve the maximum ship speed of 20 knots. They type chosen was only an example of a possible one, but since there are several manufactures on ship engines, there are also other options. For the dissertation, two Caterpillar C18 ACERT engines were chosen. In the choice of the engine there it was also taken into consideration the tight space that the engine room would have, due to the small size of the pontoons.

For the thrusters, two Rolls-Royce water jets were used, where the requirements were the bollard thrust produced by the water jet and the shape of the water jet, in order to be possible to install it in the thruster room. The type FF-340 was the one chosen for the case study. For this type of engine, the total amount of fuel allows the ship to sail during 15 days without needing of refuel.

Table 6.17. Catamaran-SWATH main engines and waterjets.

	Main Engines				**Waterjets**	
Number	2			Number	2	
	Length [m]	Width [m]	Height [m]	Length [m]	Width [m]	Height [m]
	1.854	1.134	1.300	1.975	0.880	0.846
Dimensions						
	Weigth	1950	[kg]	Weigth	270	[kg]
	Power	533	[kW]	Power	530	[kW]
	speed	2100	[rpm]			

An emergency generator was also placed onboard. This emergency generator is to be used only in case of failure of any of the other engines, and should provide enough power to maintain the communications ship's emergency systems operational. The Volvo Penta D3A TA was chosen to be the emergency generator, with a maximum power of 88 kW. This engine is to be located at the platform, inside the superstructure. It has its own ventilation and exhaust, and the fuel is to be provided by an independent tanklocated close to the emergency generator.

The dry weight of the emergency generator is 1245 kg.

Both the main engines and the emergency generator generate a voltage of 400V at 50Hz frequency.

These components are part of the SFI 600 and according to the GA the positions of the centers of gravity are shown in the next table. Note that in the transverse axis, it is assumed positive any location on the portside of the center line of the ship.

Table 6.18. Catamaran-SWATH SFI 600, position of the center of gravity.

		Weight	VCG	LCG	TCG
SFI 600 - Machinery main components					PS+
SFI	Description	(t)	(m)	(m)	(m)
600 - Diesel engines for propulsion					
	601 - diesel engines	3.90	1.20	3.74	0.00
630- propellers, transmissions, foils					
	635- special propeller plant	1.04	0.75	1.15	0.00
650- Motor aggregates dor main electric power					
	651- motor aggregates				
	Emergency GenSet	1.25	7.20	9.00	-1.18
total					
SFI 600 - Machinery main components		6.19	2.33	4.36	-0.24

Other main energy suppliers are the batteries that are part of the light weight. These batteries are not supposed to be used for cargo, like electronic components needed for the scientific researches. The main purpose of these batteries will be to supply energy for all the electronic equipment that must be onboard for the safe and possible operation of the autonomous vessel.

The other SFI groups were also defined, as well as the most of the ship equipment.

SFI 300 - Equipment for cargo: In this group it should be defined every equipment that is supposed to be used for cargo handling. In this vessel it is possible to find two main items for this purpose; the hatches that will give access for the cargo area inside the platform and the deck crane. 10 hatches were spread along the ship in order to facilitate the access from the outside to the cargo areas. In this ship it is very important to give good accesses to the areas because heavy cargo will certainly be placed onboard, like the batteries. On the other hand it was also important to give a good access to the engine room, for any maintenance needs.

The crane has the main purpose of launching and recovery of UUVs, because the catamaran-SWATH should be able to perform any kind of support for these UUVs. So the crane must have a certain reach and a certain lifting capacity at its max reach.

SFI 400 – Ship equipment: This group encompasses all the equipment that is onboard of the ship. Navigation and searching equipment, as well as the communication equipment should be stated on this group. On the other hand, equipment like the anchoring, mooring and towing system should also be presented in SFI 400.

The navigation and searching equipment is very important for this catamaran-SWATH, because the probability of failure must be as close as possible to zero, because of that, it is necessary to have more than one of each item, like the DGPS, sonars and radars. The communication equipment is also very important and stationary stations must be placed onboard and be able to work for 24h a day.

As part of the anchoring and mooring equipment, the bollards, fairleads, wires, windlasses, chains and chain lockers, anchors and chocks are to be quantified on this group.

SFI 500 – Equipment for crew and passengers: This group can be very complex, because it incorporates all the lifesaving and firefighting equipment of the ships. In this case the fact that the ship is to be autonomous and it is supposed to have no crew or passengers, this lifesaving equipment can be reduced or removed, but not all because it is still necessary to maintain safety when someone goes onboard of the ship for maintenances.

Minor lifesaving equipment is to be spread along the ship, equipment like some life vests and medical and first aids. For the firefighting it is important to have and automatic sprinkler or water mist systems, that should be activated by several fire or smoke detectors that are to be placed in the most critical or fire friendly areas, like the engine room, the thruster room and the emergency generator room.

The doors and accesses are also part of this group. Doors that give direct access from the outside to the superstructure or to the cargo area must be of watertight type. The doors inside the superstructure and inside the cargo deck must comply with the fire regulations from SOLAS.

The wall insulations, ladders and the railing that is to be placed on the weather deck are also to be included on this group.

Windows will also have an important factor on this ship. Despite not having any wheelhouse or accommodation areas, this ship must be provided with a lot of cameras that must be give a good overview of all angles of the ship and this cameras must not be placed outside of the ship because of the salt water and the probability of blurring of the camera lenses. The idea is to have the cameras close to a window, equipped with window whippers to make sure that the camera will always have a clean view for the outside.

Other equipment like the ventilation and AC unit for the engine room and the cargo area are also to be part of SFI 500.

SFI 700 – Systems for Machinery: Here are defined all the machinery that must be onboard for the ship's operation. The fuel systems, including the fuel pumps, filters and purification plants are an example of the equipment to be defined on this group.

Also the lubricating oil system, the cooling systems, the exhaust and air inlet systems, as well as the automation systems are to be defined by SFI 700.

SFI 800 – Ship common systems: The ballast and bilge systems are to be part of this group. The ballast system is to be composed by the main ballast pumps, filters and piping. The pumps are to be of vacuum type and it was suggested to use the BUSCH vacuum pumps, type Samos SB 0530D2, due to the big ballast tank and the necessity to ballast as fast as possible. Each ballast tank is to have one of these pumps.

The fire pumps are also to be defined in this group, and for this ship it was assumed to used two fire pumps, one to be in stand-by and both with a capacity of 25 m^3/h. On the other hand the two engine rooms are also to be provided of CO_2 firefighting system.

Each tank of the ship must have an air pipe and a sounding pipe which are also to be taken into consideration in the light weight calculation.

Finally all the electrical components are also to be stated in this group. Components like the main and the emergency switchboards are the most important, then it is possible to find the information regarding the weights and the position of the distribution panels and boards. This equipment is mainly located in the superstructure at the switchboard room division, than the cable trays that connect the engine room to the main switchboard room are also to be defined.

The full description of the weights and their position can be found in Annex 3, together with the SFI 200 group.

When making this type of prediction in the calculation of the light weight it is usually necessary to give a tolerance in the calculation, in this case a tolerance of +8% of the total off all group weights was given.

Table 6.19. Catamaran-SWATH light weight distribution.

Item:		**Weight**	**VCG**	**LCG**	**TCG**
					PS +
SFI no.		(t)	(m)	(m)	(m)
200	Hull	28.183	4.544	7.840	0.000
300	Equipment for cargo	1.870	6.936	3.853	0.000
400	Ship equipment	2.660	6.406	9.510	0.837
500	Equipment for crew and passengers	4.384	6.580	7.245	0.200
600	Machinery main components	6.185	2.332	4.360	-0.238
700	System for machinery main components	1.585	4.346	6.972	-0.239
800	Ship common systems	3.800	4.614	7.691	0.212
	Tolerance	**3.893**			
Total					
Total weight		**52.560**	**4.295**	**6.706**	**0.039**

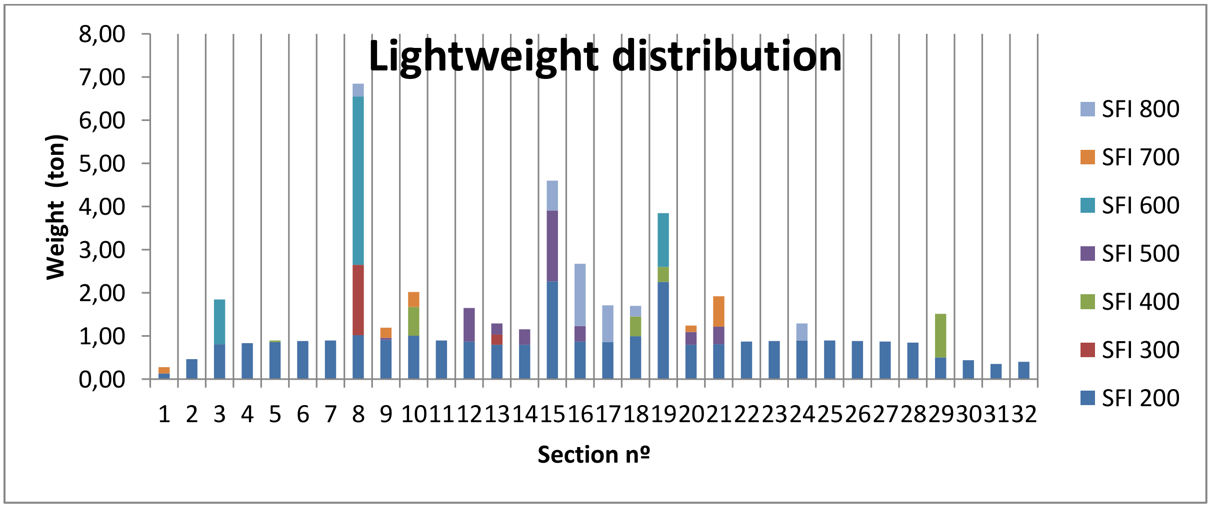

Figure 6.15. Catamaran-SWATH longitudinal distribution of the light weight.

Chapter 6.9. Preliminary Stability Check

As a preliminary stability checking, it was used the 2008 IS Code to evaluate if the vessel complies with its stability criteria. This calculation is only regarding intact stability and the righting arm only for the light weight condition (corresponding to having all the tanks and cargo spaces empty). In order to perform a complete intact stability calculation it was necessary to perform several loading conditions as the departure (100% consumables and 100% cargo), ballast condition, arrival condition and any other required condition. As for the 2008 IS Code the criteria that had to be fulfilled was:

a) The area under the curve of righting levers (GZ curve) should not be less than 0.070 meter-radians up to an angle of 15° when the maximum righting lever (GZ) occurs at 15° and 0.055 meter-radians up to an angle of 30° when the maximum righting lever (GZ) occurs at 30° or above. Where the maximum righting lever (GZ) occurs at angles of between 15° and 30°, the corresponding area under the righting lever curve should be: 0.055 + 0.001(30 - GfZmax) m*rad. Here the GfZmax is the angle in degrees at which the righting lever curve reaches its maximum.

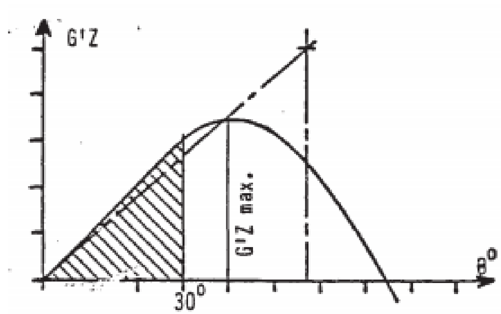

Figure 6.16: Stability 2008 IS Code requirement **a).**

b) The area under the righting lever curve (GZ curve) between the angles of heel of 30° and 40°, or between 30° and qf if this angle is less than 40°, should be not less than 0.030 meter-radians. qf is the angle of heel in degrees at which openings in the hull, superstructure or deckhouse which cannot be closed weather tight, immerse.

c) The righting lever (GZ) should be at least 0.20 m at an angle of heel equal to or greater than 30°.

d) The maximum righting lever (GZ) should occur at an angle of heel not less than 15°.

e) The initial transverse metacentric height (GM0) should not be less than 0.15 m.

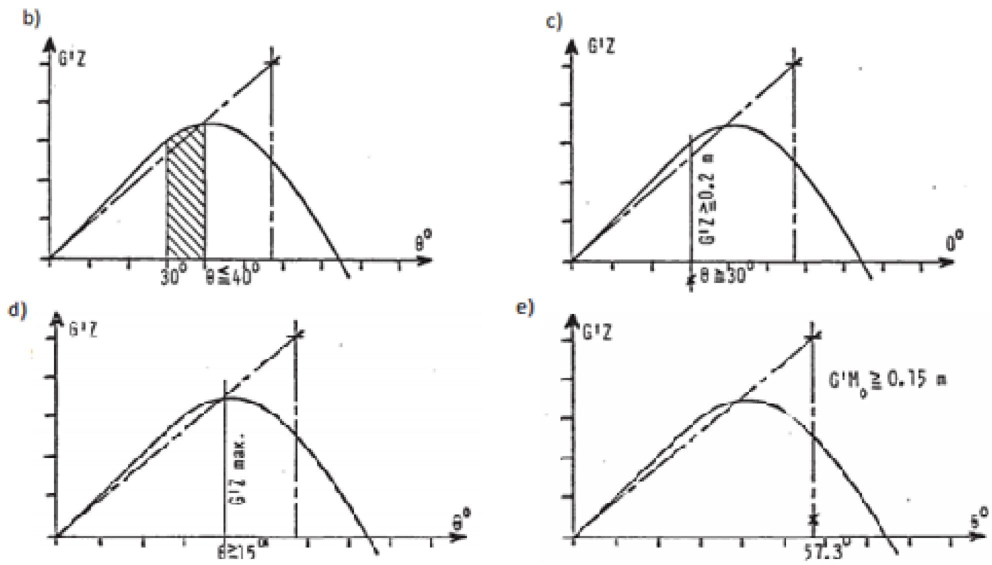

Figure 6.17: Stability requirements **b), c), d)** & **e)**.

Table 6.20. GZ values for the light weight condition, using formula (12) and results from KN curves (Table 30).

Angle (deg)	**1**	**5**	**8**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**50**	**60**
GZ (m)	0.136	0.667	1.005	1.189	1.390	1.516	1.629	1.668	1.396	1.032	0.283	-0.47315

The GZ graph can be found in Annex 5. The following table shows the results for each criteria.

Table 6.21. Catamaran-SWATH stability check for Light weight condition.

		Required	**Real**		**check**
a1)	Area 15º	0.07	0.166	m.rad	**Ok**
a2)	Area 30º	0.055	0.351	m.rad	**Ok**
b)	Area 30 to 40º	0.03	0.056	m.rad	**Ok**
c)	GZ (30º)	0.2	1.668	m	**Ok**
d)	max GZ	>15º	28º	deg	**Ok**
e)	GM0	>0.15	0.262	m	**Ok**

Chapter 7. CONCLUSIONS

This dissertation gave me the opportunity to face different problems and the ways to solve them. I found out that the majority of people that work within the marine sector are not aware of the development of the ASVs and they always get surprised when hear about the vast applications in which ASVs can be used.

The usage of drones is becoming more and more significant, not only in the marine sector, but also in land and air. The future of mankind will be followed by the development of these unmanned vehicles, because it is safer, more comfortable and is less subjected to human mistakes.

When talking about small ASVs, where the only requirement as a vessel is to have a floating platform and a small propeller, the main difficulties of the design will be on the electrical systems and on control algorithms to avoid collisions and accidents, but when the vessels start to be bigger and they need to be optimized to operate in a certain environment, it is necessary to have the hand of a naval architect to ensure that the vessel is reliable to operate.

In the dissertation, the two smaller vessels (the catamaran and the monohull) were designed to be able to perform standard and usual scientific missions, giving a lot of flexibility due to their cargo capacity and autonomy. The fact that they are both equipped with only electrical components, makes them 100% environmental friendly, meaning that there is no risk of contamination of the studied waters.

Both vessels have small water recovery tanks which can be used is necessary, and each one has its own innovations on board:

- Catamaran: the winch will allow to the scientists to recover ground and algae samples. Other innovation is the way of the division of the catamaran compartments, providing a lot of different cargo areas, each one suitable for different equipment. The propeller duct will protect the propeller from getting stuck in the existing vegetation of the lake/river.
- Monohull: The solar panels will give a bigger autonomy, which can be an important factor for the purpose of the vessel. In this craft it is also possible to find a good compartment division for the disposal of the equipment.

The future will bring new technologies and new ideas in the marine sector. Bigger ships and fasters ships are always being designed and built, and every year there is a new perspective of innovation. Intelligent ships are also innovative and they are now starting to highlight the researchers, due to the amount of success and money that they can earn/save.

All three designs were made on composite materials because of the necessity to have a light weight structure, resulting in much more payload capacity which is important to these vessels.

The catamaran-SWATH is a very good solution when speed and precise measurements are the requirements. It is significantly bigger than the other two designs and the design became much more complex. Its size allows it to perform not only simple research missions, but also another large variety of applications like coastal surveillance, towing of small pleasure crafts or even search and rescue missions, it would all depend on who would operate the vessel and where.

Despite of having a lot of electrical equipment onboard, the fact of being autonomous, saves a lot of money and required space that would be used for a wheelhouse and all control panels that must be operated on sight.

The next step on the design of the cat-SWATH would consist in performing an electrical load balance, a P&ID diagram and all the required class drawings for the ship design approval. Perhaps, it would be necessary to change some of the characteristics of the vessel and perform another turn on the design spiral.

The development of the catamaran-SWATH was done thinking about possible future crafts, where cameras and GPS coordinates will be the eyes of the captains.

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ANNEX 1.

Table of the studied ASVs

Table A. 1 List of some developed ASVs

ASV	year	country	Designer	operation waters	Hull type	Length	Beam	Draft	Weigth	Speed	Power supply	Autonomy	Hull material	Mission
[-]	[-]	[-]	[-]	[-]	[-]	[m]	[m]	[m]	[Kg]	[Knots]	[-]	[hours]	[-]	[-]
ARTEMIS	1993	USA	MIT	Calm waters	Monohull	1,3716	0,381	0,2032	29	2 - 2,25	Gasoline engine	4		Test vessel and Bathymetric data
ACES	1996-1997	USA	MIT	Calm waters	Catamaran	1,905	1,2954	0,4572	158,76	5.0 - 10.0	Gasoline engine	12		Test vessel and Bathymetric data
AutoCat	1999	USA	MIT	Calm waters	Catamaran	1,8	1	0,3	100	1.0-8.0	Electric	4	Fiber-Glass	AUV telemetry, marine life tracking and hydrographic/Sub-bottom Survey
MESSIN-Dolphin	1998-2000	Germany	German Federal Ministry of Education	Calm waters	Catamaran	3,3	1,8	0.2-0.4	250	3,85	Electric	10 hours hybrid power supply and 3h supplied by batteries	Fiber-Glass	High accuracy positioning and track guidance and carrying measuring devices in shallow waters
Delfim	1997-2000	Portugal	IST	Rough Waters	Catamaran	3,5	2	(unknown)	350	5	Electric			Provide assistance to INFANTE AUV
Kan-Chan	2000	Japan	Yamaha	Rough Waters	Monohull	8	2,8	(unknown)	3500	4	Diesel engine	700		Measurement of aerosol (colloidal particles) in the air, over the oceans
Charlie	2002-2004	Italy	CNR-ISSIA	Rough Waters	Catamaran	2,4	1,8	(unknown)	360		Electric	6	Fiber-Glass	Sea surface microlayer sampling

Table A. 1.1 List of some developed ASVs (continuation)

Scout	2004	USA	MIT	Rough Waters	Monohull	3,05			81,64	5	Electric	8	Polyethilene	Oceanographic and undersea testing
OASIS	2005	USA	NASA/GSFC	Rough Waters	Monohull	5,5	1,52	0,66	1 361	2,2-2,5	Electric + Solar panels	2160-4320	Fiber-Glass with internal aluminium stiffeners	Air-Sea measurements
Springer	2006	UK	University of Plymouth	Calm waters	catamaran	4	2,3		600		Electric			Environmental and hydrographic surveys in shallow waters
Omni-camera vessel	2006	USA	Virginia Tech	Calm waters	Catamaran	2,7	1,5	0,5	57	3	Gasoline generator	72-96		Shoreline mapping - omni-propose camera
Circe	2006	USA	Olin College of Engineering	Calm waters	catamaran	2	1,37	0.1-0.22	227		Electric			Collecting water samples
ROAZ	2006	Portugal	ISEP - Porto	Calm waters	Catamaran	1,5	1	0,52		2			FiberGlass	Support in AUV opperations and bathymetric measures
Swordfish	2006-2007	Portugal	ISEP - Porto	Rough Waters	Catamaran	4,5	2,2	0,5	190	2.33 - 3.88	Electric			Survey Vehicle and communication
Wivenhoe ASV	2009	Australia	CSIRO	Calm waters	Catamaran	4,88				1.0 - 5.83	Electric + Solar panels	> 24	Fiber glass hull	Water quality monitoring

Table A. 1.2 List of some developed ASVs (conclusion)

Bathyboat	2010	USA	University of Michigan	Calm waters	monohull	0,97		0,1	14,5	1,36	Electric	3	composite and aluminum	Bathymetric data and underwater vehicle network supervision
Heavy metal measure catamaran	2010	Italy	Scuola Superiore Sant'Anna	Calm waters	Catamaran	1,991	1,1164			2	Electric	24	Fiber glass hull with foam core layers and gel coat for UV protection	Water monitoring and measure heavy metals concentrations in the water
CatOne family	2012	Italy		Calm waters	Catamaran	1.6 - 1.9	1 - 1.2		12.0 - 20.0	2,7	Electric	8		Hydrographic measurement and environmental monitoring
Lizhbeth	2011	Germany		Calm waters	Catamaran	2,5	1,8		120 - 340	3	Electric			monitoring of water resorces and smaple of punctual meteorological events
CAN	2011	Canada	AOSL	Rough Waters	catamaran	1,5	1	0,37	146	0,514	Electric			Ocean deployment
Brizzolara_1	2013	USA	MIT	Rough Waters	SWATH	6				15	Diesel electric			Transport, deployment and recovery of AUVs and oceanographic measures
Brizzolara_2	-	USA	MIT	Rough Waters	SWATH	20	16		42000	120	Diesel electric			Transport, deployment and recovery of AUVs + oceanographic measures

ANNEX 2.

Model maker hull offsets and overview

Catamaran

Part Name: HULL
Component Name: HULL
<u>Offset for half of demi-hull</u>

Long : 1.993F
0.426S , 0.450 0.441S , 0.500 0.410S , 0.500 0.424S , 0.455 0.426S , 0.450
Long : 1.986F
0.426S , 0.400 0.441S , 0.456 0.456S , 0.500 0.395S , 0.500 0.408S , 0.465 0.423S , 0.411 0.426S , 0.400
Long : 1.979F
0.426S , 0.362 0.450S , 0.450 0.467S , 0.500 0.384S , 0.500 0.397S , 0.464 0.425S , 0.364 0.426S , 0.362
Long : 1.972F
0.426S , 0.331 0.460S , 0.457 0.477S , 0.500 0.373S , 0.500 0.381S , 0.485 0.395S , 0.446 0.419S , 0.356 0.426S , 0.331
Long : 1.965F
0.426S , 0.300 0.466S , 0.449 0.486S , 0.500 0.365S , 0.500 0.373S , 0.483 0.392S , 0.431 0.418S , 0.333 0.426S , 0.300
Long : 1.958F
0.426S , 0.269 0.455S , 0.386 0.472S , 0.441 0.495S , 0.500 0.357S , 0.500 0.372S , 0.461 0.393S , 0.398 0.426S , 0.269
Long : 1.951F
0.426S , 0.246 0.461S , 0.389 0.475S , 0.436 0.501S , 0.500 0.350S , 0.500 0.360S , 0.479 0.372S , 0.447 0.387S , 0.401 0.422S , 0.261 0.426S , 0.246
Long : 1.944F
0.426S , 0.225 0.471S , 0.406 0.497S , 0.477 0.507S , 0.500 0.343S , 0.500 0.355S , 0.477 0.384S , 0.393 0.422S , 0.240 0.426S , 0.225
Long : 1.916F
0.426S , 0.154 0.431S , 0.174 0.475S , 0.367 0.486S , 0.399 0.503S , 0.445 0.530S , 0.500 0.322S , 0.500 0.348S , 0.445 0.366S , 0.399 0.380S , 0.351 0.420S , 0.174 0.426S , 0.154
Long : 1.889F
0.426S , 0.105 0.433S , 0.127 0.466S , 0.289 0.488S , 0.369 0.507S , 0.421 0.529S , 0.469 0.547S , 0.500 0.304S , 0.500 0.322S , 0.469 0.344S , 0.421 0.364S , 0.369 0.386S , 0.289 0.414S , 0.149 0.419S , 0.127 0.426S , 0.105
Long : 1.833F
0.426S , 0.042 0.438S , 0.081 0.476S , 0.257 0.504S , 0.351 0.529S , 0.411 0.550S , 0.452 0.580S , 0.500 0.271S , 0.500 0.296S , 0.462 0.323S , 0.411 0.347S , 0.351 0.372S , 0.270 0.410S , 0.094 0.421S , 0.055 0.426S , 0.042
Long : 1.778F
0.426S , 0.013 0.436S , 0.040 0.484S , 0.222 0.515S , 0.319 0.533S , 0.364 0.554S , 0.406 0.578S , 0.450 0.613S , 0.500 0.239S , 0.500 0.249S , 0.486 0.287S , 0.427 0.308S , 0.385 0.336S , 0.319 0.368S , 0.222 0.390S , 0.139 0.407S , 0.068 0.420S , 0.026 0.426S , 0.013
Long : 1.666F
0.426S , 0.002 0.440S , 0.029 0.490S , 0.147 0.502S , 0.181 0.521S , 0.225 0.523S , 0.232 0.547S , 0.291 0.579S , 0.356 0.615S , 0.421 0.668S , 0.500 0.184S , 0.500 0.249S , 0.400 0.272S , 0.356 0.326S , 0.239 0.331S , 0.225 0.350S , 0.181 0.354S , 0.167 0.411S , 0.029 0.426S , 0.002
Long : 1.555F
0.426S , 0.001 0.445S , 0.023 0.474S , 0.071 0.495S , 0.109 0.624S , 0.360 0.703S , 0.500 0.148S , 0.500 0.220S , 0.374 0.357S , 0.109 0.361S , 0.099 0.407S , 0.023 0.426S , 0.001
Long : 1.444F
0.426S , 0.000 0.448S , 0.020 0.478S , 0.056 0.509S , 0.098 0.578S , 0.202 0.607S , 0.255 0.699S , 0.442 0.708S , 0.459 0.726S , 0.500 0.125S , 0.500 0.130S , 0.491 0.144S , 0.459 0.153S , 0.442 0.171S , 0.404 0.218S , 0.305 0.274S , 0.202 0.308S , 0.147 0.373S , 0.056

0.404S , 0.020 0.426S , 0.000
Long : 1.333F
0.426S , 0.001 0.463S , 0.030 0.520S , 0.088 0.559S , 0.134 0.598S , 0.186 0.631S , 0.238 0.658S , 0.290 0.741S , 0.500 0.110S , 0.500 0.194S , 0.290 0.220S , 0.238 0.253S , 0.186 0.292S , 0.134 0.332S , 0.088 0.389S , 0.030 0.416S , 0.009 0.426S , 0.001
Long : 1.222F
0.426S , 0.005 0.476S , 0.039 0.528S , 0.082 0.572S , 0.122 0.616S , 0.171 0.625S , 0.183 0.651S , 0.222 0.678S , 0.276 0.699S , 0.330 0.717S , 0.387 0.746S , 0.500 0.105S , 0.500 0.134S , 0.387 0.152S , 0.330 0.173S , 0.276 0.200S , 0.222 0.226S , 0.183 0.279S , 0.122 0.323S , 0.082 0.376S , 0.039 0.426S , 0.005
Long : 1.111F
0.426S , 0.012 0.479S , 0.043 0.535S , 0.079 0.582S , 0.115 0.624S , 0.153 0.650S , 0.183 0.668S , 0.209 0.695S , 0.264 0.714S , 0.322 0.728S , 0.382 0.749S , 0.500 0.103S , 0.500 0.138S , 0.322 0.157S , 0.264 0.183S , 0.209 0.202S , 0.183 0.222S , 0.159 0.269S , 0.115 0.317S , 0.079 0.373S , 0.043 0.426S , 0.012
Long : 0.889F
0.426S , 0.033 0.542S , 0.085 0.594S , 0.112 0.636S , 0.141 0.646S , 0.149 0.669S , 0.171 0.689S , 0.195 0.704S , 0.222 0.715S , 0.252 0.728S , 0.314 0.748S , 0.500 0.104S , 0.500 0.123S , 0.314 0.136S , 0.252 0.148S , 0.222 0.163S , 0.195 0.183S , 0.171 0.205S , 0.149 0.258S , 0.112 0.309S , 0.085 0.370S , 0.057 0.426S , 0.033
Long : 0.667F
0.426S , 0.057 0.543S , 0.101 0.595S , 0.125 0.650S , 0.154 0.674S , 0.171 0.694S , 0.194 0.708S , 0.221 0.717S , 0.252 0.727S , 0.314 0.740S , 0.500 0.111S , 0.500 0.124S , 0.314 0.134S , 0.252 0.144S , 0.221 0.157S , 0.194 0.178S , 0.171 0.202S , 0.154 0.230S , 0.138 0.309S , 0.101 0.369S , 0.077 0.426S , 0.057
Long : 0.444F
0.426S , 0.081 0.480S , 0.098 0.591S , 0.139 0.644S , 0.164 0.667S , 0.181 0.687S , 0.204 0.700S , 0.231 0.708S , 0.261 0.717S , 0.321 0.726S , 0.500 0.126S , 0.500 0.134S , 0.321 0.143S , 0.261 0.152S , 0.231 0.165S , 0.204 0.184S , 0.181 0.207S , 0.164 0.261S , 0.139 0.371S , 0.098 0.426S , 0.081
Long : 0.333F
0.426S , 0.092 0.479S , 0.108 0.587S , 0.147 0.613S , 0.158 0.639S , 0.173 0.661S , 0.190 0.680S , 0.212 0.693S , 0.238 0.701S , 0.267 0.709S , 0.325 0.716S , 0.500 0.135S , 0.500 0.142S , 0.325 0.150S , 0.267 0.159S , 0.238 0.172S , 0.212 0.191S , 0.190 0.213S , 0.173 0.238S , 0.158 0.265S , 0.147 0.372S , 0.108 0.426S , 0.092
Long : 0.222F
0.426S , 0.105 0.478S , 0.119 0.583S , 0.156 0.608S , 0.166 0.633S , 0.180 0.655S , 0.197 0.673S , 0.219 0.685S , 0.244 0.693S , 0.272 0.699S , 0.330 0.703S , 0.500 0.149S , 0.500 0.153S , 0.330 0.158S , 0.272 0.166S , 0.244 0.179S , 0.219 0.197S , 0.197 0.218S , 0.180 0.243S , 0.166 0.269S , 0.156 0.374S , 0.119 0.426S , 0.105
Long : 0.111F
0.426S , 0.118 0.531S , 0.148 0.604S , 0.174 0.628S , 0.187 0.649S , 0.204 0.666S , 0.225 0.677S , 0.251 0.684S , 0.279 0.690S , 0.500 0.162S , 0.500 0.164S , 0.335 0.168S , 0.279 0.174S , 0.251 0.185S , 0.225 0.202S , 0.204 0.223S , 0.187 0.248S , 0.174 0.272S , 0.165 0.375S , 0.132 0.426S , 0.118
Long : 0.000
0.426S , 0.129 0.475S , 0.140 0.529S , 0.156 0.575S , 0.173 0.622S , 0.194 0.643S , 0.209 0.660S , 0.230 0.668S , 0.256 0.671S , 0.285 0.676S , 0.500 0.176S , 0.500 0.180S , 0.285 0.184S , 0.256 0.192S , 0.230 0.208S , 0.209 0.229S , 0.194 0.277S , 0.173 0.323S , 0.156 0.376S , 0.140 0.426S , 0.129

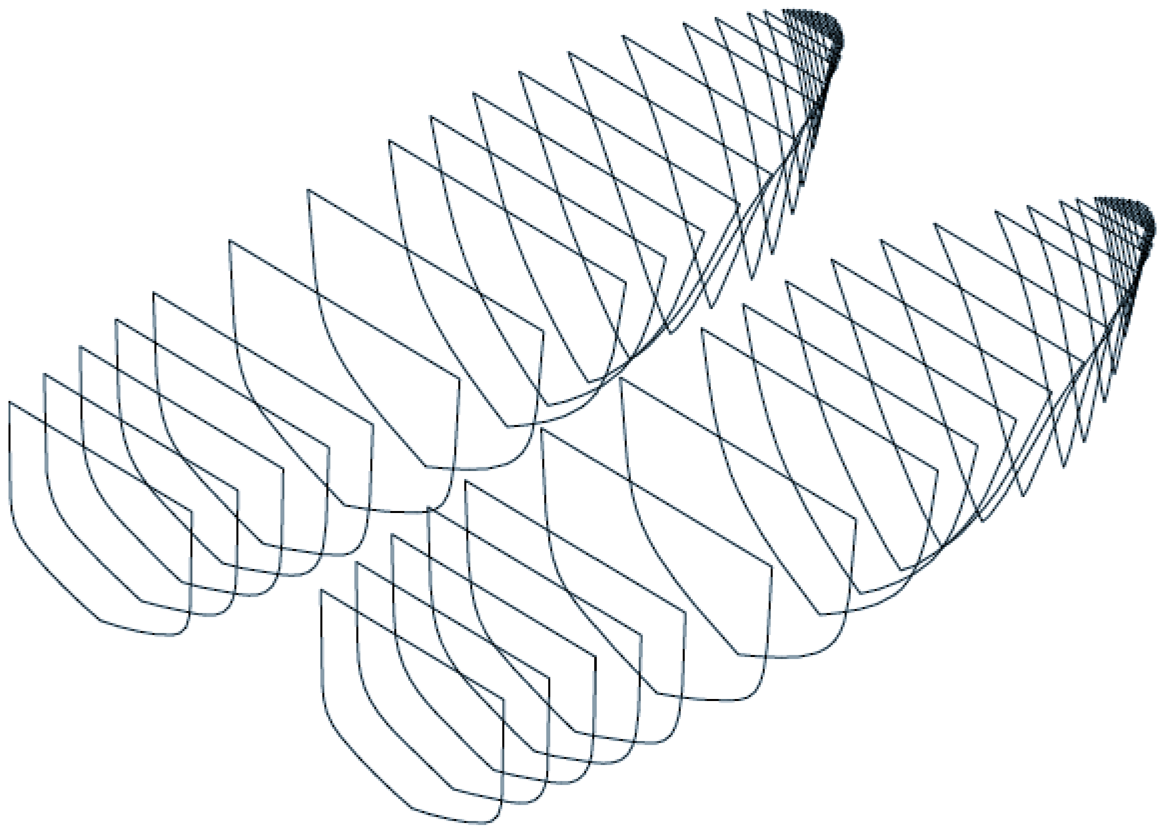


Figure A. 1. Catamaran Model maker arrangement.

Monohull

Part Name: Monohull
Component Name: Hull
Offset for half hull

Long : 16.404F
0.000 , 2.285
Long : 16.370F
0.000 , 2.217 0.016S , 2.226 0.063S , 2.285 0.000 , 2.285
Long : 16.335F
0.000 , 2.149 0.017S , 2.159 0.119S , 2.255 0.124S , 2.285 0.000 , 2.285
Long : 16.301F
0.000 , 2.081 0.082S , 2.129 0.172S , 2.226 0.186S , 2.285 0.000 , 2.285
Long : 16.267F
0.000 , 2.014 0.109S , 2.077 0.200S , 2.160 0.247S , 2.285 0.000 , 2.285
Long : 16.233F
0.000 , 1.946 0.107S , 2.008 0.234S , 2.109 0.300S , 2.227 0.308S , 2.285 0.000 , 2.285
Long : 16.199F
0.000 , 1.882 0.152S , 1.973 0.297S , 2.109 0.348S , 2.217 0.357S , 2.285 0.000 , 2.285
Long : 16.164F
0.000 , 1.821 0.174S , 1.926 0.312S , 2.047 0.391S , 2.185 0.406S , 2.285 0.000 , 2.285
Long : 16.130F
0.000 , 1.760 0.174S , 1.866 0.279S , 1.943 0.367S , 2.037 0.425S , 2.136 0.454S , 2.260 0.456S , 2.285 0.000 , 2.285
Long : 16.062F
0.000 , 1.637 0.213S , 1.769 0.317S , 1.844 0.449S , 1.980 0.524S , 2.117 0.551S , 2.239 0.554S , 2.285 0.000 , 2.285
Long : 15.994F
0.000 , 1.520 0.296S , 1.708 0.411S , 1.803 0.511S , 1.912 0.594S , 2.054 0.633S , 2.194 0.640S , 2.285 0.000 , 2.285
Long : 15.925F
0.000 , 1.412 0.335S , 1.627 0.465S , 1.735 0.578S , 1.859 0.661S , 2.003 0.706S , 2.141 0.721S , 2.285 0.000 , 2.285
Long : 15.857F
0.000 , 1.304 0.334S , 1.519 0.485S , 1.635 0.616S , 1.769 0.693S , 1.885 0.762S , 2.033 0.789S , 2.145 0.801S , 2.285 0.000 , 2.285
Long : 15.584F
0.000 , 0.924 0.468S , 1.233 0.597S , 1.328 0.773S , 1.494 0.874S , 1.620 0.966S , 1.789 1.024S , 1.937 1.058S , 2.092 1.071S , 2.253 1.071S , 2.285 0.000 , 2.285
Long : 15.310F
0.000 , 0.628 0.603S , 1.023 0.729S , 1.115 0.874S , 1.242 1.018S , 1.406 1.083S , 1.504 1.154S , 1.642 1.225S , 1.824 1.262S , 1.975 1.281S , 2.129 1.287S , 2.285 0.000 , 2.285
Long : 15.037F
0.000 , 0.409 0.621S , 0.800 0.805S , 0.923 0.946S , 1.032 1.089S , 1.172 1.215S , 1.337 1.288S , 1.467 1.360S , 1.634 1.413S , 1.801 1.441S , 1.931 1.457S , 2.062 1.467S , 2.240 1.467S , 2.285 0.000 , 2.285
Long : 14.763F
0.000 , 0.251 0.776S , 0.712 0.999S , 0.860 1.131S , 0.968 1.234S , 1.074 1.327S , 1.189 1.369S , 1.251 1.475S , 1.474 1.541S , 1.657 1.578S , 1.800 1.607S , 1.990 1.621S , 2.186 1.623S , 2.285 0.000 , 2.285
Long : 14.490F
0.000 , 0.147 0.911S , 0.652 1.111S , 0.777 1.314S , 0.953 1.429S , 1.087 1.491S , 1.175 1.565S , 1.312 1.627S , 1.461 1.676S , 1.609 1.723S , 1.814 1.753S , 2.074 1.760S , 2.285 0.000 , 2.285
Long : 14.217F
0.000 , 0.079 0.952S , 0.565 1.192S , 0.699 1.304S , 0.779 1.388S , 0.851 1.501S , 0.973

1.602S , 1.109 1.658S , 1.207 1.724S , 1.359 1.778S , 1.517 1.819S , 1.678 1.848S , 1.842 1.870S , 2.062 1.877S , 2.285 0.000 , 2.285
Long : 13.670F
0.000 , 0.017 0.017S , 0.025 1.304S , 0.580 1.407S , 0.637 1.506S , 0.705 1.596S , 0.782 1.679S , 0.869 1.754S , 0.963 1.819S , 1.066 1.870S , 1.171 1.915S , 1.284 1.967S , 1.455 2.006S , 1.630 2.040S , 1.866 2.060S , 2.223 2.060S , 2.285 0.000 , 2.285
Long : 13.123F
0.000 , 0.001 1.418S , 0.507 1.532S , 0.559 1.641S , 0.623 1.740S , 0.699 1.831S , 0.787 1.910S , 0.887 1.976S , 0.995 2.026S , 1.107 2.069S , 1.228 2.118S , 1.409 2.153S , 1.594 2.191S , 1.968 2.200S , 2.285 0.000 , 2.285
Long : 12.576F
0.000 , 0.000 1.514S , 0.450 1.637S , 0.496 1.754S , 0.555 1.863S , 0.628 1.959S , 0.716 2.040S , 0.820 2.105S , 0.935 2.153S , 1.053 2.192S , 1.180 2.235S , 1.371 2.279S , 1.695 2.304S , 2.285 0.000 , 2.285
Long : 12.030F
0.000 , 0.000 1.592S , 0.402 1.722S , 0.442 1.847S , 0.496 1.963S , 0.563 2.017S , 0.604 2.066S , 0.651 2.109S , 0.703 2.180S , 0.820 2.231S , 0.945 2.268S , 1.072 2.298S , 1.206 2.344S , 1.539 2.374S , 2.081 2.375S , 2.285 0.000 , 2.285
Long : 10.936F
0.000 , 0.000 1.703S , 0.327 1.913S , 0.378 2.047S , 0.424 2.112S , 0.454 2.172S , 0.491 2.225S , 0.539 2.269S , 0.596 2.303S , 0.659 2.330S , 0.725 2.368S , 0.862 2.392S , 0.999 2.431S , 1.426 2.451S , 2.285 0.000 , 2.285
Long : 9.842F
0.000 , 0.000 1.833S , 0.294 2.051S , 0.337 2.123S , 0.355 2.193S , 0.379 2.258S , 0.413 2.314S , 0.461 2.356S , 0.522 2.386S , 0.590 2.407S , 0.661 2.431S , 0.807 2.459S , 1.692 2.461S , 2.285 0.000 , 2.285
Long : 8.749F
0.000 , 0.000 2.080S , 0.311 2.154S , 0.326 2.226S , 0.347 2.294S , 0.379 2.351S , 0.427 2.393S , 0.489 2.421S , 0.560 2.438S , 0.634 2.455S , 0.784 2.461S , 2.285 0.000 , 2.285
Long : 7.655F
0.000 , 0.000 2.005S , 0.300 2.152S , 0.328 2.225S , 0.348 2.293S , 0.380 2.350S , 0.428 2.392S , 0.490 2.420S , 0.561 2.437S , 0.635 2.454S , 0.785 2.461S , 2.285 0.000 , 2.285
Long : 6.562F
0.000 , 0.000 2.003S , 0.299 2.150S , 0.328 2.222S , 0.349 2.290S , 0.382 2.346S , 0.432 2.387S , 0.494 2.415S , 0.564 2.433S , 0.636 2.451S , 0.785 2.461S , 2.285 0.000 , 2.285
Long : 5.468F
0.000 , 0.000 1.857S , 0.274 2.079S , 0.310 2.225S , 0.347 2.292S , 0.380 2.348S , 0.430 2.389S , 0.492 2.417S , 0.562 2.435S , 0.635 2.452S , 0.784 2.461S , 2.285 0.000 , 2.285
Long : 4.375F
0.000 , 0.000 0.150S , 0.023 2.068S , 0.326 2.213S , 0.362 2.281S , 0.392 2.341S , 0.437 2.385S , 0.498 2.414S , 0.569 2.432S , 0.644 2.450S , 0.793 2.461S , 2.285 0.000 , 2.285
Long : 3.281F
0.000 , 0.014 1.996S , 0.420 2.136S , 0.456 2.205S , 0.481 2.269S , 0.516 2.322S , 0.564 2.363S , 0.625 2.393S , 0.692 2.414S , 0.762 2.438S , 0.902 2.451S , 1.049 2.461S , 2.285 0.000 , 2.285
Long : 2.734F
0.000 , 0.065 0.015S , 0.069 2.047S , 0.574 2.129S , 0.601 2.193S , 0.630 2.252S , 0.666 2.304S , 0.713 2.346S , 0.769 2.377S , 0.832 2.415S , 0.965 2.440S , 1.166 2.461S , 2.285 0.000 , 2.285
Long : 2.188F
0.000 , 0.191 2.025S , 0.768 2.152S , 0.815 2.239S , 0.869 2.304S , 0.943 2.362S , 1.057 2.392S , 1.153 2.421S , 1.285 2.443S , 1.481 2.461S , 2.285 0.000 , 2.285
Long : 1.641F
0.000 , 0.606 0.037S , 0.615 1.995S , 1.084 2.111S , 1.126 2.231S , 1.199 2.327S , 1.288 2.378S , 1.376 2.415S , 1.488 2.437S , 1.609 2.455S , 1.854 2.461S , 2.285 0.000 , 2.285
Long : 1.094F

0.000 , 1.009 1.901S , 1.322 2.127S , 1.357 2.276S , 1.406 2.336S , 1.458 2.368S , 1.502 2.394S , 1.553 2.427S , 1.661 2.444S , 1.773 2.456S , 1.940 2.461S , 2.285 0.000 , 2.285

Long : 0.547F

0.000 , 1.101 1.736S , 1.373 2.144S , 1.422 2.203S , 1.436 2.258S , 1.457 2.307S , 1.489 2.345S , 1.526 2.377S , 1.572 2.419S , 1.675 2.441S , 1.784 2.455S , 1.947 2.461S , 2.285 0.000 , 2.285

Long : 0.000

0.000 , 1.137 2.069S , 1.449 2.179S , 1.473 2.283S , 1.514 2.325S , 1.545 2.362S , 1.586 2.391S , 1.632 2.427S , 1.736 2.446S , 1.845 2.457S , 2.008 2.461S , 2.285 0.000 , 2.285

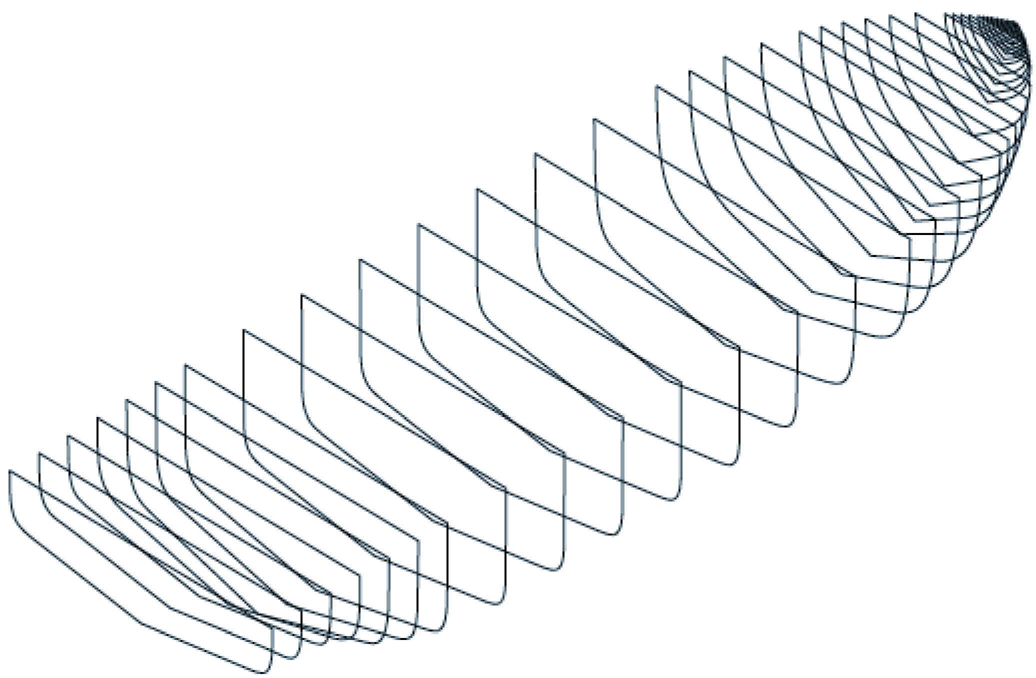


Figure A. 2. Monohull model maker arrangement

Catamaran-SWATH

Part Name: Catamaran-SWATH
Component Name: hull
Offsets for half demi-hull excluding the struts

Long : 16.000F
3.500S , 0.385 3.501S , 0.385 3.501S , 2.240 3.499S , 2.240 3.499S , 0.385 3.500S , 2.240
Long : 15.986F
3.500S , 0.343 3.503S , 0.360 3.505S , 0.376 3.511S , 1.164 3.516S , 1.617 3.516S , 1.739 3.512S , 2.240 3.488S , 2.240 3.485S , 1.739 3.485S , 1.617 3.487S , 1.391 3.494S , 0.382 3.496S , 0.360 3.499S , 0.346 3.500S , 0.343
Long : 15.948F
3.500S , 0.301 3.507S , 0.335 3.511S , 0.366 3.523S , 1.164 3.531S , 1.617 3.531S , 1.739 3.523S , 2.240 3.478S , 2.240 3.471S , 1.739 3.471S , 1.617 3.475S , 1.391 3.489S , 0.380 3.493S , 0.335 3.498S , 0.308 3.500S , 0.301
Long : 15.890F
3.500S , 0.217 3.506S , 0.230 3.515S , 0.285 3.522S , 0.348 3.546S , 1.164 3.561S , 1.617 3.561S , 1.739 3.546S , 2.240 3.457S , 2.240 3.442S , 1.739 3.442S , 1.617 3.450S , 1.391 3.479S , 0.375 3.487S , 0.285 3.498S , 0.230 3.500S , 0.217
Long : 15.754F
3.500S , 0.050 3.510S , 0.076 3.531S , 0.186 3.545S , 0.310 3.593S , 1.164 3.621S , 1.617 3.621S , 1.739 3.592S , 2.240 3.414S , 2.240 3.385S , 1.739 3.385S , 1.617 3.401S , 1.391 3.458S , 0.364 3.475S , 0.186 3.496S , 0.076 3.500S , 0.050
Long : 15.522F
3.500S , 0.043 3.524S , 0.096 3.556S , 0.190 3.569S , 0.236 3.583S , 0.301 3.593S , 0.363 3.721S , 1.503 3.737S , 1.617 3.737S , 1.739 3.671S , 2.240 3.335S , 2.240 3.269S , 1.739 3.269S , 1.617 3.299S , 1.389 3.399S , 0.482 3.422S , 0.309 3.437S , 0.236 3.450S , 0.190 3.465S , 0.143 3.482S , 0.096 3.500S , 0.043
Long : 15.291F
3.500S , 0.032 3.515S , 0.057 3.543S , 0.107 3.575S , 0.183 3.584S , 0.201 3.628S , 0.316 3.635S , 0.340 3.806S , 1.387 3.849S , 1.617 3.849S , 1.739 3.740S , 2.240 3.267S , 2.240 3.157S , 1.739 3.157S , 1.617 3.200S , 1.387 3.371S , 0.340 3.378S , 0.316 3.421S , 0.201 3.431S , 0.183 3.463S , 0.107 3.491S , 0.057 3.500S , 0.032
Long : 15.059F
3.500S , 0.022 3.571S , 0.128 3.630S , 0.232 3.681S , 0.342 3.696S , 0.402 3.900S , 1.385 3.954S , 1.617 3.953S , 1.739 3.847S , 2.073 3.798S , 2.240 3.208S , 2.240 3.053S , 1.739 3.051S , 1.617 3.106S , 1.385 3.282S , 0.550 3.310S , 0.401 3.324S , 0.342 3.376S , 0.232 3.435S , 0.128 3.500S , 0.022
Long : 14.827F
3.500S , 0.016 3.585S , 0.120 3.659S , 0.225 3.725S , 0.331 3.743S , 0.391 3.782S , 0.565 3.988S , 1.383 4.052S , 1.617 4.049S , 1.739 3.944S , 1.990 3.847S , 2.240 3.160S , 2.240 2.957S , 1.739 2.954S , 1.617 3.196S , 0.680 3.263S , 0.391 3.281S , 0.331 3.347S , 0.225 3.421S , 0.120 3.500S , 0.016
Long : 14.595F
3.500S , 0.011 3.599S , 0.113 3.687S , 0.216 3.767S , 0.321 3.788S , 0.380 3.833S , 0.557 4.104S , 1.499 4.140S , 1.617 4.135S , 1.739 4.118S , 1.768 4.107S , 1.795 4.091S , 1.823 3.887S , 2.240 3.120S , 2.240 3.040S , 2.073 2.900S , 1.795 2.887S , 1.768 2.871S , 1.739 2.866S , 1.617 3.141S , 0.672 3.218S , 0.380 3.239S , 0.321 3.319S , 0.216 3.407S , 0.113 3.500S , 0.011
Long : 14.364F
3.500S , 0.000 3.604S , 0.099 3.808S , 0.311 3.832S , 0.370 3.882S , 0.548 4.178S , 1.498 4.218S , 1.617 4.212S , 1.739 4.156S , 1.831 3.919S , 2.240 3.087S , 2.240 2.945S , 1.990 2.794S , 1.739 2.789S , 1.617 3.089S , 0.665 3.174S , 0.370 3.198S , 0.311 3.402S , 0.099 3.500S , 0.000
Long : 14.132F

3.500S , 0.000 3.625S , 0.104 3.848S , 0.301 3.874S , 0.360 3.928S , 0.539 4.242S , 1.497 4.284S , 1.617 4.277S , 1.739 3.945S , 2.240 3.061S , 2.240 2.843S , 1.906 2.729S , 1.739 2.722S , 1.617 3.042S , 0.657 3.132S , 0.360 3.158S , 0.301 3.266S , 0.201 3.433S , 0.062 3.500S , 0.000

Long : 13.900F

3.500S , 0.000 3.637S , 0.100 3.887S , 0.290 3.914S , 0.349 3.970S , 0.531 4.339S , 1.617 4.332S , 1.739 4.289S , 1.795 3.966S , 2.240 3.040S , 2.240 2.675S , 1.739 2.667S , 1.617 2.997S , 0.650 3.092S , 0.349 3.119S , 0.290 3.241S , 0.194 3.463S , 0.034 3.500S , 0.000

Long : 13.669F

3.500S , 0.000 3.649S , 0.096 3.924S , 0.280 3.952S , 0.339 4.049S , 0.643 4.385S , 1.617 4.377S , 1.739 3.983S , 2.240 3.023S , 2.240 2.629S , 1.739 2.620S , 1.617 2.957S , 0.643 3.054S , 0.339 3.082S , 0.280 3.357S , 0.096 3.500S , 0.000

Long : 13.437F

3.500S , 0.000 3.661S , 0.093 3.960S , 0.270 3.976S , 0.298 3.989S , 0.329 4.086S , 0.635 4.424S , 1.617 4.415S , 1.739 3.996S , 2.240 3.010S , 2.240 2.591S , 1.739 2.583S , 1.617 2.920S , 0.635 3.018S , 0.329 3.031S , 0.298 3.046S , 0.270 3.345S , 0.093 3.500S , 0.000

Long : 13.205F

3.500S , 0.000 3.672S , 0.089 3.994S , 0.260 4.010S , 0.288 4.023S , 0.319 4.120S , 0.628 4.455S , 1.617 4.446S , 1.739 4.006S , 2.240 3.000S , 2.240 2.560S , 1.739 2.551S , 1.617 2.886S , 0.628 2.983S , 0.319 2.996S , 0.288 3.012S , 0.260 3.334S , 0.089 3.500S , 0.000

Long : 12.974F

3.500S , 0.000 3.683S , 0.086 4.027S , 0.251 4.043S , 0.279 4.056S , 0.309 4.151S , 0.621 4.479S , 1.617 4.470S , 1.739 4.014S , 2.240 2.993S , 2.240 2.536S , 1.739 2.527S , 1.617 2.855S , 0.621 2.950S , 0.309 2.963S , 0.279 2.979S , 0.251 3.324S , 0.086 3.500S , 0.000

Long : 12.742F

3.500S , 0.000 3.693S , 0.082 4.059S , 0.241 4.075S , 0.269 4.088S , 0.300 4.180S , 0.614 4.499S , 1.617 4.490S , 1.739 4.020S , 2.240 2.986S , 2.240 2.516S , 1.739 2.507S , 1.617 2.826S , 0.614 2.918S , 0.300 2.931S , 0.269 2.947S , 0.241 3.313S , 0.082 3.500S , 0.000

Long : 12.511F

3.500S , 0.000 3.703S , 0.079 4.090S , 0.232 4.106S , 0.260 4.118S , 0.290 4.207S , 0.607 4.514S , 1.617 4.505S , 1.739 4.023S , 2.240 2.983S , 2.240 2.501S , 1.739 2.492S , 1.617 2.799S , 0.607 2.888S , 0.290 2.900S , 0.260 2.916S , 0.232 3.303S , 0.079 3.500S , 0.000

Long : 12.279F

3.500S , 0.000 3.712S , 0.076 4.119S , 0.223 4.135S , 0.251 4.147S , 0.281 4.232S , 0.601 4.525S , 1.617 4.517S , 1.739 4.025S , 2.240 2.980S , 2.240 2.489S , 1.739 2.481S , 1.617 2.774S , 0.601 2.858S , 0.281 2.871S , 0.251 2.887S , 0.223 3.294S , 0.076 3.500S , 0.000

Long : 12.047F

3.500S , 0.000 3.722S , 0.073 4.148S , 0.215 4.164S , 0.242 4.176S , 0.273 4.255S , 0.595 4.533S , 1.617 4.527S , 1.739 4.027S , 2.240 2.979S , 2.240 2.479S , 1.739 2.473S , 1.617 2.751S , 0.595 2.830S , 0.273 2.843S , 0.242 2.858S , 0.215 3.284S , 0.073 3.500S , 0.000

Long : 11.816F

3.500S , 0.000 4.175S , 0.207 4.191S , 0.234 4.203S , 0.267 4.277S , 0.589 4.539S , 1.617 4.534S , 1.739 4.027S , 2.240 2.979S , 2.240 2.472S , 1.739 2.467S , 1.617 2.729S , 0.589 2.803S , 0.265 2.815S , 0.234 2.830S , 0.207 3.275S , 0.070 3.500S , 0.000

Long : 11.584F

3.500S , 0.000 4.202S , 0.199 4.217S , 0.226 4.228S , 0.257 4.297S , 0.584 4.542S , 1.617 4.538S , 1.739 4.028S , 2.240 2.979S , 2.240 2.468S , 1.739 2.464S , 1.617 2.709S , 0.584 2.777S , 0.257 2.789S , 0.226 2.804S , 0.199 3.267S , 0.067 3.500S , 0.000

Long : 11.352F

3.500S , 0.000 4.228S , 0.192 4.243S , 0.219 4.253S , 0.250 4.317S , 0.579 4.544S , 1.617 4.542S , 1.739 4.028S , 2.240 2.978S , 2.240 2.464S , 1.739 2.462S , 1.617 2.690S , 0.579 2.753S , 0.250 2.764S , 0.219 2.778S , 0.192 3.454S , 0.015 3.500S , 0.000

Long : 11.120F

3.500S , 0.000 4.252S , 0.185 4.266S , 0.213 4.277S , 0.244 4.334S , 0.574 4.545S , 1.617 4.544S , 1.739 4.028S , 2.240 2.978S , 2.240 2.462S , 1.739 2.461S , 1.617 2.672S , 0.574 2.729S , 0.244 2.740S , 0.213 2.754S , 0.185 3.470S , 0.010 3.500S , 0.000

Long : 10.889F
3.500S , 0.000 4.275S , 0.179 4.289S , 0.207 4.299S , 0.238 4.351S , 0.570 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.655S , 0.570
2.707S , 0.238 2.717S , 0.207 2.731S , 0.179 3.243S , 0.061 3.500S , 0.000
Long : 10.657F
3.500S , 0.000 4.296S , 0.174 4.310S , 0.201 4.319S , 0.232 4.366S , 0.565 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.460S , 1.739 2.461S , 1.617 2.640S , 0.565
2.687S , 0.232 2.696S , 0.201 2.710S , 0.174 3.236S , 0.059 3.500S , 0.000
Long : 10.425F
3.500S , 0.000 4.316S , 0.169 4.329S , 0.196 4.338S , 0.227 4.381S , 0.562 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.460S , 1.739 2.461S , 1.617 2.626S , 0.562
2.668S , 0.227 2.677S , 0.196 2.690S , 0.169 3.230S , 0.057 3.500S , 0.000
Long : 10.194F
3.500S , 0.000 4.335S , 0.165 4.347S , 0.191 4.355S , 0.223 4.393S , 0.559 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.460S , 1.739 2.461S , 1.617 2.613S , 0.559
2.651S , 0.223 2.659S , 0.191 2.672S , 0.164 3.224S , 0.055 3.500S , 0.000
Long : 9.962F
3.500S , 0.000 4.350S , 0.161 4.362S , 0.188 4.371S , 0.219 4.405S , 0.556 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.601S , 0.556
2.636S , 0.219 2.644S , 0.188 2.656S , 0.161 3.219S , 0.054 3.500S , 0.000
Long : 9.730F
3.500S , 0.000 4.364S , 0.157 4.376S , 0.184 4.384S , 0.216 4.415S , 0.554 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.591S , 0.554
2.622S , 0.216 2.630S , 0.184 2.642S , 0.157 3.215S , 0.053 3.500S , 0.000
Long : 9.499F
3.500S , 0.000 4.376S , 0.155 4.388S , 0.182 4.396S , 0.213 4.423S , 0.552 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.583S , 0.552
2.611S , 0.213 2.618S , 0.182 2.630S , 0.155 3.211S , 0.052 3.500S , 0.000
Long : 9.267F
3.500S , 0.000 4.386S , 0.152 4.398S , 0.180 4.405S , 0.211 4.431S , 0.550 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.576S , 0.550
2.601S , 0.211 2.608S , 0.180 2.620S , 0.152 3.208S , 0.052 3.500S , 0.000
Long : 9.035F
3.500S , 0.000 4.395S , 0.151 4.406S , 0.178 4.414S , 0.209 4.437S , 0.549 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.569S , 0.549
2.592S , 0.209 2.599S , 0.178 2.611S , 0.151 3.052S , 0.077 3.500S , 0.000
Long : 8.804F
3.500S , 0.000 4.402S , 0.150 4.414S , 0.177 4.421S , 0.208 4.442S , 0.548 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.564S , 0.548
2.585S , 0.208 2.592S , 0.177 2.604S , 0.150 3.203S , 0.051 3.500S , 0.000
Long : 8.572F
3.500S , 0.000 4.408S , 0.149 4.419S , 0.176 4.426S , 0.208 4.446S , 0.548 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.560S , 0.548
2.580S , 0.208 2.587S , 0.176 2.598S , 0.149 3.201S , 0.051 3.500S , 0.000
Long : 8.340F
3.500S , 0.000 4.413S , 0.148 4.424S , 0.176 4.431S , 0.207 4.449S , 0.548 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.557S , 0.548
2.575S , 0.207 2.582S , 0.176 2.594S , 0.148 3.199S , 0.051 3.500S , 0.000
Long : 8.109F
3.500S , 0.000 4.416S , 0.148 4.427S , 0.176 4.434S , 0.209 4.452S , 0.548 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.554S , 0.548
2.572S , 0.207 2.579S , 0.176 2.590S , 0.148 3.500S , 0.000
Long : 7.877F
3.500S , 0.000 4.419S , 0.149 4.430S , 0.176 4.436S , 0.207 4.453S , 0.548 4.545S , 1.617
4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.552S , 0.548
2.570S , 0.207 2.576S , 0.176 2.587S , 0.149 3.500S , 0.000

Long : 7.645F
3.500S , 0.000 4.420S , 0.149 4.431S , 0.176 4.438S , 0.208 4.455S , 0.548 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.551S , 0.548 2.568S , 0.208 2.575S , 0.176 2.586S , 0.149 3.500S , 0.000
Long : 7.414F
3.500S , 0.000 4.421S , 0.150 4.432S , 0.177 4.439S , 0.209 4.455S , 0.549 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.551S , 0.549 2.567S , 0.209 2.574S , 0.177 2.585S , 0.150 3.500S , 0.000
Long : 7.182F
3.500S , 0.000 4.421S , 0.151 4.432S , 0.178 4.439S , 0.210 4.455S , 0.550 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.551S , 0.550 2.567S , 0.210 2.573S , 0.178 2.585S , 0.151 3.500S , 0.000
Long : 6.950F
3.500S , 0.000 4.421S , 0.152 4.432S , 0.180 4.439S , 0.211 4.455S , 0.551 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.551S , 0.551 2.567S , 0.211 2.574S , 0.180 2.585S , 0.152 3.500S , 0.000
Long : 6.719F
3.500S , 0.000 4.421S , 0.154 4.432S , 0.181 4.438S , 0.212 4.455S , 0.552 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.551S , 0.552 2.568S , 0.212 2.574S , 0.181 2.585S , 0.154 3.500S , 0.000
Long : 6.487F
3.500S , 0.000 4.420S , 0.156 4.431S , 0.183 4.438S , 0.214 4.443S , 0.286 4.454S , 0.553 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.552S , 0.553 2.568S , 0.214 2.575S , 0.183 2.586S , 0.156 3.500S , 0.000
Long : 6.255F
3.500S , 0.000 4.419S , 0.158 4.431S , 0.184 4.437S , 0.216 4.454S , 0.554 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.552S , 0.554 2.569S , 0.216 2.576S , 0.184 2.587S , 0.158 3.500S , 0.000
Long : 6.024F
3.500S , 0.000 4.419S , 0.159 4.430S , 0.186 4.437S , 0.218 4.453S , 0.556 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.556 2.569S , 0.218 2.576S , 0.186 2.587S , 0.159 3.500S , 0.000
Long : 5.792F
3.500S , 0.000 4.418S , 0.162 4.429S , 0.189 4.436S , 0.220 4.453S , 0.557 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.557 2.570S , 0.220 2.576S , 0.189 2.588S , 0.162 3.500S , 0.000
Long : 5.560F
3.500S , 0.010 4.418S , 0.165 4.429S , 0.191 4.436S , 0.223 4.453S , 0.560 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.560 2.570S , 0.223 2.577S , 0.191 2.588S , 0.165 3.500S , 0.010
Long : 5.329F
3.500S , 0.010 4.418S , 0.169 4.429S , 0.195 4.436S , 0.228 4.453S , 0.563 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.563 2.570S , 0.226 2.577S , 0.195 2.588S , 0.169 3.500S , 0.010
Long : 5.097F
3.500S , 0.011 4.418S , 0.174 4.429S , 0.201 4.436S , 0.232 4.453S , 0.567 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.567 2.570S , 0.232 2.577S , 0.201 2.588S , 0.174 3.285S , 0.050 3.500S , 0.011
Long : 4.865F
3.500S , 0.018 4.418S , 0.182 4.429S , 0.209 4.436S , 0.240 4.453S , 0.573 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.573 2.570S , 0.240 2.577S , 0.209 2.588S , 0.182 3.363S , 0.043 3.500S , 0.018
Long : 4.634F
3.500S , 0.040 4.418S , 0.193 4.429S , 0.219 4.436S , 0.250 4.453S , 0.581 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.581 2.570S , 0.250 2.577S , 0.219 2.588S , 0.193 3.292S , 0.074 3.500S , 0.040

Long : 4.402F
3.500S , 0.068 4.418S , 0.208 4.429S , 0.233 4.436S , 0.264 4.453S , 0.592 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.592 2.570S , 0.264 2.577S , 0.233 2.588S , 0.208 3.198S , 0.114 3.500S , 0.068
Long : 4.170F
3.500S , 0.102 4.418S , 0.226 4.429S , 0.252 4.435S , 0.282 4.453S , 0.606 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.606 2.570S , 0.282 2.577S , 0.252 2.587S , 0.226 3.198S , 0.143 3.500S , 0.102
Long : 3.939F
3.500S , 0.139 4.418S , 0.250 4.429S , 0.275 4.435S , 0.305 4.453S , 0.624 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.624 2.571S , 0.305 2.577S , 0.275 2.587S , 0.250 3.198S , 0.176 3.500S , 0.139
Long : 3.707F
3.500S , 0.179 4.418S , 0.279 4.428S , 0.304 4.435S , 0.333 4.453S , 0.645 4.545S , 1.616 4.545S , 1.739 4.026S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.616 2.553S , 0.645 2.571S , 0.333 2.578S , 0.304 2.588S , 0.279 3.198S , 0.212 3.500S , 0.179
Long : 3.475F
3.500S , 0.221 4.418S , 0.313 4.428S , 0.337 4.434S , 0.365 4.453S , 0.670 4.545S , 1.616 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.616 2.553S , 0.670 2.572S , 0.365 2.578S , 0.337 2.588S , 0.313 3.198S , 0.251 3.500S , 0.221
Long : 3.244F
3.500S , 0.265 4.418S , 0.352 4.427S , 0.375 4.433S , 0.402 4.453S , 0.698 4.545S , 1.615 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.615 2.553S , 0.698 2.573S , 0.402 2.579S , 0.375 2.588S , 0.352 3.198S , 0.294 3.500S , 0.265
Long : 3.012F
3.500S , 0.310 4.418S , 0.395 4.427S , 0.417 4.432S , 0.443 4.438S , 0.508 4.453S , 0.729 4.545S , 1.613 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.613 2.554S , 0.729 2.574S , 0.443 2.580S , 0.417 2.588S , 0.395 3.500S , 0.310
Long : 2.780F
3.500S , 0.357 4.417S , 0.441 4.426S , 0.462 4.431S , 0.488 4.452S , 0.762 4.545S , 1.611 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.611 2.554S , 0.762 2.575S , 0.488 2.580S , 0.462 2.589S , 0.441 3.500S , 0.357
Long : 2.548F
3.500S , 0.405 4.417S , 0.490 4.425S , 0.510 4.431S , 0.534 4.452S , 0.798 4.545S , 1.611 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.611 2.554S , 0.798 2.575S , 0.534 2.580S , 0.510 2.589S , 0.490 3.500S , 0.405
Long : 2.317F
3.500S , 0.454 4.417S , 0.541 4.425S , 0.560 4.430S , 0.583 4.452S , 0.835 4.545S , 1.613 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.613 2.554S , 0.835 2.576S , 0.583 2.581S , 0.560 2.589S , 0.541 3.500S , 0.454
Long : 2.085F
3.500S , 0.504 4.417S , 0.593 4.425S , 0.611 4.430S , 0.634 4.452S , 0.874 4.545S , 1.615 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.615 2.554S , 0.874 2.576S , 0.634 2.581S , 0.611 2.589S , 0.593 3.500S , 0.504
Long : 1.853F
3.500S , 0.555 4.417S , 0.646 4.424S , 0.664 4.429S , 0.685 4.452S , 0.913 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.554S , 0.913 2.576S , 0.685 2.581S , 0.664 2.589S , 0.646 3.500S , 0.555
Long : 1.622F
3.500S , 0.607 4.417S , 0.701 4.424S , 0.717 4.429S , 0.737 4.442S , 0.868 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.978S , 2.240 2.461S , 1.739 2.461S , 1.617 2.554S , 0.952 2.577S , 0.737 2.582S , 0.717 2.588S , 0.701 3.500S , 0.607
Long : 1.390F
3.500S , 0.660 4.418S , 0.756 4.424S , 0.772 4.429S , 0.791 4.443S , 0.913 4.545S , 1.617 4.545S , 1.739 4.028S , 2.240 2.979S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 0.992 2.577S , 0.791 2.582S , 0.772 2.588S , 0.756 3.500S , 0.660

Long : 1.159F
3.500S , 0.713 4.418S , 0.813 4.424S , 0.828 4.429S , 0.845 4.443S , 0.960 4.545S , 1.617 4.545S , 1.739 4.027S , 2.240 2.979S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 1.033 2.577S , 0.845 2.582S , 0.828 2.588S , 0.813 3.500S , 0.713
Long : 0.927F
3.500S , 0.767 4.418S , 0.870 4.424S , 0.884 4.429S , 0.900 4.443S , 1.006 4.545S , 1.617 4.545S , 1.739 4.027S , 2.240 2.979S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 1.074 2.577S , 0.900 2.588S , 0.870 3.500S , 0.767
Long : 0.695F
3.500S , 0.822 4.419S , 0.928 4.429S , 0.956 4.443S , 1.053 4.545S , 1.617 4.545S , 1.739 4.026S , 2.240 2.979S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 1.116 2.577S , 0.956 2.587S , 0.928 3.500S , 0.822
Long : 0.464F
3.500S , 0.877 4.419S , 0.987 4.428S , 1.012 4.545S , 1.617 4.545S , 1.739 4.026S , 2.240 2.980S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 1.159 2.578S , 1.012 2.587S , 0.987 3.198S , 0.914 3.500S , 0.877
Long : 0.232F
3.500S , 0.933 4.419S , 1.047 4.428S , 1.070 4.545S , 1.617 4.545S , 1.739 4.025S , 2.240 2.981S , 2.240 2.461S , 1.739 2.461S , 1.617 2.553S , 1.202 2.578S , 1.070 2.587S , 1.047 3.500S , 0.933
Long : 0.000
3.500S , 0.990 4.419S , 1.107 4.545S , 1.617 4.545S , 1.739 4.024S , 2.240 2.982S , 2.240 2.461S , 1.739 2.461S , 1.617 2.587S , 1.107 3.500S , 0.990

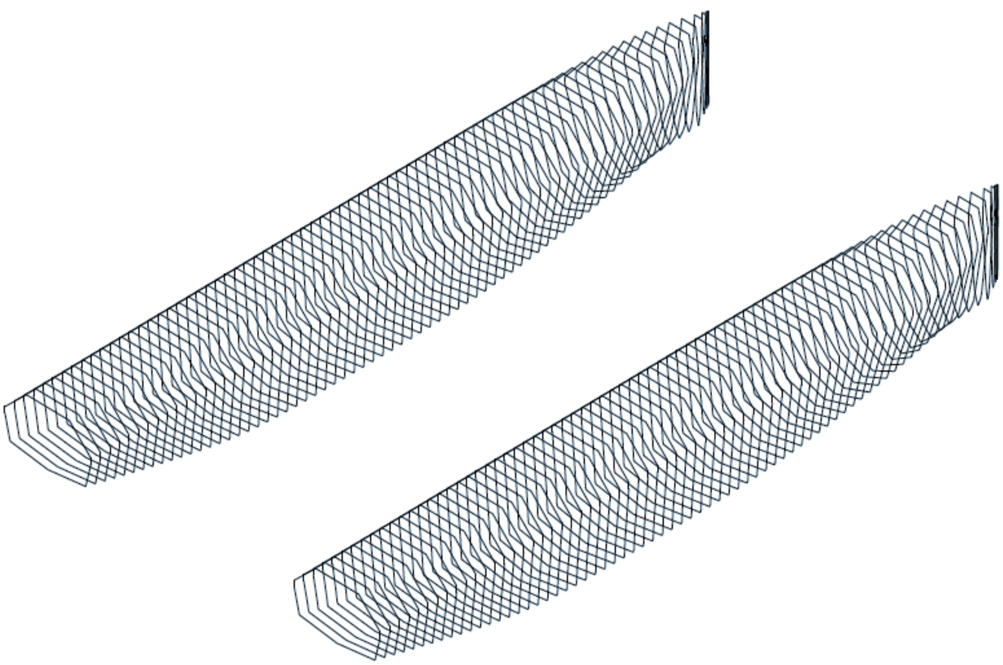


Figure A. 3. Catamaran-SWATH model maker arrangement excluding the struts.

ANNEX 3.

Catamaran-SWATH list of panels and stiffners and Light ship weight calculation

Table A. 2. List of panels and stiffeners for the catamaran-SWATH midship section

	ycg	zcg	Area A	Section Modulus Syy	Inertia Iyy	A*zcg	Distance from NA	A*d	A*d^2	Syy+A*D	I+A*d^2
item	[m]	[m]	m^2	m^3	m^4	m^3	[m]	m^3	m^4	m^3	m^4
					Panels						
1	3.503	0.101	0.093	0.009	1.164	0.009	-3.657	0.339	1.240	0.349	2.404
2	4.462	0.945	0.075	0.071	1.497	0.071	-2.814	0.212	0.595	0.283	2.092
3	3.878	1.151	0.104	0.120	1.561	0.119	-2.608	0.271	0.706	0.390	2.267
4	3.128	1.151	0.104	0.120	1.016	0.119	-2.608	0.271	0.706	0.390	1.722
5	2.544	0.945	0.075	0.071	0.487	0.071	-2.814	0.212	0.595	0.283	1.082
6	3.503	2.065	0.125	0.258	0.536	0.258	-1.694	0.211	0.358	0.469	0.894
7	0.000	4.870	0.613	2.987	6.642	2.987	1.111	0.681	0.757	3.668	7.399
8	4.028	5.629	0.082	0.462	1.332	0.462	1.870	0.154	0.287	0.616	1.619
9	0.000	6.475	0.500	3.236	4.162	3.236	2.716	1.358	3.688	4.594	7.850
10	0.500	5.500	0.095	0.523	0.024	0.523	1.741	0.165	0.288	0.688	0.312
11	-0.500	5.500	0.095	0.523	0.024	0.523	1.741	0.165	0.288	0.688	0.312
12	-4.028	5.629	0.082	0.462	1.332	0.462	1.870	0.154	0.287	0.616	1.619
13	0.000	4.870	0.613	2.987	6.642	2.987	1.111	0.681	0.757	3.668	7.399
14	-3.503	2.065	0.125	0.258	0.536	0.258	-1.694	0.211	0.358	0.469	0.894
15	-2.544	0.945	0.075	0.071	0.487	0.071	-2.814	0.212	0.595	0.283	1.082
16	-3.128	1.151	0.104	0.120	1.016	0.119	-2.608	0.271	0.706	0.390	1.722
17	-3.878	1.151	0.104	0.120	1.561	0.119	-2.608	0.271	0.706	0.390	2.267
18	-4.462	0.945	0.075	0.071	1.497	0.071	-2.814	0.212	0.595	0.283	2.092
19	-3.503	0.101	0.093	0.009	1.164	0.009	-3.657	0.339	1.240	0.349	2.404

item	ycg [m]	zcg [m]	Area A m^2	Section Modulus Syy m^3	Inertia Iyy m^4	A*zcg m^3	Distance from NA [m]	A*d m^3	A*d^2 m^4	Syy+A*D m^3	I+A*d^2 m^4
stiffener											
20	-4.316	0.688	0.002	0.000	0.000	0.002	-3.071	0.008	0.023	0.008	0.023
21	-3.951	1.078	0.001	0.000	0.000	0.001	-2.681	0.002	0.006	0.002	0.006
22	-4.380	1.432	0.002	0.000	0.000	0.004	-2.326	0.006	0.013	0.006	0.013
23	-4.240	1.891	0.002	0.000	0.000	0.004	-1.868	0.004	0.007	0.004	0.007
24	-3.503	2.141	0.001	0.000	0.000	0.002	-1.617	0.001	0.002	0.001	0.002
25	-2.766	1.891	0.002	0.000	0.000	0.004	-1.868	0.004	0.007	0.004	0.007
26	-2.626	1.432	0.002	0.000	0.000	0.004	-2.326	0.006	0.013	0.006	0.013
27	-3.055	1.078	0.001	0.000	0.000	0.001	-2.681	0.002	0.006	0.002	0.006
28	-2.690	0.688	0.002	0.000	0.000	0.002	-3.071	0.008	0.023	0.008	0.023
29	-4.847	6.034	0.004	0.023	0.089	0.023	2.275	0.009	0.020	0.032	0.109
30	-4.101	5.891	0.001	0.000	0.000	0.005	2.132	0.002	0.004	0.002	0.004
31	-2.971	6.350	0.004	0.023	0.089	0.024	2.591	0.010	0.026	0.033	0.115
32	-2.971	4.650	0.004	0.023	0.089	0.018	0.891	0.003	0.003	0.026	0.092
33	-1.471	6.350	0.004	0.023	0.089	0.024	2.591	0.010	0.026	0.033	0.115
34	-1.471	4.650	0.004	0.023	0.089	0.018	0.891	0.003	0.003	0.026	0.092
35	-0.573	5.891	0.001	0.000	0.000	0.005	2.132	0.002	0.004	0.002	0.004
36	-0.573	5.109	0.001	0.000	0.000	0.004	1.350	0.001	0.002	0.001	0.002
37	-4.143	0.328	0.024	0.008	0.197	0.008	-3.431	0.082	0.282	0.090	0.480
38	-2.863	0.328	0.024	0.008	0.197	0.008	-3.431	0.082	0.282	0.090	0.480
39	4.316	0.688	0.002	0.000	0.000	0.002	-3.071	0.008	0.023	0.008	0.023
40	3.951	1.078	0.001	0.000	0.000	0.001	-2.681	0.002	0.006	0.002	0.006
41	4.380	1.432	0.002	0.000	0.000	0.004	-2.326	0.006	0.013	0.006	0.013
42	4.240	1.891	0.002	0.000	0.000	0.004	-1.868	0.004	0.007	0.004	0.007
43	3.503	2.141	0.001	0.000	0.000	0.002	-1.617	0.001	0.002	0.001	0.002
44	2.766	1.891	0.002	0.000	0.000	0.004	-1.868	0.004	0.007	0.004	0.007
45	2.626	1.432	0.002	0.000	0.000	0.004	-2.326	0.006	0.013	0.006	0.013
46	3.055	1.078	0.001	0.000	0.000	0.001	-2.681	0.002	0.006	0.002	0.006
47	2.690	0.688	0.002	0.000	0.000	0.002	-3.071	0.008	0.023	0.008	0.023
48	4.847	6.034	0.004	0.023	0.089	0.023	2.275	0.009	0.020	0.032	0.109

49	4.101	5.891	0.001	0.000	0.000	0.005	2.132	0.002	0.004	0.002	0.004
50	2.971	6.350	0.004	0.023	0.089	0.024	2.591	0.010	0.026	0.033	0.115
51	2.971	4.650	0.004	0.023	0.089	0.018	0.891	0.003	0.003	0.026	0.092
52	1.471	6.350	0.004	0.023	0.089	0.024	2.591	0.010	0.026	0.033	0.115
53	1.471	4.650	0.004	0.023	0.089	0.018	0.891	0.003	0.003	0.026	0.092
54	0.573	5.891	0.001	0.000	0.000	0.005	2.132	0.002	0.004	0.002	0.004
55	0.573	5.109	0.001	0.000	0.000	0.004	1.350	0.001	0.002	0.001	0.002
56	4.143	0.328	0.024	0.008	0.197	0.008	-3.431	0.082	0.282	0.090	0.480
57	2.863	0.328	0.024	0.008	0.197	0.008	-3.431	0.082	0.282	0.090	0.480

		Weight	VCG	LCG	TCG
SFI 200 - Hull					PS+
SFI	Description	(t)	(m)	(m)	(m)
210 - 250 Hull structure					
	station				
	0	0.14	1.61	0.25	0.00
	1	0.47	3.67	0.75	0.00
	2	0.81	4.12	1.25	0.00
	3	0.84	4.23	1.75	0.00
	4	0.86	4.32	2.25	0.00
	5	0.89	4.25	2.75	0.00
	6	0.90	4.25	3.25	0.00
	7	0.91	4.25	3.75	0.00
	8	0.91	4.23	4.25	0.00
	9	0.91	4.24	4.75	0.00
	10	0.90	4.23	5.25	0.00
	11	0.88	4.23	5.75	0.00
	12	0.80	4.21	6.25	0.00
	13	0.80	4.20	6.75	0.00
	14	0.80	4.20	7.25	0.00
	15	0.80	4.19	7.75	0.00
	16	0.80	4.19	8.25	0.00
	17	0.80	4.20	8.75	0.00
	18	0.80	4.20	9.25	0.00
	19	0.80	4.20	9.75	0.00
	20	0.80	4.28	10.25	0.00
	21	0.88	4.24	10.75	0.00
	22	0.89	4.22	11.25	0.00
	23	0.90	4.22	11.75	0.00
	24	0.89	4.16	12.25	0.00
	25	0.89	4.09	12.75	0.00
	26	0.87	4.01	13.25	0.00
	27	0.85	3.92	13.75	0.00
	28	0.50	4.15	14.25	0.00
	29	0.44	4.23	14.75	0.00
	30	0.36	4.57	15.25	0.00
	31	0.25	6.25	15.75	0.00
250 - Deck houses & Superstructures					
	251 - Deck houses	1.48	6.58	7.01	0.00

	252 - Mast, pump. Fan & winch houses		0.20	9.58	8.57	0.00
	253 - Superstructures		1.46	7.82	9.15	0.00
260 - Hull outfitting						
	263 - foundations	engine	0.09	0.50	3.75	0.00
	264 - fender & wear bars	bow	0.16	0.50	15.50	0.00
	267 - Bulwark		0.22	7.00	7.88	0.00
	268 - Funnels		0.10	7.60	4.90	0.00
270 - Material protection external						
	274 - equipment on bulwark		0.01	0.50	7.88	0.00
	278 - external cathodic protection					
280 - material protection internal						
	281 - accommodation, deck houses store rooms		0.06	7.00	8.50	0.00
	282 - engine		0.02	1.00	3.75	0.00
	285 - ballast, sea water & stabil. tanks		0.03	2.00	7.50	0.00
	286 - fresh water tanks, misc. tanks		0.02	5.50	10.00	0.00
	288 - internal cathodic protection		0.05	1.50	7.50	0.00
SFI 200 - Hull	**total**		**28.18**	**4.54**	**7.84**	**0.00**

Table A. 3. SFI 200 cat-SWATH

				Weight	**VCG**	**LCG**	**TCG**
SFI 300 - Equipment for cargo							PS+
SFI		Description		(t)	(m)	(m)	(m)
300 - Hatches and ports							
	304 - Hatches, manhole covers						
		flush hatches	x10	0.24	6.50	6.25	0.00
330 - Deck cranes for cargo							
	331 - rotating cranes			1.63	7.00	3.50	0.00
SFI 300 - Equipment for cargo			**total**	**1.87**	**6.94**	**3.85**	**0.00**

Table A. 4. SFI 300 cat-SWATH

		Weight	VCG	LCG	TCG
SFI 400 - Ship equipment					PS+
SFI	Description	(t)	(m)	(m)	(m)
410 - Navigation & searching equipment					
411 - radar plants		0.15	9.58	8.57	0.00
412-419 - EL - navigation equipment		0.20	7.65	9.24	1.63
	sonar	1.02	0.25	14.00	1.63
	DGPS	0.30	9.58	8.57	0.00
420 - Communication equipment					
421-424 - radio/ communication equipment		0.10	7.65	9.24	1.63
425-427 - Tyfon m.m.		0.05	7.65	9.24	1.63
430 - Anchoring, Mooring & towing equipment					
431 - anchors w/ chains and equipment		0.15	13.00	4.85	0.00
432 - windlasses w/ chainstoppers, rolles		0.40	13.00	4.85	0.00
433- foundation anchor winch		0.05	13.00	4.85	0.00
435 - fixed mooring equipment		0.07	13.00	4.85	0.00
436- loose mooring equipment		0.07	13.00	4.85	0.00
437 - towing equipment		0.07	2.50	4.85	0.00
451 - Lifting & transport equip. for machinery					
451 - ER lifts		0.03	3.00	2.20	0.00
SFI 400 - Ship equipment	**total**	**2.66**	**6.41**	**9.51**	**0.84**

Table A. 5. SFI 400 cat-SWATH

		Weight	VCG	LCG	TCG
SFI 500 - Equipment for crew and passengers					PS+
SFI	Description	(t)	(m)	(m)	(m)
500- Lifesaving, protection & medical equipment					
503- lifesaving, safety & emergency equip.		0.20	7.00	7.35	0.00
504- medical, first aid & dental equipment, medicines		0.05	7.00	7.35	0.00
505- firefigthing apparatuses		0.05	8.00	7.00	0.00
510- Insulation, doors, panels					
511- insulation		1.50	7.50	7.25	0.00
512- 513 doors w/ coamings in accommodation					
	x15	0.78	5.75	5.85	0.00
514- external doors	x6	0.35	7.50	6.50	
515- side scutles & windos w/ equipment		0.10	7.50	7.50	0.00

520- Internal deck covering, ladders, steps, railing				
524- loose floor plates. steps & ladders in acc.	0.25	5.75	6.35	0.00
525- loose floor plates. steps & ladders in ER.	0.05	3.50	4.00	0.00
530- Internal deck covering, ladders, steps, railing				
533 - handrail, railing, rail gates	0.30	7.24	9.50	0.00
540- Funiture inventory, entertainment equipment				
542- office equip & special furniture	0.40	4.75	10.0	0.00
570- Ventilation, air-conditioning & heating systems				
571- Ventilation/ air conditioning systems for acc.	0.25	5.35	7.00	2.50
574- Ventilation/ air conditioning systems for ER	0.10	5.35	7.00	2.50
SFI 500 - Equipment for crew and passengers total	**4.38**	**6.58**	**7.25**	**0.20**

Table A. 6. SFI 500 catamaran-SWATH

		Weight	VCG	LCG	TCG
SFI 600 - Machinery main components					PS+
SFI	Description	(t)	(m)	(m)	(m)
600 - Diesel engines for propulsion					
	601 - diesel engines	3.90	1.20	3.74	0.00
630- propellers, transmissions, foils					
	635- special propeller plant	1.04	0.75	1.15	0.00
650- Motor aggregates dor main electric power					
	651- motor aggregates				
	Emergency GenSet	1.25	7.20	9.00	-1.18
Total					
SFI 600 - Machinery main components		**6.19**	**2.33**	**4.36**	**-0.24**

Table A. 7. SFI 600 catamaran-SWATH

		Weight	VCG	LCG	TCG
SFI 700 - Systems for machinery					PS+
SFI	Description	(t)	(m)	(m)	(m)
700- Fuel systems					
	701- fuel oil transfers & drain systems	0.12	4.84	9.99	0.00
	702- fuel oil purification plants	0.04	4.84	9.99	0.00
	703- fuel oil supply systems	0.35	4.84	9.99	0.00
710- Lube oil systems					
	711- luboil transfere & drain systems	0.14	5.30	9.50	0.00
720- Cooling systems					
	721- sea water cooling systems	0.15	4.50	0.25	0.00
740- Exhaust systems and air intakes					
	743- exhaust gas syst. Propulsion machin	0.35	2.20	4.60	0.00
	744- exhaust gas syst. motor aggregates	0.20	9.00	10.20	-1.89
790- automation systems for machinery					
	792- common automation equip. ER alarm	0.24	1.85	4.00	0.00
SFI 700 - Systems for machinery	**Total**	**1.59**	**4.35**	**6.97**	**-0.24**

Table A. 8. SFI 700 catamaran-SWATH

		Weight	VCG	LCG	TCG
SFI 800 - Ship common systems					PS+
SFI	Description	(t)	(m)	(m)	(m)
800- Ballast&Bilge systems, gutter pipes outside acc.					
	801- ballast systems	0.85	0.75	7.50	0.00
	803- bilge systems	0.15	0.30	7.50	0.00
	804- gutter pipes outside acc.	0.10	5.00	7.50	0.00
810- Fire&Lifeboat alarm, fire fighting & wash systems					
	811- fire detection, fire&lifboat alarm				
	813- fire/wash down syst., emergency fire pumps, sprinkler	0.35	5.35	8.00	0.00
	814- fire fighting systems for external fires				
	815- fire fighting systems w/ gas	0.30	5.35	8.00	0.00
820- Air&sounding system from tank to deck					
	821- Air and sounding	0.20	6.50	8.00	0.00
860- Electric power supply					

866- batteries&chargers	0.30	6.75	11.50	0.00
867- rectifiers & converters	0.20	7.00	7.00	1.65
868- Electric shore supply systems	0.10	7.00	11.50	0.00
870- Common electric distribution systems				
871- main switchboards	0.30	7.50	7.00	1.65
873- emergency switchboards	0.10	7.50	7.00	-1.85
875- distribution panels & boards	0.10	7.50	7.00	1.65
880- Electric cable instalation				
881- cable trays & instalation in ER	0.25	2.20	3.50	0.00
882- cable trays & instalation in acc.	0.25	7.75	8.50	0.00
890- Electric consumer systems				
891- electric lighting systems for ER	0.05	2.20	3.50	0.00
899- diverse	0.20	5.50	7.50	0.00
SFI 800 - Ship common systems Total	**3.80**	**4.61**	**7.69**	**0.21**

Table A. 9. SFI 800 catamaran-SWATH

Item:		**Weight**	**VCG**	**LCG**	**TCG**
					PS +
SFI no.		(t)	(m)	(m)	(m)
100	Ship general				
200	Hull	28.183	4.544	7.840	0.000
300	Equipment for cargo	1.870	6.936	3.853	0.000
400	Ship equipment	2.660	6.406	9.510	0.837
500	Equipment for crew and passangers	4.384	6.580	7.245	0.200
600	Machinery main components	6.185	2.332	4.360	-0.238
700	System for machinery main components	1.585	4.346	6.972	-0.239
800	Ship common systems	3.800	4.614	7.691	0.212
	Tolerance	3.893			
Total weight		**52.560**	**4.295**	**6.706**	**0.039**

Table A. 10. Total light weight catamaran-SWATH

ANNEX 4.

Drawings – general arrangements and Midship section

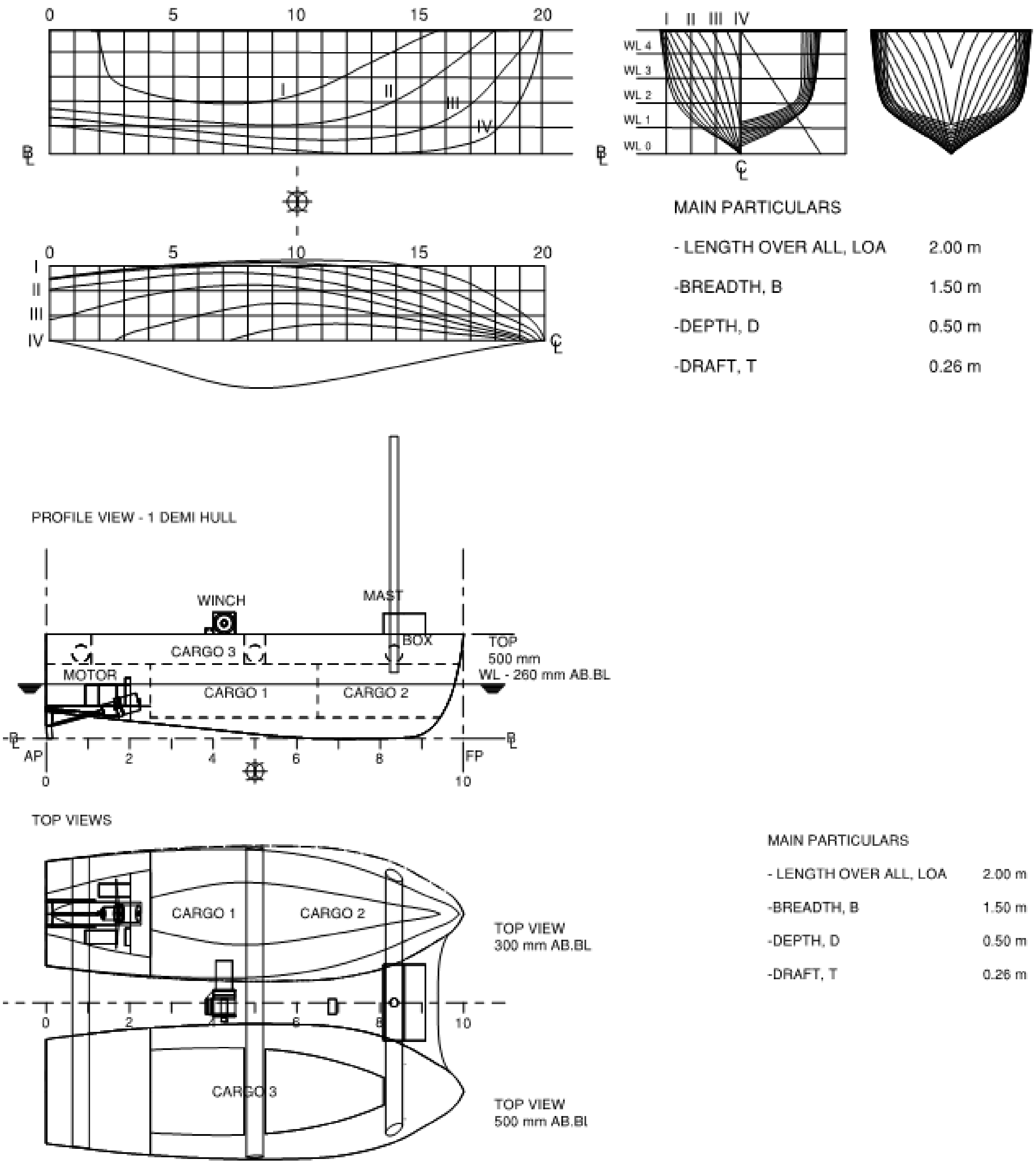


Figure A. 4. GA catamaran and linesplan

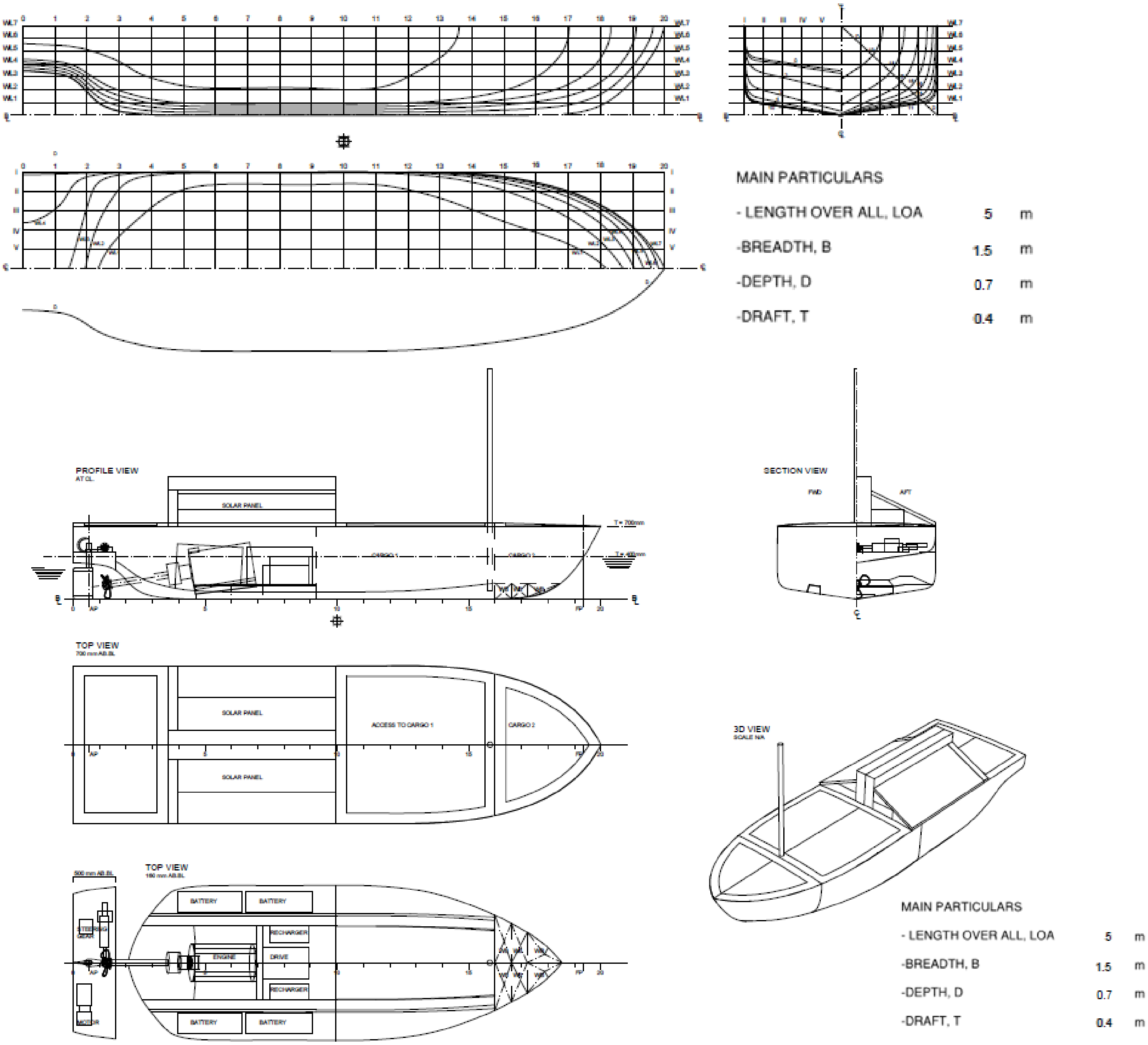


Figure A. 5. GA Monohull and linesplan

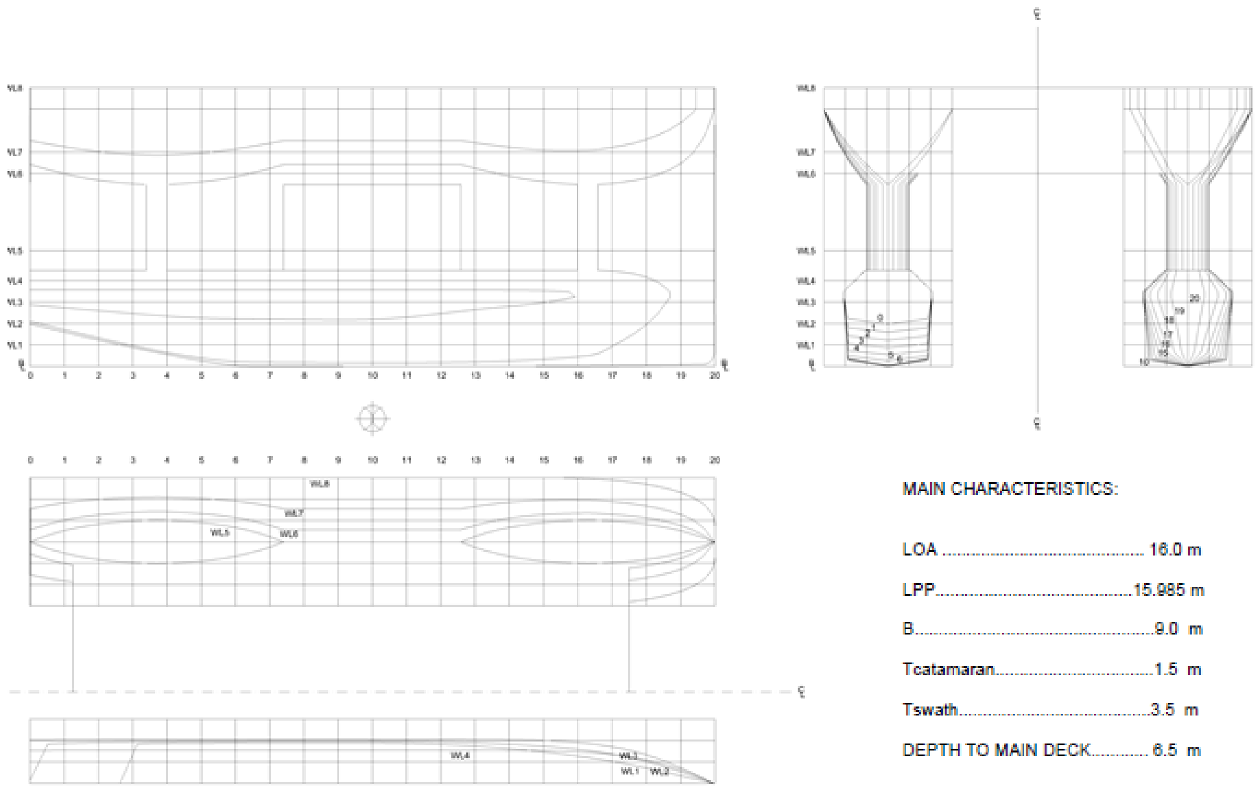


Figure A. 6.1 Catamaran-SWATH lines plan

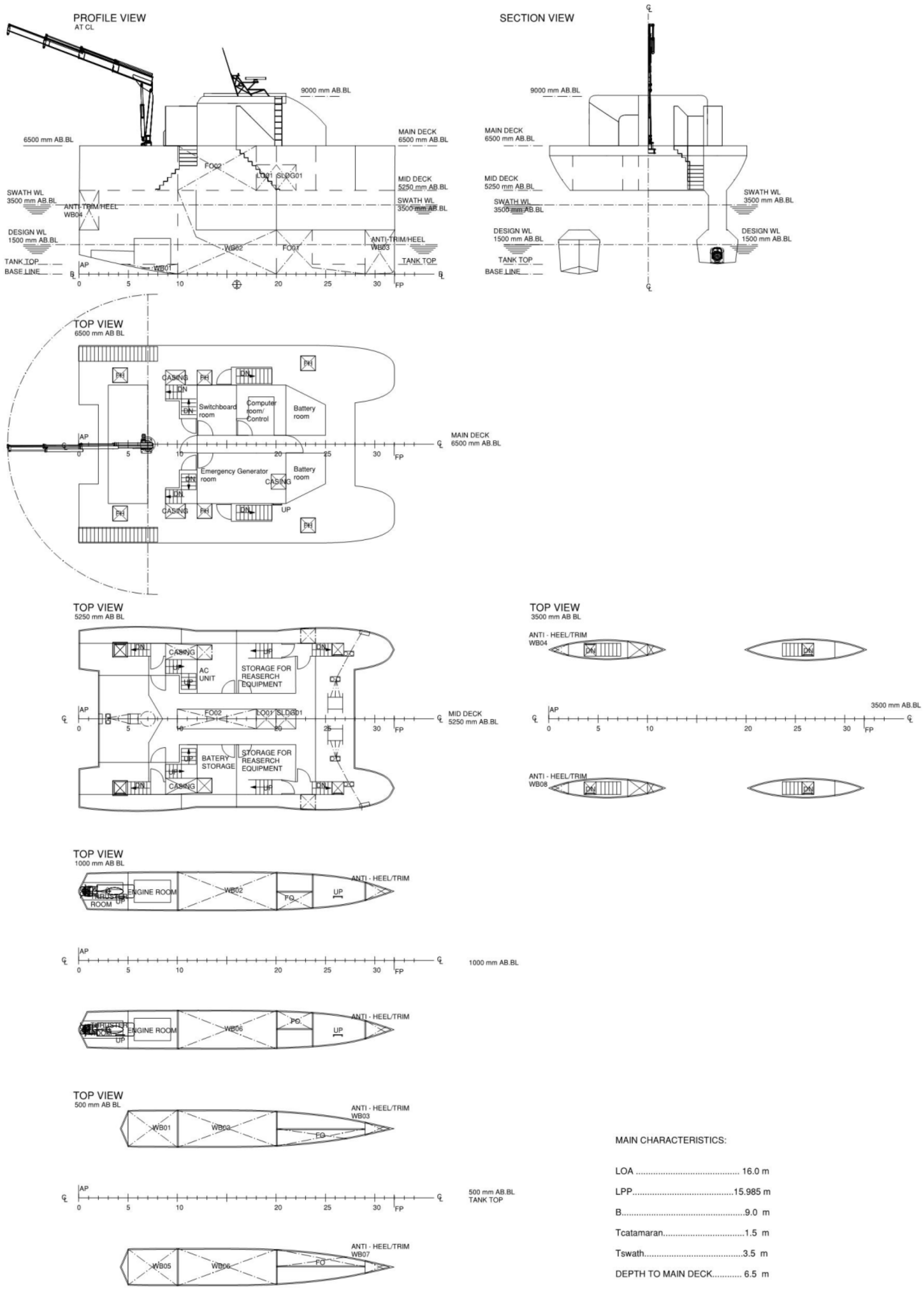
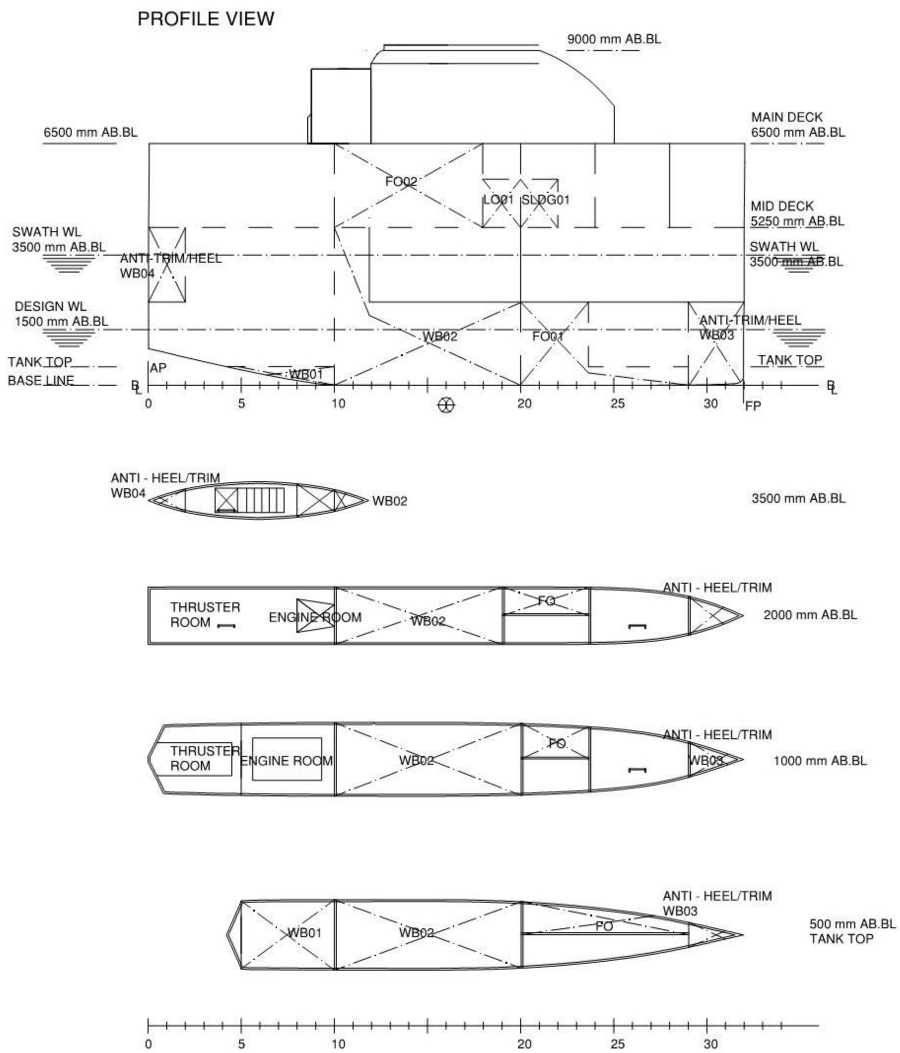


Figure A. 7.2 GA cat-SWATH



MAIN CHARACTERISTICS:

LOA .... 16.0 m

LPP...15.985 m

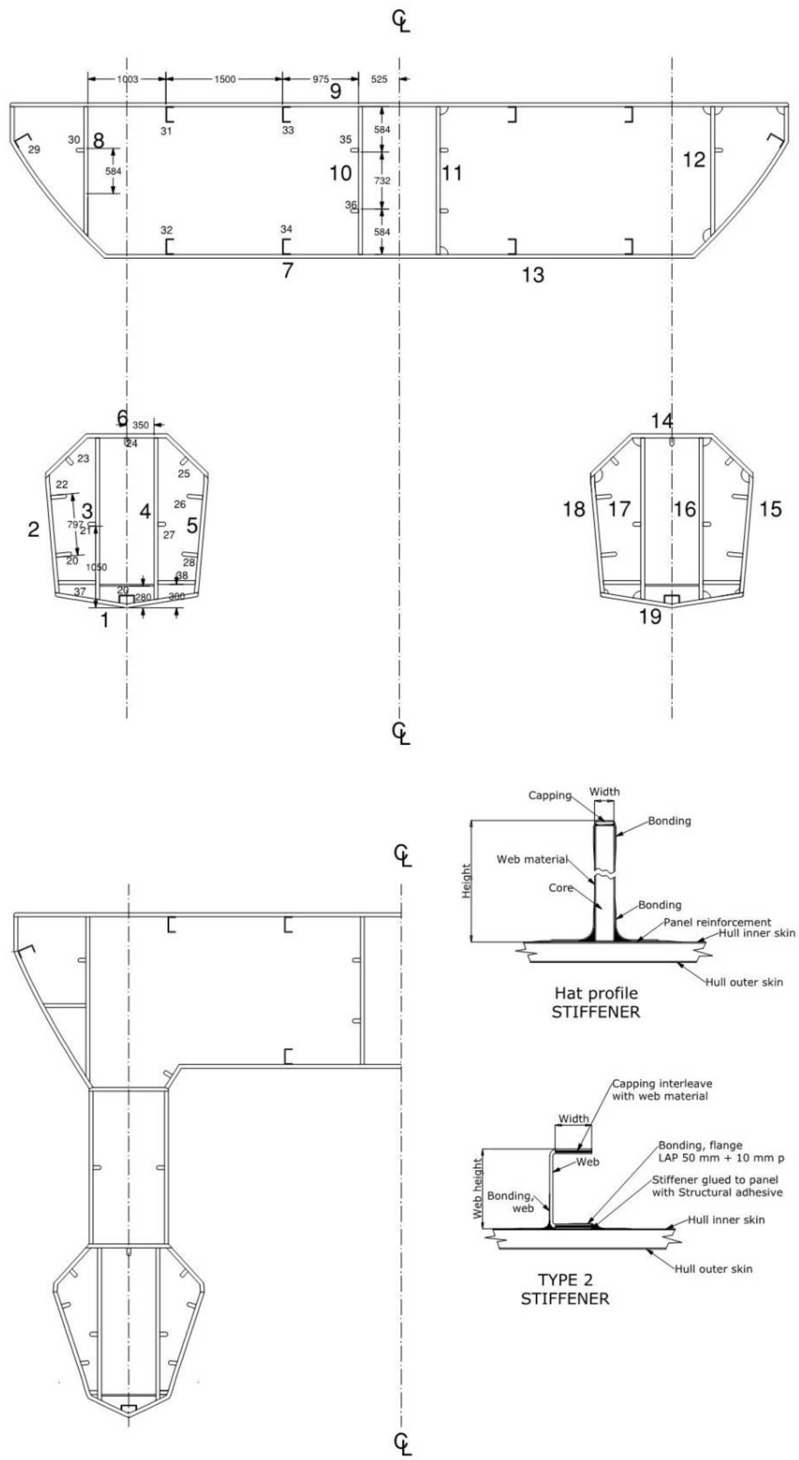
B..9.0 m

Tcatamaran.................................1.5 m

Tswath..3.5 m

DEPTH TO MAIN DECK............ 6.5 m

Figure A. 8.3 Tank plan cat-SWATH



MAIN CHARACTERISTICS:

LOA .... 16.0 m

LPP..........................15.985 m

B...................................9.0 m

Tcatamaran..................1.5 m

Tswath.........................3.5 m

D TO MAIN DECK...... 6.5 m

Figure A. 9. Midhship section – cat-SWATH

ANNEX 5.

GZ curve of catamaran-SWATH

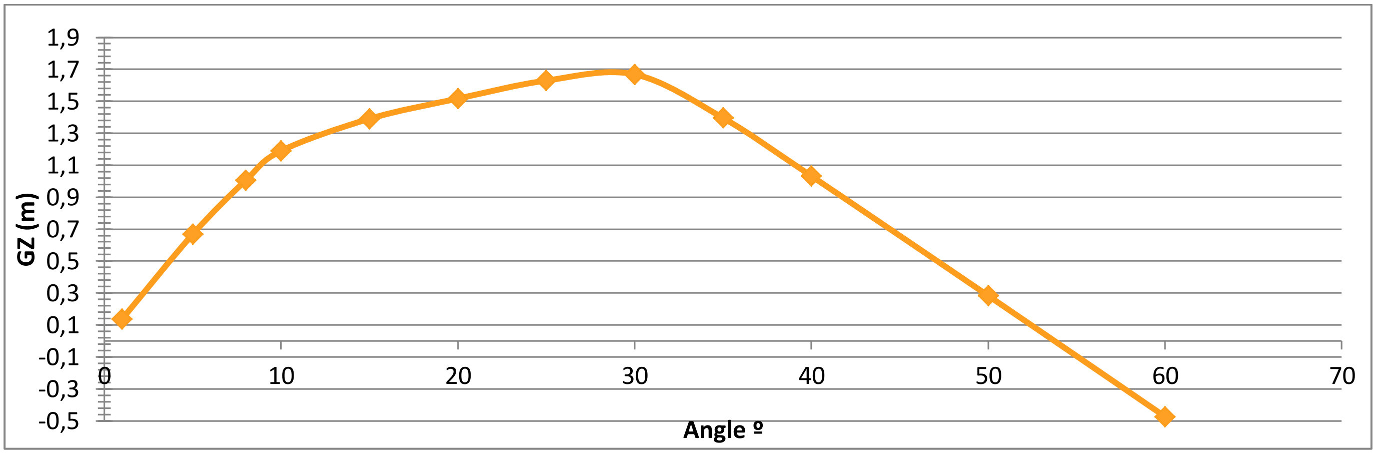


Figure A. 10. GZ curve for the light weight case study, with no trim and draft = 1.5m