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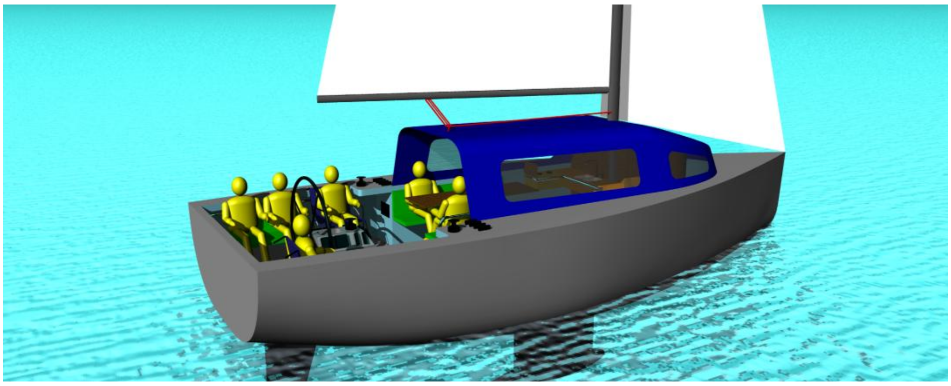

Development of a Sailing Yacht for Disabled People

Inclusion 32

Frederico José Vasconcelos de Morais Cerveira

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Júri

Presidente: Prof. Carlos Guedes Soares
Orientador: Prof. Nuno Fonseca
Vogal: Prof. Manuel Ventura

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Abstract

A new procedure was developed for the inclusion of people with physical and mental limitations in the project of sailing yachts. The initial design requirements identified mobility, safety and heel angle to be the main issues. The solution was found with modularity and simplicity. A complete view of the problem is presented with the *Inclusion 32*, a disabled friendly cruiser designed with a single sole level, similar to sport yacht but with all the equipment required for a small crew to live onboard for a few days. The mobility is solved by a wheelchair accessible general arrangement defined according to the Universal Design architecture. The safety is regarded by ergonomic postures and injury preventive considerations. In addition, the single sole level produces a structural arrangement similar to a double bottom which is unusual for sailing yachts but improves the vessel survivability. A small heel angle is accomplished by an innovative system designed to self balance the yacht. A Velocity Prediction Program was developed and validated to support the design of the Self Stability System. The *Inclusion 32* was designed to be constructed in Portugal with low cost technology and is expected to be an interesting product for the European market.

Key-words: Inclusion 32, sailing yacht design, Universal Design, wheelchair accessible, Self Stability System, Velocity Prediction Program.

Resumo

Um novo procedimento foi desenvolvido para a inclusão de pessoas com limitações físicas e mentais no projecto de embarcações à vela. Os requisitos de projecto iniciais identificaram a mobilidade, segurança e ângulo de adorno como sendo as maiores dificuldades. A solução encontrou-se através de modularidade e simplicidade. Uma análise completa do problema é apresentada pelo *Inclusion 32*, um veleiro de cruzeiro desenhado para pessoas com deficiência. Este projecto apresenta um pavimento único semelhante a um veleiro de regata, com todo o equipamento necessário para uma pequena tripulação viver abordo por alguns dias. A mobilidade foi encontrada através de um arranjo geral acessível a cadeiras de rodas, desenhado com base na arquitectura de Design Universal. Em termos de segurança promoveu-se a prevenção de lesões e posturas ergonómicas. Assim como, o pavimento único produz um arranjo estrutural semelhante a um duplo fundo, característica invulgar em veleiros mas que aumenta a capacidade de sobrevivência da embarcação. Por fim, um baixo ângulo de adorno foi conseguido por um sistema inovador projectado para auto-equilibrar a embarcação. Um programa de previsão de velocidade foi desenvolvido e validado para apoiar o desenvolvimento do sistema de auto-estabilidade. O *Inclusion 32* foi projectado para ser construído em Portugal com tecnologia de baixo custo e prevê-se que seja um produto de interesse para o mercado Europeu.

Palavras-chave: Inclusion 32, projecto de veleiro, acessível a cadeiras de rodas, Design Universal, Sistema de Auto-Estabilidade, Programa de Previsão de Velocidade.

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A_n	Nominal sail area [m^2]
AR	Aspect ratio
Aw	Water plane area at zero speed [m^2]
B	Beam of hull amidships [m]
Ballast	Weight of the keel and bulb [Kg]
b_b	Stringer width [mm]
B_{max}	Maximum beam of hull [m]
B_{WL}	Beam of waterline [m]
C_b	Block coefficient
C_D	Drag coefficient
CE	Centre of effort
C_f	Frictional coefficient
C_L	Lift coefficient
CLR	Underwater centre of lateral resistance
C_m	Midship section coefficient
C_p	Prismatic coefficient
C_T	Coefficient of total force
Disp.	Total displacement of the yacht [kg]
DSYHS	Delft Systematic Yacht Hull Series
E	Base of main sail [m]
GMt	Transversal metacentric height [m]
GZ	Righting arm [m]
h	Stringer height [mm]
$h_{1/3}$	Significant wave height [m]
H_{arm}	Vertical distance from the sails CE to CLR [m]
HR31	Halberg Rassy 31
I	Height of fore triangle [m]
IMS	International Measurement Standard
ITTC	International Towing Tank Conference
J	Base of fore triangle [m]
K	Form factor
KML	Longitudinal metacentric height [m]
K_{yy}	Longitudinal radius of gyration
LCB	Longitudinal position of the centre of buoyancy [m]
LCG	Longitudinal position of the centre of gravity [m]
L_{OA}	Length overall [m]
L_{WL}	Length of the waterline [m]
NACA	National Advisory Committee for Aeronautics
P	Height of main sail [m]

R_{AW}	Added resistance in waves [N]
R_f	Frictional resistance [N]
R_i	Induced resistance [N]
RM	Righting moment [N.m]
R_n	Reinolds number
Rrh	Hull residuary resistance of canoe body [N]
R_v	Viscous resistance [N]
S	Wetted surface [m^2]
Sc	Wetted surface of canoe body at zero speed [m^2]
STIX	Stability Index
T	Draft of the yacht [m]
T_c	Canoe body draft [m]
TCG	Transversal centre of gravity [m]
Te	Effective span [m]
t_p	Stringer thickness [mm]
TR	Tapper ratio
V_1	Apparent wing along the motion direction [m/s]
V_2	Apparent wind at right angles to the motion direction [m/s]
V_{AW}	Apparent wind speed [m/s]
V_{Awe}	Effective apparent wind speed, yacht heeled [m/s]
VCG	Vertical centre of gravity [m]
V_S	Yacht speed [m/s]
V_{TW}	True wind speed (m/s) measured at a known height above the water surface [m/s]
Z_{CE}	Height of the sails centre of effort [m]
Z_{Top}	Height of the top of the mast above the water surface [m]
β_{TW}	True wind angle measured between the yacht's track and the V_{TW} vector [^{0}]
β_{Awe}	Effective apparent wind angle [^{0}]
ε_A	Aerodynamic drag angle [^{0}]
λ	Leeway angle [^{0}]
μ	Wave incident angle [^{0}]
ρ	Density [kg/m^3]
θ	Heel angle [^{0}]
v	Kinematic viscosity
∇_c	Canoe body displacement volume [m^3]

1 Introduction

1.1 Disabled people needs

Sailing is a popular activity worldwide, some people practice it as a sport others for pleasure and disabled people may often use it for their personal development. Unfortunately, conventional yachts are usually designed for the middle age male population, most of the times not even suitable for women, young and old people. Here is the starting project of the present work, based on the concept that all products and environments should be designed to consider the needs of the widest possible array of users. This is called Universal Design, which is a way of thinking about the design that considers human people limitations not as a condition of few but as a common characteristic of all, since we all change physically and intellectually through our lives. If a design works well for people with severe limitations it works better for everyone. Therefore, the present project is focused on disabilities, which are considered to be the most severe type of human limitations, but the final result is expected to include a much larger population. This way of thinking about design is often defined as inclusive and for that reason the final result of this work will be baptized as *"Inclusion".*

The present project requires a combination of naval architecture with disabled people knowledge. However, the problem of disabled people sailing is difficult to address with a theoretical approach because there is little literature on the subject. Therefore, from the beginning of the project it was necessary to have personal contact with disabled sailors in order to identify their main limitations and only then use naval architecture to solve them. To do so, the author worked for a year as coach of the disabled sailing team of *Clube Naval de Cascais* and was responsible for the first Portuguese team going to an Access World Championship. This was an important experience for development of the present work and gave to the author an additional motivation for the success of the *Inclusion* project.

In comparison with other sports, sailing vessels require little mobility onboard and the controls may be easily adapted to different kinds of operation, these characteristics make sailing a popular activity for the disabled population. In Portugal disabled sailing started a few years ago and nowadays more than 10 centres through the country take disabled people to the water. The *Clube Naval de Cascais* is an example of the success of disabled sailing, as it runs sailing classes four days a week for sailors with different kinds of disabilities.

The majority of boats used by disabled people are small in size and crew, often dinghies commercially produced for this application. These boats solve the mobility problem by seating the sailor in a central position facing the front with all the sails and directional controls within arm reach. The controls are often modular and offer different possible operation according to the user needs. In terms of larger vessels there are only a few individual projects of yachts designed for disabled people and a few other conventional yachts extensively modified for the this purpose. The study of the sailing vessels indicates that disabled people sail mostly single handed and it is not possible to leave sheltered waters to do even small coastal passages.

The main idea of the project was to help disabled sailors in their quest for independence, and the direction of the work was decided by the disabled sailors wish and the author's opinion about is needed. It was concluded that a cruising vessel designed for costal navigation is needed with habitability for a crew of people with different disabilities to live onboard for a few days. For the project of a cruising yacht the mobility onboard is the biggest challenge since the crew must access different areas as well as entry in the boat independently. Other problems for the inclusion of disabled people in sailing yachts were identified through an initial study of the limitations associated with the most common disabilities, in particular the heel angle was found to be a characteristic to avoid since it affects negatively the mobility and balance while sailing.

Safety is an essential factor because disabled people often have more difficulties to cope with the situations and face higher risk of injury. This was accounted by a review of the literature published about injuries in amateur sailors, which identifies the most critical areas onboard, the unsafe equipment and the frequent types of injuries. A few comments are also given for particular injuries of disabled people. The study of the disabled people needs finishes with a revision of the vessels designed for disabled people and the respective auxiliary systems, which show how other projects already tried to solve these problems.

1.2 Design process

The design process starts with a design brief which defines the project limits in terms of the intended use and the overall hull and rig characteristics. Afterwards, the preliminary design search for a suitable solution for the mobility problem. It is decided that a single sole level, common to the interior and cockpit is the most acceptable solution for the disabled population, because it avoids the use of the unsafe stairs or lifting platforms which are difficult to cope with. It is also concluded that the best way to solve the mobility problem is to accept wheelchairs onboard, because most disabled people are familiar with its operation and the interface with shore is simplified. However, to accept wheelchairs onboard is necessary to have a general arrangement, with specific dimensions most of the times considerably larger than usual. Therefore, it is decided to start the design process from the general arrangement, where all the areas are designed to be wheelchair accessible according to the dimensional advice given by the Universal Design architecture.

The second major characteristic required to the operation of wheelchairs onboard is the heel angle, which is defined to be less than 10^o for the normal sailing. This heel angle limitation governed all the subsequent design decisions. The hull design was an iterative process to guarantee the internal volume required for the general arrangement, high form stability and an efficient performance. The hull main dimensions are evaluated according to the dimensions of modern cruising yachts with similar size, collected to a data base.

The appendage configuration was also designed to cope with the heel angle limitation. In order to operate with low heel a yacht may have a low sail area or a heavy keel. It is decided that a small sail planform affects negatively the external appearance of the yacht and it is chosen to design a conventional sail planform balanced by a heavy keel. The appendage design was also an iterative process, where the sail planform is decided to be constant while keel bulb weight is optimized according to the heel angles predicted by a Velocity Prediction Program build for the present project.

As is often the case for production boats, two keel configurations were designed to have the same initial stability, one was designed to have a conventional draft and operate without restrictions in marinas and shallow waters, while the other was designed with higher draft to increase the sailing performance.

Afterwards, the mass and centre of gravity of the yacht were estimated according to the structural weight, machinery and equipment onboard. The structure was design to have the *International Standard Organization* (ISO) approval. Some structural details were added to the rule minimum requirements in order to increase the life span of the yacht and to account with the inappropriate use by inexperienced people. The material and construction methods were designed to be low cost and easy to repair. The machinery is based on an electric engine because it suits better the needs of disabled people, in particular it has a silent operation and the electric energy stored in the battery bank is also used for the adaptive electric devices. Then, a list of the equipment onboard was made and positioned according to the longitudinal and transversal equilibrium. At this stage the final mass and position of the centre of gravity was predicted for the lightship and normal sailing condition.

The stability characteristics of the yacht were calculated with the *Autohydro* software, while the seaworthiness was evaluated according to the ISO 12217-2 standards. To conclude the design process was estimated the overall performance of the yacht for different situations with the Velocity Prediction Program (VPP). The present project required to build a specific VPP because the limit situation is not the maximum speed as conventional VPPs assume but a given maximum heel angle. The program estimates the hydrodynamic resistance according to the *Delft Systematic Yacht Hull Series* and the aerodynamic force with pressure coefficients of the sails, the computation process and formulations used are also described in the performance prediction chapter.

At the end of the document is described an innovative system developed during this project to minimize the heel angle. This system was designed to self balance the yacht according to the wind demands. The characteristics of this self stability system were included in the VPP made for the project and the results show a significant heel angle reduction and velocity improvements. According to the author’s knowledge this system has never been developed for other projects and may benefit cruising or racing yachts when little operational work is intended.

The *Inclusion 32* is the final result of this work, it represents a new concept of cruising yacht with a single sole level for ease of mobility onboard. Furthermore, all the requirements defined for wheelchair operation are fulfilled. The general arrangement is according to the Universal Design dimensions to be wheelchair accessible while the hull and appendage configuration guarantee a minimum heel angle of 10º. Through all the design stages the *Principles of Yacht Design* was a major reference for the development of this project. The subsequent chapters will describe in detail the present work, starting with the analysis of disabled people needs.

2 Universal Design

The present work intends to apply the Universal Design concept to the project of a sailing yacht accessible to a population with a wide range of abilities. The idea was to design an inclusive environment focused on the main human limitations, usually defined as disabilities, to create a better yacht for everyone. The initial design stage have to identify the limitations that disabled people have to the operation of sailing yachts and organise them according to an order of importance. In addition, a study on the frequent injuries related with amateur and disabled sailors was performed to increase the overall safety of the project. The Universal Design chapter ends with a practical view of the problem by presenting an overview of the sailing vessels most used by disabled people and the respective adaptive systems. This initial chapter provides a solid base fo the understanding of disabled people needs and the decisions subsequently taken through the design process.

2.1 Methodology to consider disabled people

A disability is often associated with several limitations that may change according to the demands of the activity performed, for example a paraplegic sailor may not have a mobility limitation if all the controls are within arm reach. Therefore it is important to identify which are the limitations that common disabilities have regarding the operation of sailing yachts. However, there is little information on disabled people sailing, the most relevant references are published online by the *Sailability* organisation (*www.sailability.org*) and the *International Foundation for Disabled Sailing* (*www.sailing.org/disabled*).

The main limitations to the sail practice are presented in Table 2.1.1 according to the respective disability. This classification is based on the previous information and the author's experience with disabled sailors. The disabilities are divided in physical, intellectual, sensory and secondary. Where the secondary group require some considerations but doesn't prevent the practice of sailing. The limitations identified in Table 2.1.1 are organised by the author in permanent, non-permanent and personal adaptations, according to how they affect the yacht.

Table 2.1.1 – Most common limitations to the integration of disabled people in sailing yacht.

		Permanent adaptations					Non-permanent adaptations			Personal adaptations	
	Disability	Low heel angle	Balance aids	Mobility aids	High boom	Aid to go onboard	Simple Direction/Sail Controls	Electronic equipment	Low Physical Performance	Body Protected	Large & Colourful Controls
Physical	Paraplegia e Quadriplegia	x	x	x		x		x	x	x	x
	Amputations	x	x	x		x		x			x
Intellectual	Intellectual disability	x			x		x				x
	Acquired Brain Injury	x	x		x		x	x	x	x	x
	Cerebral Palsy	x	x		x	x	x	x	x	x	x
Sensory	Blindness or Visual Impairment				x			x		x	x
	Hearing Impairment				x						
Secondary	Diabetes									x	
	Asthma								x		

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The identification of the most common limitations to the sailing practice was made to simplify the designer work, since then he is not concerned with a group of disabilities but with a group of design requirements. However, a logic procedure must be defined to organise these limitations according to different stages of the design process. The idea suggested here is to give an order of importance to the limitations, where the most important limitations are those who affect permanently the yacht, afterwards the limitations that require non-permanent adaptations, until small details are left to consider. Permanent adaptations are considered to be for example a heavy keel to reduce the heel angle or a general arrangement designed for wheelchair operation while the non-permanent adaptations are related with the operational controls and other systems that may be easily changed through the vessel life. The subsequent paragraphs divide the integration of disabled people in three design stages and the limitations to consider in each stage are according to Table 2.1.1.

First Design Stage – Permanent adaptations

The first design stage focuses on the adaptations identified to affect permanently the vessel. The heel angle is an uncomfortable characteristic of sailing yachts, because it increases the problems with balance and mobility onboard. Therefore, a major design consideration should be a low heel angle, which affects the hull shape and appendages configuration.

When sailing, most people have balance problems, but the disabled are the most affected generally due to amputations, low trunk stability or poor motor coordination. The hull and appendages should be designed to reduce the three dimensional accelerations and the general arrangement should accept balance equipment, such as chairs, hand rails, etc.

The mobility onboard a sailing yacht is a difficult problem to address because in most cases there is not enough space for conventional mobility aids. This limitation is increased by the heel angle and the three dimensional accelerations applied to the sailors. The easiest way to solve the problem is to place the sailor in a central position facing front with all controls within arm reach, which minimizes the need to move. However, in a larger yacht the crew must have access to different areas and the previous solution is not suitable. Therefore, the mobility solution must be according to the size of the vessel, the general arrangement and expected heel angle.

The main sail boom swings from one side to the other, above the cockpit and deck and must be high above the heads, since most intellectual disabled or visual impaired people may not predict when it is going to move. Attention should be also given to the main sheet and blocks which should be attached to a position from where they cannot sweep the cockpit. A collision of a crew member with one of these equipments may certainly cause a severe injury.

Second Design Stage – Non-permanent adaptations

After defining the general arrangement, the hull shape and appendage configuration, the directional and sail controls should be considered. All the considerations made in terms of the control systems are non-permanent and may be changed according to the crew needs. Modular solutions are recommended to adjust the equipment to the individual requests.

Simple controls are required when the user cannot understand intuitively the system operation or when there is no physical ability to cope with it. Electric devices are often employed because they reduce the physical demands and are operated by a variety of interfaces. However, there are people who benefit from several adaptations, but still wish to sail as a sport and search for intense physical activity. The equilibrium should be found again with modularity, providing for example the possibility to operate the systems manually or with the aid of an electric system.

Third Design Stage – Personal adaptations

After the control systems are defined a wide range of small details should be considered. The third design stage continues after the design project and build of the vessel in order to account with the needs of each particular user. This design stage is concerned with personal equipment, for example cushions to protect the user's body, Braille signs, personal grips for equipment holding, etc.

The suggested sequence seems to be the logic procedure to address a large group of problems identified to affect frequently the integration of disabled people. The subsequent section will present a few considerations to avoid the risk of injuries in the general sailing population, which is an alternative way to improve the users' integration.

2.2 Patterns of injury in sailing yachts

Little literature exists on the causes of injuries with sailing and most of the studies are concerned with high performance athletes, which suffer from specific injuries mostly related with overuse of particular areas of the body. For the regular sailing a relevant study was made on cruising sailors who spend most of the year on offshore cruising yachts (Rouvillian, et al., 2007). Figure 2.2.1 reports the most frequent places where trauma occur onboard cruising yachts. The deck is the most dangerous area due to the high exposure to the environment and equipment without effective means of protection. The cockpit is more protected than the deck but most of the sailing work is performed here with the associated risk of injury. The companionway is also a critical area because people are moving from one level to another being easy to lose balance or slip and fall. Many reported injuries also occur at the companionway by colliding with moving equipment when coming out of the interior. The kitchen is also worth of safety concerns in particular for the operation of the gimballed stove.

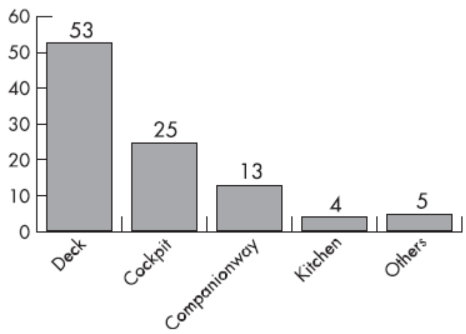

Figure 2.2.1 – Places of risk onboard cruising yachts [%](Rouvillian, et al., 2007).

The anatomical regions involved in trauma have been classified by increasing order of frequency as pelvis/abdomen (2%), head/neck (13%), chest (14%), upper limbs (35%) and lower limbs (35%), and these results are similar to those reported from an amateur around the world race, *The British Telecom Round the World Yacht Race 1996-1997* (Prince, et al., 2002).

Rouvillian et al., found that head and neck trauma are often related with a moving spar such as the boom. Accidents typically occur when there is a combination of helm error and jibing while the victim is returning from the cabin, none of them had a companionway sea hood, which is a removable structure placed in front of the cockpit to protect the crew from the sea spray, wind and sun. It seems that this hood forces the sailor to bend down to take the stair case to the cabin which protects effectively from a collision with the boom.

It was found that chest trauma occurs normally when a crew member is carrying an object up to the cockpit. If a rolling motion occurs, the body rotates about a single vertical axis, and the person is unable to grab for support because the hands are occupied. The companionway should be protected by two side walls being much safer than a simple narrow ladder, since the person can lean against a wall to free a hand while keeping three support points.

Hand injuries are generally caused by deck equipment with moving parts and is recommended to protect equipment such as pulleys, winches, windlasses, propellers and motorised deck covers. The lower limb trauma is as common as the upper limb trauma and occurs mostly due to collision with deck hardware. This can be improved with pathways clear from obstructions, with smooth and not slippery surfaces, and by wearing protective foot equipment.

The burns onboard due to solar expose made up 28% of the injuries reported by Rouvilan et al, although most of the crews had been very careful to use sun protection methods. It was in the kitchen that the most severe burns occur. The stove onboard gimballed but it also swings with the motion of the boat, which results in dishes falling off the stove or cooker’s body falling into contact with the burning hot stove. The kitchen area should be well designed with handrails available and the cook should also wear protective equipment while coking at sea.

The occurrence of low back pain in offshore cruisers is most related to the raise of the anchor. All the injuries occur in small boats without windlass and all traumas were sustained when the subject was pulling while standing upright, with full weight of the chain being held by the lumbar spine. If a windlass is not available, it is suggested that the sailor should change to a sitting position on deck with feet resting safely on the pulpit. The lower back pain can be also associated with poor positioning in repetitive motions like trimming sails or lifting objects like spinnaker poles or heavy sails (Allen, et al., 2006).

Even more limited studies have been performed on injuries related with disabled sailors, but preliminary studies suggest that they suffer from injuries similar to able-bodied people (Allen, et al., 2006). In 1999 a survey of disabled sailors during the *International Foundation for Disabled Sailing World Championship*, with 24 teams and multiple disabilities types, showed that the majority of the injuries were chronic in nature (68%) with sprains and strains being the most frequent types of injury.

The crew members were at greatest risk of injury (96%) in the three person class, with equal distribution between the fore-deck and mid-deck positions. The upper limbs were the most frequently injured body region (60%), likely due to an increased reliance on the upper limbs as a consequence of lower limb or spinal cord disability (Neville, et al., 2009). When performing actions onboard it is important that disabled people without trunk stability have means to support themselves, otherwise one hand will be working while the other is holding the position, increasing much the physical efforts in the upper extremities.

2.3 Adaptive equipment

2.3.1 Existing vessels for disabled people

The majority of boats used by disabled people are small in size and crew. Most of them solve the mobility problem by seating the sailor in a central position facing the bow with all the sails and directional controls within arm reach. The control systems of the sails and rudder are simple and often compatible with electric devices. The most relevant projects for disabled sailors will be now described.

The Access Company (*www.accessdinghy.org*) is the largest builder of sailing vessels for disabled people, these vessels search for a balance between recreation, competition and therapeutic activities at a low price. Designed for one or two sailors, the Access dinghies have light and simple operative systems. The stability is provided by a heavy centreboard and a wide beam. The high freeboard and the wide deck intend to keep the boat dry when heeling, which is important for sailors that easily suffer from hypothermia. The disadvantage of the high freeboard and wide deck is a possible loss of view to windward when heeling. Nowadays more than 1200 Access dinghies are sailed in fifteen countries and its popularity is increasing considerably. There are a few more dinghies designed for disabled people, namely the Challenger, 2.4M, Artemis 20 and Martin 16, but all of them solve the mobility and balance problems by seating the sailor in a fixed central position.

In terms of larger vessels there are only a few individual projects. A recent one from the University of S. Paulo designed a day-sailer yacht for disabled people (Simos, 2007). The POLI 19' has a simple deck layout to leave open the possibility to insert personal adaptations. This creates a flexible base for future personalisation, while a rigid layout would restrict the vessel to some particular type of limitations. The boom is relatively high when comparing with similar boats to avoid head injuries. The POLI 19' has a large cockpit with a length of approximately 55% of the length overall to avoid the need to leave the cockpit to the forward deck. It has two seats at different heights with an inclination angle relative to the horizontal to support people with balance problems while sailing with heeling angle. The stern is open and it has a small platform for easy access to the water and recover a man over board.

The *Veritas K* is another interesting project of an ocean going vessel that considers the possibility to be wheelchair accessible (*www.disabledsailing.org*). It has a centre cockpit which protects the crew from the sea spray and gives a clear view all around. All the systems are controlled from the cockpit with space for wheelchair operation. The entry to the interior is via a stairway or a wheelchair lift platform and when not in use the platform lies flush on the cabin sole and does not encumber safe access to the interior by able-bodied crew members. The saloon also has space for wheelchair operation and access to all the equipment. The Figure 2.3.1 shows the interface between the vessel and shore made sideways, where a gangplank concealed in the hull comes out to allow a section of the hull and deck to roll out, giving easy access to the cockpit for anybody including wheelchairs users.

Figure 2.3.1 – *Veritas K* with lateral entrance open.

The catamaran configuration helps the integration of disabled people because of the low heel angle and the spacious cockpit, suitable for wheelchair operation. A good example is the *Impossible Dream,* an 18 meters length ocean going catamaran designed to be wheelchair accessible (*www.impossibledream.org*). It has a flat and wide deck to allow wheelchair users to go all around the boat and there is extensive use of rails on deck and inside the cabin. The *Impossible Dream* has three navigation stations, one inside the cabin and one at each side of the deck. From here it is possible to steer the boat, control the sails, engines and operate all the electric devices such as autopilot, GPS, Plotter, etc. For comfort while skippering the boat, there are two chairs inside the cabin fixed to a rail system. The interior is also wheelchair accessible, with access to kitchen equipment and bathroom, a lift platform provides the access to the compartments under deck.

2.3.2 Adaptive equipment

A wide range of equipment adaptations have already been developed to cope with disabled people limitations, in particular for the Paralympic classes where numerous athletes improve their performance by adapting the material to their needs. Some of these interesting adaptations are provided at the *International Foundation for Disabled Sailing,* here attention is given to the recently developed electric adaptive equipment.

The design team of the Martin 16 dinghy developed an interesting seat for yachts helm position, which allows people with mobility and balance problems to steer the vessel comfortably for long periods of time. This system, presented in Figure 2.3.2, is designed to provide an ergonomic and secure seating for people with or without disability (*www.martin16.com*). The seat travels from one tack to the other, rotating through 180 degrees, allowing the sailor to adopt the conventional position facing the sails or the bow of the boat. To accommodate the heel of the boat it tilts 25 degrees forward and aft and can slide up to 8 inches towards the driving wheel, adapting to personal limitations and comfort. A four point safety harness secures and maintains the balance of the sailor in a seaway.

The same group also developed a complete set of electric adaptations to operate small vessels. This system does the interface between the main controls of the boat and a people with severe limitations. The main part of the system is a joystick module, which contains the main computer and a joystick control. The left and right axis of the joystick operates the helm drive motor to steer the boat, while the forward and backward axis of the joystick operates a windlass to trim the sails. The joystick module can control up to three motors and operate several trimming lines. Other way to control this system is with the sip and puff module presented in Figure 2.3.3, which provides a sensitive pneumatic control interface, to allow high-quadriplegic sailors to control the system functions with their breath. The sip and puff interface is a chest mounted control "stalk" with two pneumatic straws within reach of the sailor's lips, one to control the helm and one to control the windlass.

Figure 2.3.2 – Six-way Power Helmseat

Figure 2.3.3 – Sip and puff system

The development of electronic equipment is an important improvement for the sailing adaptability. A range of different interfaces between the user and the electric motor already exist. It is relevant to consider for example a quadriplegic person that is limited in most daily life activities and with an interface like the sip and puff system he or she may go to the water and enjoy a sailing day.

2.4 Summary

According to the Universal Design philosophy by solving the needs of the most limited people it is also improved the integration of everyone, in particular women, old and young people that often find difficult to cope with conventional yachts.

The most important limitations to the integration of disabled people were identified and organized according to an order of importance, where the most important limitations affect more permanently the yacht and should be considered at the initial stages of the design process. Therefore, it was decided to start the design process aiming for suitable solutions for the heel angle, balance and mobility problems. Afterwards, the directional and sails controls should be studied; these are non-permanent characteristics and may change according to the user needs. It would be a good practice to consider at this stage a few modular solutions to adapt to the individual needs. The third design stage continues after the end of the yacht design process, as it defines the adaptations required for specific users.

The study of frequent injuries was important because disabled people are often placed at higher risk of injury. The most critical areas on cruising yacht are the deck, cockpit and companion way and through the design project preventive considerations were applied.

The overview of the existing vessels designed for disabled people indicates that there are only small vessels commercially available and the larger yachts capable of leaving sheltered waters are costume made projects. A disabled friendly yacht designed for coastal navigation, suitable for individual disabled people, sailing schools and the senior population is considered to be needed.

3 Hull Design

Nowadays, there is no conventional arrangement for a disabled friendly sailing yacht and the success of the *Inclusion* project has to be based on creativity to design new solutions. The most important design decisions will be considered at the preliminary design stage. According to the Universal Design chapter the yacht designer should consider initially the limitations requiring permanent adaptations, in particular low heel angle and accessible layouts. In terms of these characteristics the catamaran is the most suitable hull type, however the mono-hull is less expensive and most sailors prefer this configuration. The factors involved with the hull type decision are discussed at the beginning of the chapter and then a design brief is presented to limit the project. The preliminary considerations also define a solution to the mobility problem and the respective general arrangement.

The general arrangement was based on dimensions advised by the Universal Design architecture. The practical information applied to this project is reported in Annex 3, and will be used to justify the design decisions. In Portugal there is a law concerning disabled people integration in public buildings, *D.L. nº 163/2006 de 8 de Agosto.* However, no literature was found concerning integration of different people applied to nautical environments and this project is based on conventional architecture principles (Goldsmith, 2000) transposed to the yacht design.

The present project followed a different procedure compared to conventional yacht design methodology. Usually the hull shape is the initial design stage and the general arrangement is then conceived within the hull limitations. The present project was developed in the opposite way, since the habitability of the vessel is more important than its sailing performance.

3.1 Hull type

The Hull types of interest to this project were the mono-hull and the catamaran, being not straightforward to decide which is the most suitable. These will be subsequently analysed according to the appropriate use, adaptability to common disabilities, costs and maintenance, academic research and market interest.

Mono-hull

Appropriate use: Suitable for sailors with experience, in particular for those who have some experience with dinghies and would like to advance to larger and more complex yachts, having the opportunity to increase distance from the harbour. The racing rules applied in conventional regattas are designed to mono-hulls.

Disabled adaptability: The heel angle characteristic of mono-hulls difficult the operation of most disabilities. It requires the development of alternative systems for mobility and balance with heel angle. The interior has a small volume and requires an efficient layout to allow disabled people to live onboard for short periods of time.

Initial and maintenance cost: The costs of acquisition are roughly half of a catamaran with the same size. The cost of a marina berth is related to the area occupied which is also about half of a catamaran. In addition the mono-hull has proportionately less maintenance costs.

Market interest: There are no cruising yachts designed for disabled people in the boats market. It can be bought by sailing schools, individual disabled sailors or families and groups friend with one or more disabled elements. In addition, it is suitable for the senior population.

Academic interest: The project of a mono-hull involves the development of creative solutions for adaptability on board, in particular mobility and balance in heeling condition. It also involves an optimization of the seakeeping characteristics and its sailing performances.

Catamaran

Appropriate use: Suitable for sailors with or without experience. In comparison with the mono-hull it is more comfortable and safe. The catamaran can do longer passages but cannot be part of local regattas.

Disabled adaptability: The spacious deck and interior allows the use of wheelchairs onboard and provides good access to difficult areas like the kitchen and toilet. The small heel angle creates good mobility conditions, similar to a floating platform, where almost all the disabilities are easily adapted.

Initial and maintenance cost: Approximately double the mono-hull price and maintenance costs. Although, it has larger volume and it is able to carry more people than a mono-hull with the same length.

Market interest: Sailing schools, associations and groups of sailors with a wide range of disabilities. Also appropriate for people interested exclusively in comfortable cruising passages.

Academic interest: The design of a catamaran has less reference material available, in particular for the structural design. In terms of disabled people adaptability it is only necessary to improve the operational systems, because all the mobility problems are already solved by the “apartment” layout.

From the previous characteristics it was decided that a mono-hull fits better the present project, because the initial and maintenance costs are considerably lower, which increase the population interested. However, the mono-hull has many problems to be solved concerning the inclusion of disabled people. This will challenge the designer creativity forcing new sailing concepts to be developed. In addition, the large majority of sailing vessels are mono-hulls and it was interesting to develop with this project inspiring ideas to integrate disabled people in the present and future yachts.

3.2 Design brief

After the definition of the hull type there were still infinite possibilities to consider and was important to limit the project from the initial stages to save time of the iterative design process. Therefore, a design brief is subsequently presented to enumerate the most important requirements.

- Project of a sailing vessel to be operated by a disabled crew, a wide range of physical and mental limitations must be considered.
- Intended use is local navigation and capable of coastal passages.
- For sheltered waters or coastal navigation the crew should be of four to six elements. There should be room for at least four people to sleep. Any time one able person must be enough to control the entire vessel.
- The heel angle and accelerations must be reduced to a minimum. It must guarantee safe navigation and provide good seakeeping and crew comfort.
- The toilet should be well accessible.

Hull characteristics

- The maximum length overall is 10 m defined according to the rates applied in most Portuguese marinas.
- The beam is defined according to the required internal volume and stability requirements.
- It must have directional stability to be easily controlled by inexperience people.
- The general arrangement should be designed to provide mobility for people with different abilities.
- The hull construction should be solid enough to withstand beginners mistakes. The materials and construction methods should be low cost, using technology available in Portuguese shipyards.

Rig characteristics

- Modern system of mainsail, jib and asymmetric spinnaker.
- The sails should be entirely operated from the cockpit area, including manoeuvres of hoist, drop and reef, which is possible with furling system in every sails.
- The jib should have a self taking system to simplify the operation.
- All the sheets must be controlled by manual and electrical equipment, as well as other secondary lines. When operating manually none of the control lines should be physically demanding.

3.3 Preliminary Design

For most yacht design projects the preliminary stage aims to define limits for the dimensions that most affect the performance of the vessel. The present project will also address these dimensions but only when defining the hull shape, before it is more important to find a general arrangement suitable for people with mobility limitations.

The conventional yacht layouts are very complex and even able-bodied sailors always have to look where to place their feet to avoid collisions with some hard surface, block, winch or rope. The differences in height from the saloon to the cockpit and from the cockpit to the deck are also difficult obstacles for people with physical limitations only possible to overcome with lifting devices. The present project decided to integrate wheelchairs onboard, because they are widely used by people with physical limitations, which provides comfort and independence for those used to operate it in daily life. The operations between the vessel and shore are also simplified if the mobility aid is the same.

It was decided to explore the concept of a yacht with flat sole levels free from obstacles to mobility, which may be the only way to incorporate wheelchairs onboard. Another concern was to eliminate complex lifting devices, as they don't fit well a wide range of disabilities, for example a paraplegic can benefit from a lifting platform but a person with intellectual limitations may not cope to it. Based on the previous concept of simplicity and of no lifting equipment, came out the idea of a yacht with a single sole level like a small sport boat. However, a sport boat does not need a toilet, cabin or kitchen, using the limited deck area only for the sailing tasks. The greatest challenge for this solution was to combine the sailing area with all facilities required to spend some days onboard at the same sole level. This became even more difficult because wheelchairs were accepted onboard, since it requires a significant extra space in the passage ways.

The study of this concept started in the plan view, by changing the position of simple geometric shapes, representing the forward cabin, toilet, galley and salon, until a reasonable disposition was found. The most interesting configuration was subsequently built in three dimensions using the *Rhinoceros* software. The equipment size was modified until accessibility of wheelchair users was guaranteed for every area.

The minimum hull dimensions were defined according to the interior demands within a maximum length of 10 m. The final result is an original yacht and a detailed description of the general arrangement will be subsequently presented.

3.4 General arrangement

Figure 3.4.1 illustrates the *Inclusion 32* general arrangement from a top view while Figure 3.4.2 presents a lateral view, the human models are positioned to illustrate the dimensions of specific area. The general arrangement has all the equipment necessary for a crew of four people to live onboard for a few days, including a forward cabin, toilet, galley and saloon. A plan view of the general arrangement with the respective dimensions is presented in Annex 1.

The sailing area was positioned aft where all the drive and sails controls are placed. The cockpit has two modular seats at each side to be used by non-wheelchair users while steering or trimming the sails. These seats were designed to be hidden at the sole level to give room for wheelchair users operation. The saloon is the social area located in front of the cockpit, it has a table and two long seats by the sides. The inner seat is also modular in order to give space for wheelchair access to the table. The galley is in front of the saloon with a passage way wheelchair accessible in between. The toilet is considered to be the private area for any need of the entire crew and was designed to be particularly well accessible. The cabin is at the bow with a 2m long bed for two people. The passage way was placed by the saloon side to avoid permanent obstructions between the crew elements; in particular, if someone is cooking the passage way remains free, the same for the toilet and forward cabin.

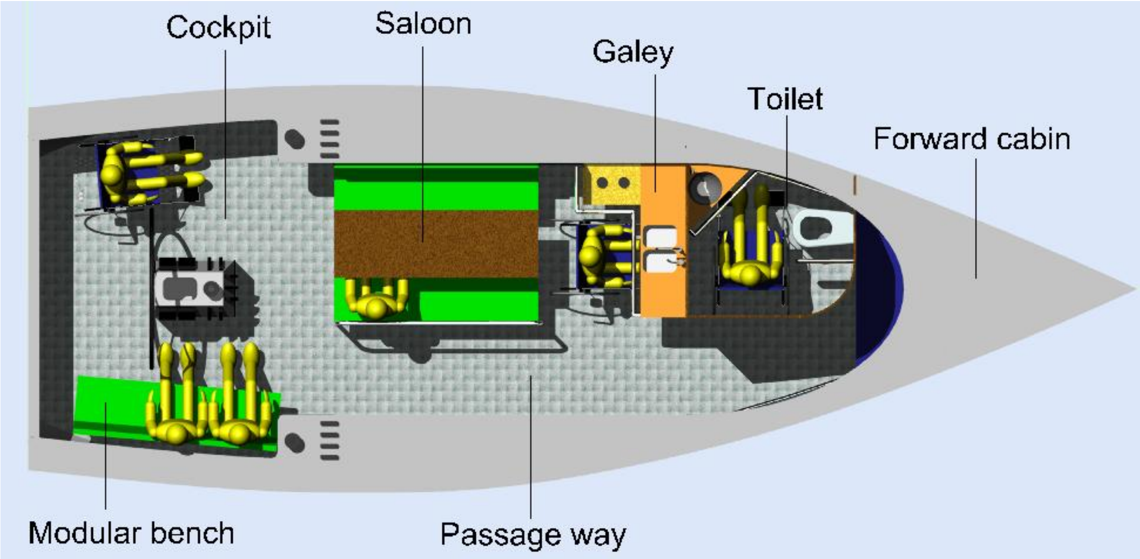

Figure 3.4.1 – *Inclusion 32* plan view with reference to the main areas (no cabin top).

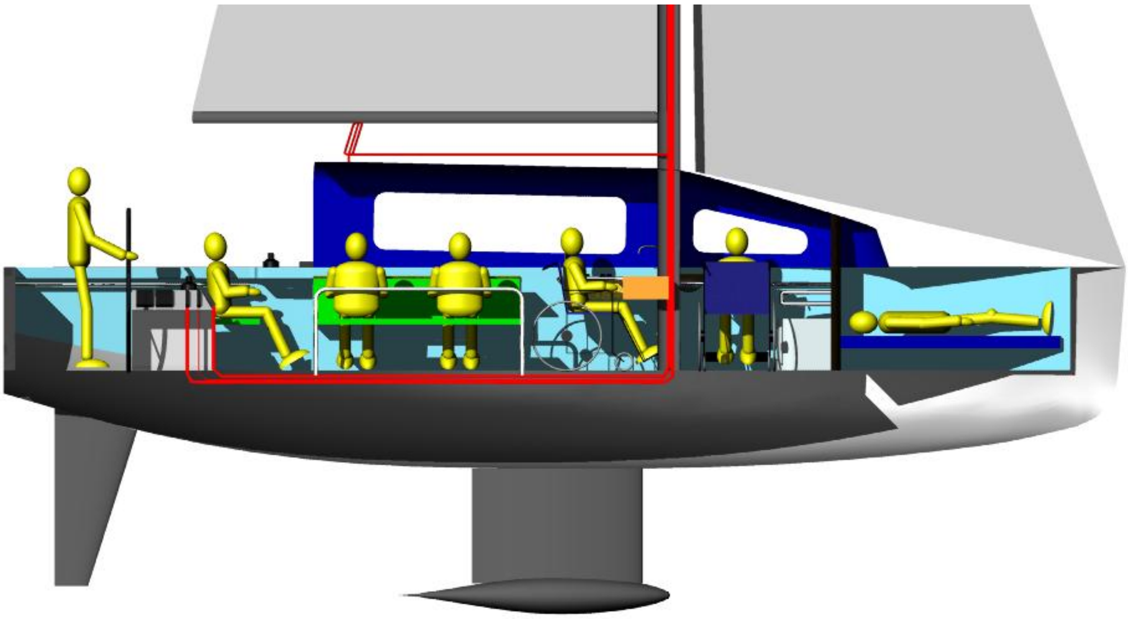

Figure 3.4.2 – *Inclusion 32 lateral view.*

The cabin top protects the social and private areas from the wind, rain, sun and sea spray. It has 1.8 m of headroom at the saloon, galley and part of the toilet, which is acceptable for the average person (Annex 3, Figure 8.4.5). The large saloon windows were designed to give a pleasurable feeling of seating comfortably with an open view to the sea. These unusual openings do not concern the safety of the vessel because the sole level is well above the waterline and water onboard is evacuated by the sole aft inclination. The cabin top aft end is designed to be normally open to the cockpit, at night or with adverse weather conditions it is closed by a canvas protection.

Figure 3.4.3 presents the pathways available for a wheelchair user designed to illustrate an average person. From this figure it is possible to have an idea of the space required for the wheelchair operation. Each area will be described in detail and the respective dimensions are justified with reference to the drawings presented in Annex 3.

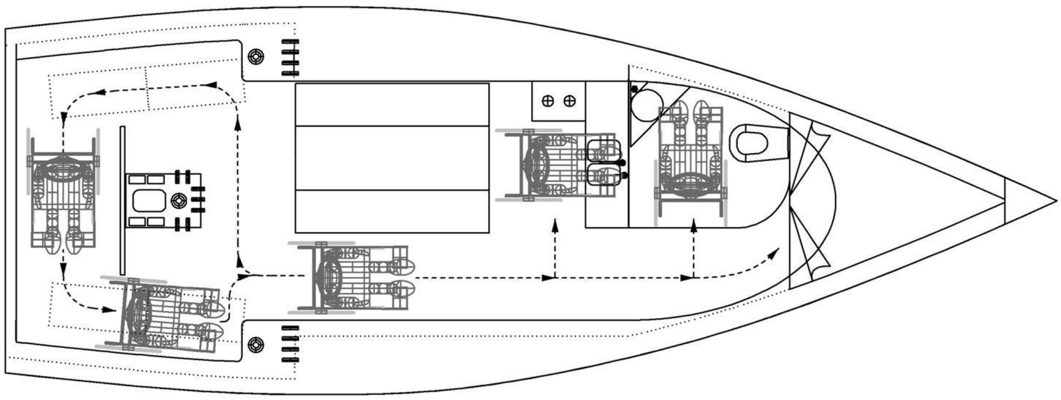

Figure 3.4.3 – Pathways available for wheelchair users.

3.4.1 Cockpit Layout

The entry to the vessel for wheelchair users' and people with physical limitations is made by the transom panel opened to the horizontal and the connection to shore is through a bridge made from a removable platform. As illustrated by Figure 3.4.4 the entry can be made aft or sideways according to the approach to the pontoon. The access to the water from the inside of the vessel is also made through the transom platform in particular to recover a man overboard.

The sailing area was organised to improve the crew comfort and safety while performing the sailing tasks. These activities are divided in two main groups, the directional control and the sails control. The steering is made with one driving wheel with 0.7 m radius, positioned at the centre line and 1m in front of the transom panel. The lateral distance from the driving wheel to the cockpit wall is 0.88 m, which according to the Universal Design dimensions (Annex 3 Figure 8.4.10) provides sufficient space for a wheelchair turn around the driving wheel as illustrated in Figure 3.4.3.

Along the cockpit exist is a handrail for wheelchair users' support while steering, trimming the sails or moving through the cockpit. The wheelchair users' steer position is by the side of the driving wheel facing the front of the boat, with view clear from the cabin top, as presented in Figure 3.4.5. The deck is horizontal at 0.9 m above the deck level to give a clear view angle from an average wheelchair seating position to the exterior of the vessel (Annex 3 Figure 8.4.6).

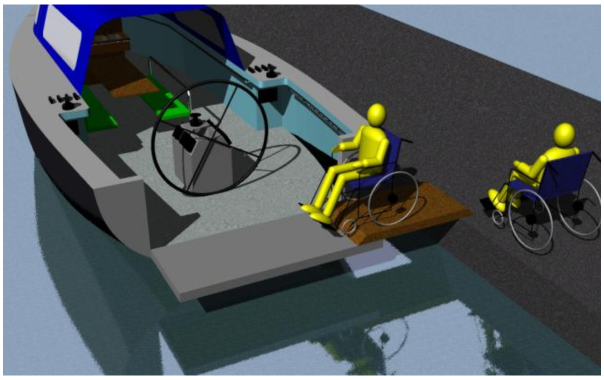

Figure 3.4.4 – Side approach to a pontoon.

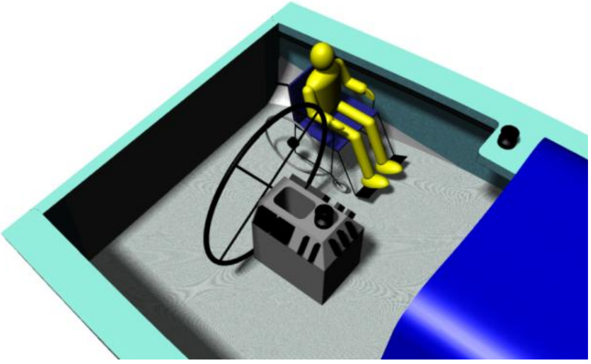

Figure 3.4.5 – Wheelchair users' driving position.

The sails operation requires the control of several systems which need to be divided by the crew members. The *Inclusion 32* has three trimming areas positioned to avoid interference between the crew members; two at the deck surface by the side of the cabin top and one central area in front of the driving wheel. The lateral areas are used to operate the sheets of the forward sails and other lines that require frequent adjustment, while the central station is used to operate the halyards and the main sheet.

The central station is presented in Figure 3.4.6, behind the winch exists a deep hole to store lose ropes and reduce the mobility obstructions at the deck. The halyards continue inside the mast until the sole level and are guided from the mast base to the central station below the sole level, hidden by a simple plank; is illustrated in Figure 3.4.2 by the red lines. The main sheet arrangement is also present in Figure 3.4.2 in red, it is fixed at the cabin top and from there it goes to the mast, joining the other lines in the way to the central station. This is a significant improvement to the crew safety, since it eliminates the violent cockpit crossing of the conventional main sheets during jibes.

At each side of the upper deck were designed the forward sails trimming areas, presented in Figure 3.4.7. The operation of these lines demands physical effort and most care should be given to promote ergonomic postures. Often disabled people find difficult to twist the trunk and neck, therefore the sailor is positioned behind the controls facing the front. The body is close to the equipment and aligned with the force direction (MacLeod, 1999). There is room for the feet and harm rests of a wheelchair under the deck surface for a closer approach of wheelchair users to the sails controls (Annex 3, Figure 8.4.4 left). Under each lateral trimming areas is situated a hole in the front wall to store lose ropes.

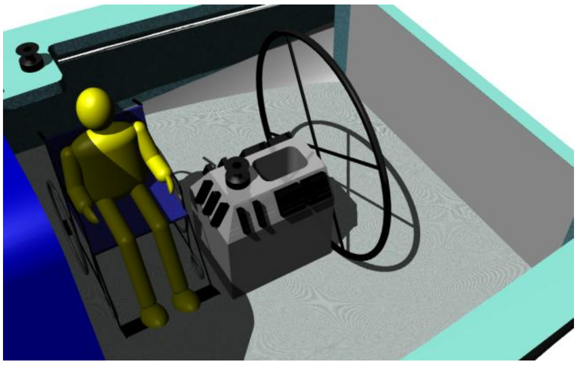

Figure 3.4.6 – Central stations designed to control the mainsail sheet and halyards.

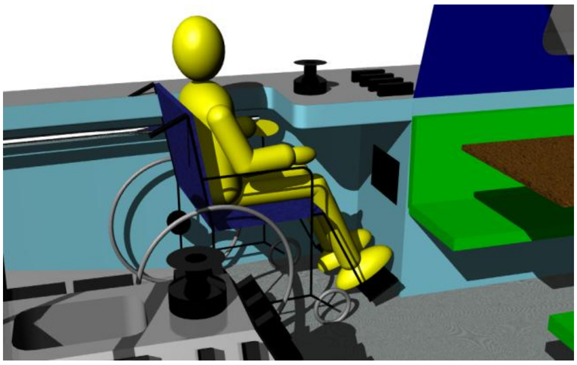

Figure 3.4.7 – Lateral trimming area is designed to control the sheets of the forward sails.

It was assumed that non-wheelchair users' can easily twist the trunk and head 90^0 and the most common position for able-bodied people when steering the boat is seating sideways facing the sails. To satisfy wheelchair users' and non-wheelchair users' a modular seat was designed to be stored at the sole level, by a simple system used for the table of the *Impossible Dream* catamaran presented in Figure 3.4.8. In the same way, the cockpit seat has two planks, the lower surface is horizontal and the upper can be unfolded for back support. According to the user choice the seat can be used folded with legs apart for front seating or unfolded with back rest for side seating as given in Figure 3.4.9. The vertical surface was designed with 10^0 of inclination backwards but if reasonable from the construction point of view the entire Seat should be rotated backwards after rising from the deck to support the sailors when heeling. The length of the cockpit Seat was designed for two people seating, considering for example the need of a helper by the side a blind or novice helm.

Figure 3.4.8 – Foldable tabled stored at sole level (*Impossible Dream).*

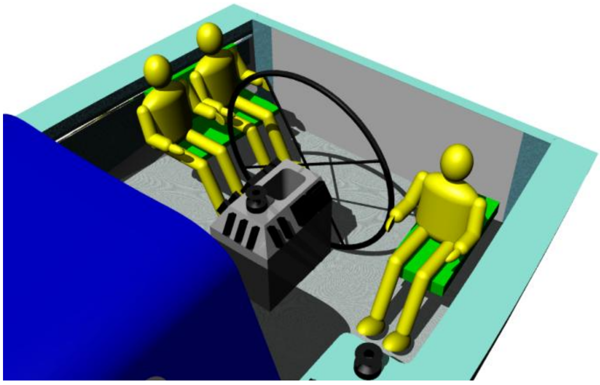

Figure 3.4.9 – Foldable cockpit Seat provide two steering positions for non-wheelchair users.

There are two modular seats at each side of the cockpit, one aft to steer and one forward to operate the lateral trim area. These seats can be used simultaneously to create a full length seat. With this simple modular seat and wheelchair accessibility a wide range of possibilities is given for the crew operation. For example, Figure 3.4.10 presents a possible crew configuration for a cruising situation with the crew members positioned sideways for a social environment, while Figure 3.4.11 illustrates an alternative crew configuration during a race with the sailors facing front or focused on the sails.

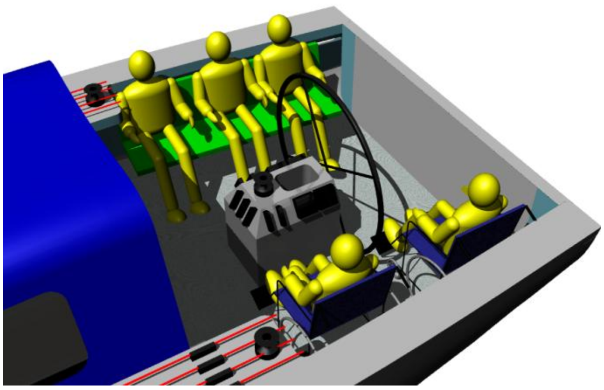

Figure 3.4.10 – Possible cruising configuration.

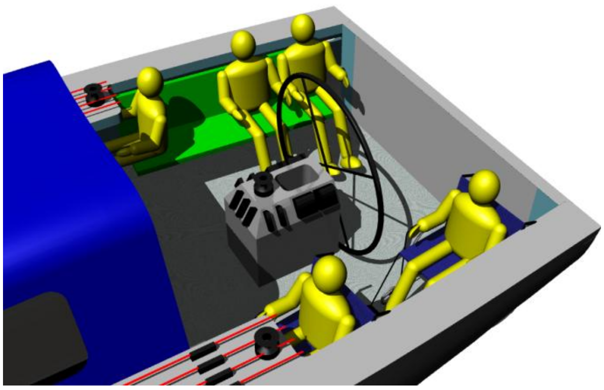

Figure 3.4.11 – Possible racing configuration.

Nowadays, electronic equipment provides most useful information and the respective displays require a visible position. They are placed at the central station on an angled surface for an easy view from the steering position. The motor handle is also placed at the starboard side of the central station while the lights panel is at the port side covered with a plastic hard surface.

3.4.2 Saloon

Figure 3.4.12 is a lateral view from the *Hallberg Rassy 31* (*www.hallberg-rassy.com*), presented to illustrate that conventional yachts have a dark saloon, inside the vessel and isolated from the environment and the crew. In contrast, the Figure 3.4.13 presents the same view of the *Inclusion* 32 with the saloon designed to be the continuation of the sailing area, which gives to the saloon users a feeling of integration with the crew. This configuration was designed to accept very disabled people onboard, because if someone doesn't have ability to cope with the sailing tasks it is possible to seat comfortably in the saloon and presence all the activity, as well as communicate with the rest of the crew and enjoying a sailing day. The saloon is protected from the wind, sun and sea spray by the cabin top but still in close contact with the environment by the large windows.

Figure 3.4.12 – *Halberg Rassy 31* lateral view ().

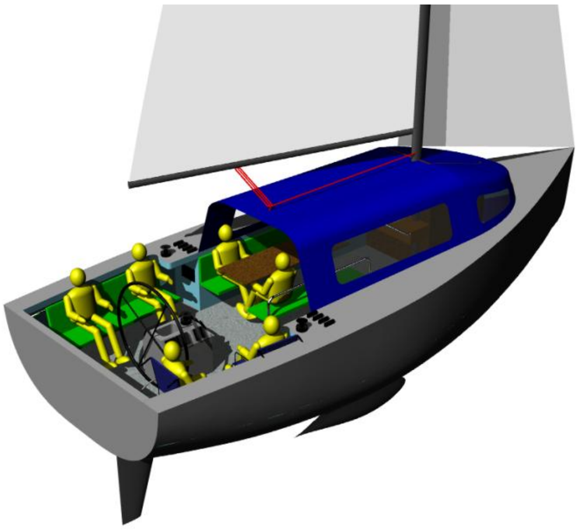

Figure 3.4.13 – *Inclusion 32* lateral view.

The saloon seats have 1.8m length and 40 cm width for a maximum of four people at each side, elevated 45cm above the floor. The starboard side seat is also modular and may be stored at the sole level to give room for a wheelchair approach. The table has 1.8 m length and 60cm width, elevated from the floor 80cm which is sufficient for a close wheelchair approach to the surface (Annex 3, Figure 8.4.4 left). The Figure 3.4.14 illustrates the sequence of steeps for a wheelchair positioning in the saloon, the table folds at the middle to increase the passage way width between the table and the central hand rail to 70 cm, and is unfolded after the wheelchairs turn to face the table. The saloon was designed to be a dormitory in harbours or while sailing at night, the table is lowered to the seats level to form a plane surface of 1.2 m x 1.8 m for two people sleep as presented in Figure 3.4.15.

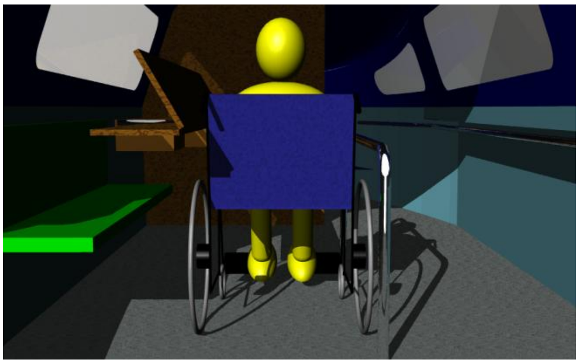

Figure 3.4.14 –The table folds at middle to increase the passage way width.

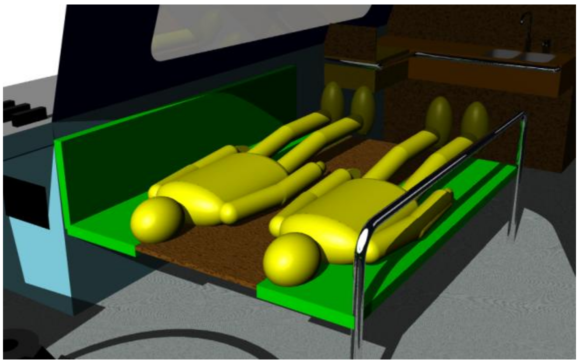

Figure 3.4.15 – Saloon table and seats create a bed for two people.

3.4.3 Galley

The galley was designed to be out of the passage way between the sailing area and the other compartments. It is wheelchair accessible with clear room for legs under the surface for wheelchair users' approach, as presented in Figure 3.4.16. The height of the double sink and stove is 82 cm above the sole, designed according to the Universal architecture dimensions to suit wheelchair users and non-wheelchair users (Annex 3, Figure 8.4.3). The galley was designed with "L" shape to minimize the body movement required to access all the surfaces. There are two cutting surfaces, a double sink, a fridge place at the corner with a storing volume below and a gimballed stove by the side. A continues handrail was placed along the entire galley to support the cooker while sailing.

The access to the galley and forward compartments is made through a passage way with 1m width and a hand rail at each side. All the handrails were designed according to the Universal Design dimensions to suit wheelchair and non-wheelchair users', positioned at 75 cm above the floor, with 4 cm of diameter and 4 cm gap to the closest surface (Goldsmith, 2000).

3.4.4 Toilet and forward cabin

The toilet is larger than normal to be wheelchair accessible (Annex 3, Figure 8.4.8 middle). The wash basin is in front of the entrance for a straight approach and the wc was positioned in the fore-aft direction at the region of less headroom. At the inner-side of the wc is a hinge handrail and at the outer-side is a fixed handrail connecting the wc to the wash basin. The shower is taken in this compartment using the movable tap of the wash basin and the water is collected from the floor. The heights and dimensions of the wc, wash basin and grab rails were based on conventional accessible toilets (Annex 3, Figure 8.4.7).The Figure 3.4.17 presents a top view of the toilet being used by a wheelchair user. The entrance to the toilet is through a reduced swinging doorset with 1m width and the rotational axis middle, folded to the exterior side of the toilet.

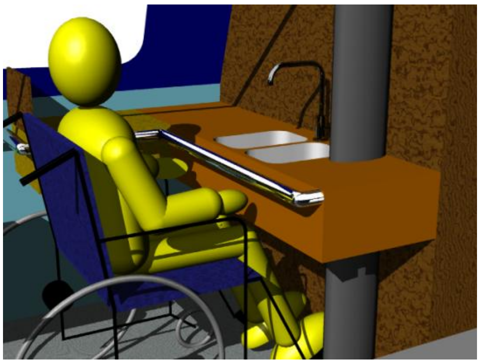

Figure 3.4.16 – Galley view.

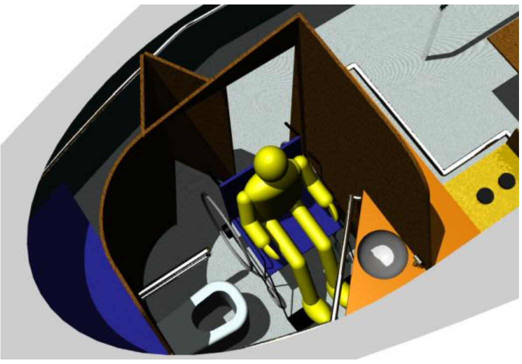

Figure 3.4.17 – Toilet view.

The toilet forward right side corner is circular to provide extra space at the forward cabin entrance. This gives space for the wheelchair to approach the bed in a slightly sideways position, which is easier than a forward approach to transfer to the bed. The bed was designed for two people with 2m long and the forward cabin is closed by a curtain.

At the end of the general arrangement discussion it is concluded that the initial complex of simplicity and no lifting equipment was essential to accept people with different abilities. Mobility based on wheelchairs guarantees the normal independence to the users and the modular seats adapt the *Inclusion 32* to the non-wheelchair users. These considerations were taken to solve the mobility problem; however the wheelchairs operation still requires a low heel angle subsequently considered by the hull shape and appendage design.

3.5 Hull Shape

This section describes the design considerations taken to define the final hull shape. Initially, the main dimensions were analysed according to a data base of similar yachts and statistical information from the literature. Afterwards, the *Inclusion 32* lines drawing is examined according to the design requirements.

3.5.1 Hull dimensions analysis

The dimensions used for the hull dimensional analysis are according to the light ship condition. The prismatic coefficient and the position of the longitudinal centre of buoyancy are evaluated for the half loaded condition (lightship plus crew and tanks half loaded), since use is made of values presented in the literature for this condition. Two keel versions will be proposed for the present project in the Appendage Design chapter, with different displacement and draft the present analysis refers to the Short Keel version. The Table 3.5.1 give the main dimensions and coefficients for both weight conditions. The longitudinal centre of buoyancy (LCB) is given in percentage of waterline length forward of amidships.

Table 3.5.1 – *Inclusive 32* main dimensions (Short Keel).

	Light Ship	Half Load
Disp. [tonnes]	6.382	6.82
L_{OA} [m]	9.8	9.8
L_{WL} [m]	9.0	9.1
B_{MAX} [m]	3.6	3.6
T [m]	1.85	1.85
Tc [m]	0.49	0.52
FB [m]	1.25	1.22
LCB [%]	0.8	-0.3
Cp	0.58	0.58

A data base with the main dimensions of modern cruising yachts with similar size is made to evaluate the present project dimensions; this information is given in Annex 4. Table 3.5.1 presents the *Inclusion 32* main dimensions in the form of dimensionless ratios and compare these values with the average, maximum and minimum results obtained from the data base.

Table 3.5.2 - Comparison between the *Inclusive 32* dimensionless ratios and the corresponding data base values.

	Inclusion 32	Average	Max.	Min.
L_{oa}/B_{max}	2.72	2.91	3.07	2.75
L_{WL}/T	4.86	4.83	5.14	4.54
B_{max}/T	1.95	1.85	2.01	1.70
$L_{WL}/Disp^{1/3}$	4.85	5.21	5.66	4.63
Ballat/Disp	0.53	0.32	0.39	0.25

Length overall/Max beam (L_{OA}/B_{MAX})

The present project beam was influenced by the internal volume required for wheelchair operation. In addition it is advantageous to have a wide beam because the form stability, which is the major stability component at low angles of heel, is inversely proportional to the L_{OA}/B_{MAX} ratio. These requirements are according to results presented by the Table 3.5.2 where the *Inclusion 32* has a L_{OA}/B_{MAX} slightly lower than the data base minimum value.

Draft (T)

The draft of a cruising yacht is a trade-off between performance and practical advantages, like the possibility of entering more shallow waters, ease of handling ashore, etc. The present dimensions correspond to the Short Keel version designed for conventional draft, consequently L_{WL}/T and B_{MAX}/T ratios are in the range of conventional values. The performance increase of a deeper keel (Long Keel version) will be discussed in the Performance Prediction chapter.

Beam waterline/Canoe body draft (B_{WL}/T_c)

Values for the canoe body draft are not published with commercial yachts dimensions; however it can be related with the waterline beam, according to experimental tank tests conducted with three models of the Delft series (Larson, et al., 2007). A beam variation was made between three models which caused changes in the beam/canoe draft ratio. The results showed that the narrow boat ($B_{WL}/T_c = 3.0$) had the smallest residuary resistance up to Froude number (F_n) of 0.375. Thereafter the medium

(B_{WL}/T_c = 4.0) boat was the best. The beamiest boat (B_{WL}/T_c = 5.35) was worse than the others in all but the highest speeds above F_n=0.4, where it became better than the narrow one. The present project operates within a Froude number range of 0.2 to 0.4 and has a B_{WL}/T_c = 6.3, which reflects a non-optimum speed performance due to the need of a wide beam.

Length/Displacement ratio ($L_{WL}/Disp^{1/3}$)

The $L_{WL}/Disp^{1/3}$ is an important ratio to evaluate the yacht performance in particular at high speeds. For a yacht to achieve surfing performance it is necessary to exceed a Froude number of about 0.45, which requires length displacement ratios above about 5.7 (Larson, et al., 2007). According to Table 3.5.2 the *Inclusion 32* is well below this value and in comparison with the data base values it is also considerably lower than the average, but within the limits. The large displacement is due to the heavy ballast carried to cope the heeling limit condition. The negative effect that this result has is acceptable for cruising yachts and as will be presented at the Performance Prediction chapter the estimated velocities for the *Inclusion 32* are satisfactory.

Ballast Ratio

For the modern fin-keel yachts the weight stability is the major stability component at large angles of heel. The *Inclusion 32* has a heavy keel bulb designed according to the stability calculations to cope with the maximum heel angle of 10º defined for disabled people operation. This requirement is evident in Table 3.5.2 where the present project ballast ratio is above the data base maximum value.

Prismatic Coefficient (C_p) and longitudinal centre of buoyancy (LCB)

The prismatic coefficient and the longitudinal centre of buoyancy are important parameters for the yacht performance but are not published with commercial information. The present project used results obtained from *Delft Systematic Yacht Hull Series (DSYHS)* and presented in *Principles of Yacht Design* to optimize these parameters. The *DSYHS* are formulations are derived from extensive series of tank tests and will be used to build a Velocity Prediction Program for the present project.

The prismatic coefficient (C_p) and the position of the longitudinal centre of buoyancy (LCB) influence significantly the residuary resistance. An optimum value for the C_p may be computed from the formula used in the Velocity Prediction Program Eq.(8.1.26) to estimate the residuary resistance (Keuning, et al., 1998). The Figure 3.5.1 presents the optimum prismatic coefficient for a range of different operational Froude numbers. The increase in residuary resistance if C_p differs from the optimum value is given in Figure 3.5.2 as a percentage of the yacht displacement.

The *Inclusion 32* is designed to have an optimum prismatic coefficient for medium wind conditions. According to the results presented in the Performance Prediction chapter, the *Inclusion 32* maximum speed with 12 knots true wind speed corresponds to a Froude number of 0.37. The respective optimum C_p is given by Figure 3.5.1 to be 0.58.

For light wind (5 knots) and strong wind (20 knots) conditions the predicted maximum velocities correspond to Froude numbers of 0.23 and 0.41. According to Figure 3.5.2 the non-optimum C_p increases the residuary resistance 0.1% and 0.02% in percentage of the half load displacement, which for the present displacement represents a residuary resistance increase of 11% for light wind and 2.2% for strong wind in percentage of the respective residuary resistance.

Figure 3.5.1 – Optimum prismatic coefficient computed from *DSYHS* (Larson, et al., 2007).

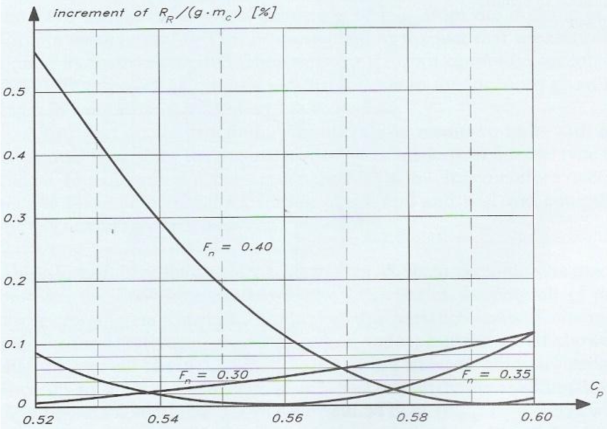

Figure 3.5.2 –Residuary resistance increase in % of displacement due to a non-optimum C_p (Larson, et al., 2007).

Figure 3.5.3 is also computed form Eq.(8.1.26) and estimates the optimum position of the longitudinal centre of buoyancy. The negative sign means aft of amidships and the number represent the distance from this section in percentage of the waterline length, being the amidships section defined at half waterline length. The residuary resistance increase due to a non-optimum LCB has also been computed and the results are given in Figure 3.5.4.

The *Inclusion 32* was designed with a non-optimum LCB, located at 0.8% of the waterline length forward amidships. This is due to the internal volume required for the wheelchair accessible toilet and passageway in the forward part of the yacht. The optimum LCB for the *Inclusion 32* medium wind performance is given by Figure 3.5.3 to be about -3.5%. The Figure 3.5.4 gives an idea of the resistance increase, but for LCB located close to amidships only Froude numbers of 0.3 can be estimated. The residuary resistance increase predicted for this situation is about 0.05% in percentage of the displacement but for higher Froude numbers the resistance increases significantly.

Figure 3.5.3 – Optimum location of longitudinal centre of buoyancy (Larson, et al., 2007).

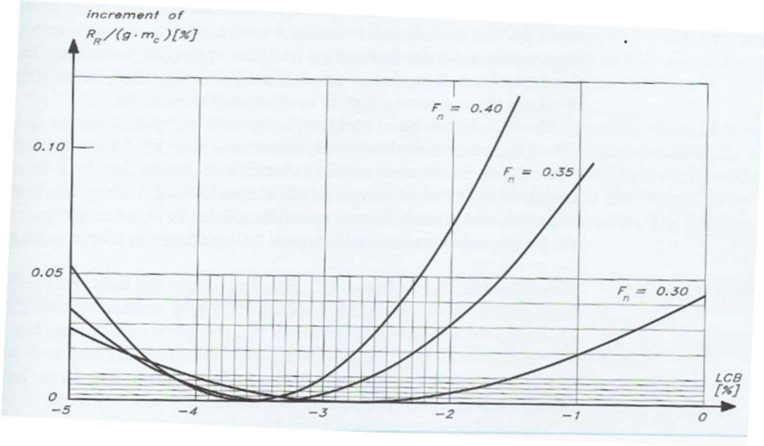

Figure 3.5.4 – Resoduary resistance increase in % of displacement due to a non-optimum LCB (Larson, et al., 2007).

3.5.2 Lines Drawing Analysis

When designing the hull shape use was made of naval architecture knowledge and the study of similar vessels. The important references are the modern cruisers *Bavaria 32* (*www.bavaria-yachtbau.com*) and the *Halberg Rassy 31.* A complete Lines Drawing of the actual hull is presented in Annex 1, and a simplified version is presented in Figure 3.5.5 with the waterline defined by the half load condition.

Edge Lines

The bow profile was designed with an almost vertical line to increase the waterline length within a constrained length overall, which may lead, assuming constant displacement, to an increased fineness of the waterlines in the forward part of the yacht, i.e. decrease in the angle which the waterlines make with the centre line of the hull (waterline entrance). Under the same assumption of constant displacement and length overall, there is also an effect on the prismatic coefficient (Cp decreases), the relative longitudinal position of the centre of buoyancy (LCB moving aft), the centroid of the waterplane area (LCF also moving aft) and the pitch radius of gyration (Keuning, et al., 2000).

The stern has a small overhang designed to accept heavier load conditions without submerging the transom which may cause flow separation and the corresponding resistance increase. The transom is designed vertical and flat, similar to the *Bavaria 32,* to create a large stern platform for the wheelchairs entry. In addition, the vertical transom increases the cockpit internal volume.

The bottom profile line was designed to increase the flow laminar region in the forward part of the yacht. Therefore, the bottom line has lower slope at the bow region and increases slightly to the stern. Attention was given to avoid large slopes in the aft part which could cause separation. The forward freeboard of conventional yachts is normally higher at the bow; however the *Inclusion 32* sheer line is restricted by the view height of a wheelchair user in the cockpit and was designed straight.

Waterlines

The waterlines were designed straight in the fore body to increase the laminar flow length. The waterlines incidence angle is considerably large which influence adversely the viscous pressure resistance. This situation is not possible to optimize since the beam is proportionally large and the large accessible toilet with the lateral passageway are located forward amidships. At the stern the waterlines end approximately vertical which guarantee a uniform bottom surface.

Cross sections

For a constant displacement and length overall, as the waterline beam increases the canoe body draft is reduced and the bottom flattens. This increases the wetted surface at the upright position, which increases proportionally the frictional resistance. Modern racing yachts are designed with a wide beam and a flat stern bottom to generate lift and achieve surfing performance for reaching and running courses. When sailing upwind, these yachts reduce the wetted surface with operation at large heel angles.

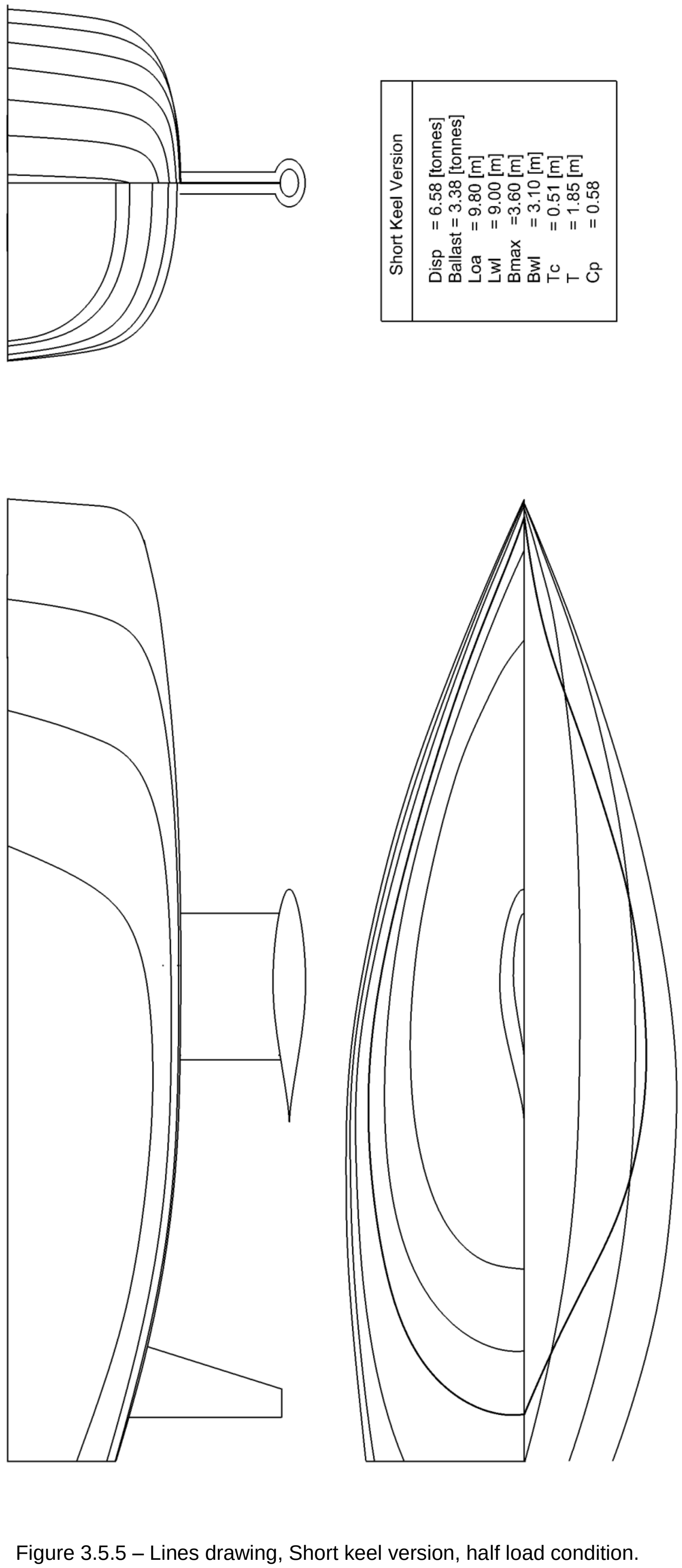

Figure 3.5.5 – Lines drawing, Short keel version, half load condition.

The *Inclusion 32* was designed to maximize the waterline beam, in order to increase the form stability and the internal volume. The underwater part was designed to avoid a flat bottom and aims for circular cross sections, because the present project does not have surfing characteristics and the circular shape is the geometry that minimizes wetted surface at low angles of heel angles.

Diagonals

Diagonals are particularly important for yacht design, because the vessel operates with a heel angle and the flow tends to follow closer the diagonals than the waterlines path. The present project was designed with smooth diagonals and particular attention was given to the fairness of the stern diagonals in order to avoid separation.

3.6 Summary

The Hull Design chapter started with the definition of the hull type, concluding that a mono-hull fits better the present project because economically it is a more viable solution. In addition, the large majority of sailing yachts are mono-hulls and was interesting to develop here some inspiring ideas to be adopted in present and future vessels, in order to increase the integration of disabled people at the sea. The most difficult problems to overcome with a mono-hull configuration were the heeling angle and small internal volume.

The design process started with the definition of a general arrangement designed to be wheelchair accessible. The idea was to create a single sole level common for all areas and free from obstructions to mobility. The accessibility of each area is guaranteed according to the dimensions advised by the Universal Design architecture. The saloon is thought to receive severely disabled people and encourage their integration with the rest of the crew. The cabin top was designed to protect the crew from the environment and large windows were designed to promote the contact with nature. Compared to conventional yachts the *Inclusion 32* has also ergonomic improvements because the physical demanding forces were designed at proper heights and aligned with the body centreline. A weakness of the present general arrangement is the forward view from the cockpit, partially obstructed by the cabin top. This problem was solved by positioning the control areas at the cockpit lateral extents.

The hull shape was designed to fit the internal volume required for wheelchair operation and to increase stability at low angles of heel. The analysis made of various dimensional parameters evaluates the global geometry of the vessel according to a data base made with similar designs. This evaluation guaranteed the dimensional consistency and underlined the extreme design characteristics, namely the large beam and heavy ballast weight. The effects of these unusual characteristics were tested at the Performance Prediction chapter and as will be seen provide satisfactory results and good confidence on the design decisions taken through this chapter.

4 Structural design

The present chapter describes the procedure and assumptions taken during the structural design process. It was decided to apply the ISO 12215-5 standards, because soon it will be a mandatory requirement for all pleasure vessels boats in the European Union market. This project used a draft version of the rules (ISO/DIS12215-5.2, 2004). The results obtained from the *ISO Standards* were compared with an alternative scantling procedure (Gerr, 2000) to validate the structural design.

The structural design is an important factor in terms of the yacht performance, reliability and cost. The objective of the present design was to produce a safe structure, to withstand an extensive use during a long service life, which often happens with sailing school boats. As the vessel is intended for disabled people with the associated limitations, it was expected that through its life it may suffer from several damaging situations, requiring a solid construction, effective protection of weak areas and easy repair. The materials and construction methods chosen for the *Inclusion* 32 used low-cost technology and were thought to be building in Portugal, where most boat-builders still use single skin hand-layup. The chapter starts with a brief description of the main loads acting on a sailing yacht and then presents all the steps taken to the final structural arrangement.

4.1 Principal loads

The Figure 4.1.1 shows the windward side of a sailing yacht beating into the wind. The shaded arrows indicate the global loads imposed on the hull girder from the rigging forces, increased when the yacht is in a sagging situation. The hull girder is subjected to bending which gives compression forces along the deck, tension along the bottom and shear forces in the topsides. On top of this, there is transverse tension in the shroud area. Sailing in rough and steep seas might induce hull hogging also, not enough for the bending moment to change sign because the rigging forces are too great to let that happen, but creating a pulsating compression and tension in the hull with the inherent risk of fatigue in the long run (Larson, et al., 2007). Furthermore, there is the local loading, the hydrostatic pressure, and additional loading from slamming in the forward part of the boat, which tries to buckle the plating and bend the stiffeners. These are the most important loads to consider when defining the structural arrangement and calculating the dimensions of the shell and stiffeners.

The yacht hull also acts as a hydrodynamic body and absorbs the loads transferred to it from the sails through the rig, appendages and the seaway motion. The combination of these loads causes the yacht to respond in different ways, for instance hull bending and torsion. The response of the yacht to the loads is controlled by its hull, deck and topsides acting as a box beam. Internal structure such as bulkheads and stiffeners are used to disperse concentrated loads more evenly back into the box beam membrane and to stabilize the hull shape (Payne, et al., 2008).

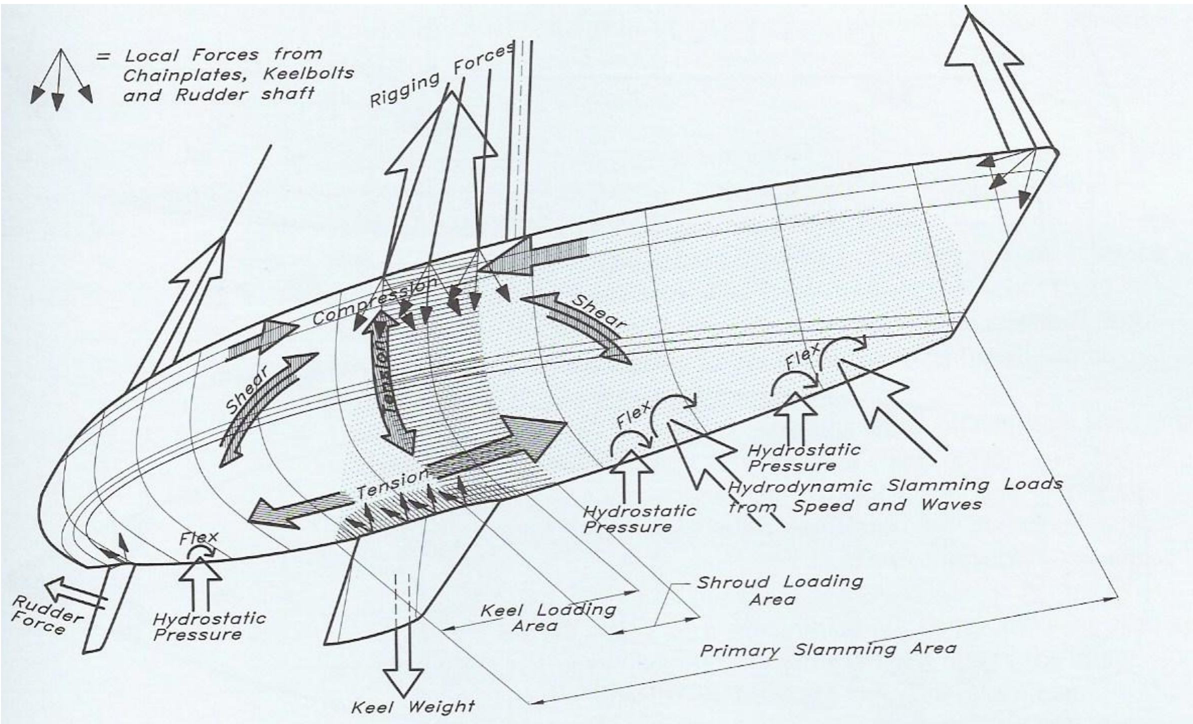

Figure 4.1.1 – Forces acting on a sailing yacht (Larson, et al., 2007).

4.2 Materials and construction methods

The selected materials and construction methods intend to minimise as possible the final cost, regarding it is solid enough to survive a long life dealing with inexperienced people. The most widely used reinforcement in the boat building industry is the E-glass. There are better materials strengthwise, but the combined cost, strength and effectiveness has not been equalled (Du Plessis, 2002). Glass reinforcements exist in a variety of shapes, the most common type is the chopped strand mat (CSM), which consists of short fibres, 4-5cm long, evenly distributed and held together by a binder, with more or less isotropic properties. The Woven Roving (WR) is the other commonly used reinforcement. Having long continuous strands it is stronger than mat and more sensible to the direction of the load. Being woven, the long fibres do not intermesh so interlamina bond is weak. It is recommended to interlayer WRs with CSM, where WRs support the main loads while the CSM ensure sufficient interlamina strength(Du Plessis, 2002). Manufactures of glass reinforcement developed a mat/roving combination (Combi-mat), a roving sew to a mat, to reduce the lay-up process.

An important parameter regarding strength properties of the laminate is the fibre content, expressed as a percentage of the total laminate weight. With a mix of CSM and WR in the laminate the fibre content usually varies from 35% to 45% according to the building quality. For the scantling calculations the glass content and laminate thickness are estimated from the *ISO Standards* (ISO/DIS12215-5.2, 2004) and are presented in Table 4.2.1.

The most common matrix for fibreglass reinforcement is the ortho-polyester resin. The liquid polyester is mixed with a catalyst and an accelerator to solidify. Gel coats are also polyester resins specially formulated to be applied on the mould surface to give good appearance, colour, avoid cracking, and resistance water infiltration.

Table 4.2.1 – Glass content and thickness for the chosen fabric style and weight.

Specification	Fabric Weight [g/m^2]	Thickness [mm]	Glass Content
CSM			
1.0 oz CSM	305	0.71	0.3
1.5 oz CSM	457.5	1.07	
WR			
18 oz WR	610	0.79	0.48
24 oz WR	814	1.05	
Combi - Mat			
18-10 Combi-Mat	915	1.45	0.41
24-15 Combi-Mat	1271.5	2.02	0.41

In terms of panel construction, the options were sandwich and single skin laminate. The greatest advantage of sandwich construction compared to solid laminate is the increase in strength and stiffness without a corresponding increase of weight. However, due to practical considerations the outer skin cannot be made to thin or else will be insufficient strength to withstand docking, grounding and boatyard handling. This means that the weight advantages are not so apparent in yachts below 9m (Larson, et al., 2007). It is also considered that sandwich is more easily damaged than single skin, being at the same time more difficult to repair. Delamination is the commonest defect that may occur through damage, use, age, ingress of water, and poor construction. It occurs mainly in sandwich panels, between the outer skin and the core. Due to the previous reasons it was decided to use single skin construction because it is less expensive, more reliable and easier to repair. The weight increase is acceptable for the *Inclusion 32* intended use, even though it is expected to be small since the project length is close to 9 m.

Generally, hand lay-up is the industry standard laminating method. A properly hand-laid-up hull has smooth surfaces, a constant thickness and mechanical properties adequate for the majority of average vessels (Gerr, 2000). The normal building produce starts with a hollow female mould, which then is coated with a mould-release agent, alternating next layers of resin and reinforcement. It is possible to reduce weight and increase performance by adding to the lay-up a vacuum bag before the resin cures. Some of the air is sucked out by a pump, causing an even pressure on the entire plastic sheet. Vacuum-bagged laminates are denser, with less resin in proportion the fibre reinforcement and higher mechanical properties for the same thickness. Even though, it was decided to use common hand lay-up because it has a better performance/cost relation for the intend use of the vessel.

To summarize the materials and construction methods selection, it was chosen to construct a single skin hand laminate, of ortho-polyester resin, reinforced with alternate plies of woven roving and chopped stand mat made of E-glass.

4.3 Structural layout

A fibreglass boat is essentially a thin shell made of expensive material, it is wasteful to build thickness so it requires a stiffening system. The easiest form of stiffener for fibreglass is the top hat stiffener, which is made by fibreglass moulded over a core to form a channel section.

The *Inclusion 32* longitudoinal stiffening is presented in Figure 4.3.1, with two engine beds located equidistant from the centre line and two lateral stingers. The single sole planform was also considered to act as a stiffener. The engine bed stringers are the principal longitudinal stiffeners, they run continiously over the bottom between the aft bulkhead and the 2nd bulkhead because high loaded stringers should end at a transversal stiffening componente. From 2nd bulkhead to the forward bulkhead the engine beds were reduced to one bow stringer.

The lateral stringers run contiuously from the stern to the forward bulkhead and were designed to support the hydrostatic and slamming loads applied when the hull is heeling. To support the sole planform was designed a longitudinal stiffener located at the centre line, to divide the sole panels and distributes concentrated loads like the crew weight. In addition, a set of longitudinal and transversal floors were designed at the hull bottom keel area. These floors provide additional strength to the bottom and spread the high concentrated loads applied to this critical area.

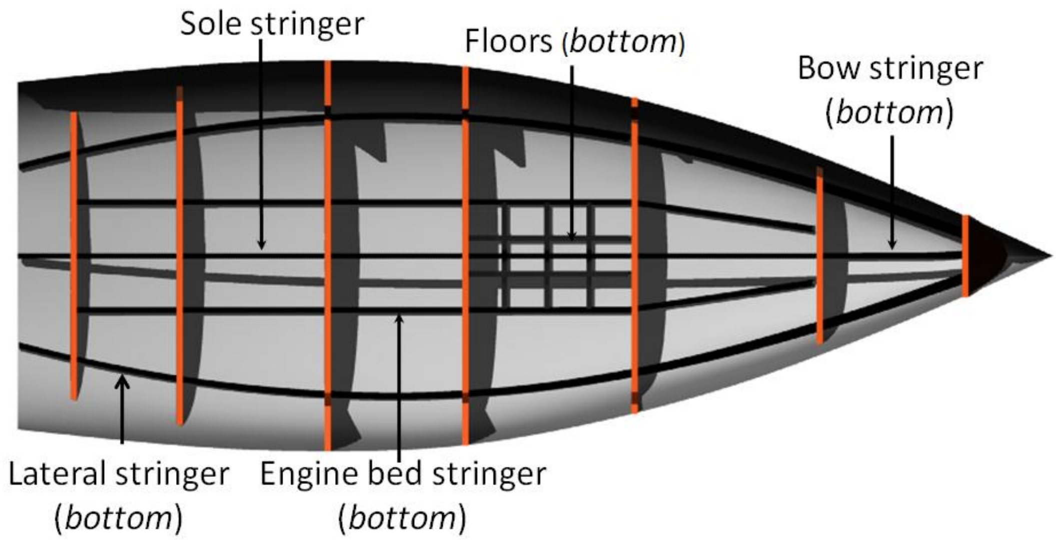

Figure 4.3.1 – Longitudinal stiffen configuration.

A set of transverse bulkheads were designed to strength the torsion rigidity of the hull/deck beam, in order to resist the rig's transverse forces and other concentrated loads. It was chosen to use watertight plywood bulkheads, because it is cheaper and lighter than fibre glass, for the same weight eight times stiffer, as well as less inclined to delaminate (Du Plessis, 2002). Sandwich bulkheads could also be used but are more expensive and time consuming. The extent bulkheads are dimensioned according to the *ISO* standards to be crash bulkheads. The 3rd, 5th and 6th bulkheads are positioned to withstand a concentrated load while the other bulkheads are placed to reduce the unsupported length of the panels as presented in Figure 4.3.2.

Starting from the bow, the forward bulkhead was angled backwards to increase the bow storage space and produce a larger opening from the deck, while consuming a useless volume of the forward cabin. The 2nd bulkhead was placed at middle distance to the 3rd bulkhead in order to divide the unsupported length of the panels at the critical slamming area. The 3rd bulkhead was positioned at the mast location and withstands the mast and rig loads plus the keel torsion effect. The 4th bulkhead was placed at the end of the keel in connection with the floors, to withstand the torsion loads of this area. The 4th bulkhead was also positioned to withstand the concentrated loads at the aft edge of the keel in a situation of going aground or colliding with a submerged object. The 5th bulkhead was placed close to the end of the top cabin to support the loads from the main sheet, lateral trimming lockers and winch. The 6th bulkhead was positioned under the central station, to withstand the loads from the halyards and other lines locked to this box. The aft bulkhead was designed to be a collision bulkhead and to support the loads from the rudder.

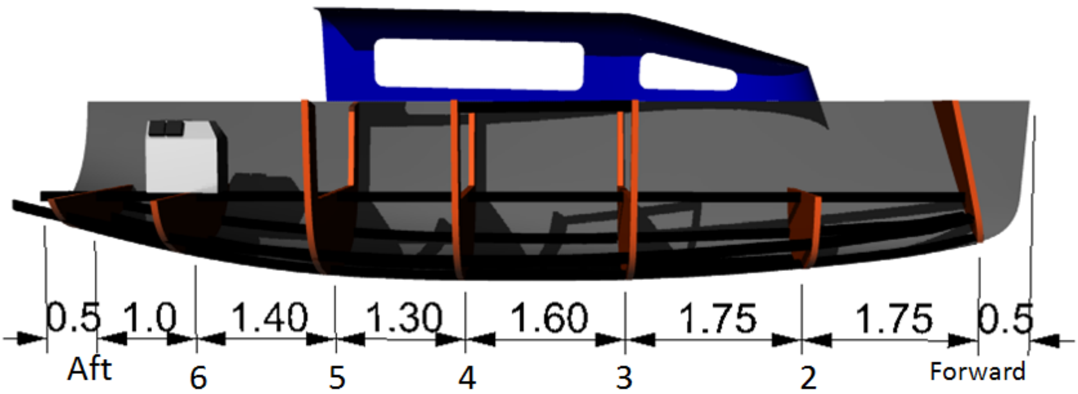

Figure 4.3.2 – Bulkheads location (m).

The height of the internal stiffeners in conventional yachts is limited in order to don't interfere with the interior headroom. This was not a problem for the present project and a more efficient structure could be designed. Therefore, the vertical height of the longitudinal stringers could be increased and the conventional ring frames were substituted by watertight bulkheads below the sole level. The *Inclusion 32* has structural arrangement close to the conventional ship double bottom which is a considerable safety improvement, it was considered that most collisions are bow against topsides, the bow is strong and sharp while the topsides are not, being the last boat the one who sinks. Also, most of the accidents occur by hitting something under water, in both situations the collision bulkhead is not useful and a double bottom makes more sense (Du Plessis, 2002).

4.4 Structural calculations

The present structure was dimensioned to obtain *ISO* approval, using the material and construction methods previously defined. An alternative method presented by *The Elements of Boat Strength* (Gerr, 2000) was used to validate results obtained from the *ISO* standards, because the present project used a draft version of *ISO* rules. Both scantling procedures divide the boat in specific areas (bottom, side, deck and superstructure) and calculated the required thickness for the chosen material. The bottom is defined by the *ISO* rules to be the area from the bottom of the canoe body up to 150mm above the waterline in the fully loaded condition. For the present structure was decided to increase this area up to 150mm above the sole level, because the bottom is normally thicker than the sides and support better the loads from the unconventional single sole level. The side is the area from the bottom extent to the sheer line.

The *ISO Standards* assume that the forward part of the yacht is the most critical due to slamming loads and it is possible to reduce the laminate thickness from $0{,}6L_{WL}$ backwards. This weight saving was considered to be not relevant for the intended use of the present project and was decided to apply a longitudinally constant laminate thickness for whole bottom because it is easier to build.

Hull panels

The following results, evaluate the required shell thickness from the *ISO Standards* and *Elements of Boat Strength* for the main areas of the hull. The calculations were made for different panels of each specific area and the results presented in Table 4.4.1 correspond to the maximum thickness required. The *ISO Standards* are assumed to be the mandatory requirement.

Apart from the bottom panels the *ISO Standards* provide more conservative results. At the bottom the *ISO Standards* require less thickness than at the sides, because the present structure has the conventional stiffener configuration plus the sole planform which works as an additional stiffener. It was decided not to change the stiffeners geometry since the engine beds are essential, and without lateral stringer the unsupported area from the engine beds to the floor level was excessively large. It was decided to apply a uniform thickness to the bottom and sides defined by the side value in order to increase the reliability of the hull shell and simplify the building procedure.

To protect the bottom from severe impacts like grounding the *Elements of Boat Strength* advice to increase the laminate thickness at the keel area (assumed to be the area inside the engine beds and the 3rd and 4th bulkhead) by 1,5 times the bottom laminate. It was also suggested to increase the laminate thickness by 1,25 times at high-loaded hardware areas for example, mooring cleats, winches and chainplates. These areas should extent the base of the hardware and to be at least two times the hardware footprint in all directions.

When defining the laminate schedule it was essential to search for uniform materials and building patterns because it is easier to construct, the material wastage is reduced and the builder will get better prices buying large quantities of the same material. According to the previous material selection, Table 4.2.1, it was still necessary to specify the weight of reinforcement to use. From the structural point of view, it is better to have more plies of a thinner reinforcement than a heavier one, though this requires more labour and the respective cost increase. Calculations were made for 24-15 Combi-Mat and 18-15 Combi-Mat, concluding that the thinner solution requires in average two more layers of reinforcement. If the building method were resin infusion or even vacuum bagging this would not represent a significant increase in the cost; however for hand layup it represents an increase of about 33% of the total lamination time. Therefore it was decided to build the laminate with layers of 24-15 Combi-mat and add a single layer of 1.5 oz Mat if a small increase in thickness is required.

The laminate specified in Table 4.4.2 defines the entire vessel to be made of the same fabric styles and weights (i.e. 24-15 Combi-mat and 1.5-oz mat). In addition, the construction layup process is most straight forward: skin coat and gel coat are applied, followed by four layers of 24-15 Combi-mat at all parts of the vessel and a single layer of 1.5-oz mat is added to the bottom and side. The keel area and the hardware areas have one extra layer of 24-15 Combi-mat. The sole laminate is equal to the upper deck.

Table 4.4.1 – Hull Shell thickness.

Panel Location	Minimum thickness [mm]	
	ISO Standards	Elements of Boat Strength
Bottom	7.46	9.47
Side	8.83	7
Deck	8.12	7
Superstructure	8.13	7
Keel (Bottom)	11.19	
Hardware Areas (Deck)	10.15	

Table 4.4.2 – Laminate schedule.

Laminate construction			
Panel Location	Number of layers		Final Thickness [mm]
	24-15 Combi-Mat	Mat	
Bottom	4	1	9.2
Side	4	1	9.2
Deck	4	0	8.1
Superstructure	4	0	8.1
Keel (Bottom)	5	1	11.2
Hardware Areas (Deck)	5	0	10.1

Internal structure

The following results, evaluate the minimum dimensional requirements for the internal structure elements, from the *ISO Standards* and the alternative method from *Elements of Boat Strength*, once again the ISO Standards are assumed to be the mandatory requirement. The longitudinal stringers were designed to have constant cross-sections with dimensions defined by the segment more loaded, the results are given in Table 4.4.3. The *ISO Standards* requires this time a less conservative result, which is balanced by the thicker shell panels.

The structural bulkheads were defined to be watertight in both methods. The chosen plywood material has 7 plies and a density of 400 kg/m^3, the respective mechanical properties are given in the *ISO Standards*. The results are presented in Table 4.4.4 for both scantling methods.

Table 4.4.3 – Top hat stringer dimensions.

Rule	Dimensions		
	h [mm]	b_b[mm]	t_p [mm]
ISO Standards	75	75	5
Elements of boat Strength	99	99	6

Table 4.4.4 – Plywood bulkhead thickness.

Rule	Thickness [mm]
ISO Standards	14.0
Elements of boat Strength	14.4

The building procedure for the stringers is: shape a foam core to the cross section dimensions, place above it two layers of 24-15 combi-mat, plus one layer of 1.5oz mat, apply the resin to each layer and finally apply a thin layer of gel coat to protect the composite from humidity. The building procedure for the bulkheads is: draw the bulkheads over the plates of plywood in order to minimise wastage, cut it and finally apply a thin layer of polyester resin on both surfaces to avoid the degradation.

4.5 Structural details

The contact between the bulkheads and the shell can cause stress concentrations that weakens the hull. Before installing the bulkhead, a backing strip of of 24-15 Combi-mat with 112mm width (like a ring running transversally around the hull) was decided to be applied for the bulkhead to land on (Gerr, 2000).

The *ISO Standards* do not present a rule to dimension the keel bolts. The load per bolt was calculated with the *Elements of Boat Strength* according to Eq.(4.5.1) and a safety factor of 8 advised by the same reference. The Ballast Depth is the distance from the hull bottom to the underside of the ballast and the Bolt Bearing Distance is the average distance from the one row of bolts to the opposite side of the top edge of the ballast keel (Gerr, 2000). It was decided to use 16 stainless steel keel bolts, 8 at each side and according to the results presented in Table 4.5.1 was decided to use bolts with 22 mm of diameter and an ultimate tensile strength of 12 900 kg (Gerr, 2000).

$$Load\ per\ bolt = \frac{SF \times\ Ballast\ Depth \times BallastWeight}{2 \times Bolt\ Bearing\ Width \times n.of\ bolts\ on\ one\ side} \qquad (4.5.1)$$

Table 4.5.1 – Data used for keel bolts dimension (Short Keel version)

Number Bolts (each side)	8	
Safety Factor (S.F.)	8	
Ball st Depth	1.34	[m]
Bolt Bearing Width	250	[mm]
Ballast Wheight	3381	[Kg]
Load per Bolt	9061	[Kg]

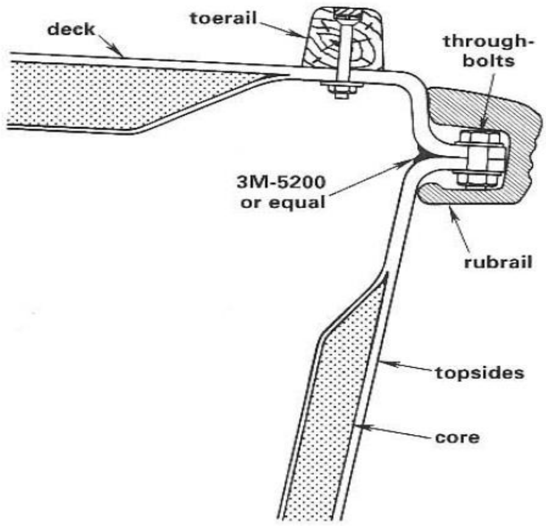

Figure 4.5.1 – Out-turned flange hull to deck joint (Gerr, 2000).

There are different types of hull-to-deck joint according to the hull construction, boat type and desired finished appearance. For the *Inclusion* 32 it was decided to use the out-turned flange joint, illustrated in Figure 4.5.1, because it is suggested to be the most reliable and practical solution (Gerr, 2000). The topsides are turned outboard to form a flat shelf at the sheer, and the deck is extended outboard to form a matching flange above. During assembly, the deck can be rested on the hull and manoeuvred around for a proper fit. The parts are then clamped in place, marked and drilled for the vertical through-bolt fasteners. Then the deck is lifted off, bedding compound is applied, and the whole is reassembled and bolted together permanently. The joint is finished with a vinyl, aluminium or wooden rub strip, which hides the joint and acts as an effective chafe guard. Most commercial yachts choose other joints mostly due to aesthetic reasons, avoiding the not good looking rubrail. However, this vessels is designed for people with limitations and it must withstand small collisions in particular when lying alongside, either on another boat or marina berth. The hull-to-deck joint is a critical area and in most situations the rubrail is an effective way to protect the vessel and may even avoid the need of fenders, in case of damage this solution provides easy repair.

4.6 Weight Calculations

The subsequent calculations estimate the total weight of the vessel's structure. The mass of each component was obtained from the reinforcement weight and the glass content (by mass). The final mass of the hull and the respective components are given in Table 4.6.1. The longitudinal position of the centre of gravity is measured from the vessel aft extent, while the vertical position is measured from the hull bottom base line and the transversal position is measured from the centreline.

Table 4.6.1 – Mass and location of the hull centre of gravity.

Component	Xcg [m]	Ycg [m]	Zcg [m]	Mass [kg]
Hull (Bottom and side)	4.55	0.00	0.69	687.4
Ground plane	3.45	0.00	1.43	467.9
Deck	5.01	0.00	2.33	199.6
Superstructure	2.08	0.00	0.85	277.7
Total Stringers	4.53	0.00	0.39	83.4
Total Bulkheads	4.25	0.00	0.63	67.1
Total Reinforcement	4.61	0.00	0.35	16.4
Gel Coat	3.83	0.00	1.04	45.0
Total	3.83	0.00	1.04	1 844.6

4.7 Summary

The structure was designed to be reliable and to withstand an extensive use during a long service life, which is the common use for sailing schools. As the vessel was designed for disabled people with the associated limitations, it was expected that through its life it may suffer from several damaging situations, requiring a solid construction, easy to repair. These considerations lead to the use of single-skin laminate, made of E-glass and polyester resin. It also requires protection of weak areas, in particular the hull-to-deck joint was protected by a rubrail.

The scantlings are defined according to the *ISO* Standards and these results were validated with an alternative method proposed by *Elements of Boat Strength.* Additional structural details are considered to improve the vessels reliability. The layup schedule was defined according to the *ISO* minimum requirements, except at the bottom where the laminate wass increased to the sides thickness, keel area and hardware areas. It was chosen to use only one reinforcement type and the building sequence is designed to be simple. Finally, the total weight and centre of gravity of the hull structure was calculated from the values of the respective elements.

5 Appendage Design

The previous chapters defined the general arrangement, hull shape and structure according to the intended use of the vessel and the particular needs of disabled people. The general arrangement focused on a suitable layout for wheelchair operation, while the hull was concerned with the required internal volume and form stability. The present chapter will continue the aim to minimise the heel angle in what concerns the sails and underwater appendage design.

The easiest way to reduce the heel angle is either to design a reduced sail plan or a heavy keel, and this relation was a critical part of the project. However, the sails affect considerably the outward image of the vessel, which means that a yacht with proportionally large sails of high aspect ratio looks more attractive than the same hull with smaller sails. The same doesn't happen with the underwater appendages because they are unseen. Therefore, it was decided that the "good looking" of the yacht was a relevant characteristic and the design aimed for a relatively conventional sail plan balanced by a heavy or deep keel.

The definition of the sails planform was the initial part of the appendage design since data was available from similar yachts. Only afterwards the underwater appendages were considered because use was made of dimensionless ratios presented in the literature to relate the underwater appendage lateral area with the sails area already defined. Two different keel configurations were designed with the same lateral area and initial transversal stability. A Short Keel version was designed according to the dimensions of similar yachts to have a conventional draft, while a Long Keel version with higher draft was designed to improve the yacht performance. The relation between longitudinal position of the sails and the underwater appendages was considered to achieve directional stability.

The methodology used for the appendage design starts with a review of the theory and experimental results relevant for the present project and subsequently presents the practical design decisions justified with the previous information.

5.1 Sails design

From the yacht design point of view the sails aspect ratio and sail area are the most important parameters to consider. Other characteristics like the sail roach, camber and twist are normally studied independently by the sail maker. The aspect ratio affects the sail effectiveness according to the angle of attack, while the sail area affects the magnitude of the sail forces. Here, aspect ratio (AR) is defined as the luff length (P or I) divided by half of the foot length (E or J).

$$AR_{Main} = \frac{P}{E/2} \tag{5.1.1}$$

$$AR_{Jib} = \frac{I}{J/2} \tag{5.1.2}$$

5.1.1 Wind-tunnel experiments

Interesting wind-tunnel tests are reported by C A Marchaj with sails of varying aspect ratios (Marchaj, 2003). The Figure 5.1.1 shows a polar diagram of force coefficients for four aerofoils having the same camber but different aspect ratios AR=6, 3, 1 and 1/3. For small angles of incidence up to 10º, relevant to close hauled work, the sails can be placed in order of merit corresponding to their aspect ratios, being AR=6 the best. This sail can develop larger forces at smaller drag angles (ε_A), which is a consequence of having a low induced drag.

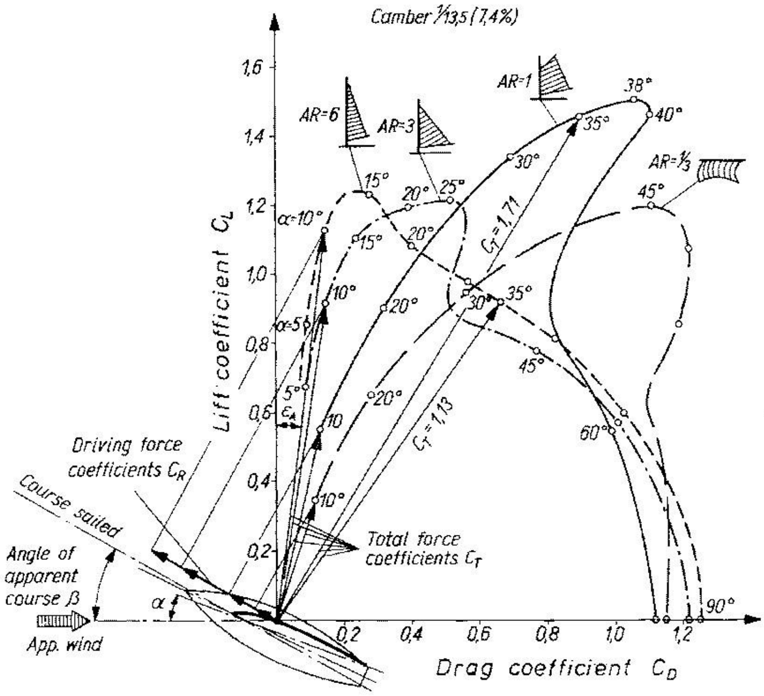

Figure 5.1.1 – The qualitative effect of aspect ratio on the aerodynamic properties of sails (Marchaj, 2003).

The efficiency of the high aspect ratio sails at low incidence angle is theoretically explained by the aerodynamic drag formulations, Eq.(8.1.20), discussed in the Performance Prediction chapter. The induced resistance is directly proportional to the lift coefficient squared, which is maximum at low angles of incidence. On the other hand, it is inversely proportional to the aspect ratio. Therefore, at low angles of incidence the induced resistance is the relevant drag component and a high aspect ratio minimizes it.

In order to assess the advantages of one rig over another it is necessary to consider all sailing courses. For races over a triangular course, where windward ability is of prime importance the high aspect ratio rig is better. While in cruising passage or off-shore races where upwind sailing may not prevail, the lower aspect ratio yacht is superior. The Figure 5.1.1 shows that there is no sail better than other and the optimum aspect ratio changes according to the angle of incidence. However, at the respective optimum angle of incidence the lower aspect ratio sail produces higher total force.

The mast also reduces the positive effect of the high aspect ratio main sail. For a given sail area, the higher the aspect ratio, the thicker the mast and the smaller the average chord length of the main-sail.

Both effects tend to increase the proportion of the sail which is ineffective due to the mast disturbance (Larson, et al., 2007).

Similar qualitative trends have been observed in the case of slope-rigged models of three different aspect ratio presented in Figure 5.1.2 and wind-tunnel tested (Marchaj, 2003). This time the relative merits of the three rigs are evaluated according to different distributions of sail area between the main and jib, all sailing close hauled. This study is particularly interesting for the present project because it evaluates the ratio of driving force coefficient to the heeling moment as a criterion. The underlying assumption was that at the same heading angle if a rig develops a larger driving force at an equal or preferably smaller heeling moment than another rig, it can be considered superior. Again, no one rig was superior over the whole range of heading angles from 15 to 30 degrees. Up to 22 degrees the sail plan A is clearly better than B or C, but beyond this heading B and C gradually improved their performance.

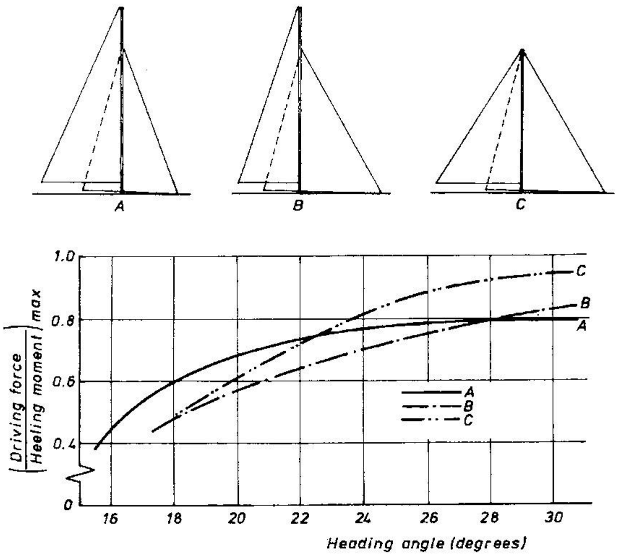

Figure 5.1.2 – The relative merits of three rigs with different area distribution(Marchaj, 2003).

5.1.2 Sails statistics

Until now only the aspect ratio has been considered, to judge whether the sail area is large enough it must in some way be compared with the resistance characteristics of the yacht, which may be the wetted surface or the displacement. The former is proportional to the frictional resistance which is dominant at low speed, while the latter is proportional to the wave resistance, the largest component at high speeds. Suitable non-dimensional parameters to evaluate the sail area are therefore: sail area/wetted surface and sail area/(volume displacement)$^{2/3}$.

Statistics presented by *Principles of Yacht Design*, based on the *IMS* (*International Measurement Standard*) fleet in the USA, show that practically all the boats have a sail area/wetted surface ratio between 2.0 and 2.5, with mean value equal to 2.25. The sail area/displacement ratio defined above, is within 15 and 22 for the vast majority of the yachts and the mean value is 19. The sail area is defined as the sum of the fore and main triangle, and the average area distribution between the two triangles in the *IMS* fleet is in 50/50. The minimum main sail is 27% and the maximum one is 58% of the total area. Data is also given for the mainsail aspect ratio with average equal to 5.9 and the minimum and maximum are 4.2 and 7.0 respectively.

According to the dimensions collected from the data base of modern cruising yachts made for the present project the results are not exactly the same. The data base average, maximum and minimum values are presented in Table 5.1.1 The sail area/displacement ratio is within 15.6 and 19.6, these limits are according to the *IMS* statistics but the mean value of 16.9 is considerably lower. The average area distribution between the sails is 53/47. The main aspect ratio varies from 4.5 to 5.8 being 5.5 the mean value. While the jib aspect ratio varies is between 6.4 and 7.1 being 6.7 the average value.

The yachts are usually measured for the *IMS* fleet to be part of races, which doesn't mean that all of them are racing boats; it is similar to cars, which have races of all types of cars. However the majority is interested in racing performance and it is relevant to note the differences between the *IMS* statistics and the modern cruiser data base. The sail area/displacement ratio from the IMS fleet is considerably higher, denoting the interest in speed performance. The average distribution of sail areas indicates that cruising yachts prefer to have smaller jibs, which may decrease the handling work. As expected the *IMS* main sail aspect ratio is slightly higher, because the cruisers are designed for a good overall performance, not focused on the upwind.

The project of a sailing yacht for disabled people has different characteristics than a conventional cruiser and for the present project it is decided to design a conventional sails planform balanced by a heavier keel. Even though, the sail area is slightly smaller than the cruiser average to reduce the force required to operate the sails and the aspect ratio is also lower to decrease the heeling arm.

Table 5.1.1 – Comparison between the project dimensions and the respective data base values.

Dimension	*Inclusion 32*	Average	Maximum	Minimum
$A_{sail}/Vol^{2/3}$	12.1	16.9	19.6	15.6
A_{main} [m^2]	22.5	23.6	28.2	21.1
A_{jib} [m^2]	20.2	20.8	24.1	14.7
A_{upwind} [m^2]	42.7	44.3	51.1	37.8
$A_{main\ \%}$	53	53	61	50
$A_{jib\ \%}$	47	47	50	39
AR_M	5.1	5.5	5.8	4.5
AR_J	5.6	6.7	7.1	6.4
P [m]	10.7	11.3	12.7	10.2
E [m]	4.2	4.2	4.5	3.9
I [m]	10.6	11.8	12.7	9.9
J [m]	3.8	3.5	3.9	3.0

5.1.3 Planform Design

The sails planform was designed according to the previous information and practical considerations. The jib was designed for self-tacking operation which simplifies the handling operation; therefore the foot length (J) is equal to the horizontal distance from the bow to the mast. The main sail foot (E) was also defined by the hull geometry as the distance from the mast to approximately the centre of the sail controls central station. Due to the interior arrangement the longitudinal position of the mast was defined just aft the toilet wall in order not to interfere with mobility in the cabin.

After a systematic change of the aspect ratio of each sail it was concluded that the dimensions presented in Table 5.1.1 are the most suitable for the present project. The main sail aspect ratio is lower than the average data base value but within its limits, while the jib aspect ratio is lower than the minimum limit. These values will reduce the centre of effort height, and according to Figure 5.1.2 improve the overall performance of the yacht in detriment of the upwind performance.

The aspect ratio of the jib is particularly low to increase the distance from the jib attachment to the top of the mast. This distance allows the mast to bend in the longitudinal and transversal plane, which flattens the sail and reduces the lifting forces. In practice, the control of the mast curvature is one possible way to operate the flattening coefficient, discussed when presenting the Velocity Prediction Program made for the present project in the Performance Prediction chapter. The total sail area is less than the average value to reduce the sail forces which ease the crew operation and the area distribution between the main and jib follows the average value of 53/47.

The sail area/volume displacement ratio is considerably lower than the minimum values defined by the *IMS* fleet and the data base, because of the heavy displacement required to avoid large heeling angles, which limits considerably the yacht performance. The wetted surface is proportional to the volume displacement and the sail area/wetted surface area of the *Inclusion 32* is equal to 1.6 which is also lower than the *IMS* minimum and will also affect negatively the yacht performance.

In order to improve the yachts performance when reaching or running it is common to hoist a special sail, spinnaker, designed to operate at large apparent wind angles. The modern asymmetric spinnakers with furller systems at the bow are the most suitable for the present project, because it can be operated from the cockpit area. The vertical height of the spinnaker is equal to the jib height (I) while the foot is 50% larger than the jib's foot length ($1.5 \cdot J$), which gives a spinnaker area of about 50 m^2. Once again this value is lower than the data base average, 57.6 m^2, to require an easy and safe operation

The complete set of sails with the respective dimensions is presented in Figure 5.1.3, the main and jib are drawing with a triangular shape to illustrate their main dimensions. In reality the leech (trailing edge of the sail) of each sail and the foot of the jib will be curved, to produce an elliptical shape, which minimizes the induced drag of a foil with finite span, however this dimension is usually defined by the sail maker. No reef configuration is suggested here because all the sails are reefed with furller systems and the crew may choose for each situation the most suitable area reduction. Figure 5.1.4 illustrate the *Inclusion 32* external appearance and is considered that the present sail planform is well balanced with the hull geometry.

The sail configuration defines the physical efforts applied to the vessel and crew, subsequently will be defined a suitable underwater appendage configuration to balance the transversal aerodynamic force and guarantee directional stability.

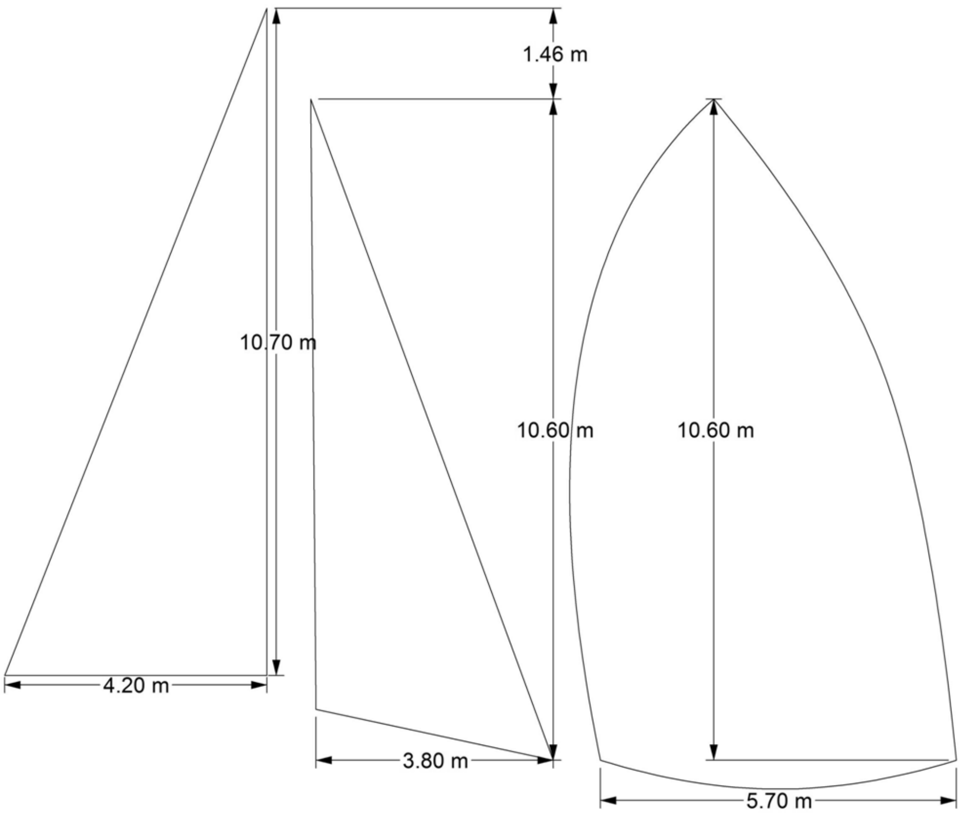

Figure 5.1.3 – Inclusion 32 sails with the respective dimensions; from left: main, jib, asymmetric spinnaker.

Figure 5.1.4 – External appearance of the *Inclusion 32.*

5.2 Underwater appendage

The conventional underwater appendage configuration is a rudder and a keel. When high transversal stability is required a bulb may be fitted at the keel tip. These appendages contribute in different ways for the global equilibrium of a sailing yacht. The main function of the keel is to provide the side force required to balance the aerodynamic side force and together with the bulb balance the heeling moment. The main function of the rudder is to provide directional control and contribute to the side force generation. Before discussing individually each appendage a common analysis of the foil theory is presented.

5.2.1 Foil theory

The most important parameter for the efficiency of the keel is the aspect ratio, defined by the keel depth divided by the mean chord. The second parameter to consider is the taper ratio (TR), which is simply the ratio of the tip chord to the root chord. Most keels are not exactly vertical, but have a sweep angle backwards, which is defined here by the inclination of the line joining points at 25% of the chord in various sections. The parameters used to define the planform of a trapezoidal appendage are given in the Figure 5.2.1.

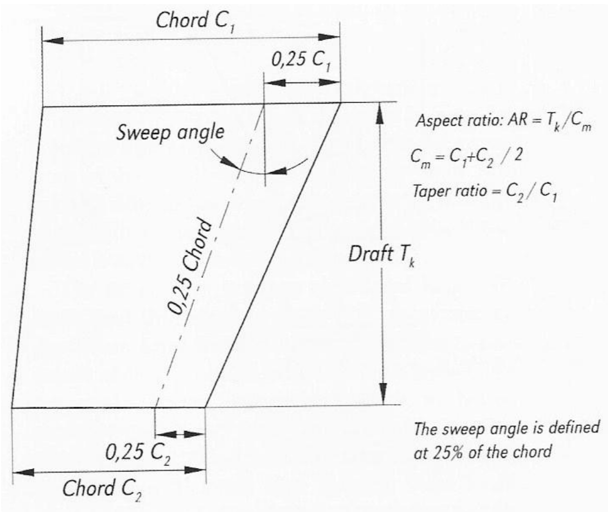

Figure 5.2.1 – Definition of a trapezoidal appendage (Fossati, 2009).

Aspect ratio

Figure 5.2.2 shows the variation of the lift and drag coefficient at different angles of attack for the same airfoil section with aspect ratios (AR) between 1 and 3, these results are based on wind-tunnel experiments (Larson, et al., 2007). In the left hand diagram very different curves are obtained depending on the angle and aspect ratio. A typical leeway angle and therefore the keel angle of attack is 5^0 where a wing with AR=1 produces about half of the lift produced by a wing with AR=3. The task of the keel is to produce a given side force with a minimum resistance. To produce a given side force the leeway angle is higher for the lower aspect ratio keels which increases considerably the drag. The left-hand graph shows that all aspect ratios have approximately the same maximum lift coefficient, but the angle of attack required to produce the maximum lift coefficient decreases as the aspect ratio increases. This also means that the greater the aspect ratio the smaller the stall angle.

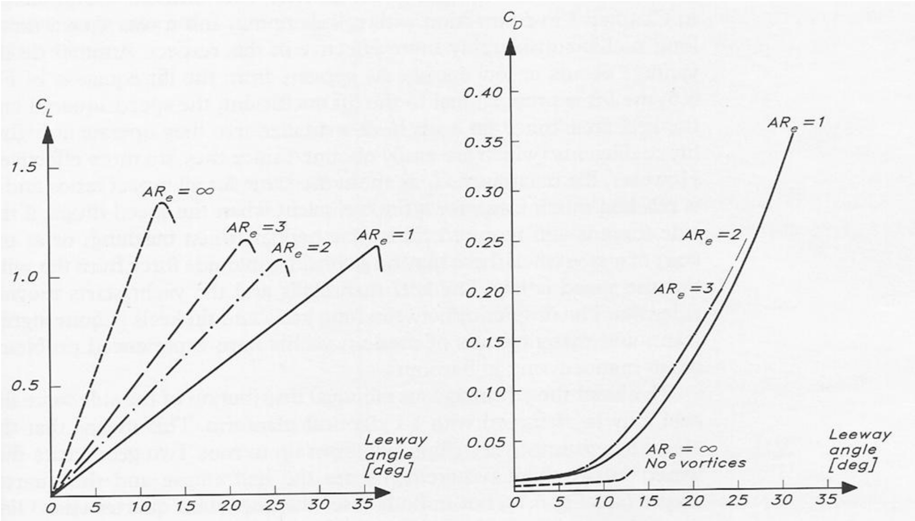

Figure 5.2.2 – Influence of the aspect ratio on lift and drag coefficients (Larson, et al., 2007).

Taper ratio/sweep angle

The induced resistance is minimized if an elliptical distribution of lift is achieved. To achieve this distribution the appendage may be designed with an elliptical planform, but it is also possible to obtain a nearly elliptical distribution with a trapezoidal form which is more practical and common, provided that the taper ratio is chosen to fit the sweep angle. Figure 5.2.3 gives the optimum taper ratio in relation to the sweep angle, computed from the lifting line theory.

Most keels have a sweep-angle of 20^0 to 30^0, which should call for a taper ratio of about 0.1. This is not practical since the centre of gravity would then be too high. In practice, most designers use much higher taper ratios, 0.4 to 0.6, for stability reasons (Larson, et al., 2007). Figure 5.2.4 shows the penalty if the force distribution is not elliptical, for the zero sweep angle. The vertical axis shows a percentage increase in drag for the trapezoidal keel as compared with the elliptical one. It is interesting to note that the importance of a correct lift distribution is dependent on the aspect ratio.

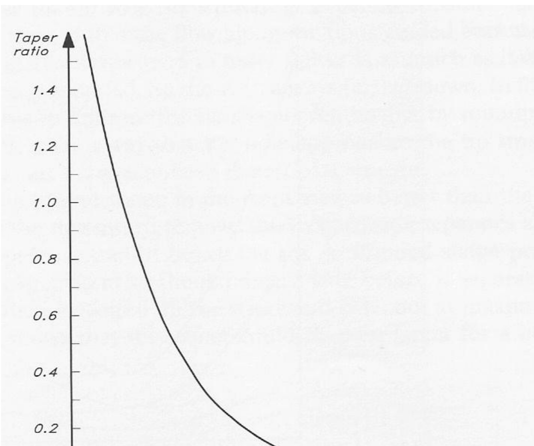

Figure 5.2.3 – Optimum relation between the sweep angle and the taper ratio (Larson, et al., 2007).

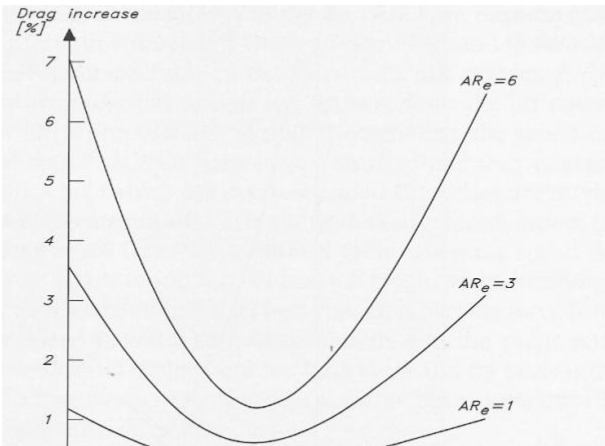

Figure 5.2.4 - Increase in induced resistance due to the non-optimum taper ratio (Larson, et al., 2007).

Section profile

For the present project it is considered that the *NACA* (*National Advisory Committee for Aeronautics*) airfoil sections are the most suitable section profiles, in particular the four-digit series and the six-series. The sections geometry and characteristics are taken from *Theory of Wing Sections* (Abbot, 1959). Figure 5.2.5 presents de drag coefficient of these *NACA* series for a range of thickness to chord ratios at zero angle of attack. It can be seen the six-series have considerably less drag than the four-series and the drag is proportional to the ratio.

The maximum lift coefficient for the chosen *NACA* series is given in Figure 5.2.6 as a function of the thickness ratio. It should be considered that the given angle of attack is for two-dimensional wings, for practical aspect ratios the angle is about twice as large. This figure shows that the highest lift may be achieved by sections with a thickness ratio in the range 12 to 15%, and the four digit series produces the maximum lift. Figure 5.2.6 also presents the angle where stall occurs, which is associated with the maximum lift but also to a significant increase in resistance for higher angles of attack. Therefore, thin keels work well in the range of small angles while thicker section accept larger angles of attack. The most suitable section for each appendage changes according to the operational angle of attack, and is important to guarantee that stall is avoided.

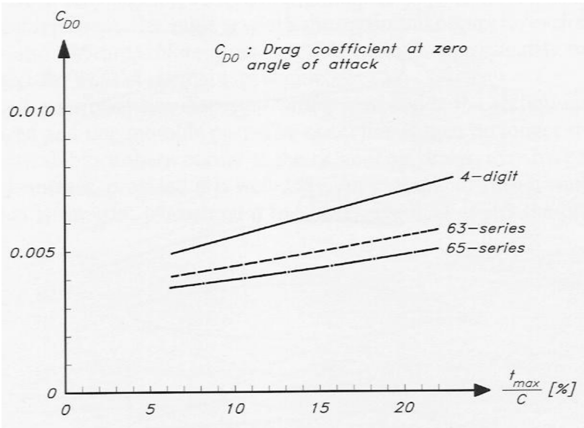

Figure 5.2.5 – Influence of thickness on drag at zero angle of attack (Larson, et al., 2007).

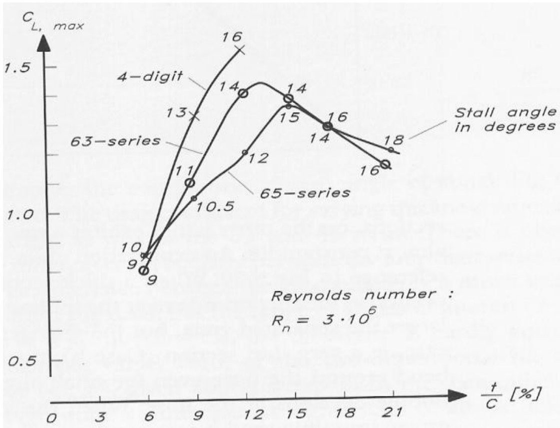

Figure 5.2.6 – Maximum lift for different profiles (Larson, et al., 2007).

5.2.2 Keel Design

Two alternative keel configurations with similar stability performance but different drafts are going to be presented. The Short Keel version was designed to have a conventional draft defined according to the data base dimensions. This keel has a span of 1.4 m which gives a total draft of 1.85m, suitable to sail in deep or sheltered waters and may easily enter in most harbours. The Long Keel version has 30% more span, 1.8 m, which gives a total draft of 2.40 m.

The keel area is often presented as a fraction of the sail area (sum of the main and fore triangle area). An average keel area to sail area ratio for fin-keel yachts is 3.5%, and the spread is approximately 0.75% (Larson, et al., 2007). Considering that the lift force produced by the keel is function of the keel area and boat speed, a higher keel area is expected to balance the low cruising speed performance. However, the present yacht was designed to sail at heel angles lower than conventional yachts, which increases significantly the effective lateral area. Therefore, it was decided to use the average keel area to sail area ratio of 3.5%. The total sail area is 42.7 m^2 which gives a keel lateral area of 1.49 m^2. Both keels version have the same lateral area but different aspect ratios, the respective main dimensions are presented in Table 5.2.1, while the Figure 5.2.7 and Figure 5.2.8 present a lateral view of both *Inclusion 32* versions. The Short Keel version has a longer root which for the same thickness to chord ratio gives a larger volume and displacement. This is acceptable since the Short Keel version was designed for lower performance. Both keel spades are made from steel.

As presented in Figure 5.2.2, the higher aspect ratio foils produce less induced resistance for the same required lift; consequently the Long Keel version is expected to be more efficient. According to the results presented in Annex 5 the keel area is considered to be adequate, because the leeway angles are within the normal values for both keels.

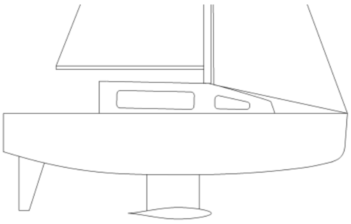

Figure 5.2.7 – Short Keel version profile view

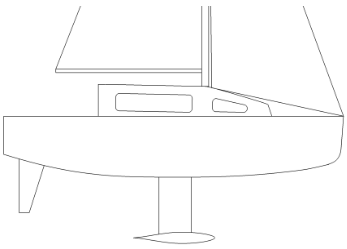

Figure 5.2.8 – Long Keel version profile view.

Table 5.2.1 – Short and long keel dimensions

	Short Keel	Long Keel	Units
T	1	1.6	[m]
A_{keel}	1.49	1.49	[m^2]
AR_{Keel}	0.67	1.71	
TR	1	1	
C_{Root}	1.49	0.93	[m]
C_{Tip}	1.49	0.93	[m]
Section	NACA 65-015		
ρ_{Iron}	7834		[kg/m^3]
Volu e	0.215	0.134	[m^3]
M ss	1681	1047	[kg]

These keels have a heavy bulb at the end of the keel which affects the tip circulation, based on de analysis of conventional keel and bulb arrangement it was decided to have zero sweep angle. According to Figure 5.2.3 the optimum taper ratio for a keel with zero sweep angle is 0.45, which gives a tip chord structurally too thin to support a heavy bulb. For the present project it was decided to use a taper ratio equal to 1 in both keels, which provides a stronger keel with lower centre of gravity and easier to build. According to Figure 5.2.4 the drag increased is about 2% in relation to the elliptical planform. Since the induced resistance is approximately 10% of the total resistance upwind and less downwind, the increase in total resistance due to the non-optimum taper ratio is less than 0.2% which is considered to be irrelevant.

The keel operates at the leeway angle which is normally lower than 5^0; therefore, it was decided for a keel section profile from the 65-series, because according to Figure 5.2.5 it has lower drag at small angles of attack and according to Figure 5.2.6 it has a higher stall angle, which ensure manoeuvrability in extreme situations. The lift production is not relevant since at small angles of attack there is no significant difference between the *NACA* series. Concerning the thickness chord ratio, large values are not useful because the keel operates at low angle of attack and most of the weight is carried by the bulb. For small angles of attack low thickness chord ratios produce less resistance for similar lift. Based on Figure 5.2.6 it was chosen to use a thickness ratio of 15% in order to benefit from the 65-series maximum lift in extreme situations like manoeuvring inside the harbour, tacking, etc.; this thickness ratio is also advised by *Principles of Yacht Design* as a suitable value.

5.2.3 Rudder Design

The most important parameters to define the rudder geometry are also the blade area and the aspect ratio. An average value for the sail area to rudder area is 1.4%, with 1% and 2% the lower and maximum limits (Larson, et al., 2007). In terms of rudder area, it was also considered that the low cruising speed is balanced by the low heel angle, and a value close to the average is appropriate. Therefore, it was chosen to use a sail area to rudder area of 1.5%, to guarantee good steering control which according to the actual sail area gives a rudder lateral surface of 0.68 m^2.

In order to have a balanced steer, the rudder shaft must be slightly forward of the centre of effort, which is approximately located along the sweep angle line (25% of the section chord length). The Figure 5.2.9 presents the rudder shaft, centre of effort and sweep angle of the present project. The shaft should be positioned at right angles to the bottom, since the gap between the hull and the rudder may then be sealed by the rudder at all angles. Therefore, the rudder sweep angle was defined according to the bottom surface perpendicular at the shaft location, measured in the present project to be 15^0. In the upper part of the rudder the flow follows the bottom surface and the sweep angle equal to zero; but at the tip the flow direction is about horizontal and the sweep angle is close to 15^0. Therefore, the optimum taper ratio was defined for the average sweep angle between the root and the tip, which according to Figure 5.2.3 is equal to 0.4.

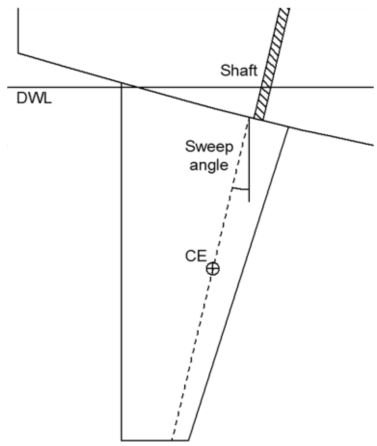

Figure 5.2.9 – Rudder shaft perpendicular to the bottom surface.

For the chosen rudder area and taper ratio it was considered that an aspect ratio of 2.7 is a suitable value. The rudder operates most of the time at higher angles than the keel and normally corrections to the course are continuously made, in particular inexperienced sailors often apply large rudder angles when learning how to control the boat. Therefore, the flow around the rudder is constantly disturbed and sections that promote laminar flow such as the 65-series are not useful. The Figure 5.2.6 shows that the four-digit series and the 63-series have the same maximum stall angle, but the four-digit produces considerably higher lift. According to the same figure it was decided to use a rudder profile from the *NACA* four-digit series with a thickness ratio of 12%, to achieve the maximum lift coefficient and amplify the rudder operational angles.

5.2.4 Bulb Design

The keel bulbs are used to increase the transversal stability, since it doesn't produce any lift the design goal is to minimize drag. Little literature exists for the bulb design and the performance evaluation of bulb shapes may only be accessed by computational fluid dynamics, towing tanks or wind tunnels experiments. The bulb is made of a heavy material, lead for the present project, and its volume was defined by the stability calculations to guarantee heeling angles acceptable for disabled people.

For the same volume a long bulb with small cross-section diameter has more wetted surface and proportionally more frictional drag, but has low form drag. A short and fat bulb produces a low frictional drag, but is large in form drag. Figure 5.2.10 presents these resistance components for a range of thickness to chord ratios, showing that the minimum total drag of a foil section at a zero angle of attack is achievable for thickness chord ratios between 2 and 3. According to Figure 5.2.5 it is concluded that the 65-series have the lowest drag at small angles of attack. Therefore it was decided to use for the longitudinal profile of the bulb the NACA 65-021 section. For the transverse sections of the bulb it was decided to use an elliptical shape to act as an end plate, increasing the effective draft and reducing the induced resistance.

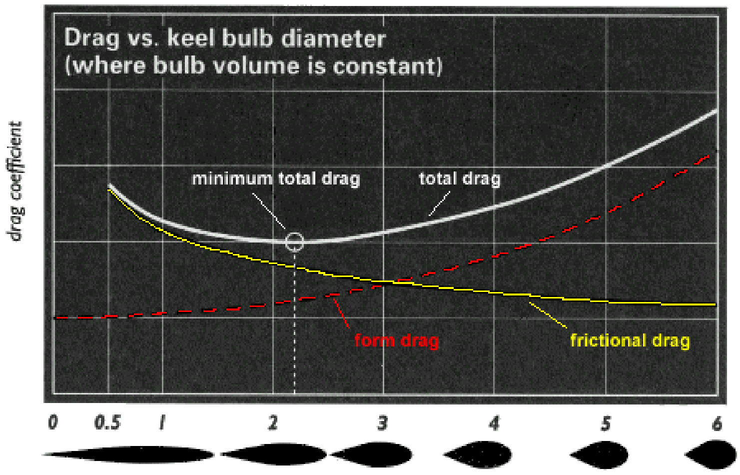

Figure 5.2.10– Relationship between form drag and friction drag for a range o thickness to chord ratios between 0 and 6 (Marchaj, 1980).

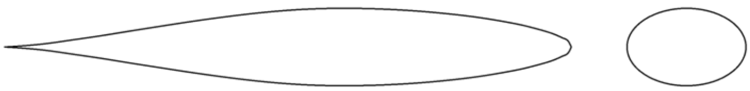

Figure 5.2.11 – Longitudinal and transversal bulb profile.

An individual bulb was designed for each keel spade previously defined. The horizontal and transversal section profiles are the same, presented in Figure 5.2.11, but the volume was scaled to achieve the same initial stability for both keel versions, these calculations are presented in the Stability Analysis chapter. The Long keel and Short keel bulbs have approximately the same weight, 1650 and 1700 respectively, because the Short keel spade is heavier due to the larger thickness for the same lateral area.

Directional stability

The directional stability of the boat is defined by the longitudinal position of the sail plan in relation to the underwater body. There is no simple analytical method to establish the position of the sails centre of effort or the underwater centre of lateral resistance. In fact the position of the underwater centre of lateral resistance is strongly influenced by the free surface effects, the hull and appendages shape, heel and leeway angle assumed by the yacht. As regards the position of the sails centre of effort, this is strongly dependent not only on the kind of sails set and apparent wind angle but also on the shape of the sails. The accurate position of these points can only be determined by experimental tests in wind tunnel and towing tanks.

When a yacht heels the aerodynamic force will tend to act behind the hydrodynamic one, and the yacht will tend to luff up. To counteract this, the helmsman has to give some weather helm, which will bring the hydrodynamic force astern until it acts at the same line as the aerodynamic force. If the heel angle is smaller than the equilibrium condition, the opposite situation occurs and the yacht tends to bear away. It is impossible to position the sail plan in such a way that the yacht is balanced at all angles of heel. Normally, the emphasis is placed on small angles, for which a good balance is wanted and larger weather helms are then tolerated under more heel. From a safety point of view there is an advantage in having a yacht that automatically tends to luff up in a gust, thus unloading the sails and reducing the risk of excessive heel.

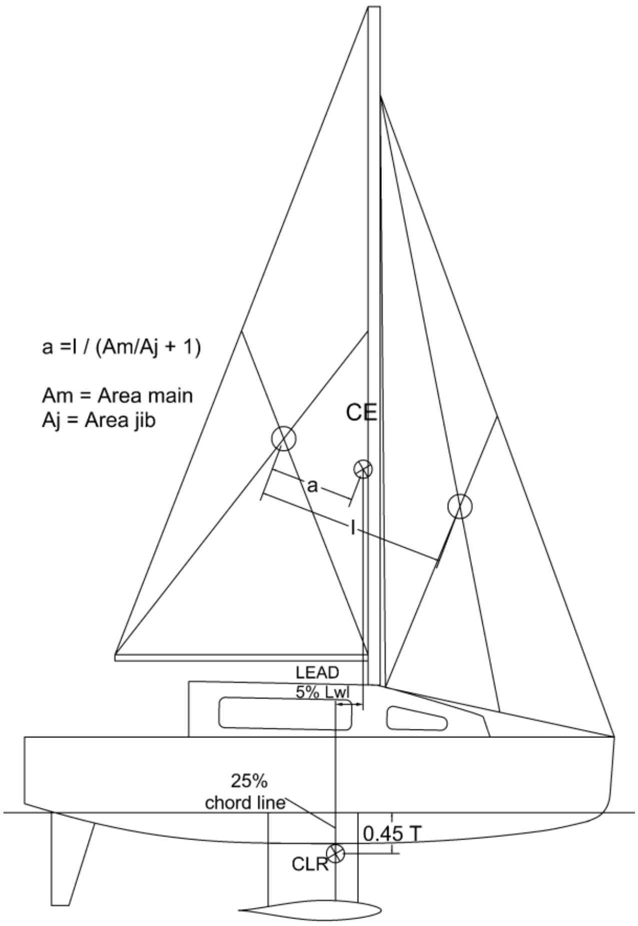

Figure 5.2.12 – Dimensions involved in de Lead calculation.

Table 5.2.2 – Lead calculation.

l	3.13	[m]
a	1.41	[m]
0.45xT	0.68	[m]
$CE_{Sails\ XX}$	5.62	[m]
CLR_{xx}	5.16	[m]
LEAD	5	%

There are a few empirical methods useful to find a balanced boat, the procedure used is subsequently explained with reference to Figure 5.2.12. The estimation of the position of the sails centre of effort was assumed to coincide with the centre of gravity of the sail plan. The centre of each sail was found first as the intersection between straight lines from two corners to the opposite side mid-point. The final centre of gravity was located in the line connecting the individual centres according to the area average, this calculation is also given in Figure 5.2.12.

The estimation of the underwater centre of lateral resistance was based on the assumption that for fin-keel yachts the effect of the rudder and fore body cancels each other (Larson, et al., 2007). The keel was extended to the waterline and the centre of lateral resistance is found by connecting the points at 25% of the chord at waterline and at the tip of the keel by a straight line, and finding the point at 45% of the draft on this line, these dimensions are illustrated in Figure 5.2.12.

The horizontal distance between the sails centre of effort and the underwater centre of lateral resistance is called “lead”. The amount of lead is defined by experience and values from 3 to 7% of the water line length are suggested by *Principles of Yacht Design* for fractional rigs. The sail plan position is restricted by the mast position and the keel spade was positioned to achieve a lead of 5%, the calculation values are given in Table 5.2.2. It was decided to use 5% of lead because beamy hulls get more asymmetric under heel and require more lead but the present project was designed to operate at low heel angles and therefore an average value is the most reasonable solution.

5.3 Summary

The *Inclusion 32* was designed to have the appearance of a conventional cruiser with an unseen heavy keel to reduce the heel angle to values acceptable for wheelchair operation. The sails planform was designed according to the knowledge from wind-tunnel experiments with sails of different aspect ratios. The *Inclusion 32* was designed to have average performance for the overall heading angles where low aspect ratio sails are advantageous. These also reduce the centre of effort height and the respective heeling moment. The sail planform area is slightly smaller than the average to reduce the sail forces, which simplifies the crew handling. In comparison with the data base values the spinnaker also has a smaller area because this sail is particularly difficult to control.

The underwater appendages were designed from the sails dimensions and statistical data presented in the literature. The keel taper ratio was defined above the optimum value in order to provide a larger keel tip chord to support the heavy bulb. The sweep angle of the rudder and the shaft inclination were defined to be perpendicular to the bottom surface. The bulb was designed to minimise resistance with the volume defined by the calculations presented in the stability chapter.

At the end of this chapter the most important components of the project were already defined, but to predict the *Inclusion32* performance it was still necessary to define the vessel displacement with the respective centre of gravity and perform the stability calculations discussed in the following chapter.

6 Stability analysis

A major concern of the present project was to minimize the heel angle, in order to reduce the balance problems and improve mobility onboard. This aspect governed many decisions taken through different stages of the design process. In particular, when designing the hull geometry the beam was designed larger than conventional yachts to improve the form stability of the yacht, the keel and bulb were also designed heavier to avoid the possibility of heeling up to large angles. In order to perform the hydrostatic calculations use was made of the software *AutoHydro*, which for a given hull shape, mass and centre of gravity calculates the respective hull data and the stability properties at different angles of heel.

The displacement estimation was an important step before the stability calculations. The lightship weight is composed by the structure, machinery and equipment weight, while the half load weight relative to the sailing condition is composed by the lightship weight plus the crew and the tanks half loaded. The *Inclusion 32* was designed to operate an electric engine which is unusual for sailing yachts but has interesting advantages, in particular for disabled people. After the machinery an extensive list of equipments onboard with the respective mass and centre of gravity was defined and given in Annex 2. The transversal equilibrium was found with the position of some equipment while the longitudinal equilibrium was balanced by the bulb is position.

The stability calculations assumed a limit heel angle for the operation of disabled people operation and defined the initial stability of the yacht to cope with it. This value is found by an iterative process with the Velocity Prediction Program made for the present project which computes the heel for a given situation. The two keel versions were defined to have the same initial stability and its righting moment at large heeling angles is subsequently compared according to the respective curve of static stability. The curve of static stability is also compared with a modern cruiser to evaluate the overall stability of the project.

The evaluation of the seakeeping characteristics of the present project was made according to the ISO 12217-2 standard which deals with the seaworthiness of sailing yachts from 6 m to 24 m length. This rule assess different seaworthiness characteristics and the final results classify the type of navigation suitable for the yacht, during this process particular attention was given to flooding situations in severe weather conditions.

6.1 Machinery

Recently, electric engines have been developed for marine environment with interesting characteristics for the present project. These engines are particularly interesting for the present project because the auxiliary systems for disabled people also require considerably electric power, as well as the navigation instruments and lights, and therefore with an electric engine a single power source is used onboard.

An electric engine suitable for a sailing yacht up to 35 feet is a small box of approximately 20cm x 40cm x 40cm with about 30 kg. It is more environmental friendly as it doesn't burn or eliminate fuel outboard. These engines are appropriate for lakes especially where diesel engines are forbidden; this type of inland navigation is popular within disabled sailors because of the safety conditions.

Conventional diesel engines produce a significant noise pollution while operating, which create communication problems onboard. This noise is uncomfortable and may increase the anxiety on sensible people. The electric engine has a much more quiet operation and therefore is particularly suitable for a disabled people sailing yacht. An advantage of the conventional diesel engines concern the long experience that manufactures have with the marine environment and the ease to find people with knowledge to repair and maintain the equipment. However, the electric engines are maintenance free and are assumed to have high reliability.

The electric engine may also generate power under sail, using the propeller rotations to recharge the batteries. Solar panels or wind generators can be added to supplement regeneration and shore power charging. This is especially useful for moored boats where solar or wind power with regenerative charging can allow the boat owner to be completely free from power grid and fossil fuel power.

Electric engine selection

At the moment there are still few electric engines commercially available for sailing yachts, for the present project it is decided to use a *QueiTorque System* produced by the *Electric Yacht* (*www.electricyacht.com*). According to the data base made with similar yachts it was calculated that the average engine power of similar yachts is 21 hp. It was decided to install slightly more power than the data base to guarantee fast return ashore in case of emergency onboard. Therefore, it was chosen to use the model *QueiTorque 360ibl* because from the manufacturer information it is equivalent to a diesel engine of 23 to 30 hp.

The main dimensions of the *QueiTorque 360ibl* are still not available in the company web site, but a similar engine from the same manufacturer has 21cm x 42cm x 37cm. This engine is compatible with a sail drive shaft and the propeller should be considered according to the regenerative charging characteristics. As no information was found in terms of commercial propellers for this application it was decided to ask the engine manufacture for an advice, but until the time of writing no answer was received.

Batteries selection

In terms of batteries type, only the Absorbed Glass Mat (AGM) and the Lithium Ion types should be considered as they perform well in deep discharge applications and can be mounted in any position. The Lithium Ion type provide twice the energy density/unit volume and nearly three times the density/unit weight, however the price is considerably higher and should only be used when sailing performance matters. It was chosen to use AGM batteries and the engine manufacturer suggests a battery bank within 250 to 550 AH. Therefore, it was chosen to use 4 batteries of 100 AH/battery and 12V, which is enough for the daily operation. A small generator will guarantee exceptional demands.

Charging batteries

The electric engine operates with the power supplied from the batteries. However, the *QueiTorque*^{TM} *System* may also recharge the batteries wile sailing, with the propeller rotation created as the boat moves through the water. The manufacturer refers that an afternoon of sailing can replace the power normally used to motor in and out of the marina, it is further explained that most boats will start regenerating at 3.5 to 4 knots creating a charging current of 4 to 6 amperes. This source of power is only significant after a few hours of sailing. The normal battery charging is made from shore power, since the yacht is expected to operate from a conventional marina where electrical power is normally available. According to the manufacturer, for the regular sailing day a full battery bank provide enough power to enter and exit the harbour, motor up to 10 nautical miles at reduced speed, operate electric instruments and adaptive devices.

The shore power charging is made by a "smart" charger designed to operate in marine environment, *Dual Pro*^{TM} Model SS4, that provides a total output of 40 A divided by the four batteries (*www.dualpro.com*). This "smart" charger has a microprocessor that controls individually each battery and step down the charging current as full charge is approached. When the batteries are fully charged, they will turn off, preventing overcharge.

If the vessel is moored or without access to the grid power there are plenty of solar and wind generative systems to be chosen according to each situation. For the actual project a generator must be carried onboard to be used sporadically since it increases the reliability of the system. A conventional diesel tank with 150 L was designed to ensure long passage autonomy. The chosen generator was a *Fisher Panda AGT-DDC 4000* designed for marine battery charging with a constant operative rate of 220A (*www.fisherpanda.de*).

The *Inclusion 32* requires a generator to ensure safe returns ashore which increases the total weight of machinery, and reduces the weight efficiency of the electric systems compared to the conventional diesel engine. Even though, this difference is not relevant for the present project since the electric engine (30 Kg), four AGM batteries (123 kg), charger (10 kg) and generator (90 kg) weights 251 kg, while a proportional *Volvo Penta* (*www.volvopenta.com*) engine (150 kg) (11Vo) with two batteries (60 kg) weights 210 Kg. The position onboard of the generator and batteries were defined according to the transversal and longitudinal equilibrium of the yacht.

6.2 Weight position

In addition to the machinery equipment a list of the equipments onboard is made with the respective weight and centre of gravity, presented in Annex 2. However, from the equipment listed only the previous generator and the batteries were free to move in the transversal direction. These weights are positioned slightly to the starboard side in order to balance the galley and toilet equipment predominantly at port.

The longitudinal equilibrium was more difficult to balance since the aerodynamic drive force and the hydrodynamic create a bow down trimming moment with a proportional resistance increase. The problem was that the drive force is not constant but change according to the course and wind intensity, and therefore there was no optimum position for the longitudinal centre of gravity (LCG).

The weight condition considered through the LCG optimisation was the normal sailing condition, half loaded, which includes the crew and the tanks half loaded. The easiest way to optimise the LCG for a specific sailing situation is changing the crew weight position, which is a common practice for racing crews. This is not expected for disabled people that normally suffer from mobility limitations. The longitudinal equilibrium was then calculated for a crew of four elements, three positioned at the cockpit and one at the saloon, which was considered to be an average distribution of the crew weight.

The equipment free to move in the longitudinal direction was the water and diesel tanks, generator and batteries. These were positioned close to the final position of the LCG (Annex 2), to minimise the mass moment of inertia around the transverse axis through the centre of gravity and reduce the added resistance in waves as explained in the Performance Prediction chapter, Eq.(8.1.38).

The longitudinal balance is achieved by the longitudinal position of the bulb. It was decided to design the yacht for zero trim angle at an average wind speed sailing situation, assumed to be 10 knots, to minimize the overall trim resistance component. The Figure 6.2.1 illustrates the forces and moments involved in the longitudinal balance while sailing, the horizontal forces create a bow down trim moment and the vertical forces a restoring moment. The bow down trimming moment (M_{sails}) was obtained multiplying the drive force (F_x) by the vertical distance from the sails centre of effort to the underwater centre of lateral resistance (h_{arm}), Eq. (6.2.1). The drive force is obtained from the Velocity Prediction Program, as the average drive force computed for all headings at 10knots true wind speed. The centre of underwater resistance is not constant and change form example with the heel angle, for the present calculations assumed it to be coincident with the CLR. In order to balance the sails bow down moment the final LCG must be aft of the centre of buoyancy (CB), which was estimated with the *Autohydro* software for a condition of zero trim. The restoring moment was obtained by the multiplication of the distance between the LCB and LCG by the total displacement, Eq. (6.2.2). Table 6.2.1 gives the forces and distances involved in the calculation for the Short Keel version.

$$M_{sails} = h_{arm} \cdot F_X \tag{6.2.1}$$

$$M_{Hull} = (LCB - LCG) \cdot Disp \cdot g \tag{6.2.2}$$

Table 6.2.1 – Results from the longitudinal balance.

Trim Balance (Short Keel version)			
Bow down trim moment, 10 knots true wind.	M_{sails}=M_{Hull}	5231	[N.m]
Average drive force at 10 knots true wind, computed from VPP.	F_x	747	[N]
Distance from aerodynamic CE to underwater CE, assumed to be the CLR.	h_{arm}	7	[m]
Computed from *Autohidro* at zero trim angle.	LCB	4.57	[m]
LCG defined by the bulb longitudinal position.	LCG	4.49	[m]

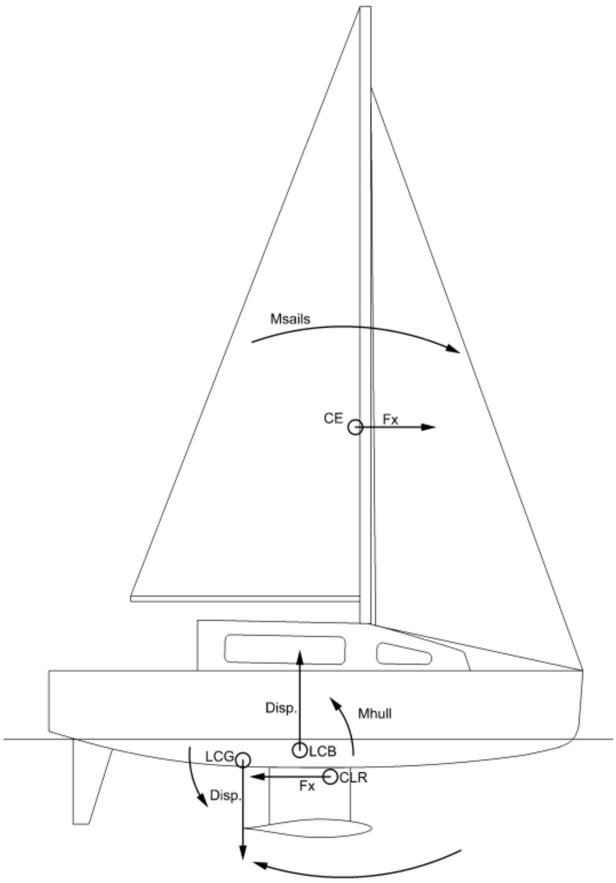

Figure 6.2.1 – Illustration of the forces involved the in the longitudinal balance while sailing.

6.3 Load conditions

The lightship condition was defined by the weight of the hull and deck house structure, keel, bulb and the equipment mentioned in Annex 2. The mass and respective centre of gravity of is given in Table 6.3.1 and Table 6.3.2 for the Short Keel and Long Keel versions respectively. The longitudinal position of the centre of gravity is measured from the vessel stern, while the vertical position is measured from the hull bottom base line and the transversal position is measured from the centreline.

Table 6.3.1 –Lightship weight and centre of gravity.

Short Keel version

Item	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Structure	1850	3.83	0.00	1.04
Equipment	1149	5.03	0.00	1.86
Keel	1681	4.93	0.00	-0.50
Bulb	1700	4.95	0.00	-1.11
Lightship	6380	4.63	0.00	0.21

Table 6.3.2 – Lightship weight and centre of gravity.

Long Keel version

Item	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Structure	1850	3.83	0.00	1.04
Equipment	1149	5.03	0.00	1.86
Keel	1047	5.00	0.00	-0.81
Bulb	1650	5.12	0.00	-1.75
Lightship	5696	4.66	0.00	0.06

The normal sailing situation correspond to the half load condition, defined by the lightship weight plus the tanks half loaded and the crew weight in normal positions. The weight and centre of gravity for each equipment is given in Table 6.3.3 and Table 6.3.4 for the Short Keel and Long Keel versions respectively.

Table 6.3.3 – Half load condition.
Short Keel version

Item	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Light Ship	6380	4.63	0.00	0.21
Fuel	62	3.83	0.00	0.37
Water	75	5.40	0.00	0.40
Crew1	75	0.76	0.76	1.57
Crew2	75	1.92	1.17	1.57
Crew3	75	1.92	-1.17	1.57
Crew4	75	4.05	-0.76	1.57
Total	6817	4.53	0.00	0.27

Table 6.3.4 – Half load condition.
Long Keel version

Item	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Light Ship	5696	4.66	0.00	0.06
Fuel	62	3.83	0.00	0.37
Water	75	5.40	0.00	0.40
Crew1	75	0.76	0.76	1.57
Crew2	75	1.92	1.17	1.57
Crew3	75	1.92	-1.17	1.57
Crew4	75	4.05	-0.76	1.57
Total	6133	4.540	0.00	0.139

6.4 Initial stability

The initial heel angle limit situation for disabled people was assumed to be 10º with 20 knots of wind and no reefing of the sails. This condition was evaluated iteratively by the Velocity Prediction Program and the transversal stability calculations. If the predicted heeling angle was above 10º the bulb weight was increased until achieve the desired condition. The result was an extremely heavy bulb which could lead to several structural problems. The solution was to maintain a 10º heel angle but to reduce the maximum wind to 15 knots, above this condition the crew is advised to reef the sails. Therefore, the *Inclusion 32* was designed to cope with a maximum heel angle of 10º with 15 knots of wind speed and no reefing of the sails.

At the Appendage Design chapter two different keel configurations were designed for different performance characteristics. To be suitable for the same sails plan and to cope with the limit heel angle defined for disabled people these keels were projected to have the same initial stability defined by the transversal metacentric height (GMt) and the total displacement, Eq. (6.4.1). The initial metacentric height was obtained from the *AutoHydro* for the two keel versions and the Table 6.4.1 presents the respective values.

$$M_{initial} = GMt \cdot Disp \cdot g \cdot \sin(1^0) \qquad (6.4.1)$$

Table 6.4.1 – Initial stability values.

Version	Short Keel	Long Keel
GMt [m]	1.69	1.86
Disp. [kg]	6817	6133
$M_{initial}$[N.m]	1973	

6.5 Curve of static stability

The curve of static stability represents the righting moment (RM) at varying angles of heel. The righting moment was obtained from the righting arm (GZ) times the displacement and the gravity acceleration, Eq. (6.5.1). The righting arm values for both keel versions were computed with the

Autohydro software for a range of heeling angles from 0^0 to 180^0, which corresponds to the upright and upside-down positions respectively.

$$RM = \overline{GZ} \cdot Disp \cdot 9.81 \tag{6.5.1}$$

The curve of static stability for the two keel versions is presented at Figure 6.5.1. As both keel versions have the same initial stability the curves are approximately equal until 60^0 of heel. The maximum righting moment is also approximately the same, 63.5 kN.m, achieved for the Short Keel at 71^0 and for the Long Keel at 76^0, if the heeling moment exceeds the maximum value the yacht will capsize.

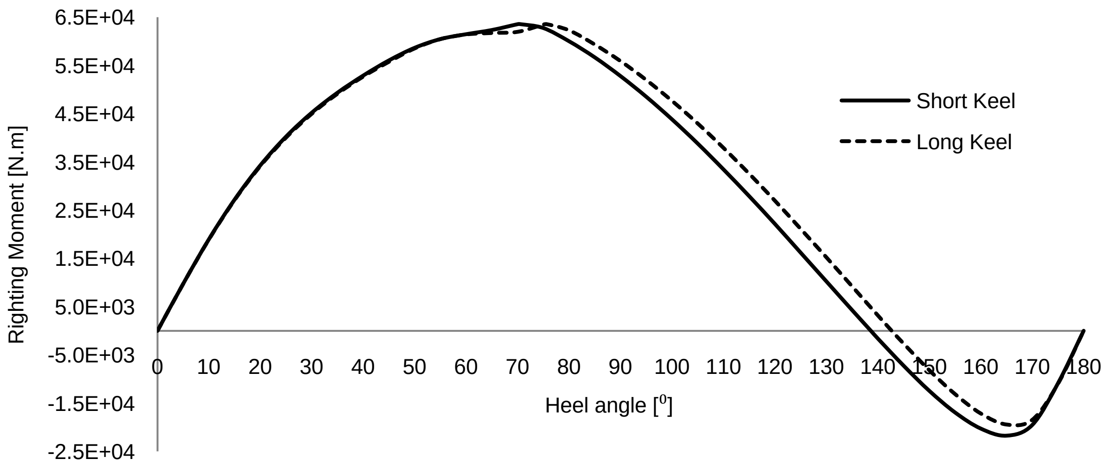

Figure 6.5.1 – Short Keel and Long Keel curves of static stability.

The stability range is the range of angles for which a positive righting moment is developed, for larger angles the hull is stable upside-down. The stability range of the Short Keel version is lower than the Long Keel version, 139^0 and 143^0. The minimum righting moments are 21.7 kN.m and 19.4 KN.m, for the Short Keel and Long Keel respectively. The area under the RM curve up to a certain heel angle represents the work, by the waves for instance, needed to heel the hull to this angle. From Figure 6.5.1 is seen that the area of negative righting moment is larger for the Short Keel version, which means that more work is needed to recover this yacht from an upside-down position.

Figure 6.5.2 compares the curve of static stability of the present project, Long Keel version, with a similar plot of a commercial cruiser, *Halberg-Rassy 31* (*HR31*), frequently used as a reference through the design process. The curves are considerably different, the larger difference is found in the maximum righting arm which is about 120% higher for the present project. The initial stability, defined by the slope of the curve at zero heel angles, is also significantly higher for the present project.

Conventional yachts are designed to operate at an average heeling angle of 30^0 (Larson, et al., 2007), which is more than twice the present project design value. At 30^0 the *HR31* has a righting arm of 21.4 kN.m, which corresponds to a heel angle of 12^0 in the present project. As the sail area of the present project is slightly lower than the *HR31*, the inclining moment demands will be proportionally lower. Therefore, when the *HR31* is sailing in an average situation, with a heel angle of 30^0, the present project will be sailing with less than 12^0, which is perfectly according to the design objective. This result is particularly important and improves the confidence on the design decisions taken to guarantee a suitable heeling angle for disabled people.

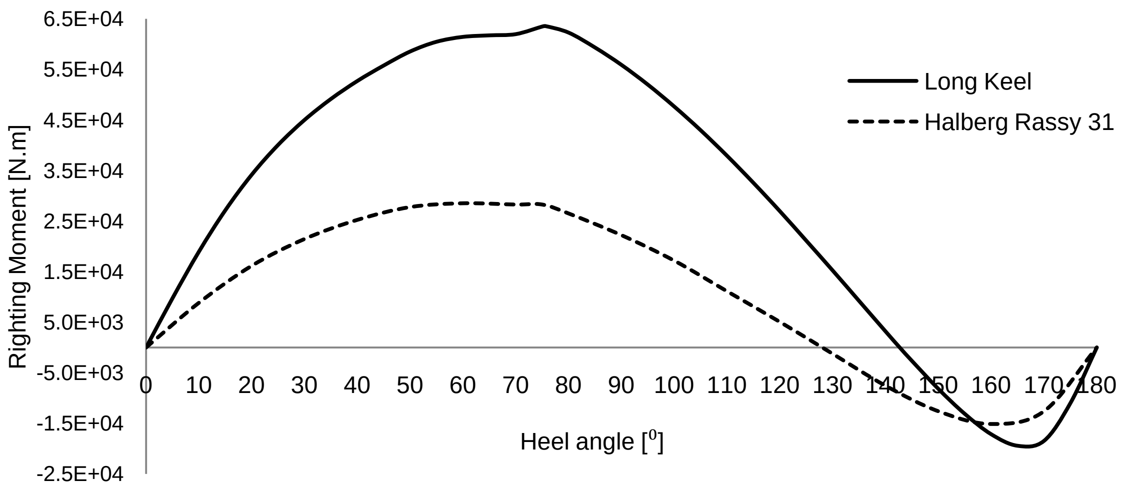

Figure 6.5.2 - *Halberg-Rassy 31* and Short Keel version curves of static stability.

6.6 Seakeeping analysis

The method used to estimate the seaworthiness of the *Inclusion 32* is presented by the ISO 12217-2 standard, the methodology and formulas used are presented in *Principles of Yacht Design.* The idea is to define a "stability index", STIX, obtained from the main dimensions of the yacht and its righting moment curve. Different qualities of the project relevant to the seakeeping and safety are calculated in the form of factors, which are finally multiplied to obtain the STIX. These factors are obtained from formulas, not presented here, designed to yield a value of 1.0 for a "normal" yacht. The higher the factor the more seaworthy the yacht is in terms of the characteristic evaluated, within a minimum and maximum limits. For results out of this range it must be considered the closest limit value. Each factor will be discussed individually according to the present project results.

Particular attention was given to flooding situations in severe weather conditions. The sole inclination was compared with the maximum predicted trim angle to assess the water evacuation. The operation of the yacht is always guaranteed by the large reserve of buoyancy under the deck. The dimensions and results used to define the STIX of the present project are given in Annex 4 and the summary of the main factors involved in the calculations is presented in Table 6.6.1**.** As no significant difference exists between both keel versions a common discussion of the results will be presented.

Table 6.6.1 – Summary of STIX results for the Short Keel and Long Keel versions.

Factor	Short Keel	Long Keel
LBS	9.33	9.27
FDL	1.03	1.02
FBD	1.04	1.04
FKR	1.5	1.5
FIR	1.15	1.18
FDS	0.5	0.51
FWM	1	1
FDF	0.5	0.5
δ	5	5
STIX	24.1	24.2

Base length factor

The *base length factor* (LBS) is a weighted average of the length overall and the waterline length, with the waterline length twice as important as the overall length. The size of the yacht is an important parameter since it defines a scale with which the waves are measured, the larger the yacht the smaller the relative size of the waves.

Displacement length factor

The *Displacement length factor* (FDL) of the present project is close to the value of a "normal" yacht. A lighter displacement relative to the size of a yacht is penalized as it is considered less seaworthy than a heavier yacht.

Beam displacement factor

The beam to displacement relation is considered to be highly influential on the seaworthiness. A combination of large beam with light displacement is considered to accentuate the risk of wave-induced capsize, leaving the hull more stable in the upside-down position. On the other hand, a small beam to displacement ratio may have a negative effect on the form stability. Therefore, large deviations in both directions from the norm are penalized. When compared with conventional yachts, the *Inclusion 32* beam and displacement are the most extreme dimensions. However, they seem to balance each other well because the *Beam displacement factor* (FBD) is close to the normal value.

Knockdown recovery factor

The *Knockdown recovery factor* (FKR) refers to the ability of the yacht to spill water out of the sails after a knockdown, which is function of the relation between righting moment and the heeling moment with the sails just dipped into the water. The present project has a FKR limited by the rule maximum value, which means that it performs better than the "normal" yacht in knockdown situations.

Inversion recovery factor

The *Inversion recovery factor* (FIR) represents the ability to recover unaided after an inversion. It is function of the displacement and the angle of vanishing stability. These results are close to the "normal" yacht.

Dynamic stability factor

The *Dynamic stability factor* (FDS), represents the work needed by the external forces (wind and waves) to heel the yacht up to the first occurring downflooding angle, which is proportional to the area under the righting arm curve up to this angle. The downflooding angle is defined as the heel angle at which the first downflooding opening becomes immersed.

For a conventional displacement yacht the most critical point is normally the top corner of the companionway hatch, corresponding to a downflooding angle normally around 120^0 (Larson, et al., 2007). The present project is open from the cockpit to the interior cabin, and the critical situation is when the sheer line is immersed at the cockpit, which occurs at a heeling angle of about 35^0. The *dynamic stability factor* is below the rule minimum value for the Short Keel version and a slightly higher for the Long Keel version. This result penalises severely the present project final STIX result.

As previously discussed the longitudinal balance was calculated to give zero trim angle in the average sailing condition, which minimize the overall resistance of the yacht. The deck has an inclination of 1.5^0 aft in relation to the horizontal to evacuate the flooded water. This is adequate for the average sailing, but as the wind increases for extreme situations the bow down moment increases above the average values and the deck inclination in relation to the horizontal is reduced.

The trim angle was consequently predicted for the Short Keel version at the maximum drive force predicted with 20 knots of wind and no reefing of the sails. The bow down trimming angle was predicted according to Eq.(6.6.1) and the respective trim variation was calculated with Eq.(6.6.2), solved in order to $d\theta_{sails}$, Eq.(6.6.3). The longitudinal metacentric height (KML) was predicted with the *Autohydro* software, all the dimensions and results are given in Table 6.6.2.

$$M_{Sails} = F_{x\,max} \cdot h_{arm} \tag{6.6.1}$$

$$M_{sails} = Disp. \cdot g \cdot (KML - VCG) \cdot \sin(d\theta_{sails}) \tag{6.6.2}$$

$$\Leftrightarrow \quad d\theta_{sails} = \sin^{-1}\left(\frac{M_{sails}}{Disp. \cdot g \cdot (KML - VCG)}\right) \tag{6.6.3}$$

To predict the maximum forward trim angle it was also necessary to account with the natural trim angle when heeling, due to the asymmetry of the bottom surface ($d\theta_{heel}$), which is significant for yachts with slender bows and full sterns. The heel angle predicted by the Velocity Prediction Program for the maximum drive force situation was 30º and the respective forward trim angle when no external forces are applied was computed by the *Autohydro* software to be 1.7º. The natural trim angle due to heel alone plus the trim angle due to the maximum driving force is 3.4º as given by Table 6.6.3. In this situation the deck inclination is not sufficient and the water will not evacuate through the stern.

Table 6.6.2 – Maximum trim angle due to the drive force.

Fx_{max} [N]	3858
h_{arm} [m]	7
M [N.m]	27009
Disp [kg]	6854
VCG [m]	0.27
KML [m]	13.7
$d\theta_{sails}$ [^{o}]	1.71

Table 6.6.3 – Components of maximum trim angle

$d\theta_{sails}$ [^{o}]	1.7
$d\theta_{Heel@30}$ [^{o}]	1.7
θ_{Final} [^{o}]	3.4

It could be possible to move the bulb aft until the maximum forward trim angle is equal to zero, however this would lead to a large aft trim in normal conditions, which is not good for the wheelchair operation and increases considerably the hydrodynamic resistance. The external appearance of a yacht with an unbalanced trim angle is also not acceptable.

A solution to the problem can be a pipe connecting the forward sole extent to the bottom surface. In the case of water onboard without sufficient aft inclination to evacuate from the stern, the water would move forward and from here out from the bottom surface as illustrated in Figure 6.6.1.

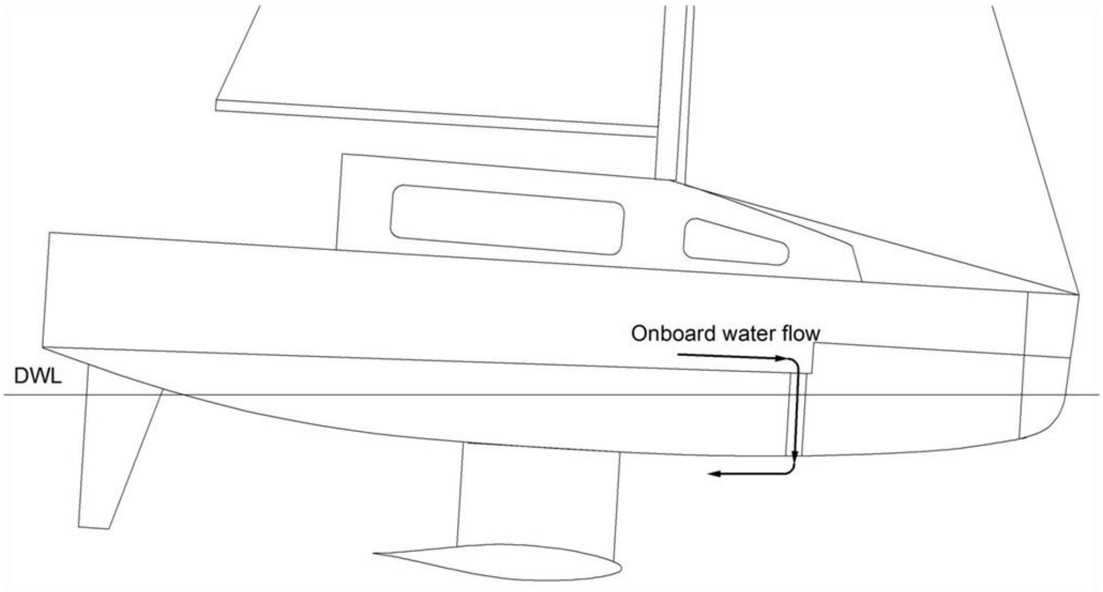

Figure 6.6.1 – Evacuation of water onboard with 3.5^0 of forward trim.

The present project has a water tight reserve of buoyancy of 13.4 m^3 under the lower deck which corresponds to a displacement larger than twice the normal sailing displacement. The Figure 6.6.2 presents the buoyancy volume with inclined lines and the respective centroid position (centre of buoyancy, CB) in relation to the centre of gravity (CG). The centre of buoyancy is forward of the centre of gravity to promote an aft trim angle in a complete flooding situation to evacuate the water faster through the stern. In reality, the boat may heel more than the downflooding angle by an unexpected situation like a strong gust, and water enters to the cockpit. Afterwards, the boat may trim forward and move the water onboard to the bow region. However, a complete flooding situation is not possible to occur since all the water that comes in must go out due to large reserve of buoyancy, either through the stern or through the forward pipe.

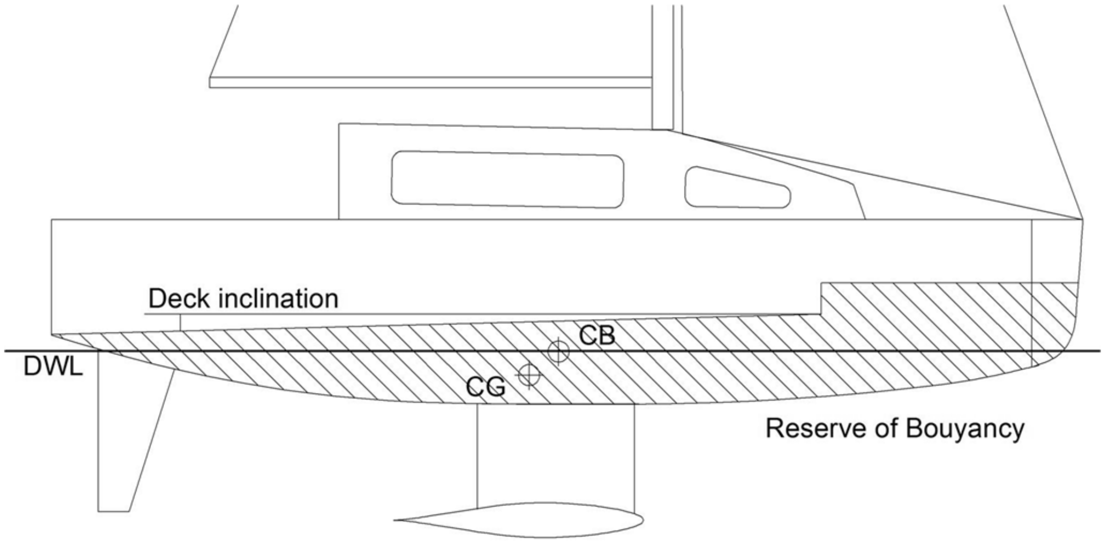

Figure 6.6.2 Reserve of buoyancy and deck inclination.

The present project benefits from a small increase in the final STIX result (δ), for vessels that guarantee a reserve of buoyancy when fully loaded with water. Even though, this is not the situation of our project since it will always evacuate the water and not remain flooded.

Wind moment factor

The *wind moment factor* (FWM) is applied for hulls with downflooding angle smaller than 90^0 to account with risk of downflooding due to a gust heeling the unreefed vessel. The FWM cannot be larger than 1, and the present project is qualified with the maximum value due to the high transversal stability.

Downflooding factor

The last factor to consider is the *downflooding factor* (FDF), which represents the risk of downflooding in a knockdown and it is proportional to the downfloding angle. Due to the reasons previously discussed for the *dynamic stability factor* this factor also penalizes considerably the present project.

STIX result

The stability index is calculated from the Eq.(6.6.4) and the final result classify a yacht in four different categories, from A to D with the respective minimum values given in

Table 6.6.4. A yacht in category A is considered very sea worthy and should be fit for ocean passages, while a yacht in category D should only be used in sheltered waters (Larson, et al., 2007). The present project has a STIX value to qualify B (Table 6.6.1). However, to qualify an A or B the yacht must have a quick draining cockpit and a downflooding angle of at least 90^0, and therefore the final stability rating of the present project is C.

$$STIX = (7 + 2.25 \cdot L_{BS}) \cdot (FDL \cdot FBD \cdot FKR \cdot FIR \cdot FDS \cdot FWM \cdot FDF)^{0.5} + \delta \tag{6.6.4}$$

Table 6.6.4 – STIX categories and respective lower limits

Design Categories:	A	B	C	D
STIX lower limit	32	23	14	5

The author considers that the class C doesn't correspond to the seaworthy qualities of the present project. It is considered that the rule over penalizes the present project due to the open interior to the cockpit and doesn't account with the amount of the buoyancy stored in the water tight tanks below the deck. The entrance of water onboard may occur in particular situations and it may be uncomfortable to the crew but the operation of the vessel is guaranteed even after a flooding situation. However, the class C is compatible with close coastal navigation which is still suitable for the intended use of the yacht.

For the subsequent improvements of the project particular attention must be given to the seakeeping performance. It is important to accurately evaluate if the present project is over penalized by the rule or not, and what are the possible improvements, a few ideas will be subsequently presented. The present analysis is based on a summary of the original standards presented by *Principles of Yacht Design* relative to conventional yachts and would be important to have access to the complete version of the ISO 12217-2 standard.

6.7 Seakeeping improvements

According to the "stability index" the yacht would benefit to have a rigid boundary from the cockpit to the interior cabin. However, this is against the project main idea of designing a single mobility deck, free from obstructions. Also, an obstruction in between the cockpit and the interior isolate people and increase communication problems.

The freeboard height can be slightly increased to amplify a few degrees the downflooding angle. In this situation the lower deck height should increase the same value to maintain the view angle of wheelchair users to the exterior.

Modifications to the hull shape may also be beneficial to seaworthiness of the yacht. The present hull shape is designed with circular underwater stations profile to minimise resistance at low angles of heel. This could be changed to a more rectangular profile similar to a tanker ship, in order to increase the hull form stability and proportionally the work required to heel the vessel up to the downflooding angle. In alternative, the hull shape could be also rectangular but with slightly less displacement which raise the freeboard height and increases the downflooding angle.

6.8 Summary

The stability chapter starts with the definition of the lightship and normal sailing displacement. The lightship condition is defined by the hull structure, machinery and equipment onboard. The *Inclusion 32* was designed to operate an electric engine because it has a silent operation, is suitable to inland sailing and is compatible with electric auxiliary systems. In order to complete the lightship displacement a list of the equipment onboard was made, with the respective mass and centre of gravity.

The subsequent stability calculations defined a suitable bulb mass to guarantee a maximum heel angle of 10º with 15 knots of wind speed and no reefing of the sails. Both keels were defined with the same initial stability and the curves of static stability are very close for heel angles up to 60º. In comparison with the *Halberg-Rassy 31* the present project has a maximum righting moment approximately 120% higher. When the *HR31* is sailing in an average situation, with a heel angle of 30^{0}, the present project will be sailing with less than 12^{0}, which is perfectly according to the design objective.

The seaworthiness of the present project was evaluated according to the ISO 12217-2 standard, briefely presented in *Principles of Yacht Design*. The present project STIX is severely penalised by the open entrance from the cockpit to the cabin, since the first downflooding occurs when sheer line is immersed, at 35º of heel. In a flooding situation, the water will normally leave the cockpit through the stern due to the aft inclination of the sole. If the boat has a large forward trim angle the water will move forward and out of the interior through a pipe connecting the deck to the bottom surface. The operation of the yacht is guaranteed by the reserve of buoyancy of more than twice the normal sailing displacement.

The STIX calculations qualified the *Inclusion 32* with a B, however A and B ratings must have a downflooding angle above 90^{0}, which gives a C as the final grade. The class C allows close coastal navigation and is still suitable for the present project. For further development of the project an analysis of the complete ISO 12217-2 standard is required to evaluate possible considerations to yachts with unusual characteristics.

7 Innovative Self Stability System

The heel angle is the major limitation for the integration of disabled people onboard mono-hull sailing yachts, in particular if mobility is based on wheelchairs. The most common mechanisms to reduce the heel angle are water ballast or a canting keel; both mechanisms move the centre of gravity to windward to increase the righting moment. An alternative solution to control the swing of a canting keel is designed for the present project needs. This system connects the shroud tension to a keel lever arm above water and swings the keel according to the sails demands. It doesn't require any expert crew for manual operation or any expensive electric control system. According to the author's knowledge this is a new system not yet developed for other projects.

The idea behind the self stability system is subsequently explained, followed by a numerical model to be used in performance prediction computations. Finally, a performance prediction is made for the present project and the results evaluate the *Inclusion 32* with and without self stability system.

7.1 The idea

The inclining moment is originated by the sails and is mostly balanced by the hull form stability and the heavy weight of the keel. For the present project it would be advantageous if only the keel could balance the sails demands, leaving the hull in the horizontal position due to the form stability.

The aerodynamic side force is normally transferred from the sails to the hull through the shrouds. The idea is to connect the shrouds directly to the canting keel arm and balance the sails demands with the swing of the keel. The transversal balance is then achieved automatically. For example, stronger winds increase the sails aerodynamic side force, this increases the shroud tension which swings the keel to windward. In a steady situation the keel guarantees the windward shroud tension, as it swings to windward and increases the righting moment. The hull doesn't remain completely independent of the process and it will heel slightly to complete the required righting moment. The mast must be fitted to the cabin top, and it rotates to leeward due to the windward shroud length increase.

Figure 7.1.1 illustrates the system, for simplicity only the starboard shroud is presented. However, the system is symmetric and operates as a closed loop. The shroud tension may be multiplied/decreased to optimize the relation between the force applied to the keel and the respective swing angle, Figure 7.1.2 presents a closer view of the system. The respective increase in shroud length is also half which reduces the mast rotation. A system with not sufficient multiplication may swing too much the keel and force the hull to heel to the windward side. The optimum system must be defined for each situation according to the rig and keel dimensions.

In practice, the swing of the keel may need to be limited to avoid the loss of lateral area associated with excessive swing. A damping system may also be required to reduce the continuous keel movement associated with wind and waves oscillations. The cabin top must be well reinforced to support the mast compression load, because when the mast heels in relation to the hull the angle between the mast and the shroud decreases, which increases the mast compression.

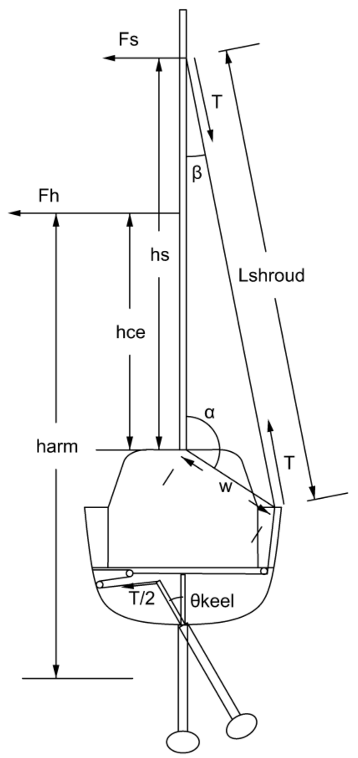

Figure 7.1.1 -– Main dimensions of the self stability system

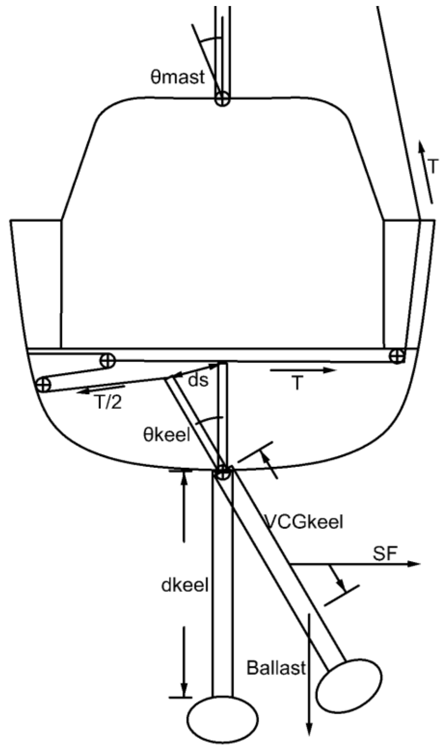

Figure 7.1.2 - Dimensions related to the moment generated by the keel.

7.2 Numerical model

The calculation of the forces involved with this mechanism relates to the interaction between the sails, keel and hull. Figure 7.1.1 presents the main dimensions used through the subsequent formulations. This computation is an iterative process, for the first cycle the heel angle of the keel alone and the heel of the hull may be assumed to be equal to zero.

For a given heeling moment (M_{heel}) applied by the wind to the yacht, the respective heeling force (F_h) at the sails centre of effort may be computed according to the heeling arm (h_{arm}), which is the distance from the sails centre of effort to the underwater centre of lateral resistance, Eq.(7.2.1).

$$F_h = \frac{M_{heel}}{h_{arm}} \tag{7.2.1}$$

The heeling force is then transformed from the sails centre of effort to the shrouds attachment height (F_s). The heeling force is multiplied by the distance from the cabin top to the sails centre of effort (h_{CE}) and divided by the distance from the cabin top to the shrouds attachment (h_s), Eq.(7.2.2).

$$F_s = \frac{F_h \cdot h_{CE}}{h_s} \tag{7.2.2}$$

The shroud tension (T) must withstand the sails transversal force, being proportional to the angle between the shroud and the vertical (β), Eq.(7.2.3).

$$T = \frac{F_s}{\sin(\beta)} \tag{7.2.3}$$

With the multiplication system previously described only half of the shrouds tension is applied to the keel arm. The moment created to swing the keel (M_{keel}) is defined by half of the shroud tension applied at the top of the keel arm (h_{keel}) and by the underwater side force applied at half of the keel depth (d_{keel}), Eq.(7.2.4). The shroud tension is not always perpendicular to the keel arm and must be multiplied by the cosine of the keel rotation angle. The vertical distance from the keel centre of rotation to the side force is also reduced as the keel rotates. The underwater side force is equal to the heeling force times the cosine of the total keel heel, which is the keel swing alone plus the hull heel angle, Eq.(7.2.5). Figure 7.1.2 presents a close view of the canting keel and the respective dimensions.

$$M_{Keel} = h_{keel} \cdot \frac{Tension}{2} \cdot \cos(\theta_{Keel}) + SF \cdot \frac{d_{keel}}{2} \cdot \cos(\theta_{Keel}) \tag{7.2.4}$$

$$SF = F_{heeling} \cdot \cos(\theta_{Keel} + \theta_{Hull}) \tag{7.2.5}$$

The keel swing angle is defined by the balance between the keel moment and the keel mass (Ballast) at a given vertical centre of gravity (VCG_{Keel}). The keel moment is equal to the keel mass times the distance that the vertical centre of gravity is moved sideways (dy) and the final angle may be taken from here, Eq.6.

$$\begin{cases} M_{keel} = dy \cdot Ballast \cdot g \\ \sin(\theta_{keel}) = \dfrac{dy}{VCG_{keel}} \end{cases} \Leftrightarrow \theta_{keel} = \sin^{-1}\left(\frac{M_{keel}}{Ballast \cdot g \cdot VCG_{keel}}\right) \tag{7.2.6}$$

The moment that the hull must withstand with form stability (M_{hull}) is the difference between the initial heeling moment and the restoring moment generated by the keel, Eq.(7.2.7). The hull heeling angle (θ_{hull}) is obtained from the curve of static stability.

$$M_{hull} = M_{heel} - M_{Keel} \tag{7.2.7}$$

The tension swings the keel and the windward shroud is extended, which rotates the mast to the leeward side. The length of shroud left by the keel arm rotation (ds) is calculated according to the trigonometric cosine law, Eq.(7.2.8).

$$ds = \sqrt{h_{keel} + h_{keel} - 2 \cdot h_{keel} \cdot h_{keel} \cdot \cos(\theta_{Keel})} \tag{7.2.8}$$

Due to the multiplication system the shroud is extended by half of ds, Eq.(7.2.9). The leeward rotation of the mast is also calculated according to the cosine law, Eq.(7.2.10). The sides of the triangle are the distance from the mast base at the cabin top to the shrouds attachment (h_s), the length of the extended shroud ($L_{shroud\ i}$) and the distance from the mast base to the entrance of the shroud in the upper deck (w). The angle between h_s and w (α) defines the rotation of the mast, which is equal to the difference of the angle for the upright position (α_{up}) and the angle after the shroud extension (α_i), Eq.(7.2.11).

$$L_{shroud\ i} = L_{shroud\ i-1} + \frac{ds}{2} \tag{7.2.9}$$

$$\alpha_i = \cos^{-1}\left(\frac{L_{shroud\ i}^2 - d^2 - h_s^2}{-2 \cdot d \cdot h_s}\right) \tag{7.2.10}$$

$$\theta_{mast} = \alpha_i - \alpha_{up} \tag{7.2.11}$$

The cosine law is applied again to the same triangle to define the angle between the mast and the shroud (β_i), Eq.(7.2.12). This value is subsequently iterated in Eq.(7.2.3) and the process is repeated until the values converge.

$$\beta_i = \cos^{-1}\left(\frac{d^2 - h_s^2 - L_{shroud\ i}^2}{-2 \cdot h_s \cdot L_{shroud\ i}}\right) \quad (7.2.12)$$

The previous equations describe numerically the self stability system and may be used to predict the heel angle of the system components for a given heeling demand. These equations were subsequently used to evaluate the self stability system effect on the *Inclusion 32*. An initial simulation is presented only for the transversal direction and then with the Velocity Prediction Program altered for the system operation in order to evaluate the overall performance.

7.3 Self stability simulation

Transversal direction analysis

The system is applied to the *Inclusion 32* (Long Keel version) and numerically simulated in the transversal direction. The curve of static stability is used to obtain the aerodynamic side force and the sequence of formulations previously presented is built in an *Excel* spread sheet, enabling iterative calculations. These simulations permit to compare the heeling angle of the standard yacht, i.e. fixed keel, and the yacht with the self stability syst1em, since both suffer the same heeling moment. The results are given in Table 7.3.1, where the keel and mast hell angle correspond to the component inclination in relation to the vertical.

Table 7.3.1 – Heel angle differences for the same righting angle.

	Standard Version	Self stability version		
RM [N.m]	Heel [^{0}]	θ_{Hull} [^{0}]	θ_{Keel} [^{0}]	θ_{Mast} [^{0}]
9748	5	3.6	8.2	5
18955	10	7	16.1	9.9
27139	15	10.4	23.1	14.4
34179	20	13.6	29.4	18.6
40076	25	16.5	34.7	22.4
45011	30	19.4	39.4	25.8
49163	35	22	43.5	29
52713	40	24.6	47.1	31.9
55782	45	27.1	50.5	34.7

The hull of the self stability version sails in average with 34% less heel angle than the standard version, this value increases with the heel angle. When the standard version is sailing with 20^0 the self stability version hull has 13.6^0. Even at low angles of heel the difference is significant and is a considerable improvement for the disabled people operation. The self stability keel sails at higher angles than the standard keel, therefore attention must be given to provide sufficient lateral area to balance the aerodynamic side force. The mast rotates to leeward but because the hull heels much less than the standard version, the angle between the mast and the vertical is smaller with the self stability system which improves the aerodynamic performance of the sails.

Self stability performance prediction

One of the reasons to build a specific Velocity Prediction Program (VPP) described in the Performance Prediction chapter was the possibility to estimate changes in performance caused by the self stability mechanism. Therefore, the equations previously presented are introduced in the Velocity Prediction Program and the results are subsequently presented.

The shrouds tension is obtained from the sails aerodynamic side force and then all the equations follow the previous sequence. The frictional and residuary resistance are calculated according to the hull heel angle. While the induced resistance and leeway angle are calculated with the total keel heel angle, and the apparent wind is calculated with the total mast heel angle. The VPP results were validated by the transversal simulation since for the same heeling moment the components heeling angles are the same.

In terms of the velocity prediction for a given wind speed the self stability system is in average 1.3% faster than the standard version, the difference increases slightly with the wind intensity, and there is no significant change with the course angle. In alternative, Figure 7.3.1 presents the velocity achieved with and without the system at a given hull heeling angle instead of at a given wind condition. This is relevant for the present project since the heel angle is often the performance limiting factor. These velocities are predicted for different wind speeds at a constant heading ($\beta_{TW}=70^0$).

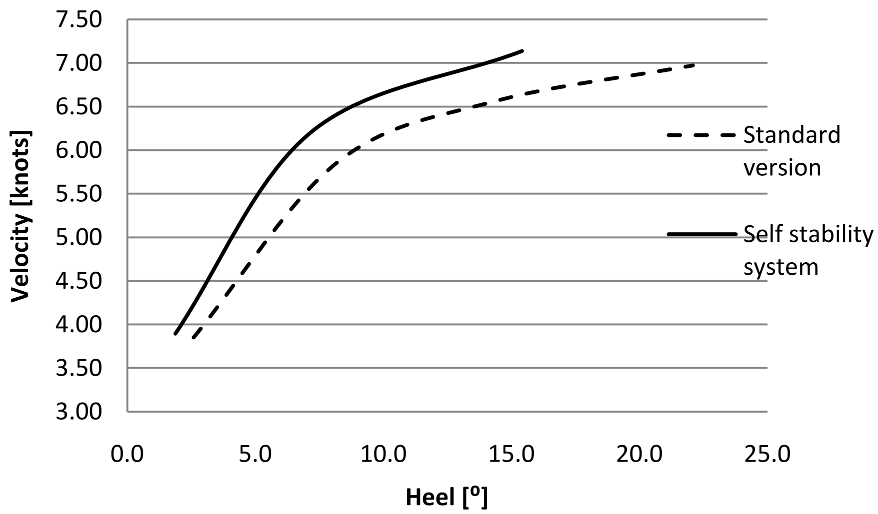

Figure 7.3.1 – Velocity difference at a given heel angle.

Disabled people will sail in the range of 5^0 to 10^0 of heel and may increase speed in more than half knot with the self stability system. For other angles the speed increase is approximately the same. This increase in velocity is particularly important for the present project, since its performance was adversely affected by the heavy displacement and large beam designed reduce the heel angle. For further development of the project the keel displacement could be optimized for the self stability operation, which will improve the yacht performance due to a weight reduction.

7.4 Summary

In conventional yachts the sails transfer the heeling loads through the shrouds to the hull, which heels to produce the required righting moment. The self stability system connects the shrouds directly to a canting keel lever arm, which supports the shroud tension by swinging the heavy bulb to windward. The balance between the sails and the keel is established according to the shrouds tension, and the hull heels to produce the missing righting moment.

The balance between the sails and the keel is modified by the use of multiplication/decrease systems. The present project was studied with one multiplication in the system, which reduced the force applied to the keel, as well as the keel and mast rotation. A successful implementation of this system requires a well designed cabin top structure to withstand the mast compression loads at different angles. The canting keel systems are already a reliable technology being straightforward to implement.

The system is described numerically and the sequence of given formulations is used to predict the heeling angle of each component and the respective loads. The transversal direction analysis compares the heeling angle of the present project with a fixed keel and with the self stability system. The results show that the system with one multiplication reduces the heeling angle in average by 34%. According to the results obtained with the VPP the average speed difference is about 1% for a given true wind. However, for the present project the heel angle is often the speed limiting factor, and prediction results indicate that at the same heading and heel angle the yacht with self stability system sails about half knot faster.

The heel angle is an uncomfortable situation for most sailors but the disabled people are the most affected and this system may represent an important step for their integration onboard sailing yachts. According to the presented results the self stability system is also suitable to reduce the heel angle or improve the performance of conventional yachts.

8 Performance prediction

The *Inclusion 32* performance was predicted with a Velocity Prediction Program developed for the present project. A Velocity Prediction Program is used to optimize various components of the yacht and to estimate the yacht's performance in a wide range of sailing conditions. The Velocity Prediction Program solves the mathematical equations of the aerodynamic and hydrodynamic forces until an equilibrium situation is found. During this process some parameters are permanent and decided by the user, while the others are automatically iterated. If more than one equilibrium condition is possible the program maximizes the vessel's speed.

With a conventional Velocity Prediction Program (VPP) it is not possible to assume a maximum heeling angle different than the corresponding angle at the maximum speed. In addition, to perform the performance prediction for the self stability system required purpose built computer code to implement the numerical model previously defined. Due to these reasons a dedicated VPP was necessary and the initial part of this chapter reports the procedure applied to the development of a specific program for the present project, the results are validated against the VPP *PCSAIL2.5.*

With the VPP made it was possible to predict the *Inclusion* 32 performance for different situations. The velocity predicted was initially compared with a modern cruiser, *Hanse 32*, to validate the overall performance of the project. Afterwards, the velocity predictions for the two keel configurations defined at the Appendage design chapter are compared, and a detailed analyse of the resistance components is presented to identify the physical differences between the two models. To conclude, it is presented the velocity predicted for both models considering the operation of a disabled crew.

8.1 Velocity Prediction Program

The equilibrium of a yacht depends on six degrees of freedom, but only two are routinely considered on a VPP, the longitudinal force and the rolling moment. The vertical force and the pitching moment are assumed to be balanced by the hydrostatic forces, and the yawing moment is assumed to be balanced by the rudder moment. The side force is balanced when the yacht assumes a leeway angle, required to resist the aerodynamic side force.

In order to solve these equilibrium equations the present program has three main parts; the Hydrodynamic Model, the Aerodynamic Model, and a Solution Algorithm. These parts are described individually with the respective formulations and assumptions. Figure 8.1.1 presents a diagram of the process and special attention is given to the relevant parameters between each step.

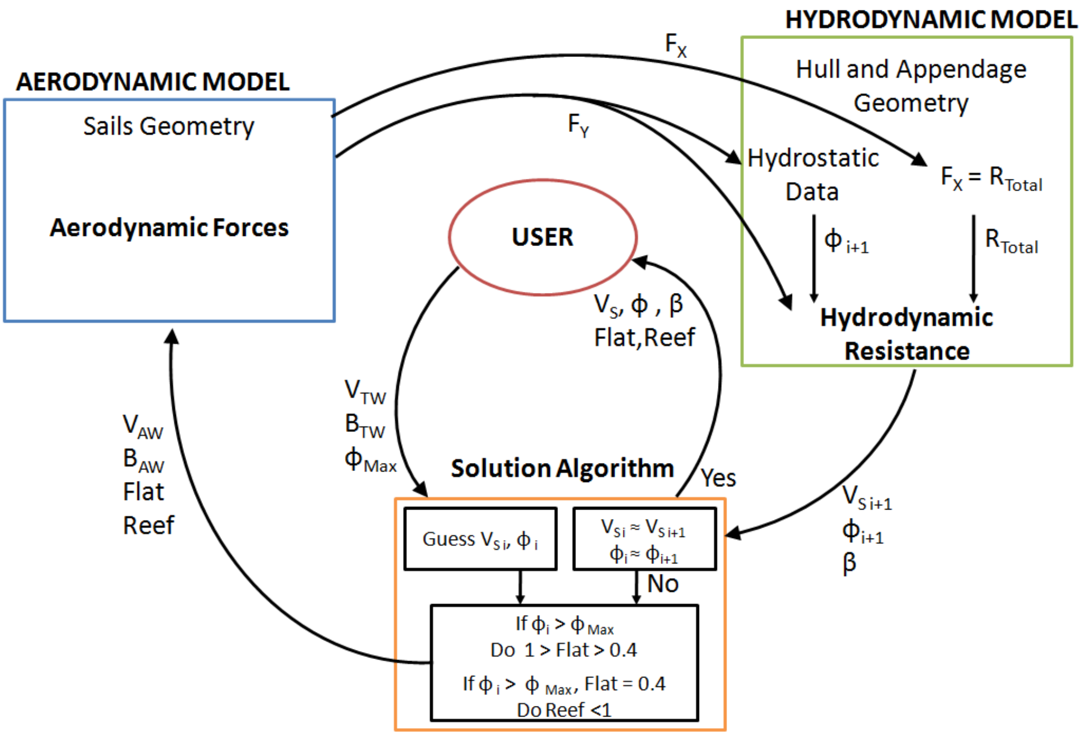

Figure 8.1.1 – Calculation process of the VPP

8.1.1 Calculation process

The calculation process described in Figure 8.1.1 is subsequently presented with the respective formulations. The solution algorithm search for the balance between the aerodynamic and hydrodynamic forces, by adjusting the sail controls (flat and reef coefficients) for a given wind condition. The function of these coefficients is described at the Aerodynamic Force section.

To start the process, the user specifies the true wind speed (V_{TW}) and the true wind angle (B_{TW}). The true, or natural, wind is modified by having moved across the water surface and under normal circumstances, blows stronger as the height above the sea increases. The wind is assumed to be measured at the top of the mast, where most electronic devices are located; though it is necessary to transform the wind speed form here to the sails centre of effort (Claughton, 2006).

$$V_{TW}(CE) = V_{TW}\,(Top).\left(\frac{z_{CE}}{z_{Top}}\right)^{1/7} \qquad (8.1.1)$$

The Solution Algorithm guesses an initial yacht velocity (V_S) and heeling angle (φ). For the present project it is important that under a critical situation the vessel doesn't heel more than a maximum heeling angle suitable for wheelchair operation, for example 10º. Thus if the heeling angle guess is above the maximum, the solution algorithm assume a Flat coefficient between 1 and 0.4, if the heeling angle is still above the maximum when the Flat coefficient is at minimum value, the Reef coefficient must be assumed between 1 and 0. The sails are not rig foils and the flat coefficient represents a reduction of the sail camber performed by the crew to optimize the sails performance. The reef corresponds to a reduction of the sails area to cope with above normal wind speeds. Once the heeling condition is satisfied the process searches for the maximum yacht speed.

The true wind velocity plus the yacht velocity gives the apparent wind. A geometrical transformation has to be made to obtain the forces at the heeled condition. The component of the apparent wind velocity along the hull is unchanged by heel, Eq.(8.1.2), while the component at right angles is proportional to the cosine of the heel angle, Eq.(8.1.3). The leeway is neglected in this computation, so the two directions to consider are along (V_1) and at right angles (V_2) to the direction of motion. The effective apparent wind speed (V_{AW}) and effective apparent wind direction (B_{AW}) may then be obtained (Larson, et al., 2007).

$$V_1 = V_S + V_{TW}.\cos(\beta_{TW}) \tag{8.1.2}$$

$$V_2 \approx V_{TW}.\sin(\beta_{TW}).\cos(\phi) \tag{8.1.3}$$

$$V_{AWe} = \sqrt{V_1^2 + V_2^2} \tag{8.1.4}$$

$$\beta_{AWe} = \mathrm{acos}\left(\frac{V_1}{V_{AWe}}\right) \tag{8.1.5}$$

The apparent wind angle is used in the aerodynamic model to interpolate the lift and drag coefficients of the complete set of sails. To be useful for predictions the components parallel to, and at right angles to the direction of motion are required. The subsequent equations convert the lift (C_L) and drag (C_D) into driving (C_X) and side (C_Y) coefficients.

$$C_X = C_L.\sin(\beta_{AWe}) - C_D.cos(\beta_{AWe}) \tag{8.1.6}$$

$$C_Y = C_L.\cos(\beta_{AWe}) + C_D.\sin(\beta_{AWe}) \tag{8.1.7}$$

The driving and side forces are easily obtained from the respective coefficient, total sail area and the effective apparent wind velocity.

$$F_X = 0.5 \cdot \rho_{air} \cdot A_n \cdot V_{AWe}^2 \cdot C_X \tag{8.1.8}$$

$$F_Y = 0.5 \cdot \rho_{air} \cdot A_n \cdot V_{AWe}^2 \cdot C_Y \tag{8.1.9}$$

The righting moment (RM) is calculated from the aerodynamic side force and the vertical distance from the sail plan centre of effort to the underwater centre of lateral resistance (h_{arm}). The righting moment is interpolated in the curve of static stability from the hydrostatic calculations, to estimate the heel angle.

Finally, the total resistance of the hull and appendages must be equal to the previous drive force. The total resistance is estimated from *Delft Systematic Yacht Hull Series* (DSYHS), for a range of velocities and heeling angles. The resistance calculation is also a cyclic process in itself because the induced resistance is a function of the aerodynamic side force and the trim resistance is a function of the aerodynamic driving force. The resistance calculations are discussed at the Hydrodynamic Force section. The yacht's velocity is then obtained by interpolating the driving force and heeling angle in the final resistance values. The leeway angle (λ) is computed at the end of the calculation process from the aerodynamic side force. Once the new heeling angle and new yacht's speed is computed the large loop presented in Figure 8.1.1 is closed. If the new values are close enough to the previous ones the process ends, otherwise, the new values are assumed to be the guesses for the next cycle. The output of the program is the yacht's final velocity, heeling angle, leeway angle, Flat and Reef coefficients.

8.1.2 Aerodynamic force model

The model for the aerodynamics of sailing yachts used here is presented by the *Principles of Yacht Design*. In this model the lift and viscous drag of each sail are described as a function of the apparent wind angle. Only five angles are given and interpolation is done using spline functions.

Lift Coeficients			
Angle	$C_{L M}$	$C_{L J}$	$C_{L S}$
27	1.5	1.5	0
50	1.5	0.5	1.5
80	0.95	0.3	1
100	0.85	0	0.85
180	0	0	0

Viscous Drag Coeficients			
Angle	C_{DPM}	C_{DPJ}	C_{DPS}
27	0.02	0.02	0
50	0.15	0.25	0.25
80	0.8	0.15	0.9
100	1	0	1.2
180	0.9	0	0.66

Table 8.1.1 – Lift and parasitic drag coefficients for main (M), jib (J), and spinnaker (S).

The original model gives coefficients for five sails (main, jib, spinnaker, mizzen, and mizzen staysail), however only the main, jib and spinnaker are relevant for conventional yachts and the respective areas and centre of effort height above the sheer line are calculated from Eq.(8.1.10) to Eq.(8.1.16). The total lift or viscous drag (also called the parasitic drag, which explains the index P) is obtained according to the sails average, Eq.(8.1.18) and Eq.(8.1.19), each sail is to be multiplied by the corresponding coefficient, and divided by a nominal sail area, which is the sum of the fore triangle and main sail areas Eq.((8.1.17). All areas are computed as triangular, ie the roach is neglected, the relevant equations for the program are subsequently presented.

The induced drag, which is more important than the viscous drag for upwind sailing, is computed from simple wing theory. The induced drag coefficient is thus proportional to the square of the lift coefficient, and inversely proportional to the aspect ratio Eq.(8.1.20). In the present method the entire nominal sail plan is considered when computing the aspect ratio and the induced drag. This model considers the drag of the mast and topsides Eq.(8.1.21), the frontal area is taken as the average freeboard times the maximum beam, while the mast is computed from the mean diameter times the mast height above deck. The total drag is the sum of the viscous, induced and mast/topsides components Eq.(8.1.22).

Main:

$$A_M = 0.5 \cdot P \cdot E \quad (8.1.10)$$

$$CE_M = 0.39 \cdot P + BAD \quad (8.1.11)$$

Jib: $$A_J = 0.5 \cdot \sqrt{I^2 + J^2} \cdot LPG \quad (8.1.12)$$

$$CE_J = 039 \cdot I \quad (8.1.13)$$

Spinnaker: $$A_S = 1.15 \cdot SL \cdot J \quad (8.1.14)$$

$$CE_S = 0.59 \cdot I \quad (8.1.15)$$

Foretriangle: $$A_F = 0.5 \cdot I \cdot J \quad (8.1.16)$$

Nominal area: $$A_N = A_F + A_M \quad (8.1.17)$$

Lift: $$C_L = \frac{C_{LM} \cdot A_{M+} C_{LJ} \cdot A_J + C_{LS} \cdot A_S}{A_N} \quad (8.1.18)$$

Viscous/Parasitic drag: $$C_{DP} = \frac{C_{DPM} \cdot A_{M+} C_{DPJ} \cdot A_J + C_{DPS} \cdot A_S}{A_N} \quad (8.1.19)$$

Induced drag: $$C_{DI} = C_L^2 \cdot \left(\frac{1}{\pi \cdot AR} + 0.005\right) \begin{cases} close\ hauled: AR = \dfrac{(1.1 \cdot (EHM + FA))^2}{A_N} \\ other\ corses: AR = \dfrac{(1.1 \cdot EHM)^2}{A_N} \end{cases} \quad (8.1.20)$$

Drag of mast and topsides: $$C_{DO} = 1.13 \cdot \frac{(BMAX \cdot FA) + (EHM \cdot EMDC)}{A_N} \quad (8.1.21)$$

Total drag: $$C_D = C_{DP} + C_{DI} + C_{DO} \quad (8.1.22)$$

Flattening: Multiply C_L by flat coefficient (Flat).

Reefing: Multiply height of CE by the reef factor (Reef), multiply C_L and C_{DP} by reef factor squared.

Notation:

P: Mainsail hoist

E: Foot of mainsail

I: Height of foretriangle

J: Base of foretriangle

LGP: Perpendicular of longest jib

SL: Spinnaker leech length

BMAX: Max beam of yacht

FA: Average Freeboard

EHM: Height of mast above sheer

EMDC: Average mast diameter

BAD: Height of main boom above sheer

An important feature of this sail model is the possibility of considering reefing and flattening of the sails. Reefing defines the reduction of sail height, Reef is equal to 1 for the unreefed sail. The new height of centre of effort is thus obtained as Reef times the original height, while the new area is found by multiplying by the Reef squared. The flattening factor specifies the reduction in lift due to the flattening of sails, being equal to 1 for the normal sail and assumed to be not less than 0.4. This factor is related with the sail camber and has no effects on the heeling arm. Since the lift is proportional to Flat and the induced drag proportional to $Flat^2$, the flattening reduces more drag than lift. Therefore it is better to flatten the sail before reefing. In most VPPs optimum values of Reef and Flat are found to maximize yacht's speed, while the present project uses these coefficients to avoid excessive heeling angles as well.

8.1.3 Hydrodynamic force model

The estimation of the hydrodynamic forces acting on the yacht is based on the formulations identified as *Delft Systematic Yacht Hull Series* (Keuning, et al., 1998). The DSYHS are very extensive series of tank test with models of sailing yachts that has been carried out at the Delft University of Technology over a period of more than 30 years. It presents formulations to estimate the bare hull and appended hull resistance in the upright and the heeled condition, the resistance increase due to the longitudinal trimming moment of the sails, the side force production and induced resistance due to side force at various combinations of forward speeds, leeway angles and heeling angles.

Upright Hull Resistance

The upright resistance of the hull is the starting point of the resistance calculations. For the determination of the frictional resistance (R_f) use is made of Eq.(8.1.23).

$$R_f = \frac{1}{2} \cdot \rho_{water} \cdot V_s^2 \cdot S \cdot C_f \qquad (8.1.23)$$

In the determination of the frictional resistance is used the ITTC-57 (International Towing Tank Conference 1957) extrapolation line.

$$C_f = \frac{0.075}{(Log(R_n) - 2)^2} \qquad (8.1.24)$$

In which the hull Reynolds number (R_n) is determined by:

$$R_n = \frac{V_s \cdot 0.7 \cdot L_{wl}}{\nu} \qquad (8.1.25)$$

For normal ships the still waterline length is used for the calculations of the Reynolds number, while for yacht hulls this does not represent the path of travel of the particles in the actual flow. As may be seen from the previous expression 70% of the waterline length appears to be a reasonable approximation. No form factor is used in the DSYHS for transformation of the frictional into viscous resistance of the hull. This decision is based on the absence of a generally accepted formulation of the form factor, leaving any differences in the viscous resistance due to the hull shape in the residuary resistance component (Keuning, et al., 1998). The residuary resistance of a sailing yacht hull in the upright condition for a rage of Froude numbers is given by Eq.(8.1.26). The coefficients of this polynomial expression from a_0 to a_8 are in Annex 6 Table 8.4.1.

$$\frac{Rrh}{\nabla_{c \cdot \rho \cdot g}} = a_0 + \left(a_1 \cdot \frac{LCB_{fpp}}{Lwl} + a_2 \cdot Cp + a_3 \cdot \frac{\nabla_c^{2/3}}{Aw} + a_4 \cdot \frac{Bwl}{Lwl} \right) \cdot \frac{\nabla_c^{1/3}}{Lwl} + \left(a_5 \cdot \frac{\nabla_c^{2/3}}{S_c} + a_6 \cdot \frac{LCB_{fpp}}{LCF_{fpp}} + a_7 \cdot \left(\frac{LCB_{fpp}}{Lwl}\right)^2 + a_8 \cdot Cp^2 \right) \cdot \frac{\nabla_c^{1/3}}{Lwl} \qquad (8.1.26)$$

Heeled Resistance

When the yacht heels over there is a change in resistance, which can be split in a viscous and a residuary part, each being treated separately. Here, no account is made for the lift forces acting on the hull and appendages, leaving it for the induced resistance component. The change in viscous resistance due to heel of the canoe body is solely attributed to a change in wetted area of the yacht hull. Once again no form factor is taken into account. Based on the hydrostatic calculations which have been carried out for all the models of the DSYHS the change in wetted area of the hulls with heeling angle can be determined by the following expression. The respective coefficients are given in Annex 6,

Table 8.4.2.

$$S_{C\theta} = S_{C\theta=0} \cdot \left(1 + \frac{1}{100} \cdot \left(s_0 + s_1 \cdot \frac{Bwl}{T_c} + s_2 \cdot \left(\frac{Bwl}{T_c}\right)^2 + s_3 + Cm\right)\right) \tag{8.1.27}$$

The change of residuary resistance due to the heel is determined from a polynomial expression formulated just for this small change (delta). The delta residuary resistance at 20 degrees of heel (as an average sailing angle) can be approximated by the given expression, with the coefficients presented in Annex 6 (

Table 8.4.3).

$$\frac{\Delta Rrh_{\theta=20^0}}{\nabla_c \cdot \rho \cdot g} = u_0 + u_1 \cdot \frac{Lwl}{Bwl} + u_2 \cdot \frac{Bwl}{T_c} + u_3 \cdot \left(\frac{Bwl}{T_c}\right)^2 + u_4 \cdot LCB + u_5 \cdot LCB^2 \tag{8.1.28}$$

For other angles of heel, the change in residuary resistance is proportional to the previous result (20 degrees of heel) and the heeling angle in radians to the power of 1.7.

$$\Delta Rrh_{\theta} = \Delta Rrh_{\theta=20^0} \cdot 6.0 \cdot \theta^{1.7} \tag{8.1.29}$$

Appendage Resistance

The resistance of the bare hull and the appendages are dealt with separately. The viscous resistance (R_v) of the appendages is considered to be a summation of the frictional resistance and other viscous effects accounted by the introduction of a form factor (k).

$$R_v = R_f \cdot (1 + k) \tag{8.1.30}$$

For the calculation of the appendage frictional resistance (R_f) use is made of Eq.(8.1.23), Eq.(8.1.24) and Eq.(8.1.25). The Reynolds number is defined by the average chord length of the appendage. The viscous and form drag is taken into calculation by making use of the formulation given in *Fluid Dynamic Drag*, Eq.(8.1.31) (Hoerner, 1965). Each of the appendages (keel, rudder and bulb) is treated in a similar manner.

$$(1 + k) = \left(1 + 2 \cdot \frac{t}{c} + 60 \cdot \left(\frac{t}{c}\right)^4\right) \tag{8.1.31}$$

The appendage residuary resistance is accounted only for the keel according with Eq.(8.1.32). For lower Froude numbers the contribution of the keel residuary resistance in the total resistance is not very large, but it increases for the high speeds. The respective coefficients are presented in Annex 6, Table 8.4.4.

$$\frac{Rrk}{\nabla_k \cdot \rho \cdot g} = A_0 + A_1 \cdot \frac{T}{Bwl} + A_2 \cdot \frac{(T_c + Zcbk)^3}{\nabla_k} + \frac{\nabla_c}{\nabla_k} \qquad (8.1.32)$$

The viscous resistance of the appendages is considered not to be influenced by the heeling of the yacht, since the wetted surface remains the same. However, the keel residuary resistance is strongly influenced by the fact that the volume of appendage is brought closer to the free surface. Hence, the following expressions are used to approximate the keel residuary resistance due to heel. The respective coefficients are presented in Annex 6

Table 8.4.5.

$$\frac{\Delta Rrk\theta}{\nabla_k \cdot \rho \cdot g} = Ch \cdot Fn^2 \cdot \theta \qquad (8.1.33)$$

$$Ch = H_1 \cdot \frac{T_c}{T} + H_2 \cdot \frac{BWL}{T_c} + H_3 \cdot \frac{T_c}{T} \cdot \frac{Bwl}{T_c} + H_4 \cdot \frac{Lwl}{\nabla_c^{1/3}} \qquad (8.1.34)$$

Induced Resistance

The induced resistance estimation is based on the fundamental principle of the added resistance due to the side force production of a wing with finite span. This is related to the circulation around the foil and its geometry. Eq. (8.1.35) calculates the induced resistance as a function of the heeling force (F_h), which acts at 90 degrees with the keel plate and is equal to the aerodynamic side force.

$$Ri = \frac{F_h^2}{\pi \cdot Te^2 \cdot \frac{1}{2} \cdot \rho \cdot V^2} \qquad (8.1.35)$$

The effective span (T_e) of the hull with appendages is also determined from measurement data for a range of heeling angles and as a function of the Froude number Eq.(8.1.36). The respective polynomial coefficients are also presented in Annex 6

Table 8.4.6..

$$\frac{Te}{T} = \left(A_1 \cdot \frac{T_c}{T} + A_2 \cdot \left(\frac{T_c}{T}\right)^2 + A_3 \cdot \frac{Bwl}{T_c} + A_4 \cdot TR\right) \cdot (B_0 + B_1 \cdot Fn) \qquad (8.1.36)$$

The hydrodynamic side force balances the aerodynamic side force and the yacht will assume a leeway angle to produce such a side force. The leeway angle can be estimated from Eq.(8.1.37) as a function of the heeling force, heeling angle, draft and wetted surface. The respective coefficients are presented in Annex 6

Table 8.4.7.

$$\frac{Fh \cdot \cos(\theta)}{\lambda \cdot {}^{1}/_{2} \cdot \rho \cdot V^2 \cdot Sc} = b_1 \cdot \frac{T^2}{Sc} + b_2 \cdot \left(\frac{T^2}{Sc}\right)^2 + b_3 \cdot \frac{T_c}{T} + b_4 \cdot \frac{T_c}{T}\frac{T^2}{Sc} \tag{8.1.37}$$

Added resistance in waves

The added resistance in waves (R_{AW}) is calculated for wind generated waves with an incident angle (μ) ranging from 135^0 (corresponding to close hauled condition) to 110^0, and is assumed to be zero for incident angles lower than 90^0. It is function of the significant wave height ($H_{1/3}$), defined as the mean height of the largest one third of the waves and assumed to be presently equal to 0.4 meters. The wave period is also considered and is assumed to be 2.8 seconds. The natural frequency in pitch is accounted by the longitudinal radius of gyration (k_{yy}), which is defined by the mass moment of inertia around the transverse axis through the centre of gravity (I_{YY}) and the total mass.

$$\frac{R_{AW} \cdot 10^2}{\rho \cdot g \cdot Lwl \cdot H_{1/3}^2} = a \cdot \left(10^2 \cdot \frac{\nabla_c^{1/3}}{Lwl}\frac{K_{yy}}{Lwl}\right)^b \tag{8.1.38}$$

$$K_{yy} = \sqrt{\frac{I_{yy}}{m}} \tag{8.1.39}$$

The two coefficients “a” and “b” are presented in Annex 6

Table 8.4.8. They are determined by the Froude numbers, heading angle and the mean wave period.

Resistance due to trim

It is known that a considerable resistance increase may occur from the bow down trimming moment, which is generated by the driving force applied at the sails centre of effort. The crew might be capable of balance this trimming moment by moving their weight aft. This is not the case of the current project, where the crew is expected to be most of the time in the cockpit area, with reduced mobility. The Eq. 41 is based on the hydrostatic calculations and the series of measured data. This resistance is only accounted in the present program for true wind angles above 50 degrees. The respective coefficients are presented in Annex 6 Table 8.4.9.

$$\frac{\Delta Rrh\varphi}{M\varphi /_{KML \cdot \tan(1^0)}} = T_0 + T_1 \cdot \frac{Lwl}{Bwl} + T_2 \cdot \frac{Bwl}{T_c} + T_3 \cdot \frac{Aw}{\nabla_c^{2/3}} + T_4 \cdot LCB + T_5 \cdot LCF \tag{8.1.40}$$

Total Resistance

The total resistance is the sum of the total components presented before. It is a function of a large number of parameters in particular: vessels speed (Froude number), heeling angle (frictional and residuary), aerodynamic side force (induced resistance), aerodynamic driving force (trim resistance) and the true wind angle (wave resistance).

8.1.4 Results validation

The output obtained by the present Velocity Prediction Program was compared with the results from a conventional VPP, PCSAIL 2.5.xls, developed by the University of Michigan. The Short Keel version of the actual design was tested in both programs and the results compared in Figure 8.1.3 and Figure 8.1.2. The results are close for most situations and provide good confidence in the estimations of the present VPP. However, at low true wind angles there is a considerable difference that decreases with the wind speed. For the present project the velocity performance is not a major concern and these differences are acceptable. Also important is the heel angle prediction presented in Figure 8.1.2 according with the two programs. The results are also close as in this case the differences are in the area around true wind angles of 90^0 where the maximum difference is 2^0.

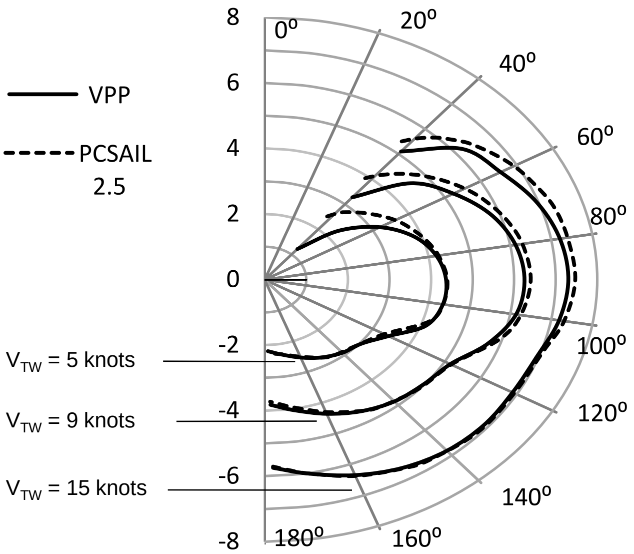

Figure 8.1.3 – Velocity compare between present project VPP with PCSAIL 2.5

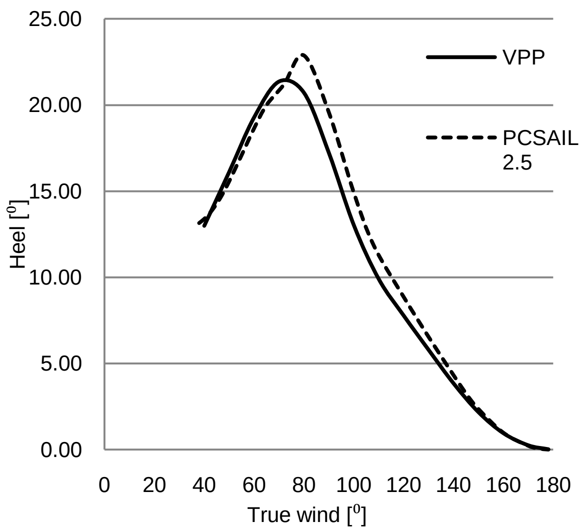

Figure 8.1.2– Heel angle compare between present project VPP with PCSAIL 2.5.

The two programs are constructed in *Excel* and use similar formulations, however the *PCSAIL 2.5* predicts the hydrodynamic resistance based on the *Delft Systematic Yacht Hull Series* published in 1993. Therefore small differences between both programs may be found on the calculation process and in the hydrodynamic force estimation due to the improvements of the DSYHS from 93 to 98. The latter publication of the DSYHS presents additional data, as well as new formulations for the resistance due to appendages, heel and trim. The hydrostatic calculations are also different, while the present program uses the curve of static stability, the PCSAIL computes the heeling equilibrium based on the initial metacentric transversal height. These considerations don't intend to say that the present VPP is more developed than the *PCSAIL 2.5* but to highlight the differences. In fact the velocity results obtained by the *PCSAIL 2.5* at β_{TW}=40º seem more fair. Even with these slightly differences the VPP results are considered satisfactory for the present project.

8.2 *Inclusion 32* performance prediction

8.2.1 Maximum velocity prediction

The main dimensions of the Short keel version and Long keel version are given in Table 8.2.1. The long keel version has a lower centre of gravity, which leads to lower displacement and wetted surface for the same initial stability.

Table 8.2.1 – Main dimensions of both versions

	Short Keel Version	Long Keel Version
Disp. [ton]	7.14	6.33
LOA [m]	9.79	9.79
Lwl [m]	9.1	8.97
B [m]	3.62	3.62
Bwt [m]	3.16	3.12
Draft [m]	1.84	2.41
Sw_{Total} [m^2]	27.31	26.48

The velocity predicted for the Long Keel version is initially compared with velocity of a modern cruiser, *Hanse 32*, to validate the overall performance of the design. The *Hanse 32* velocity is obtained from the company website (*www.hanse.com*), and the main dimensions are presented in the data base of similar yachts, Annex 4. The predicted results are plotted in a polar diagram presented in Figure 8.2.1, the *Inclusion 32* velocity is plotted in green while the *Hanse 32* is in red, for true wind speeds of 8 and 14 knots. In a velocity polar plot each curve represents a true wind velocity, and the yacht speed is found as the length from zero to the point in the curve. The true wind angle is defined from this line to the vertical.

The *Hanse 32* has a higher average speed, 17% for the true wind speed of 8 knots and 11% for the true wind speed of 14 knots. The differences are higher at close hauled courses and less significant for running courses. These results are satisfactory since the *Inclusion 32* performance is restricted by the heavier displacement and lower sail area, defined to cope with disabled people needs.

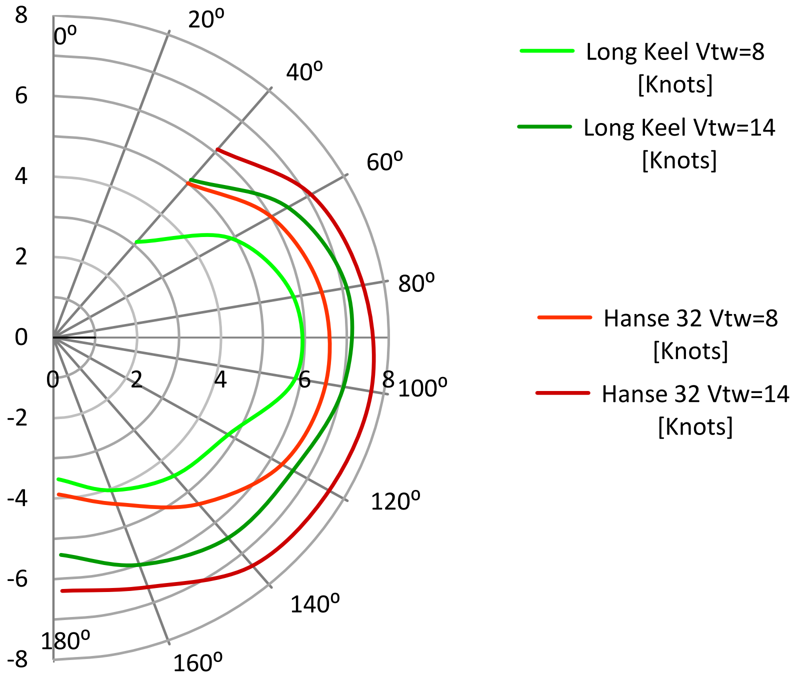

Figure 8.2.1 - Polar velocity diagram for velocity comparison between the current project and a modern cruiser, *Hanse 32*.

When comparing the velocity predicted for the two keel versions, the Long Keel has better performances. The polar diagram for the two *Inclusion 32* keel versions is given in Figure 8.2.3, presenting the velocity prediction for true wind speeds of 5, 9, 12 and 15 knots and the respective numerical results are presented in Annex5. Figure 8.2.3 provides an overall view but the differences are hardly noticed. Figure 8.2.2 presents the velocity of the two keel versions in percentage of the Long Keel velocity advantage.

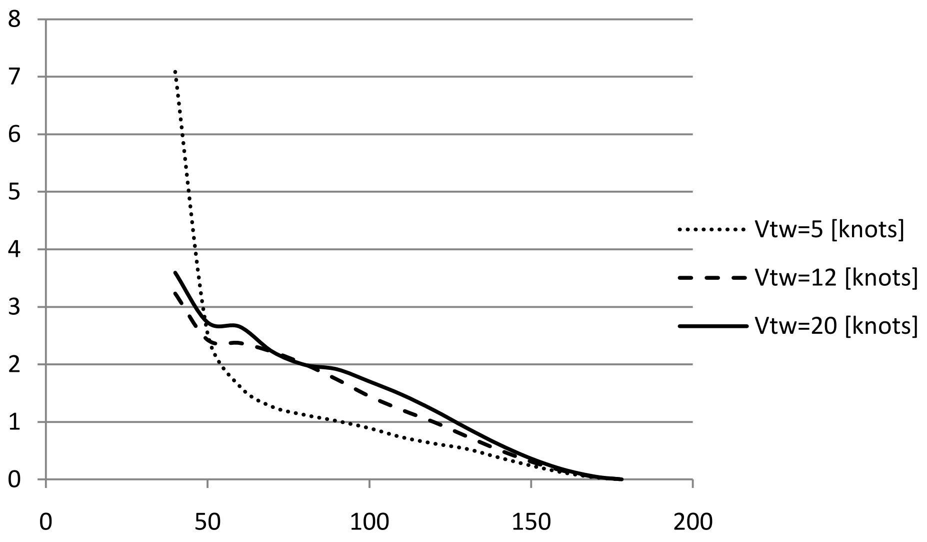

Figure 8.2.2 - Velocity advantage of the Long Keel version in percentage for three different wind speeds.

The Long Keel version is in average 1.5% faster than the short keel, which value is relevant for a racer yacht but not for a present project. According to Figure 8.2.2 the differences are considerably large when sailing close hauled, in particular for light wind conditions, 15% faster at 5 knots of wind. Once again, the upwind performance is only particularly important for racing yachts. The Long Keel advantage decreases drastically from the true wind angle of 40^{o} to 50^{o}, and then more gradually approaches zero for running courses.

The previous results are directly proportional to the leeway angle evolution. The Short Keel version has a low aspect ratio keel, which is less efficient and requires a higher leeway angle to produce the same hydrodynamic side force. This creates a resistance increase responsible for the velocity difference between both models. The advantage of the Long keel version, as well as the leeway angle, increases with the wind speed due to the side force increase. The combination of low keel efficiency and low velocity is the responsible for the large disadvantage of the Short Keel Version when sailing at close hauled courses with light winds.

The velocity disadvantage of the Short Keel version is considered to be irrelevant for the objective of the present project. However, if the yacht is going to sail in a place without depth restriction or if the owner has different intentions to use the vessel the Long Keel version may be more suitable.

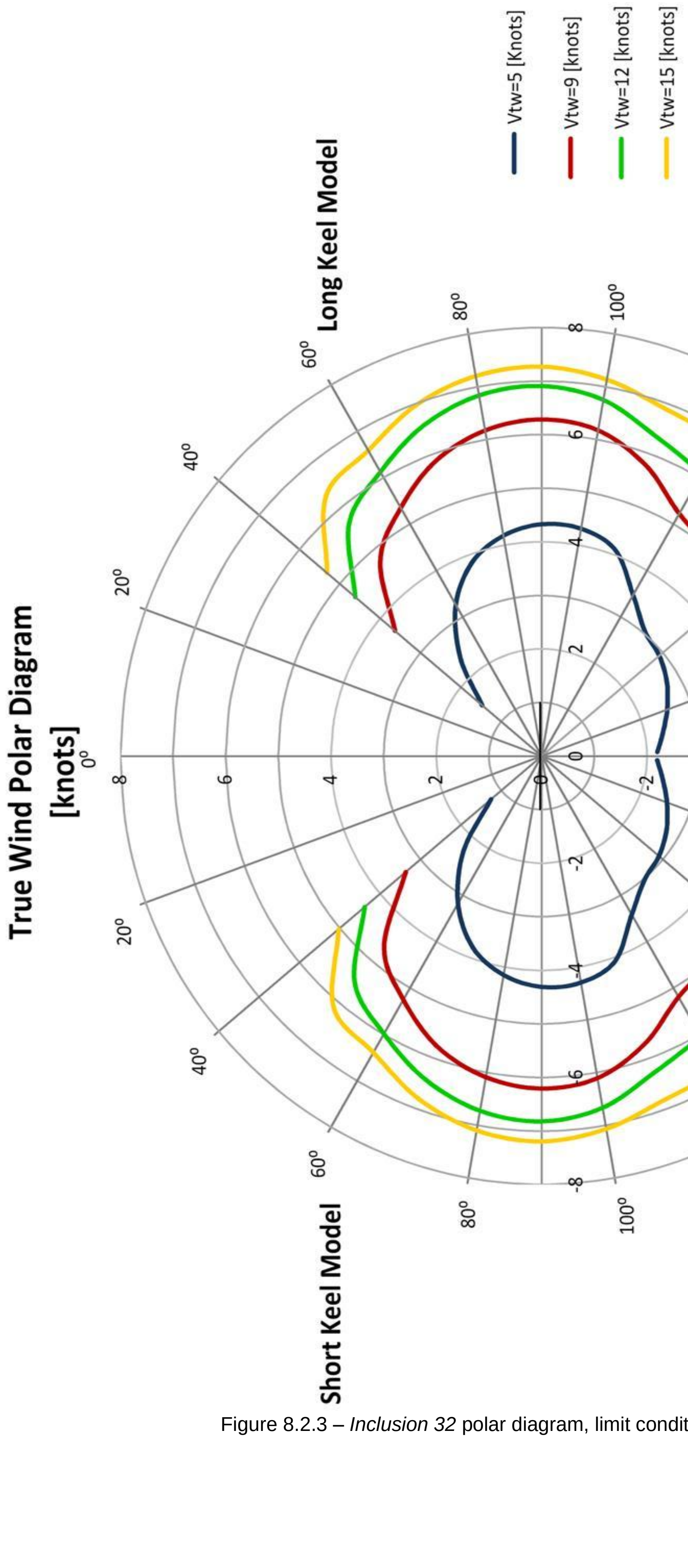

Figure 8.2.3 – *Inclusion 32* polar diagram, limit condition maximum speed [knots].

8.2.2 Resistance components analyse

This section analyses the resistance components of both *Inclusion 32* keel versions to identify the physical differences. The Figure 8.2.4 compares the values of each resistance component at medium wind speed condition (V_{tw}=12 knots) for close hauled, reaching and running courses. A comparison of the resistance component absolute value is not interesting because the boats sail at different velocities; therefore, the results are expressed as percentage of the respective total resistance.

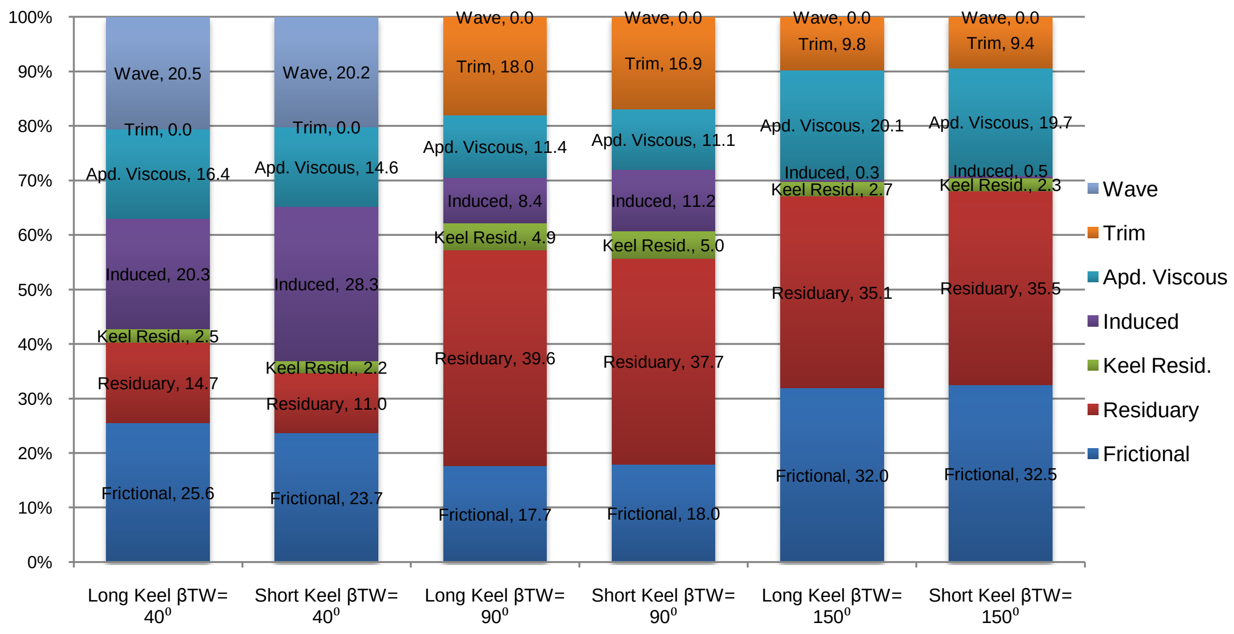

Figure 8.2.4 - Resistance components for the Long Keel and Short Keel versions at 40^0, 90^0 and 150^0 of 12 knots of true wind.

For close hauled courses ($\beta_{TW}=40^0$) the induced resistance (Induced) is the major difference between the Long Keel (20.3% of total resistance) and the Short Keel versions (28.3% of total resistance). This was theoretically expected due to the higher efficiency of the high aspect ratio keel. As the true wind angle increases the leeway angle decreases, reducing proportionally the induced resistance percentage as well as the Long Keel advantage, these results are according with Figure 8.2.2.

The differences between the frictional resistances (Frictional) of both models are small. The frictional resistance is proportional to the boat velocity and wetted surface which for the current project is reduced by the heel angle. At a true wind speed of 12 knots both versions have about the same heel angles, 8^0, 12^0 and 2^0 for the true wind angles of 40^0, 90^0 and 150^0 respectively. This explains that the minimum frictional resistance occurs at the maximum heel angle course, $\beta_{TW}=90^0$.

The appendage viscous resistance (Apd. Viscous) is function of the yacht speed, appendage wetted surface and section form. Despite from a little more wetted surface for the Short Keel version, the results are proportional to the velocity difference between both models.

The residuary resistance (Residuary) include all the resistance factors not accounted by the other resistance components and therefore its percentage value changes according to the other resistance components. The values of the keel residuary resistance (Keel Resid.) are proportional to the residuary resistance component.

The trim resistance (Trim) is proportional to the drive force, being accounted by the *Delft Systematic Yacht Hull Series* (Keuning, et al., 1998) only for reaching and running courses. The added resistance in waves (Waves) is proportional to the angle between the vessel and the wind generated waves, being zero for true wind angles greater than 90^{0}. The trim and added resistance in waves are not normally studied as a relevant resistance component but each of them may be responsible for up to 20% of the total resistance.

The analysis of Figure 8.2.4 provides a good understanding of the evolution of each individual resistance part with the course angle. It also relates the Long Keel version advantage to the induced resistance, which is minimized by the high aspect ratio of the keel.

8.3 Disabled crew performance prediction

When considering the operation of disabled people it was assumed that at any heading the heel angle should be less than 10º for true wind velocities lower than 15 knots, without reefing the sails. This condition was considered when defining the transversal stability of both keel models and verified by the results obtained with the Velocity Prediction Program.

When predicting the performance of a yacht use was made of a flattening function coefficient discussed in the Velocity Prediction Program section. This coefficient represents the flat of the sails shape to cope with a given limit situation. Before, when presenting the differences in velocity predicted for both models the limit situation was the yacht maximum velocity for each sailing condition. The results presented in Figure 8.3.1 shows the velocity performance of the Short Keel and Long Keel versions predicted for the limit condition defined for the disabled people operation, the respective numerical results are given in Annex 5.

For true wind speeds of 5 and 9 knots the velocity predictions for a disabled crew correspond to the maximum values of the respective keel version. For true wind speeds of 12 and 15 knots the flattening coefficients affect the velocity performance to comply with the limit condition defined for disabled people. Therefore, the velocity is only reduced for the courses with larger heel angle. For 15 knots wind speed the velocity reduction is particularly large indicating that the performance of the boat could benefit from reefing the sails, which must be considered by the crew for higher wind speeds. These results guaranty an acceptable sailing condition for the disabled crew at all courses and common wind speeds.

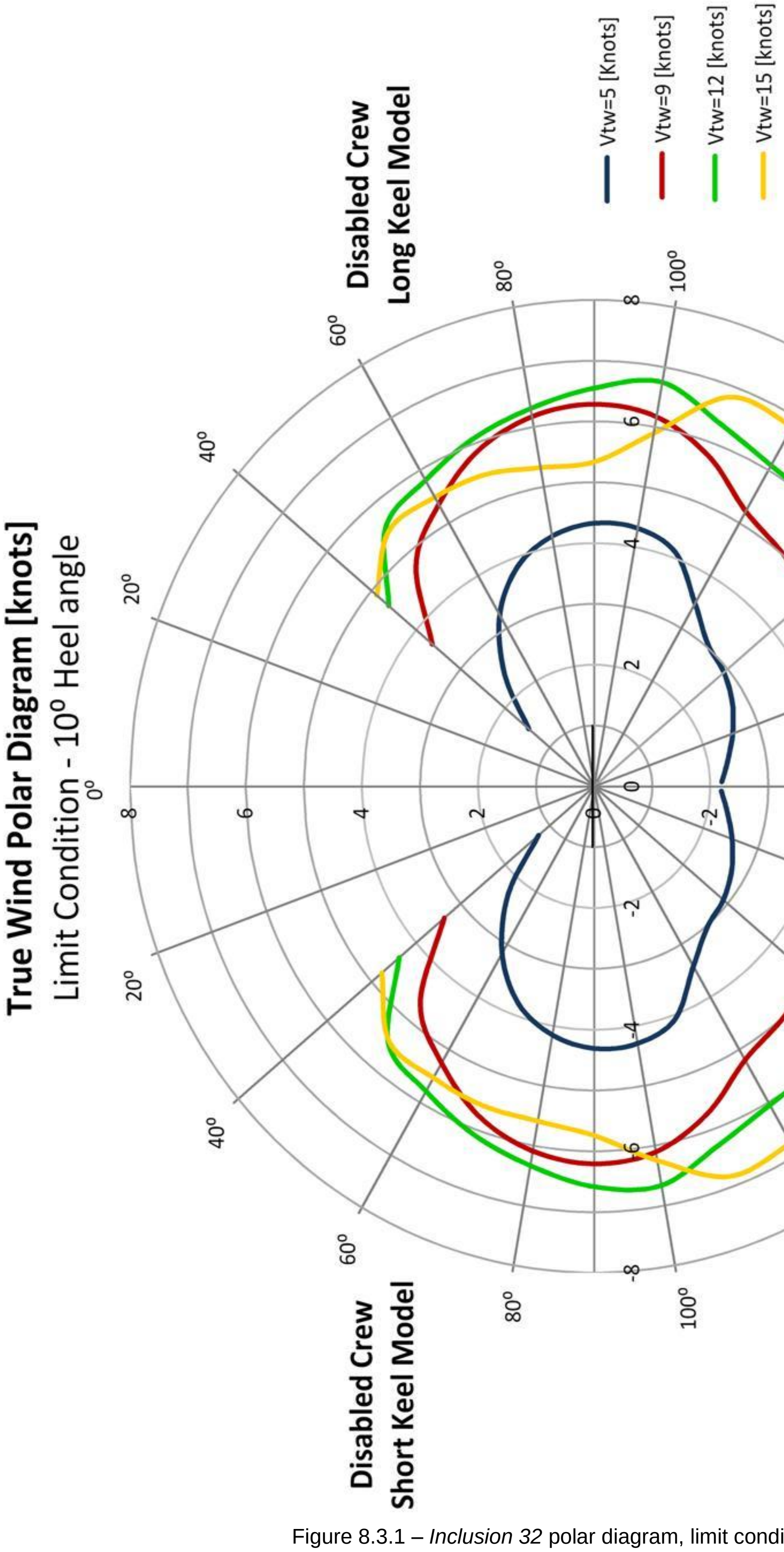

Figure 8.3.1 – *Inclusion 32* polar diagram, limit condition 10º of heel [knots].

8.4 Summary

The development of a specific VPP was necessary to predict the performance of the *Inclusion 32* when crewed by disabled people and limited by the heel angle. The same program was the base to the implementation of the self stability system in order to evaluate the performance improvements of this mechanism. In addition, the VPP was an important tool for the optimization process of the appendage design.

The maximum velocity predicted results were satisfactory and provide good confidence on the design decisions. When compared with a modern cruiser, *Hanse 32*, the velocity predicted for the present project was about 17% and 10% lower, for wind speeds of 8 and 14 knots respectively. This performance difference is justified by the heavier displacement and smaller sail area, defined to account with the disabled people needs.

The Long Keel version proved to be more efficient in particular for close hauled courses, this advantage is proportional to the leeway angle that decreases with the true wind angle increase. An individual analyse of the resistance components is presented, describing the factors that influence the change of each component with the course direction. As expected the induced resistance was identified to be responsible for the difference between both models performance. The velocity predictions for a disabled crew were satisfactory and fulfil with the maximum heel angle of 10^0, considered to be the limit situation for disabled people operation.

9 Conclusion

The *Inclusion* project aimed to include disabled people and people who feel conventional yachts too difficult to cope with in the project of a small cruiser capable of coastal passages. The initial design requirements identified mobility, safety and heel angle to be the main problems. The *Inclusion 32* design process started with the definition of a disabled friendly general arrangement and iteratively searched for a balance between the interior demands and an efficient hull shape. Afterwards, defined a structure, appendage configuration and concluded with the performance prediction.

The mobility problem was simplified by a single sole level, common to the interior and cockpit, similar to a sport yacht. It was decided to have a single sole level to avoid the use of the unsafe ladders or lifting platforms, which are not suitable for the large disabled population. In addition, it was decided to accept wheelchairs onboard because most disabled people are familiar with its operation and the entry from shore is also simplified. However, to accept wheelchairs onboard it was necessary to have a general arrangement with dimensions larger than usual, defined according to Universal Design architecture. In addition, a modular solution based on removable seats was designed to accommodate wheelchair users and non-wheelchair users in the same space.

The saloon was designed as a continuation of the cockpit to improve the social contact between the saloon users and the crew involved with the sailing tasks. This arrangement gives the opportunity for people high limitations to go onboard, seat comfortably in the saloon and presence all the activity. The large openings at the saloon and toilet were designed to improve the contact with the environment. The *Inclusion 32* was designed to operate an electric engine with silent operation in order to reduce communication problems and to provide electrical power for the adaptive systems. In case of collision with another boat or a floating object the *Inclusion 32* benefits from a structural arrangement similar to a double bottom and watertight bulkheads instead of the conventional ring frames.

The second design requirement for the integration of disabled people was low heel angle. The present project assumed a maximum heel angle for the normal sailing conditions of 10^0, guaranteed by the hull shape and appendages design. The hull shape was designed with large waterline beam to increase the form stability, while the appendages were designed with a conventional cruiser sail planform balanced by the unseen bulb keel. The bulb weight was defined to cope with the limit heel angle, according to the results of a Velocity Prediction Program made for the project.

A dedicated Velocity Prediction Program was also necessary to predict the performance improvement of an innovative system designed to adapt automatically the yacht righting moment to the wind demands. Further development of the self stability system is needed but the preliminary performance prediction indicates a significant heel reduction as well as speed increase. This system may solve important problems to the integration of disabled people in sailing yachts but its application may also benefit conventional cruisers and racers.

Further development of the project should concern seakeeping analysis, particularly on flooding situations. The view angle from the cockpit is also worth of attention since it is partially obstructed by the cabin top.

The *Inclusion* project aims to cover a wide population not yet considered by commercial yachts. This project developed a new concept of cruising yacht with a single sole level and several other characteristics designed to improve the comfort, safety and accessibility of conventional yachts. The *Inclusion 32* was designed to be constructed in a Portuguese shipyard with low-cost technology and is expected to be an interesting product for the European market.

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Annex 1 – Technical drawings

Annex 2 – List of equipment

Group	*Item name*	Weight [kg]	LCG [m]	TCG [m]	VCG [m]
Instalations	Engine	28	3.00	0.00	0.30
	Batteries	123	4.64	0.07	0.23
	Generator	90	4.52	0.54	0.41
	Charger	10	4.50	0.14	0.40
	Propeller	4	2.10	0.00	0.00
	Ruddder Blade	0	1.10	0.00	-0.50
	Rudder Shaft	30	1.10	0.00	0.75
	Rudder Wheel	5	1.10	0.00	1.55
	Fuel tank and Piping	35	3.83	0.00	0.37
	Water tank and Piping	40	5.40	0.00	0.40
Deck equipment	Whinch 1	15	2.33	-1.35	1.88
	Whinch 2	15	2.33	1.35	1.88
	Whinch 3	15	1.62	0.00	1.68
	Central Station	24	1.46	0.00	1.13
	Bow anchor	20	9.80	0.00	1.75
	Anchor Windlass	25	9.30	0.00	1.75
	Anchor Chain	70	9.30	0.00	0.85
	Lifelines	10	3.90	0.00	1.80
	Chain plates	10	5.80	0.00	1.74
	Port seat	30	1.31	-1.11	1.34
	Starboard seat	30	1.31	1.11	1.34
	Forw. Stay attachment	5	9.80	0.00	1.75
	Aft Stay attachment	5	0.00	0.00	0.80
	Hand Rails	6	1.00	0.00	1.60
	Main Sail track & Cars	6	2.93	0.00	2.67
	Jib Furler	18	9.80	0.00	1.75
Rig and Sails	Mast & Spreaders	100	5.80	0.00	8.35
	Boom	20	3.00	0.00	2.85
	Geona Hoisted	12	7.00	0.00	5.00
	Main Hoisted	12	4.00	0.00	6.00
Saloon	Port seat	15	3.60	-0.90	1.28
	Starboard seat	15	3.60	-0.10	1.66
	Table	20	3.60	-0.40	1.28
	Hand Rails	8	4.59	0.77	1.53
	Large Window port	15	4.33	-1.00	2.13
	Large Window starbord	15	4.33	1.00	2.13
Galley	Stove	22	5.15	-0.95	1.57
	Fridge	15	5.65	-0.95	1.57
	Locker	15	5.60	-0.10	1.57
	Sinks	5	5.60	-0.10	1.57
	Small Windows port	5	6.47	-0.94	2.03
	Small Windows starboad	5	6.47	0.94	2.03
	Hand Rails	3	5.17	-0.47	1.65
	Cutting Surface	20	5.60	-0.46	1.57
Head	Wash basin	10	5.97	-0.89	1.65
	Door	18	6.30	0.25	1.60
	Walls	75	5.81	0.39	1.70
	Hand Rails	3	6.50	-0.83	1.60
	WC locker	10	5.97	-0.89	2.35
	WC & pumping	15	7.10	-0.55	1.30
Forward Cabin	Bed	15	8.00	0.00	1.15
	Cushion	14	8.00	0.00	1.15
Total	Equipement	1149	5.03	0.00	1.86

Annex 3 – Universal Design dimensions.

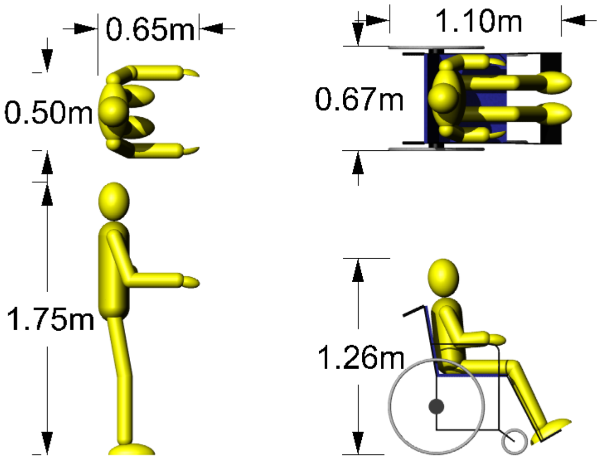

Figure 8.4.1 – Human model designed for the present project.

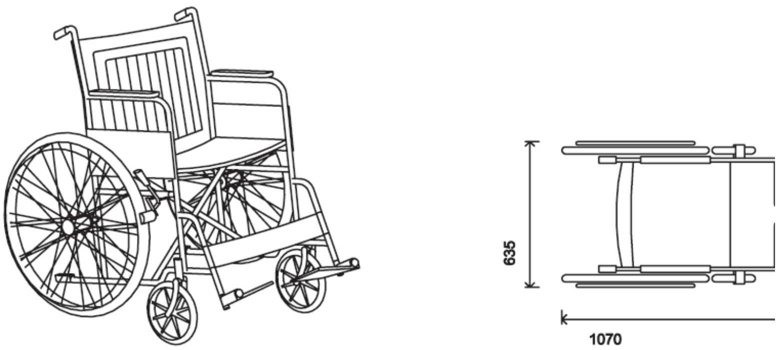

Figure 8.4.2 – Wheelchair dimensions [mm] (Goldsmith, 2000).

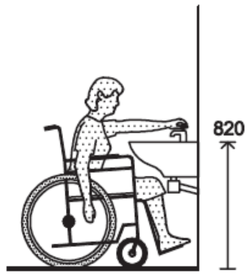

Figure 8.4.3 – Wash basin height (Goldsmith, 2000).

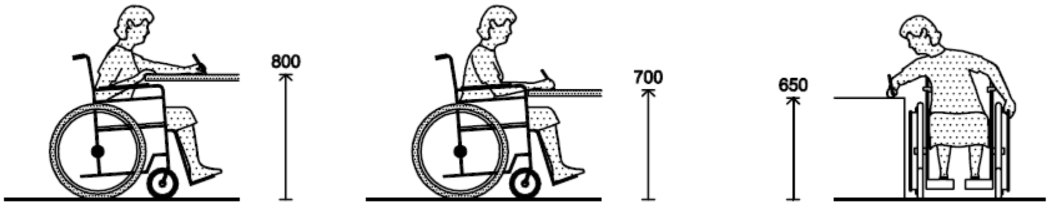

Figure 8.4.4 – According to the table height wheelchair users have different approach (Goldsmith, 2000).

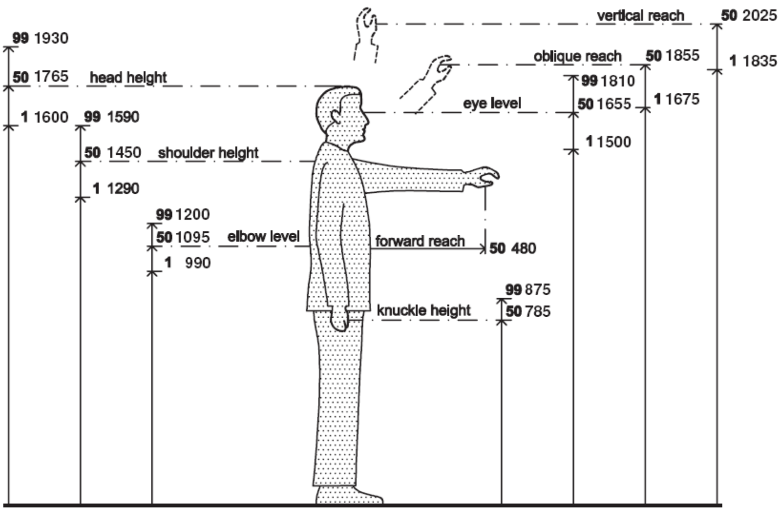

Figure 8.4.5 – Upright dimensions (Goldsmith, 2000).

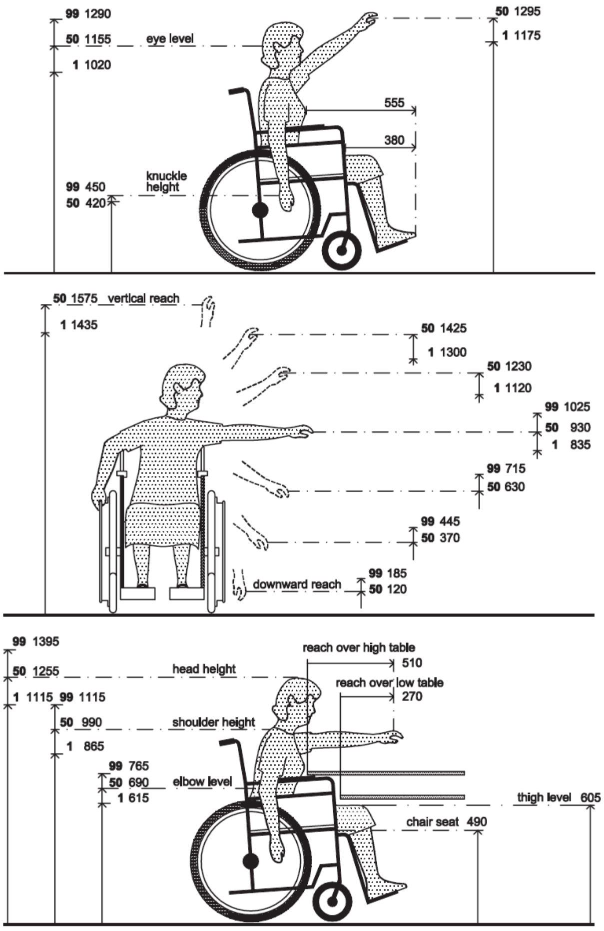

Figure 8.4.6 – Wheelchair users dimensions [mm] (Goldsmith, 2000).

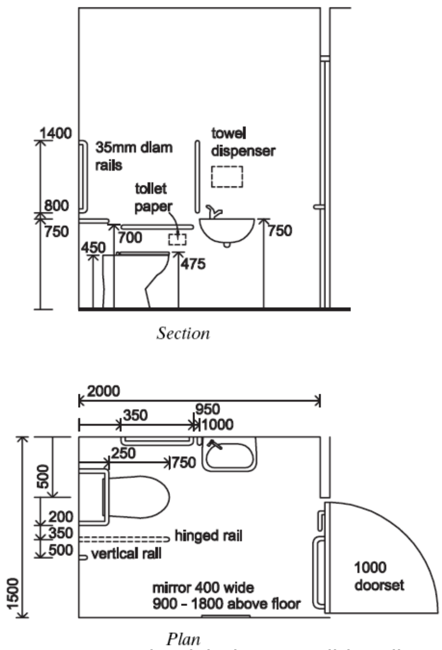

Figure 8.4.7 – Wheelchair accessible toilet [mm] (Goldsmith, 2000).

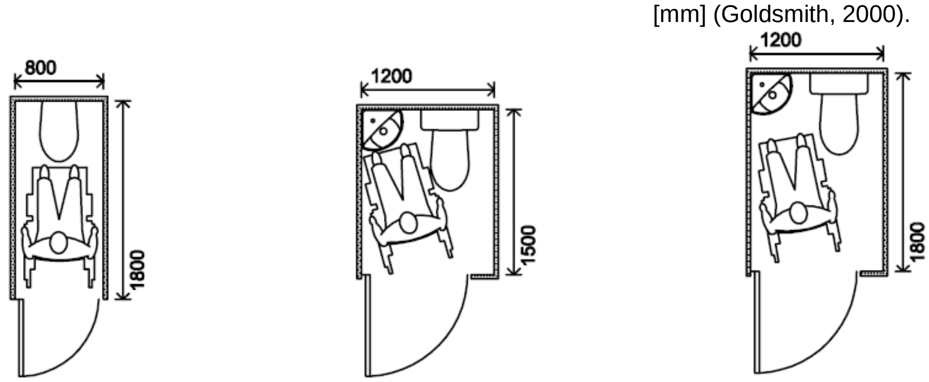

Figure 8.4.8 – Reduced wheelchair accessible toilet [mm] (Goldsmith, 2000).

Figure 8.4.9 – Reduced swingdoorset [mm] (Goldsmith, 2000).

Doorway clear opening width	Passageway width
750 mm or wider	900 mm (when approach is head-on)
750 mm or wider	1200 mm (when approach is not head-on)
775 mm or wider	1050 mm (when approach is not head-on)
800 mm or wider	900 mm (when approach is not head-on)

Figure 8.4.10 – Passageway width [mm] (Goldsmith, 2000).

Annex 4 – Data base & STIX results

Data base of similar designs

Model	LOA [m]	LWL [m]	Beam [m]	Draft [m]	Sail Area upwind [m2]	Disp. [kg]	Ballast [kg]	Mast Height [ft]	Power [hp]	Fuel Tank [l]	Water Tank [l]
First 27.7	8.6	8.3	3	2.2	48.8	2795	870	13.7	14	30	50
Sirius 31	9.3	8.55	3.38	1.75	42.9	6300	2.4				
Hunter 31	9.39	8.55	3.38	1.68	39.21	3858	1114	13.44	21	75.7	189.3
Hallberg-Rassy31	9.42	8.8	3.18	1.8	47.2	4350	1680	14.35	22	100	200
First 31.7	9.61	8.8	3.23	1.9	52.5	3750	1025	13.9	21	30	160
Hanse 32	9.63	8.72	3.3	1.84	51.36	5200	1480	14.77	22	120	240
Oceanis 31	9.66	8.69	3.39	1.8	49.2	4620		14.2	21	130	130
Sirius 32	9.75	8.4	3.18	1.7	40.5	5500	2300				
Dheler 32	9.8	8.94	3.25	1.74	60	4310	1500	15.55	21	80	100
Etap 32s	9.84	8.38	3.42	1.8	54.8	3700	1100		19	82	170
Bavaria 32	9.99	8.85	3.42	1.95	49	5200	1300	14.8	18	150	150
Albatroz 35	10.7	9.91	3.7	1.92	61.5	7050	2330	15.42	29	170	330
First 35	10.9	9.33	3.64	2.2	72.47	5500	1670	17.26	29	75	200

Results from the STIX calculation

Factor	Short Keel	Long Keel	*Factor*	Short Keel	Long Keel
δ	5	5	A_{GZ}	18.8	25.3
L_H	9.8	9.8	V_{AW}	17.18	18.33
B_H	3.62	3.62	L_{BS}	9.33	9.27
L_{WL}	9.1	9	F_L	0.97	0.97
B_{WL}	3.15	3.11	FDL	1.03	1.02
m_{MSC}	6817	6133	F_B	2.03	2.1
A_S	42.6	42.6	FBD	1.04	1.04
h_{CE}	6.17	6.2	F_R	10.23	10.79
h_{LP}	0.57	0.7	FKR	1.5	1.5
GZ_{90}	0.79	0.93	FIR	1.15	1.18
GZ_D	0.74	0.88	FDS	0.5	0.51
ϕ_V	139	143	FWM	1	1
ϕ_D	35	40	FDF	0.5	0.5
			STIX	24.11	24.22

Annex 5 – Performance prediction tables

Long Keel and Short Keel maximum velocity performance.

Long Keel Results						
V_{TW} [kn]	β_{TW} [º]	V_{yacht} [m/s]	V_{yacht} [knots]	θ_{Heel} [º]	Flat	λ [º]
5	40	0.76	1.47	1.4	1	3.3
5	50	1.23	2.40	1.8	1	1.6
5	60	1.67	3.25	2.3	1	1.1
5	70	1.98	3.85	2.6	1	0.9
5	80	2.15	4.18	2.8	1	0.8
5	90	2.23	4.33	2.7	1	0.7
5	100	2.22	4.31	2.4	1	0.7
5	110	2.11	4.09	1.8	1	0.5
5	120	1.79	3.47	1.0	1	0.4
5	130	1.57	3.05	0.7	1	0.4
5	140	1.50	2.92	0.5	1	0.3
5	150	1.41	2.75	0.3	1	0.2
5	160	1.30	2.54	0.1	1	0.1
5	170	1.20	2.33	0.0	1	0.0
5	178	1.13	2.20	0.0	1	0.0
9	40	1.87	3.64	5.0	1	2.0
9	50	2.45	4.77	6.1	1	1.4
9	60	2.75	5.35	7.3	1	1.4
9	70	3.02	5.86	8.2	1	1.3
9	80	3.17	6.17	8.5	1	1.2
9	90	3.23	6.28	7.9	1	1.1
9	100	3.17	6.17	6.3	1	0.9
9	110	2.97	5.78	4.4	1	0.7
9	120	2.69	5.22	3.0	1	0.6
9	130	2.58	5.02	2.2	1	0.5
9	140	2.52	4.89	1.5	1	0.3
9	150	2.40	4.68	0.8	1	0.2
9	160	2.27	4.41	0.4	1	0.1
9	170	2.12	4.12	0.1	1	0.0
9	178	2.01	3.91	0.0	1	0.0
12	40	2.37	4.61	8.8	1	2.3
12	50	2.92	5.68	10.7	1	1.9
12	60	3.15	6.12	12.8	1	2.0
12	70	3.38	6.56	14.4	1	2.1
12	80	3.52	6.83	14.4	1	1.9
12	90	3.55	6.91	12.5	1	1.5
12	100	3.47	6.75	9.5	1	1.2
12	110	3.27	6.35	6.9	1	0.9
12	120	3.14	6.10	5.2	1	0.7
12	130	3.10	6.03	3.9	1	0.6
12	140	3.05	5.92	2.6	1	0.4
12	150	2.94	5.71	1.4	1	0.2
12	160	2.78	5.40	0.6	1	0.1
12	170	2.59	5.03	0.2	1	0.0
12	178	2.45	4.77	0.0	1	0.0
15	40	2.73	5.31	13.6	1	2.9
15	50	3.27	6.36	16.7	1	2.8
15	60	3.39	6.59	19.9	1	3.5
15	70	3.59	6.97	22.1	1	3.8
15	80	3.71	7.21	21.4	1	3.3
15	90	3.74	7.27	17.7	1	2.3
15	100	3.67	7.14	13.4	1	1.6
15	110	3.55	6.89	10.2	1	1.2
15	120	3.51	6.82	8.0	1	0.9
15	130	3.51	6.83	6.0	1	0.7
15	140	3.47	6.74	4.0	1	0.5
15	150	3.37	6.56	2.2	1	0.3
15	160	3.23	6.27	1.0	1	0.1
15	170	3.06	5.94	0.3	1	0.0
15	178	2.93	5.69	0.0	1	0.0

Short Keel Results						
V_{TW} [kn]	β_{TW} [º]	V_{yacht} [m/s]	V_{yacht} [knots]	θ_{Heel} [º]	Flat	λ [º]
5	40	0.64	1.25	1.3	1	10.4
5	50	1.18	2.30	1.7	1	4.2
5	60	1.63	3.17	2.1	1	2.7
5	70	1.96	3.81	2.5	1	2.2
5	80	2.13	4.15	2.6	1	1.9
5	90	2.22	4.31	2.6	1	1.8
5	100	2.21	4.29	2.2	1	1.5
5	110	2.09	4.07	1.7	1	1.3
5	120	1.76	3.42	1.0	1	1.1
5	130	1.56	3.03	0.7	1	0.9
5	140	1.49	2.90	0.4	1	0.7
5	150	1.41	2.74	0.2	1	0.4
5	160	1.30	2.53	0.1	1	0.2
5	170	1.20	2.32	0.0	1	0.1
5	178	1.13	2.19	0.0	1	0.0
9	40	1.73	3.37	4.6	1	5.2
9	50	2.39	4.65	5.8	1	3.5
9	60	2.70	5.25	6.9	1	3.2
9	70	2.97	5.78	7.7	1	3.0
9	80	3.13	6.09	8.0	1	2.8
9	90	3.19	6.21	7.4	1	2.5
9	100	3.14	6.10	5.9	1	2.1
9	110	2.94	5.72	4.2	1	1.6
9	120	2.67	5.20	2.9	1	1.4
9	130	2.58	5.01	2.1	1	1.1
9	140	2.52	4.89	1.4	1	0.7
9	150	2.41	4.68	0.8	1	0.5
9	160	2.27	4.41	0.3	1	0.2
9	170	2.12	4.12	0.1	1	0.1
9	178	2.01	3.90	0.0	1	0.0
12	40	2.25	4.38	8.1	1	5.5
12	50	2.84	5.52	10.1	1	4.3
12	60	3.08	5.99	12.0	1	4.4
12	70	3.31	6.43	13.5	1	4.3
12	80	3.46	6.73	13.5	1	3.9
12	90	3.51	6.82	11.7	1	3.3
12	100	3.43	6.67	8.9	1	2.6
12	110	3.23	6.28	6.5	1	2.1
12	120	3.11	6.05	4.9	1	1.7
12	130	3.09	6.00	3.7	1	1.3
12	140	3.04	5.90	2.4	1	0.9
12	150	2.93	5.69	1.4	1	0.5
12	160	2.77	5.39	0.6	1	0.3
12	170	2.59	5.03	0.2	1	0.1
12	178	2.46	4.78	0.0	1	0.0
15	40	2.59	5.03	12.6	1	6.5
15	50	3.16	6.13	15.6	1	5.5
15	60	3.29	6.39	18.7	1	6.1
15	70	3.51	6.81	20.6	1	6.0
15	80	3.65	7.10	19.9	1	5.3
15	90	3.70	7.19	16.5	1	4.2
15	100	3.64	7.07	12.5	1	3.3
15	110	3.51	6.83	9.6	1	2.7
15	120	3.49	6.78	7.6	1	2.1
15	130	3.49	6.79	5.6	1	1.6
15	140	3.46	6.72	3.7	1	1.1
15	150	3.36	6.53	2.1	1	0.6
15	160	3.22	6.25	0.9	1	0.3
15	170	3.05	5.93	0.2	1	0.1
15	178	2.92	5.68	0.0	1	0.0

Long Keel and Short Keel disabled crew performance.

Long Keel Disabled Crew Performance						
V_{TW} [knots]	β_{TW} [°]	V_{yacht} [m/s]	V_{yacht} [knots]	θ_{Heel} [°]	Flat	λ [°]
5	40	0.76	1.47	1.4	1	3.3
5	50	1.23	2.40	1.8	1	1.6
5	60	1.67	3.25	2.3	1	1.1
5	70	1.98	3.85	2.6	1	0.9
5	80	2.15	4.18	2.8	1	0.8
5	90	2.23	4.33	2.7	1	0.7
5	100	2.22	4.31	2.4	1	0.7
5	110	2.11	4.09	1.8	1	0.5
5	120	1.79	3.47	1.0	1	0.4
5	130	1.57	3.05	0.7	1	0.4
5	140	1.50	2.92	0.5	1	0.3
5	150	1.41	2.75	0.3	1	0.2
5	160	1.30	2.54	0.1	1	0.1
5	170	1.20	2.33	0.0	1	0.0
5	178	1.13	2.20	0.0	1	0.0
9	40	1.87	3.64	5.0	1	2.0
9	50	2.45	4.77	6.1	1	1.4
9	60	2.75	5.35	7.3	1	1.4
9	70	3.02	5.86	8.2	1	1.3
9	80	3.17	6.17	8.5	1	1.2
9	90	3.23	6.28	7.9	1	1.1
9	100	3.17	6.17	6.3	1	0.9
9	110	2.97	5.78	4.4	1	0.7
9	120	2.69	5.22	3.0	1	0.6
9	130	2.58	5.02	2.2	1	0.5
9	140	2.52	4.89	1.5	1	0.3
9	150	2.40	4.68	0.8	1	0.2
9	160	2.27	4.41	0.4	1	0.1
9	170	2.12	4.12	0.1	1	0.0
9	178	2.01	3.91	0.0	1	0.0
12	40	2.37	4.61	8.8	1	2.3
12	50	2.87	5.58	10.0	0.94	1.8
12	60	2.99	5.81	10.0	0.79	1.7
12	70	3.13	6.09	10.0	0.70	1.5
12	80	3.25	6.31	10.0	0.70	1.4
12	90	3.37	6.55	10.0	0.81	1.3
12	100	3.47	6.75	9.5	1	1.2
12	110	3.27	6.35	6.9	1	0.9
12	120	3.14	6.10	5.2	1	0.7
12	130	3.10	6.03	3.9	1	0.6
12	140	3.05	5.92	2.6	1	0.4
12	150	2.94	5.71	1.4	1	0.2
12	160	2.78	5.40	0.6	1	0.1
12	170	2.59	5.03	0.2	1	0.0
12	178	2.45	4.77	0.0	1	0.0
15	40	2.51	4.88	10.0	0.76	2.4
15	50	2.82	5.49	10.0	0.61	1.9
15	60	2.82	5.49	10.0	0.49	1.9
15	70	2.81	5.46	10.0	0.43	1.9
15	80	2.74	5.32	10.0	0.42	2.0
15	90	2.74	5.34	10.0	0.46	2.0
15	100	3.03	5.90	10.0	0.59	1.6
15	110	3.51	6.81	10.0	0.95	1.2
15	120	3.51	6.82	8.0	1	0.9
15	130	3.51	6.83	6.0	1	0.7
15	140	3.47	6.74	4.0	1	0.5
15	150	3.37	6.56	2.2	1	0.3
15	160	3.23	6.27	1.0	1	0.1
15	170	3.06	5.94	0.3	1	0.0
15	178	2.93	5.69	0.0	1	0.0

Short Keel Disabled Crew Performance						
V_{TW} [knots]	β_{TW} [°]	V_{yacht} [m/s]	V_{yacht} [knots]	θ_{Heel} [°]	Flat	λ [°]
5	40	0.64	1.25	1.3	1	10.4
5	50	1.18	2.30	1.7	1	4.2
5	60	1.63	3.17	2.1	1	2.7
5	70	1.96	3.81	2.5	1	2.2
5	80	2.13	4.15	2.6	1	1.9
5	90	2.22	4.31	2.6	1	1.8
5	100	2.21	4.29	2.2	1	1.5
5	110	2.10	4.07	1.7	1	1.3
5	120	1.76	3.42	1.0	1	1.1
5	130	1.56	3.03	0.7	1	0.9
5	140	1.49	2.90	0.4	1	0.7
5	150	1.41	2.74	0.2	1	0.4
5	160	1.30	2.53	0.1	1	0.2
5	170	1.20	2.32	0.0	1	0.1
5	178	1.13	2.19	0.0	1	0.0
9	40	1.73	3.37	4.6	1	5.2
9	50	2.39	4.65	5.8	1	3.5
9	60	2.70	5.25	6.9	1	3.2
9	70	2.97	5.78	7.7	1	3.0
9	80	3.13	6.09	8.0	1	2.8
9	90	3.19	6.21	7.4	1	2.5
9	100	3.14	6.10	5.9	1	2.1
9	110	2.94	5.72	4.2	1	1.6
9	120	2.67	5.20	2.9	1	1.4
9	130	2.58	5.01	2.1	1	1.1
9	140	2.52	4.89	1.4	1	0.7
9	150	2.41	4.68	0.8	1	0.5
9	160	2.27	4.41	0.3	1	0.2
9	170	2.12	4.12	0.1	1	0.1
9	178	2.01	3.90	0.0	1	0.0
12	40	2.25	4.38	8.1	1	5.5
12	50	2.83	5.51	10.0	0.99	4.3
12	60	2.98	5.79	10.0	0.84	3.9
12	70	3.13	6.09	10.0	0.75	3.5
12	80	3.26	6.33	10.0	0.75	3.3
12	90	3.39	6.59	10.0	0.86	3.0
12	100	3.43	6.67	8.9	1	2.6
12	110	3.23	6.28	6.5	1	2.1
12	120	3.11	6.05	4.9	1	1.7
12	130	3.09	6.00	3.7	1	1.3
12	140	3.04	5.90	2.4	1	0.9
12	150	2.93	5.69	1.4	1	0.5
12	160	2.77	5.39	0.6	1	0.3
12	170	2.59	5.03	0.2	1	0.1
12	178	2.46	4.78	0.0	1	0.0
15	40	2.45	4.77	10.0	0.82	5.7
15	50	2.82	5.48	10.0	0.65	4.4
15	60	2.85	5.54	10.0	0.52	4.3
15	70	2.88	5.59	10.0	0.46	4.2
15	80	2.88	5.59	10.0	0.47	4.2
15	90	2.95	5.74	10.0	0.53	4.0
15	100	3.21	6.25	10.0	0.69	3.4
15	110	3.51	6.83	9.6	1	2.7
15	120	3.49	6.78	7.6	1	2.1
15	130	3.49	6.79	5.6	1	1.6
15	140	3.46	6.72	3.7	1	1.1
15	150	3.36	6.53	2.1	1	0.6
15	160	3.22	6.25	0.9	1	0.3
15	170	3.05	5.93	0.2	1	0.1
15	178	2.92	5.68	0.0	1	0.0

Annex 6 – Delft series coefficients

Table 8.4.1 - Coefficients for polynomial residuary resistance of bare hull (Eq.(8.1.26) (Keuning, et al., 1998)).

Fn	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
a_0	-0.0014	0.0004	0.0014	0.0027	0.0056	0.0032	-0.0064	-0.0171	-0.0201	0.0495	0.0808
a_1	0.0403	-0.1808	-0.1071	0.0463	-0.8005	-0.1011	2.3095	3.4017	7.1576	1.5618	-5.3233
a_2	0.0470	0.1793	0.0637	-0.1263	0.4891	-0.0813	-1.5152	-1.9862	-6.3304	-6.0661	-1.1513
a_3	-0.0227	-0.0004	0.0090	0.0150	0.0269	-0.0382	0.0751	0.3242	0.5829	0.8641	0.9663
a_4	-0.0119	0.0097	0.0153	0.0274	0.0519	0.0320	-0.0858	-0.1450	0.1630	1.1702	1.6084
a_5	0.0061	0.0118	0.0011	-0.0299	-0.0313	-0.1481	-0.5349	-0.8043	-0.3966	1.7610	2.7459
a_6	-0.0086	-0.0055	0.0012	0.0110	0.0292	0.0837	0.1715	0.2952	0.5023	0.9176	0.8491
a_7	-0.0307	0.1721	0.1021	-0.0595	0.7314	0.0223	-2.4550	-3.5284	-7.1579	-2.1191	4.7129
a_8	-0.0553	-0.1728	-0.0648	0.1220	-0.3619	0.1587	1.1865	1.3575	5.2534	5.4281	1.1089

Table 8.4.2 - Coefficients for the polynomial wetted surface under heel expression (Eq.(8.1.27) (Keuning, et al., 1998)).

φ	5	10	15	20	25	30	35
s_0	-4.112	-4.522	-3.291	1.850	6.510	12.334	14.648
s_1	0.054	-0.132	-0.389	-1.200	-2.305	-3.911	-5.182
s_2	-0.027	-0.077	-0.118	-0.109	-0.066	0.024	0.102
s_3	6.329	8.738	8.949	5.364	3.443	1.767	3.497

Table 8.4.3 - Coefficients for polynomial delta resistance hull due to 20 degrees heel (Eq.(8.1.28) (Keuning, et al., 1998)).

Coefficients are multiplied by 1000							
Fn	0.25	0.30	0.35	0.40	0.45	0.50	0.55
u_0	-0.0268	0.6628	1.6433	-0.8659	-3.2715	-0.1976	1.5873
u_1	-0.0014	-0.0632	-0.2144	-0.0354	0.1372	-0.1480	-0.3749
u_2	-0.0057	-0.0699	-0.1640	0.2226	0.5547	-0.6593	-0.7105
u_3	0.0016	0.0069	0.0199	0.0188	0.0268	0.1862	0.2146
u_4	-0.0070	0.0459	-0.0540	-0.5800	-1.0064	-0.7489	-0.4818
u^5	-0.0017	-0.0004	-0.0268	-0.1133	-0.2026	-0.1648	-0.1174

Table 8.4.4 - Coefficients for polynomial residuary resistance of keel (Eq.(8.1.32) (Keuning, et al., 1998)).

Fn	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
A_0	-0.00104	-0.00550	-0.01110	-0.00713	-0.03581	-0.00470	0.00553	0.04822	0.01021
A_1	0.00172	0.00597	0.01421	0.02632	0.08649	0.11592	0.07371	0.00660	0.14173
A_2	0.00117	0.00390	0.00069	-0.00232	0.00999	-0.00064	0.05991	0.07048	0.06409
A_3	-0.00008	-0.00009	0.00021	0.00039	0.00017	0.00035	-0.00114	-0.00035	-0.00192

Table 8.4.5 - Coefficients for polynomial delta resistance of the keel due to heel (Eq.(8.1.34) (Keuning, et al., 1998)).

H_1	-3.5837
H_2	-0.0518
H_3	0.5958
H_4	0.2055

Table 8.4.6 - Coefficients for the polynomial effective span (Eq.38 (Keuning, et al., 1998))

φ	0	10	20	30
A_1	3.7455	4.4892	3.9592	3.4891
A_2	-3.6246	-4.8454	-3.9804	-2.9577
A_3	0.0589	0.0294	0.0283	0.0250
A_4	-0.0296	-0.0176	-0.0075	-0.0272
B_0	1.2306	1.4231	1.5450	1.4744
B_1	-0.7256	-1.2971	-1.5622	-1.3499

Table 8.4.7 - Coefficients for polynomial lift curve slope ((Eq39) (Keuning, et al., 1998)).

φ	0	10	20	30
b_1	2.025	1.989	1.980	1.762
b_2	9.551	6.729	0.633	- 4.957
b_3	0.631	0.494	0.194	-0.087
b_4	-6.575	-4.745	-0.792	2.766

Table 8.4.8 – Coefficients for polynomial added resistance in waves ((Eq.40) (Keuning, et al., 1998))

Fn 0.15

T1	μ °	a	b
2.0	100	0.0064	1.8012
2.0	115	0.0702	1.2351
2.0	125	0.1778	0.1778
2.0	135	0.3367	0.752
2.0	145	0.5349	0.5876
2.5	100	0.0022	2.1441
2.5	115	0.0217	1.6837
2.5	125	0.0537	1.467
2.5	135	0.0999	1.309
2.5	145	0.136	1.1874
3.0	100	0.001	2.3044
3.0	115	0.0092	1.8811
3.0	125	0.0226	1.6904
3.0	135	0.0418	1.5562
3.0	145	0.0642	1.4592
[illegible]	[illegible]	[illegible]	[illegible]

Fn 0.25

T1	μ °	a	b
2.0	100	0.0094	1.6076
2.0	115	0.1253	0.0662
2.0	125	0.2924	0.7191
2.0	135	1.979	0.5351
2.0	145	0.7386	0.3868
2.5	100	0.0031	1.9747
2.5	115	0.0383	1.4654
2.5	125	0.0884	1.2926
2.5	135	0.1515	1.1733
2.5	145	0.2196	1.0797
3.0	100	0.0014	2.1272
3.0	115	0.0161	1.6875
3.0	125	0.0369	1.5517
3.0	135	0.063	1.4652
3.0	145	0.0908	1.4015
[illegible]	[illegible]	[illegible]	[illegible]

Fn 0.35

T1	μ °	a	b
2.0	100	0.0131	1.426
2.0	115	0.202	0.7105
2.0	125	0.4691	0.4367
2.0	135	0.7962	0.2292
2.0	145	1.1418	0.0633
2.5	100	0.0043	1.7986
2.5	115	0.0609	1.2603
2.5	125	0.1408	1.0782
2.5	135	0.2403	0.9466
2.5	145	0.3444	0.8444
3.0	100	0.0019	1.9711
3.0	115	0.0255	1.5033
3.0	125	0.0585	1.3686
3.0	135	0.0993	1.2809
3.0	145	0.1423	1.2141
[illegible]	[illegible]	[illegible]	[illegible]

Table 8.4.9 – Coefficients for polynomial delta residuary resistance due to trim ((Eq.43) (Keuning, et al., 1998))

Fn	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60
Const	0	0.00191	0.00150	0.00255	0.00188	0.00696	0.00628	0.00262	-0.00458
Lwl/Bwl	0	0.00142	0.00085	0.00266	0.00291	0.00334	0.00290	0.00333	0.00370
Bwl/Tc	0	0.00360	0.00270	0.00549	0.00583	0.00738	0.00721	0.00736	0.00723
$Aw/\nabla c^{2/3}$	0	-0.00396	-0.00300	-0.00663	-0.00687	-0.00894	-0.00802	-0.00756	-0.00654
LCB	0	-0.00035	0.00016	0.00037	0.00110	0.00165	0.00133	0.00178	0.00172
LCF	0	0.00068	0.00001	0.00004	-0.00031	-0.00050	-0.00024	-0.00044	-0.00066