NEXT GENERATION ULTRA-LUXURY CRUISE SHIP: A PASSIVE DESIGN ECO-LUXURY CRUISE SHIP FOR THE MEDITERRANEAN

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The ultra-luxury small cruise ship sector has experienced significant growth in recent years. This paper reports on a design proposal for a catamaran eco-luxury cruise ship, which integrates a Passive Design methodology within the marine design process, with the objective of reducing the energy consumption of the vessel as an ecological statement enhancing the sense of luxury within the design. The design is an engagement in luxification, an evolution of luxury in cruising, creating a new market through Design-Driven Innovation, with the objective of offering green luxury user experience with a sense of intimacy similar to that of a superyacht. The concept design shows the potential of Passive Design as a means of reducing emissions in line with EEDI legislation, by reducing hotel loads such as HVAC systems and lighting.

Passive Design is employed in over 200,000 buildings across Europe and has resulted in the reduction and in some cases elimination of conventional mechanical HVAC systems by adapting the morphology of a building to the area of operation, resulting in a low cost solution with minimum environmental impact. This design project is a transfer of innovation from Architecture and is informed by a RIBA Passive Design best practice case study. The orientation and location of a vessel is voyage dependant, an analysis of solar variations for a potential vessel route was carried out as an integral part of the design process. The resulting hybrid passive design solution is user responsive, minimising energy consumption and reducing operational costs. It is an engagement in Design-Driven Innovation creating the opportunity for a new eco-luxury sub-sector within the ultra-luxury cruise ship market sector.

NOMENCLATURE

γ	Orientation of the structure (°)
β	Solar altitude (°)
θ	Vertical shadow angle or profile angle (°)
α	Azimuth angle (°)
I_l	Distance between louvers (m)
l	Width of louver (m)
a_l	Optimal inclination angle of louver (°)
γ_{rad}	Annual global radiation (w/m^2)
φ	Latitude (°)
df	Daylight factor
T	Diffused transmittance of the glazing material
A_w	Area of glazing (m^2)
A	Total area of internal surfaces (m^2)
M	Maintenance factor
$\emptyset$	The vertical angle subtended by visible sky (°)
R	The area weighted average reflectance

1.0 INTRODUCTION

In recent years the cruise industry has responded to ecological and economic pressures through the development of sustainability programs as outlined in the ISO 4001[1]. From waste heat recovery for pre-heating water and desalinization plants [2] to incorporating at shore electrical supplies [3] and material waste flow management schemes [4], the breadth of sustainable initiatives is growing, as the industry becomes more aware of client perceptions of environmentalism and plans to address future environmental legislation.

Due to the increase of user expectations and more demanding itineraries, combined with the pressures of rising fuel prices and legislative pressures from the IMO such as the EEDI, the industry is intending to become more commercially and ecologically streamlined. Although a significant impact could be made through the use of hull optimization [5] programs; Roy et al [6] identified that significant savings could be made through the reduction of auxiliaries such as HVAC systems which account for the majority of hotel energy loads. Since the energy crisis of 1973 the architectural industry has had a similar interest in reducing auxiliaries through bioclimatic design [7]. As the world's building stock accounts for nearly 50% of global energy use [8] government initiatives such as the EU 2002 energy performance directives, proposed that all new buildings built after 31st December 2018 will have to produce as much energy as they consume [9]. This has resulted in a proliferation of innovative energy reduction strategies to adapt architecture to its environment of operation, with the objective of reducing heating, cooling and lighting loads. As these are the dominant energy uses within domestic & commercial buildings [10].

In the 1990's the concept of bioclimatic design was further developed by Dr. Wolfgang Feist [11], with the introduction of the Passive Hause. This design adopted passive technologies such as solar shading, proper orientation, natural lighting, ventilation, good insulation and a heat recovery system, resulting in heating and cooling loads no greater than 10 W/m^2. This offered a reduction in auxiliary energy of 80-90% in comparison to other residential projects [12]. There are over 200,000 properties all over Europe demonstrating this approach to design with marked reductions in operational energy. This paper presents a preliminary design concept which investigates the potential of the passive design approach in the marine industry to reduce the energy requirements of auxiliaries. This was achieved by implementing solar shading and natural lighting strategies within a virtual design, the potential reduction in energy consumption of the heating and cooling loads during its annual operation was determined through simulation using IES.

1.1 BENCHMARKING THE ULTRA-LUXURY CRUISE SECTOR

This study focuses on 3 key areas types of the vessel: cabin space; dining areas; lounge areas. As they attribute to over 60% of the guest area following a spatial analysis of over 31 different cruise ships and super yachts. The cabins within the small luxury cruise market are typically 15-20m^2. Having a typical passenger to crew ratios 1.6 – 2.5 they offer a more tailored experience than its larger competitors through the delivery of a more personalized service. Of the three key area types, cabins are most susceptible to solar gain as they tend to occupy the perimeter of the vessel and typically have large window to wall ratios. Given that the façade design has a typical U-value of 0.4 W/m^2/ºC [13] it is critical that a solar gain strategy for cabins is developed.

To address the solar thermal gain in cabins, cooling loads are provided by the HVAC system, which is the largest electrical load of a vessel's auxiliary system [6]. Therefore a reduction in cabin thermal loads will reduce energy consumption and hence CO_2.

1.2 DESIGN-DRIVEN INNOVATION

The process of Design-Driven Innovation is an exploratory research project, which aims to create an entirely new market sector for a given product through changing the design meaning the user has for the product. It occurs before product development and is not the fast creative brainstorming sessions that are typical of concept generation but a design investigation similar to technological research [14]. In essence, it is the development of a design scenario through engaging with a range of interpreters in technology and cultural production. Knowledge is generated from immersion with the design discourse of the interpreter's groups. The process can be structured or unstructured and is dependent upon the nature of the relationship of the client with the interpreters. In this project there was unstructured design discourse between researchers with the EBDIG-IRC group at Coventry University, Cruise ship operators, marine HVAC specialists and a range of Passive Design experts including architects. It also included input from their industry networks and a review of the luxury travel global trend report [15]. This informed the design scenario used to develop the design brief.

"The Future of Luxury Travel, A Global Trends Report" is a qualitative and quantitative research project that is being carried from 2011 to 2013 [15]. To measure the main trends and challenges of the luxury travel industry, an Internet survey with luxury travel buyers and suppliers has been launched, and one-on-one interviews with CEOs or senior representatives from major luxury travel groups worldwide are being conducted. In addition, focus groups with buyers (tour operators and travel agents who provide a distribution channel for reaching the consumer, i.e., the luxury traveller) and suppliers (including airlines, cruise lines, hotels, etc.) took place in Singapore and New York. The key observations of the luxury travel market report were:

- differentiation of ultra-luxury from affordable luxury
- A re-direction of supply to meet the resilient demand by the super-wealthy
- To recover ultra-luxury positioning, authenticity, content, knowledge, real relationships, customisation and personalisation are redefined as ruling principles.
- The real luxury culture of service has returned.
- Traditional know-how, choice of materials, craftsman's products all contribute to the uniqueness of product and a one-to-one relationship with customers.
- Luxury travel providers now focus on sustainable development and luxury customers feel more entrusted with social responsibility as opposed to ostentation.
- By 2020, 100 million outbound tourists from China are expected.
- The Chinese market is considered the key driver of global luxury, with an estimated 250 million Chinese now able to afford luxury products.
- The primary destination for luxury travel is Europe, listed as the top luxury destination by 41% of the interviewees. France (14%) and Italy (9%) remain favourites.
- a small number of operators offer cruises aboard smaller ships (50-100 guests) that can carry a limited number of passengers and are exclusively reserved for high-end customers.

The 2012 PSA Cruise Review [16] reported that the most significant destination development in the UK cruise market was in the sales of cruises into Western Europe. These grew 30% in 2011. With Mediterranean cruises increasing by 10%. There was a significant increase in winter ultra-luxury cruise bookings in 2011 of 33% resulting in an annual increase of 7.6%. The ultra-luxury cruises have maintained a 1.5% share of the total UK cruise bookings for 3 years of overall market growth. This consumption trend combined with the global luxury review identifies the Mediterranean as a growth market for ultra-luxury cruises. Designed for an international socially responsible clientele seeking a differentiated ultra-luxury sustainable small vessel experience.

Destination	2001	2007	2008	2009	2010	2011	% change 10/11
Mediterranean	334	543	606	592	697	766	10
Northern Europe	98	213	247	296	303	342	13
Caribbean	146	228	255	275	272	238	13
Atlantic Islands	77	93	108	102	98	117	19
Other areas	121	258	261	268	252	237	6
Total	776	1335	1477	1533	1622	1700	5

Table 1 Destinations Booked By UK Passengers (in thousands)

Year	Summer	Winter	Total	% of all cruises
2005	12765	6311	19076	1.8
2006	12860	5655	18515	1.5
2007	13816	7552	21368	1.6
2008	13238	6427	19665	1.3
2009	14710	7960	22670	1.5
2010	16125	7899	24024	1.5
2011	15371	10498	25869	1.5

Table 2 UK Ultra-luxury Cruise Passengers 2005-2011

Although propulsive power dominates the energy profile of a cruise vessel, considerable gains could be made from the reduction of auxiliary electrical loads, which are in use all year round [6]. This identifies HVAC systems and associated HECA's (High Energy Consuming Application) as design issues to considered by the perspective of ecological designers.

A holistic design approach has led to a concept which tackles the issue of both propulsive and auxiliary power, by adopting a multihull platform. The concept presented in this paper therefore offers greater stability, lower drag and greater internal volume which is typically a premium in most cruise ship designs – with the added benefit of being able to access shallower locations, adding to the ultra-luxury experience. This addresses the expectations of passengers of the small cruise industry, and as a platform can also support advanced passive strategies such as the use of thermal mass as implemented in work of McCartan and Kvilums [17].

The technology platform comparison was developed through benchmarking current super-luxury mono-hull cruise ships in term of GA spatial allocation and benchmarking catamaran designs that could provide comparable GA areas. Generic hulls (specifications are shown in Table 3) for the given vessel operational speed were then compared in terms of hull power requirements as shown in Fig. 1

	Monohull	Catamaran
Loa (m)	90	81
Beam (m)	18	5.5
Hull spacing (m)	NA	22
Displacement (tonnes)	4000	650
Wetted Area (m^2)	1500	400

Table 3: Specification of Generic Hulls

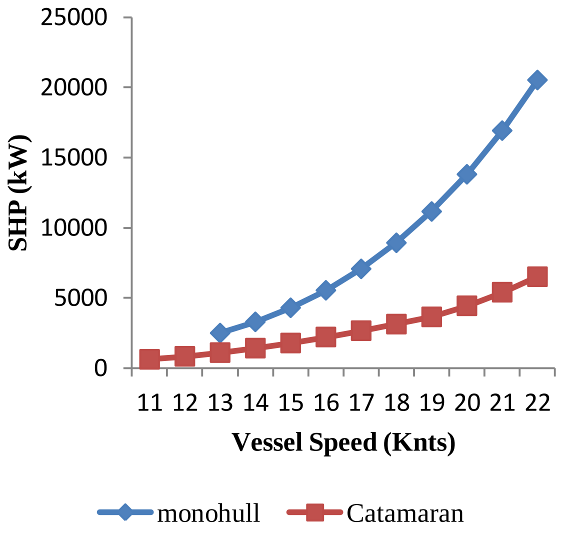

Fig.1 Graph of hull speed against shaft power requirement for comparable monohull and catamaran platforms.

2. THE PASSIVE STRATERGY

Bioclimatic design [7] creates a design envelope which takes advantage of natural energy flows within the environment of operation to reduce energy demand in order to create a thermally comfortable interior. Design guidelines from ASHRAE [18] indicated that shading of fenestration alone can reduce solar heat gain by as much as 80%.

In examining the importance of fenestration and its relationship to thermal loads, Aste' [19] developed an adaptive shading algorithm to optimise the utilisation of onsite solar control to maximize natural lighting, while at the same time reduce solar heat gain. His work on an office building in Milan Italy demonstrated that the inclination profile of a shading device is dependent on the systems geometrical profile, in terms of location, orientation and time of year.

Figure 2: Route of cruise ship from Rome to Lisbon

Kim [20] used IES (Intergraded Environmental Solutions) software simulations to conduct a comparative analysis of various shading strategies such as louvers, overhangs and light shelves for an apartment buildings in the hot humid climate of South Korea. Through dynamic modelling an optimized shading device was developed combining the practices of natural lighting and solar shading which resulted in a 70% energy saving of the cooling load. This proposal significantly reduces the cooling load whilst still retaining visibility and natural lighting potential which supports the work of Cheng [21], who suggested that the geometry of shading devices can facilitate the lighting performance of the room.

Similarly the work of Hammad [22] demonstrated that a dynamic louver system, with light dimming technology reduce energy demand by 28.57% - 34.02% for west, east and southerly facades accordingly, in office buildings situated in Abu Dubai. Furthermore it identifies that the gains of a dynamic shading strategy are marginal compared to an optimized static louver design. These energy savings may differ when considering the changes in orientation and climatic variation that the vessel is likely to experience during an annual itinerary.

Loe [23] identified that interior trim, colour scheme and surface reflectance have an impact on the potential of natural light harvesting, and can prevent a gloomy atmosphere. Interior design is therefore a critical consideration impacting the performance of natural lighting and artificial lighting energy requirements. The European standard SS-EN 12464-1, proposes a list of surface reflectances that support natural lighting systems whilst taking into consideration glare and other visual properties. Dubois [24] reported that increasing the ceiling reflectivity has a positive effect on energy savings and leads to a more uniform distribution of daylight throughout a space.

Informed by the work of Robertson [25] the cabin interior design aims to support the natural lighting strategy through the incorporation of furniture and walls that have a reflectivity of 25% to 45%. An important consideration identified in the work of Reinhart [26] is ensuring that the internal arrangement does not obstruct natural light into the deepest parts of the cabin by limiting the height and transparency of internal partitions.

2.1 SOLAR GEOMETRY EVALUATION

The objective of a passive shading strategy is to block direct solar flux whilst maximising the potential for natural light into the interior at times appropriate to the operational profile of the room. Solar geometry evaluation is critical to the construction, development and design of a passive shading device. The evaluation is complicated by variation of latitude and orientation of the vessel during a journey compared to the fixed location and orientation of a building.

The first objective of solar geometry evaluation is to define the shading period. This is typically defined by the equinoxes in September and March, which approximate the periods of cooling and heating. However, this is not necessarily the case as the seasonal changes do not always lie symmetrical to the summer solstice. It is common practice therefore to use other methods of defining the shading period such as degree day selection proposed by Sargent [27] or dynamic thermal analysis of a structure to more accurately determine the shading periods. Dynamic thermal analysis was implemented in this study through the use of the IES software. The sensible thermal loads of the test cabin throughout the year are shown in Figure 3, identifying the periods of heating and cooling for the southern façade in Barcelona. It indicates that shading is required from early May to late October.

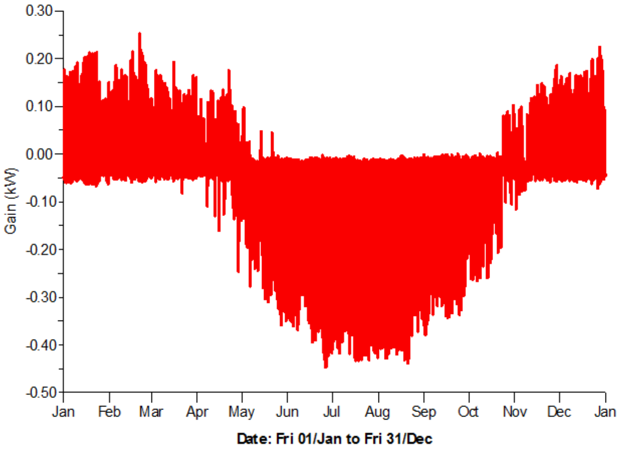

Figure 3 - Sensible thermal loads of a test cabin with 1.5m balcony

The second objective of solar geometry evaluation is to define the form of the shading device which is a function of solar geometry. Solar position algorithms were developed in Matlab, based on the work of Reda [28] and the evaluation of shading geometry and louver tilt profiles carried out by Aste [19]. To examine the influence of latitude variation, the extremities of the latitude range and the mean value of the proposed vessel route (Figure 2), are considered by carrying out the analysis at three location: Nice; Barcelona; Malaga. The solar geometry data for these locations are shown in Table 4 for a south facing cabin.

	Nice (France)	Barcelona(Spain)	Malaga (Spain)
Latitude	43°41'34.19"N	41°28'0"N	36°40'11.60"N
December 21st	**22.5749**	**24.1135**	**29.1743**
Shadow Angle	22.7387	24.6314	29.5955
Inclination/tilt	49.6290	45.3043	34.3684
March 21st	**45.9886**	**46.9534**	**52.0889**
Shadow Angle	46.8184	49.0536	53.8429
Inclination/tilt	1.8171	6.4286	16.2774
June 21st	**68.6540**	**68.8038**	**73.7399**
Shadow Angle	69.9636	72.5515	77.1573
Inclination/tilt	49.2292	54.5018	63.8788
September 21st	**35.2908**	**36.9736**	**42.0128**
Shadow Angle	22.0249	37.4962	42.3507
Inclination/tilt	1.7279	17.5726	7.4380

Table 4 - Solar geometry at solar equinox and solstice for a southern façade at 12 noon (solar time) – showing the shadow angle and optimum inclination angle of a louver shading device

Santamouris [29] proposed the following relationship between location and climatic variables such as, temperature, relative humidity, wind and cloudiness:

$$log\ \gamma = a + b\varphi \qquad \text{Formula 1}$$

Where γ (the annual value of global radiation) varies with φ (latitude). From this Reinhart [26] proposed that the thermal performance of the vessel will be a function of the vessels latitude. The vertical shadow angle and optimum inclination angle for a louver based shading devices are calculated using equation 2 and 3 respectively – based on the works of Aste [19]. The variation in these angles over the latitudinal extremities of the journey profile are shown in Table 4.

$$\theta = arctan\left[\frac{\tan\beta}{\cos(\gamma - \alpha)}\right] \qquad \text{Formula 2}$$

$$a_l = \arcsin\left(\frac{I_l \times \cos\theta}{l}\right) - \theta \qquad \text{Formula 3}$$

3. METHODOLOGY

This preliminary design concept was develop by bench marking current super luxury cruise ships in order to elucidate the specifications of the GA. As described in the DDI section, the use of a catamaran hull to reduce propulsion energy requirements was achieved through benchmarking suitable catamaran platforms and determining their hull powering requirements in comparison to the existing mono-hull vessels for a range of cruising speeds. This enabled a reduction in propulsion CO_2 to be estimated and compared to the reduction of auxiliaries CO_2 due to Passive Design. Once the GA had been developed on the platform using the principles of Passive Design, the exterior styling was developed, with the challenge of integrating the louvers into the exterior form language. The front 3/4 view is shown in Figure. 4. As the majority of the GA is cabin space with high glazing ratios, it was decided to focus the Passive Design analysis on a test cabin geometry.

Implementing the shading geometry methodology for vessels develop by the EBDIG-IRC at Coventry University, the study employed the use of IES; a dynamic simulation software. It was used to evaluate the influence of balcony depth and 3 passive design strategies using louvers, namely: static; occupancy based modulated louver control; solar radiation based louver control.

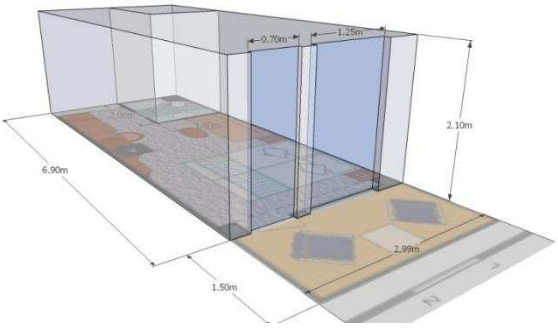

Figure 4 - Test cabin geometry

The general configuration of the test cabins has been based on benchmarking of typical cruise ship designs. The room geometry shown in figure 4 is a double bed cabin with a balcony area of 4.67m^2. It has a private balcony access and a large floor to ceiling window, resulting in a large glazing ratio of 0.53 which is representative of outside cabins. The thermal attributes of the test cabin are derived from ISO 7547 [30]. Operational profiles have been developed in accordance to predicted occupancy levels (typically between 6pm to 8.30am in the morning) which is synchronised with other potential internal heat gain sources such as media devices and lighting also outlined in table 5.

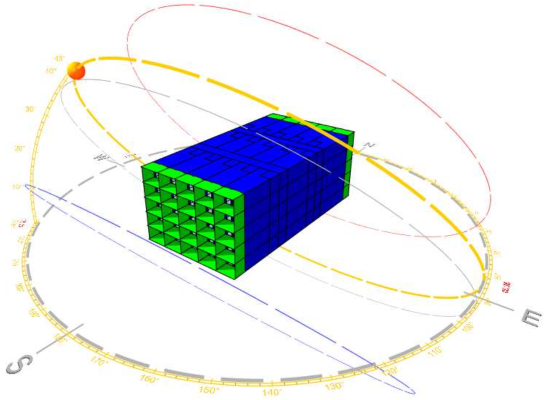

Figure 5 - Test cabin configuration inside virtual testing environment IES

To account for heat transfer to and from the test cabin the thermal model has been designed so that two additional cabins are attached in each direction around the test cabin as shown in Fig. 5 this reduces the negative impacts of sol air temperature and direct solar radiation as recommended by Kim [20]. As the internal partitions are not considered adiabatic this configuration helps to create realistic boundary conditions in respect of the thermal characteristic and behaviour of the vessel envelope.

IES presented itself as a viable means of simulating a shading systems within the marine environment as the weather and climate data for simulations could be easily modified. This enabled the weather and climate data to be altered to represent that experienced during a voyage.
Mansour's [31] study on the validity of IES in a shading study indicated a good correlation between simulation and actual results of a self-shading room in kuala Lumpur, Malaysia, with a variation of less than 10% of the actual recorded data.

This study utilised three applications within IES, ModelIT, Suncast and Apache. Apache is used to conduct dynamic simulation models accounting for thermal transmissions to and from the test cabin in accordance to varying external and internal climatic parameters. Suncast is used to understanding solar geometry and conducting an initial solar shading analysis. ModelIT is the CAD package used to model the primary dimensional and geometric properties of the vessel and to define the location of operation.

Setting out to identify the relationship between form, fabric and energy consumption the primary outputs of the simulations will be based on the cooling, heating and lighting loads. The results will thus indicate the best performing design in terms of energy in an evaluation of the potential of passive shading devices on board cruise ships. The basis of the methodology is illustrated in figure 6.

3.1 TEST CABIN GEOMETRY

3.1 (a) Balcony Depth

To evaluate the influence of balcony depth on the sensible loads of the interior with no additional shading device Balcony depths from 0m to 2.5m in increments of 0.5m were evaluated at orientations from 0-360 degrees in increments of 90º.

3.1 (b) Adaptive and Static Louvers

The test cabin geometry used to evaluate the influence of static and adaptive louvers on solar gain, is shown in Fig. 7. The static louvers test cabin design is based on a system of fixed position louvers positioned horizontally across the cabins fenestration. The following angles of louver inclination will be examined:0;10;20; 30;40;50;60;70. The adaptive louvers test cabin will be evaluated under occupancy actuated control and solar tracking control.

Occupancy actuated control is a system based on an 0 angle louver which completely closes to 90° when the client leaves the room and reopens when the door handle is opened. Through dialogue with cruise ship crew a representative operational profile was developed in accordance to predicted occupancy levels typically between 6pm to 8.30am. In solar tracking control the louvers will dynamically align themselves perpendicular to the suns position in the sky when solar radiation rises above 100W/m².

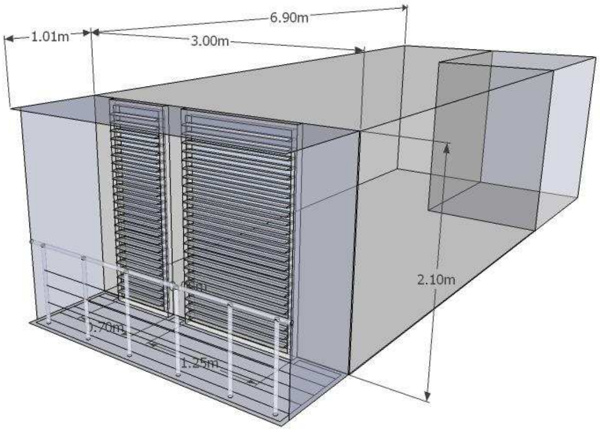

Figure 7: Test cabin exploring the impacts of louvers on thermal loads

4. RESULTS

4.1 EXTERIOR FORM DEVELOPMENT AND GA

The exterior form is shown in Fig.8, it has a sleek flowing dynamic form, which visually integrates the lines of the louvers with the aft deck lines. The integrated hull and superstructure act as a single form clasping the balconies, giving a sense of balance to the visual mass of the bridge deck, due to the perceived high shear line at the fore end of the superstructure. The thin deck lines and sun deck form combine with the hull glazing features to visually accentuate the perceived length of the vessel.

Figure 8: Side view of vessel

The GA, shown in Fig.9 and Fig.10, has been developed from the principles of Passive Design. The design is a hybrid passive systems, which utilises cross ventilation and stack ventilation techniques in addition to the shading principles discussed, to further reduce thermal and ventilation loads on the HVAC system. The GA is configured so that high heat gain areas such as the dining area and galley are positioned in locations (Wheel House Deck) which can be purged of heat gains quickly and can take advantage of a natural lighting scheme, complimenting the locations demands.

External vertical louvers on the upper decks helps funnel prevailing wind, during desirable climatic periods so that pressure differentials occur across the vessel to induce a flow of air. This flows through the internal structure and out through the stairwells. The stairwells have venturi apertures on the Sun Deck and all deck level doors are kept open, in order to maximise stack ventilation potential. To meet SOLAS fire regulations all doors and venturi apertures are spring loaded and secured by electromagnetic locks, which are controlled by the fire safety system. These are released when fire is detected closing the doors and apertures, thus containing and protecting the means of escape.

4.2 EFFECT OF BALCONY DEPTH ON COOLING LOAD

The results of the influence of balcony depth on cooling load are shown in fig 11, where by a general trend is observed which indicates that a greater balcony depth results in reduced solar gains with those of the south orientation being more significant. The reduction in cooling load with balcony depth becomes less significant after 1.5m.

4.3 EFFECT OF LOUVER SHADING SYSTEM ON COOLING LOAD

The results of the effect of the different louver control systems on sensible cooling load for a south facing cabin are shown in fig 12. Where they are compared to a balcony with no shading device. The adaptive louvers control systems are occupancy actuated control and solar tracking control. Occupancy actuated control is a system based on an 0^o angle louver which completely closes to 90^o when the client leaves the room and reopens when the door handle is opened. In solar tracking control the louvers will dynamically align themselves perpendicular to the suns position in the sky when solar radiation rises above 100W/m². Compared to a 1.5m balcony without louvers the solar radiation based louver control and the occupancy actuated control systems offer a reduction in cooling load of 46% and 59% respectively for the south orientation, and a reduction in cooling load of 25% and 43% respectively for the North orientation.

4.4 STATIC LOUVER SYSTEM

The simulation results of the annual sensible cooling loads of the static louver devices, which remain in the same position throughout the year, are shown in Fig.13. The column on the left represents a 1.5m balcony without louvers acting as a comparison to the other results. The increase in static louver inclination results in a reduction in sensible cooling with a similar trend observed with the same system on the northern façade. The 0 degree louver offering a reduction of 28% in cooling load compared to a balcony without louvers.

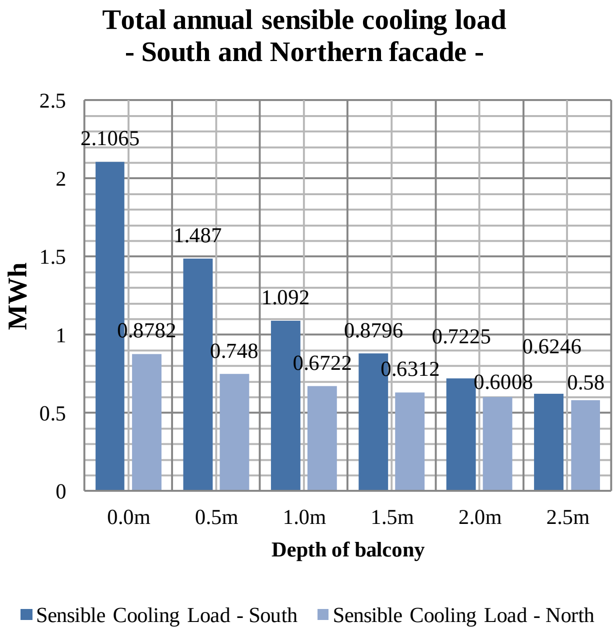

Figure 11: Effects of balcony depth on cooling load (south façade)

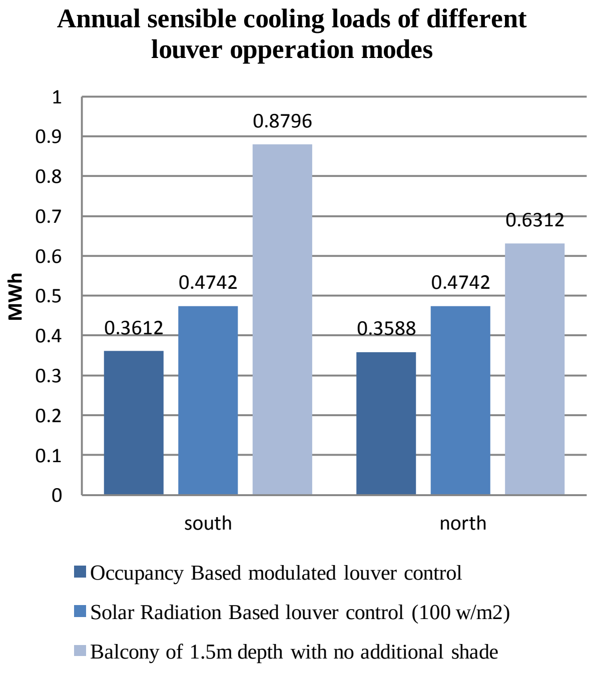

Figure 12 - Effects of louver control on sensible cooling load on the south facing cabin

The simulation results of the monthly sensible cooling loads of the static louver devices are shown in Fig.14. Where they are compared with a balcony without louver. The results indicate the effectives compared to a façade with no louver system. The results show that a static louver system is most effective during the winter and autumn periods where low lying sun is more likely to result in solar exposure to the interior and most likely to affect radiant temperatures inside the cabin.

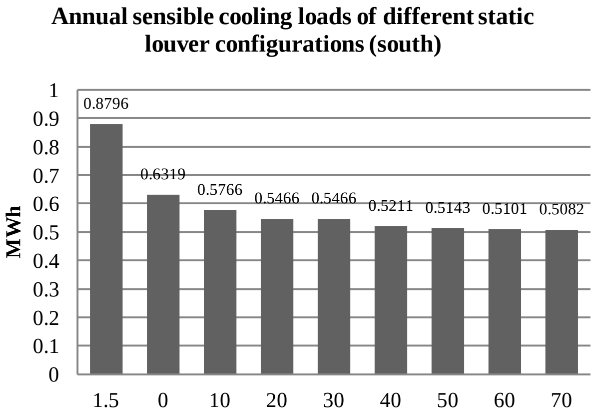

Figure 13 - Effects of static louver control on sensible cooling loads on the south facing cabin (description)

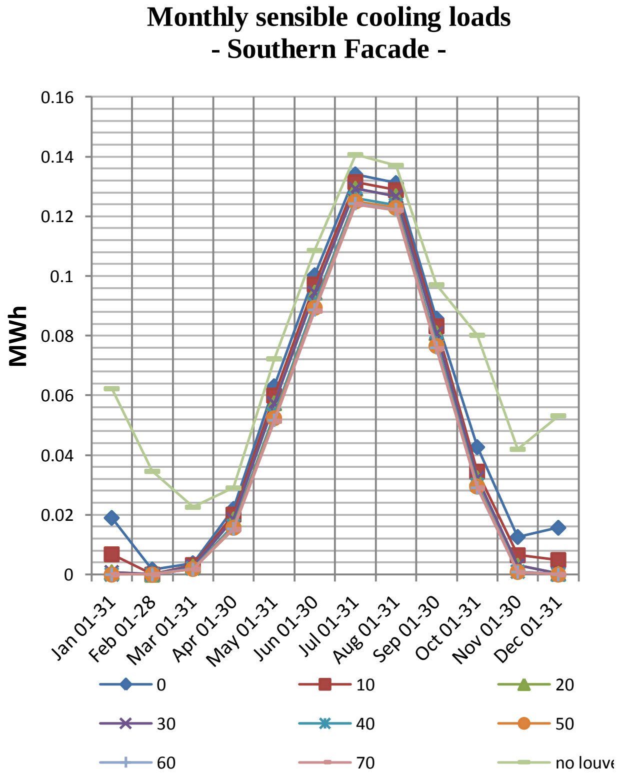

Figure 14 - Monthly sensible load profile for a south facing cabin

5. DISCUSION

The Design-Driven Innovation approach applied to this vessel design has used technology innovation from architecture to reduce the auxiliary loads combined with the use of a catamaran hull to reduce propulsive power requirement compared to monohull with the same GA area, resulting in a vessel which embodies the meaning of eco-luxury. This is further enhanced by the use of a gas turbine operating LNG. All of these factors help address future CO_2 legislation such as EDDI. The beam/length ratio of the catamaran platform enabled it to more effectively engage in best practice passive design strategies inspired by the CTU building which is a RIBA case study of best practice Passive Design.

In the thermal simulation of the test room using IES, a number of assumptions were made in terms of the fabric properties of the room and the thermal connection to the rest of the vessel. The material properties we set to those stated in ISO 7547 [30] and it was assumed that there was no thermal bridging. Due to the nature of ship construction it is highly likely that thermal bridging will occur, this could be mitigated through evaluating the construction process and identifying innovative architecture technical solutions introduce insulation to critical areas. This is also a consideration for the implementation of Passive Design in refit, where thermal imaging technology, currently used to condition monitor buildings for heat loss, could be used to identify key thermal bridges in need of insulation.

In discussing the Passive Design results for the cabin it is important to consider the significant difference between applying the principles of Passive Design to architecture and naval architecture. An architect analyses the site of a building to determine the optimum fixed orientation of the building in the environment. Whereas, a naval architect must consider the passage of the vessel and statically analyse the range of latitude and orientation experienced for the whole of the passage. To this end, the latitude mid-point was chosen for the purpose of the analysis, with both North and South orientations being used to respectively represent the minimum and maximum extremes of solar exposure that the test cabin could experience under passage. Using these conditions we can determine maximum and minimum energy saving potential of the Passive Design strategy. A more detailed journey analysis will be carried out in further work to accurately quantify the energy saving and determine the effectiveness of a given Passive Design proposal to a variation in vessel route as vessels are used in a range of passages during their operational lifetime.

Examining the effect of balcony depth on cooling load, shown in Fig. 9, there is a marked effect in reduction from 0 to 1.5m for both North and South orientations of 28% and 58% respectively, with a lesser reduction effect between 1.5m and 2.5m, of 8% and 28% respectively. It was on the basis of these results that the balcony depth was fixed at 1.5m to evaluate the further potential cooing load reduction that could be provided by louvers. A further evaluation will be required to determine the potential cost benefit of greater balcony depths in terms of material and construction costs against CO_2 and fuel cost reduction. Given the significant displacement of cruise ships the additional balcony mass would be insignificant in term of hull performance. The implication of implementing the 1.5m depth balcony in a vessel is that it will reduce the cooling load of between

28% and 58% depending on its orientation time history. Further work will examine the sensitivity of the balcony depth to variations in vessel passage in terms of latitude and orientation time history.

Three types of louver were evaluated to determine their ability to further reduce the cooling load in addition to the use of a 1.5m depth balcony, namely: static; occupancy based modulated louver control; solar radiation based louver control. The static louver system involved evaluating a fixed angle louver systems with the following louver angles: 0;10; 20; 30 ; 40 ; 50; 60; 70. The annual sensible cooling loads of the different static louver configurations is shown in Fig. 13 for South orientation, with the 1.5m depth balcony without louver included for comparison. Here the 0 angle louver system reduces the cooling load by 28%. The increase of louver system angle from 0 to 70 degrees decreases the cooling load by an additional 20%, this relationship needs to be considered in the context of solar illumination of the room. The louver angle of 50 degrees can achieve a cooling load reduction of 19% while maintaining a reasonable level of solar illumination of the interior. This will need to be considered as part of the interior design process to select the reflectivity of colour, trim and furniture geometry to achieve suitable levels of illumination. The monthly sensible cooling loads of the different static louver configurations are shown in Fig. 14. The difference in cooling load with the implementation of louvers is most pronounced in the autumn and winter seasons from October to March. Here the cooling load in February without louver is a factor of 17 higher than the cooling load with the 0 degree louver, in March it is a factor of 11 higher. The factor by which the cooling load without louver is higher than the cooling load with the 0 degree louver has lower values in Oct (1.8), Nov (3.5), Dec (3.25) and Jan (3). This is due to the low Winter sun penetrating the test room, illustrated by the fact that the cooling loads for 0 degree louvers are a factor higher than the 10 degree louvers of 3.5 in December and 3 in January.

The occupancy based modulated louver control is a system based on an 0^o angle louver which completely closes to 90^o when the client leaves the room and reopens when the door handle is opened, so that the users experience of the room is unaffected. Through dialogue with cruise ship crew a representative operational profile was developed in accordance to predicted occupancy levels typically between 6pm to 8.30am, which assumes that for the most of the day the occupants are enjoying on-board facilities or exploring the port of call. In contrast to this the solar radiation based louver control varies the tilt angle of the louver to fixed values depending upon the level of solar radiation detected by a sensor. This system would require a more complex control system than the occupancy based control. The result of both systems is shown in Fig. 12 compared to a balcony of 1.5m depth without a louver system for both north and south orientations. For both orientations the occupancy based modulated louver control has the lowest cooling load. For the south orientation it is 59% less than balcony without louvers and 24% less than the solar radiation based louver control. For the North orientation it is 43% less than balcony without louvers and 24% less than the solar radiation based louver control. The consistent results of the solar radiation based louver control regardless of orientation are a consequence of it being a closed loop control system. The implication of occupancy based modulated louver control results is that a vessel using it will have a reduction in cooling load of between 43% and 59% depending on its orientation time history, in addition to the reduction achieved in using a balcony. Both occupancy based modulated louver control and solar radiation based louver control show superior performance when compared to the static louver control, where they are superior to the 70 degree angle offering a greater reduction in heat loss of 29% and 7% respectively for South orientation. Further work will examine the sensitivity of the various louver control systems to variations in vessel passage in terms of latitude and orientation time history.

It is important to note the subsequent negative impact on natural lighting of the interior, which reduces as a consequence of greater balcony depths. The southern façade experienced a reduction in average daylight factors from 2.2% to 0.3% with a balcony depth increase from 0.0m to 1.5m, encouraging the use of artificial lighting systems which act as parasitic heat gain source to the internal thermal environment. However, considering the periods of occupancy and the associated heat gains of natural lighting within the cabins this may be negligible. The depth of the balcony therefore obstructs the sky and reduces the visible sky angle, typically measured from the geometric centre of the glazed façade (Θ), reducing daylight factors (formula 4). This will have a greater importance in areas occupied during the day such as dinning and lounge areas, which could benefit from a natural lighting scheme to reduce the use of artificial lighting technology. This has to be carefully considered during the design phase and is a factor dependant on the function and use of the room, as well as the glazing area.

$$df = TA_w\theta M/\{A(1-R^2)\} \qquad \text{Formula 4 – [32]}$$

In summary the combined effects of both an occupancy dependant louver system and a balcony depth of 1.5m provides an optimum reduction in sensible cooling loads showing a total reduction of 83% (1.7453 MWh) and 59% (0.5194 MWh) for south and north orientation respectively compared to a facade with no balcony depth or shading. Additionally an occupancy based louver system would benefit from the maximum natural lighting potential when the room is occupied instead of being obstructed.

In order to estimate the annual CO_2 reduction and fuel reduction achieved by these potential reductions in cooling load through passive design, it is assumed that the cooling load is provided by a MAN ME-GI engine operating on LNG. The efficiency losses in generating electricity, electricity transmission losses and the HVAC system efficiency losses in converting electrical energy into cooling load are ignored, resulting in a underestimate which will be refined through further work. A MAN ME-GI engine operating on LNG has a SFC of 0.125kg/kwh and CO_2 emissions of 462g/kwh [33]. On this basis:

Maximum annual CO_2 reduction per room
= 462g/kwh x 1745.3kwh = 806kg

Minimum annual CO_2 reduction per room
= 462g/kwh x 519.4 kwh = 240kg

Maximum annual fuel reduction per room
= 0.125kg/kwh x 1745.3kwh = 218kg

Minimum annual fuel reduction per room
= 0.125kg/kwh x 519.4 kwh = 65kg

	Min	Max	Min	Max
No. Rooms	CO2 (kg)	CO2 (kg)	LNG (kg)	LNG (kg)
30	7,200.00	24,180.00	1,950.00	6,540.00
50	12,000.00	40,300.00	3,250.00	10,900.00
100	24,000.00	80,600.00	6,500.00	21,800.00
300	72,000.00	241,800.00	19,500.00	65,400.00
700	168,000.00	564,200.00	45,500.00	152,600.00
1100	264,000.00	886,600.00	71,500.00	239,800.00

Table 6: Range of potential annual CO_2 and LNG reduction for different vessel sizes operating in the Mediterranean

The potential of Passive Design to reduce annual CO_2 emission and LNG consumption is shown in table 6. This needs to be evaluated in terms of the propulsion CO_2 emissions. The graph of hull speed against power requirement for comparable monohull and catamaran platforms (Fig.1) shows a power saving and hence CO_2 reduction of 56% for the catamaran over the monohull at 13Knots which increases to 68% at 22Knots. This clearly shows the potential of the catamaran platform based on the target displacement of 650tonnes, which will be evaluated in further work to determine the potential of sustainable manufacturing technology to meet this target.

To develop an analysis of operation profile, it is assumed that each cruise is 14 days in duration, resulting in 25 cruises per year with 15 days for vessel maintenance and the journey distance is assumed to be 1425Nautical Miles. The comparison of potential CO_2 reduction of Passive Design as a percentage of annual propulsion CO_2 for a range of vessel speeds are shown in Table 7. Here the potential of Passive Design to reduce HVAC CO_2 ranges between 21% and 70% at 11Knts decreasing to between 4% and 13% at 22knots. This is due to the significant increase in propulsive power with increasing vessel speed. For an average cruise speed of 11 Knots, the potential reduction is significant in the context of propulsion CO_2 and will be evaluated in the context of EDDI in further work. As previously discussed the range are a consequence of the vessel orientation, dependant on its orientation time history.

While the key objective of the preliminary design presented was to engage in Design-Driven Innovation, creating the opportunity for a new eco-luxury sub-sector within the ultra-luxury cruise ship market sector, the significant reduction in CO_2 and fuel has significant implication for large cruise vessels in terms of operating costs and future emission legislation.

Vessel Speed (Knts)	Annual Propulsion CO_2 (kg)	Max PD potential CO_2 Reduction as % of annual Propulsion CO_2	Min PD potential CO_2 Reduction as % of annual Propulsion CO_2
11	36,733	70%	21%
12	45,454	57%	17%
13	55,406	47%	14%
14	66,395	39%	12%
15	77,973	33%	10%
16	90,732	28%	8%
17	102,865	25%	7%
18	114,221	23%	7%
19	126,056	20%	6%
20	145,765	18%	5%
21	169,176	15%	5%
22	194,521	13%	4%

Table 7 Comparison of potential CO_2 reduction of Passive Design as a % of annual propulsion CO_2 for a range of vessel speeds

The design proposal demonstrates the potential for engaging in the drivers of the eco-luxury market through the reduction in CO_2 from both propulsion (catamaran hull and LNG fuelled engine) and Passive Design, it needs to be quantified in terms of Design-Driven Innovation from a user perspective. Further work will examine the psychological impacts of shading and natural lighting schemes on users experience and concepts of luxury. It could be argued that a Passive Design strategy ameliorates psycho-pleasures as defined by Jordan [34] as well as the ecological and economic benefits.

6. CONCLUSION

The ultra-luxury small cruise ship sector has experienced significant growth in recent years, which is predicted to continue, with the Mediterranean showing significant potential for this market sector. In this operational area HVAC has been show to be a significant requirement and a major contributor to vessel auxiliary loads.

The preliminary design proposal of a catamaran eco-luxury cruise ship, integrates a Passive Design methodology within the marine design process, resulting in a potential reduction in cooling load between 519.4kwh and 1745.3kwh per cabin per annum. Achieved through the use of a 1.5m balcony and an occupant responsive louver control system. A more detailed statistical analysis of vessel orientation and latitude during a journey will be required to determine the actual cooling load reduction for a given journey. The cabin dimensions and fabric properties were determined from benchmarking and ISO 7547 respectively[30]. This assumed no thermal bridging in the vessel structure connecting to the cabins, which may not be the case due to vessel construction methods.

While the design proposal demonstrates the potential for engaging in the drivers of the eco-luxury market through the reduction in CO_2 from both propulsion (catamaran hull and LNG fuelled engine) and Passive Design, it needs to be quantified in terms of Design-Driven Innovation from a user perspective. Further research will be required to examine the psychological impacts of shading and natural lighting schemes on users experience and concepts of luxury. This will inform future interior design methodologies.

The potential of Passive Design to reduce the CO_2 and fuel consumption for large vessels, while not being the key objective of this work has been shown to be significant. On this basis Passive Design could become an integral part of a future strategy to enable large cruise ships to address EEDI and other future emission legislation.

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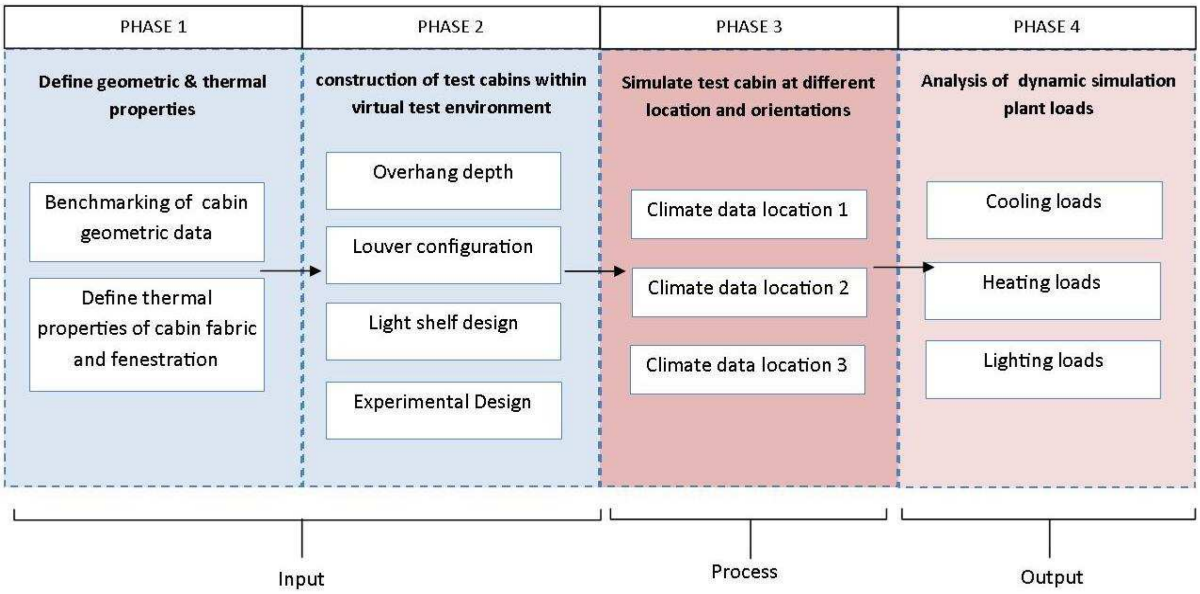

Figure 6 - data collection and simulation sequence

Width	3.0m	Length	6.90m
Height	2.10m	Plan area and volume	22.1m^2 (including balcony)
Surface to volume ratio	0.47	Infiltration airflow rate	0.167 ach
Window to wall ratio	0.11	Window height	2.0m *door height
Window area	4.09m^2		
T Summer-set-point	27ºC	T Winter set point	22ºC
Humidity set point (max)	50% relative	Humidity set point (min)	n/a
U glazing	2.4	Glass G value	0.70
U Frame	2.7	U wall (external/internal)	0.4014/0.5065
U ceiling	0.4089	U floor	0.4089
Occupancy Density	18.58 m^2/person	Occupancy scheduling	7 days a week 6pm – 8am the following morning
illuminance level on work plane (min)	300lux	illuminance level on work plane (max)	500 lux
Heat gains electrical	Fluorescent light bulbs 9.69 W/m2	Heat gains occupants	73.27 W(Sensible gain) 58.61 W (Latent gain)
Cooling SEER (fan coils + water chiller)	Complete chiled water air conditioning system with individual air handlers in each cabin	Heating SCOP (fan coils + heat pump)	Complete chiled water air conditioning system with individual air handlers in each cabin
Weather data	Barcelona ESP_Barcelona.081810_IWEC.epw	Roma ITA_Roma-Fiumicino.162420_IGDG.epw	Nice FRA_Nice.076900_IWEC.epw

Table 5 - Basic geometric data and thermal characteristics of test cabin

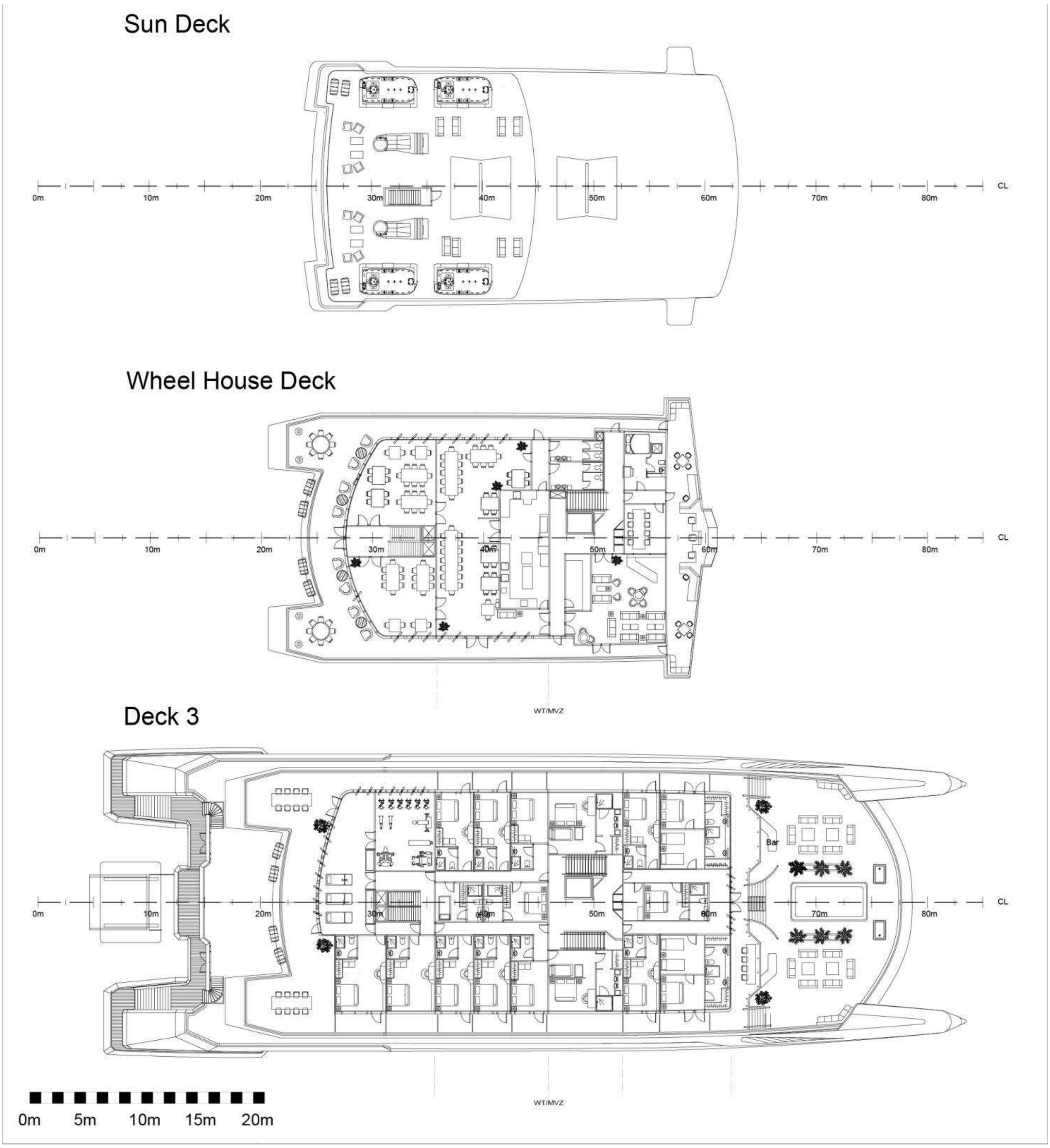

Figure 9: GA of Helios

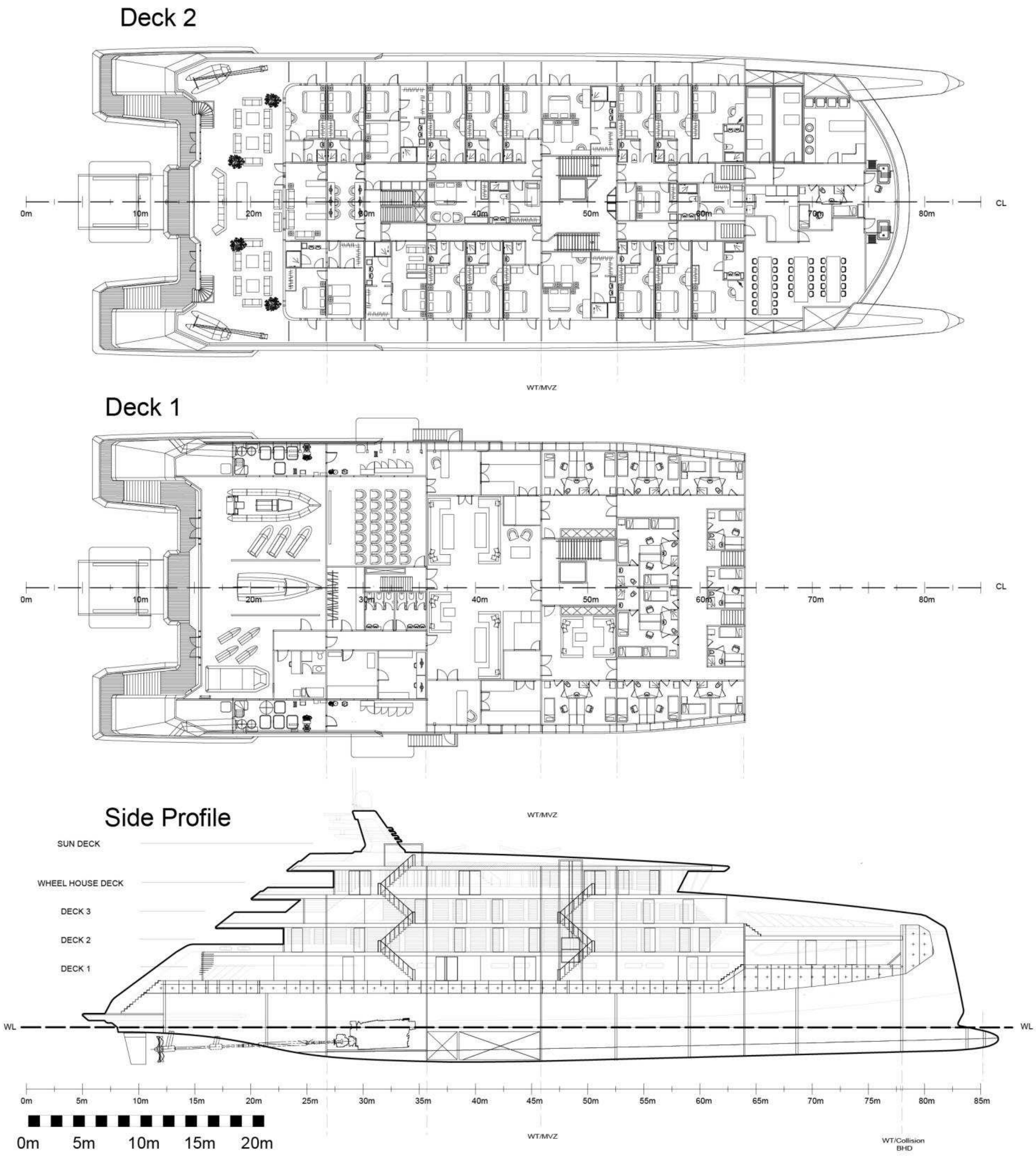

Figure 10: GA of Helios