University of Strathclyde

Department of Naval Architecture, Ocean and Marine Engineering

"A dynamic energy modelling approach to low energy ship design"

PhD Thesis

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Signed: *Date:*

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ABSTRACT

Despite remarkable advances in naval architecture in the past few years, limited effort has been expended to improve the energy efficiency of ships due to the relatively low price of fuel oil and lack of stringent environmental regulations. However, the ever-growing intercontinental trade has resulted in an increase of greenhouse gas emissions from ships that triggered the introduction of mandatory environmental measures and shifted the focus of the shipping industry towards more energy efficient designs and operations.

This thesis focus is on improving the energy efficiency of ships during design and operation by adopting a direct approach to estimating the requisite thermal energy on board ships over their life cycle. This is achieved by dynamically modelling the thermal energy flows on board, drawing from the considerable developments in Building Energy Simulation (BES), which precedes developments in the maritime industry by five decades. To this end, and in broad terms, the thesis focus is on and embodies the technology transfer from the Buildings Industry to the Marine Industry ("marinisation of BES") whilst accounting for the differences and complexities implicit in some of the ship types as well as the marine environment and operations. This, in turn, necessitates focus on applicability, functionality and limitations of BES in ships with the view to enable developments to fill pertinent gaps and to demonstrate such developments with purposely selected case studies.

During the investigation of the applicability of BES in ships, the main differences between ships and buildings were identified, and their effect on energy simulation was pointed out. The results of this comparison served as the basis for the marinisation of the selected building energy simulation

software ‘ESP-r’, which was enhanced to also cater for energy flows present in the marine environment, leading to the development of ‘ESP-r marine’. Despite the ability of the tool to model the majority of thermal energy flows on board ships, several modelling and computational problems were presented during the development of large accommodation models that triggered necessary simplification considerations. In an attempt to allow energy modelling of smaller groups of spaces and drop the requirements for explicit and topologically correct model representation, the geometrical decoupling of major space types was examined. A verification process based on energy simulation was used to construct guidelines, indicating acceptable assumptions for the boundary conditions of individually modelled or groups of accommodation spaces. This methodology was then used to facilitate further simplification of thermal modelling, which was achieved through the concept of space grouping that encompassed the process of the consecutive merging of adjacent spaces, until groups of spaces were represented by a single thermal zone. Throughout this process the loss of accuracy in the results was quantified, and results were used to develop design guidelines for the group representation of major types of on board spaces.

All findings were used to form a methodology for the design of the most common ship accommodation spaces and relevant HVAC systems which outer performs current practices, since it provides detailed information about state variables in accommodation spaces and energy systems components, and allows for the calculation of the power consumption of the energy systems serving the accommodation over the ship’s life-cycle at a low computational cost. Implementation of the methodology was exhibited with two case studies, one for a cargo and one for a passenger ship.

The work undertaken and the derived results clearly demonstrate the applicability of BES to ships and the extent to which it can be simplified during the design process, thus introducing the concept of Dynamic Energy Modelling as a platform in shipping to support life-cycle energy management. This constitutes a significant development in shipping.

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1 INTRODUCTION

Without international shipping half the world would starve and the other half would freeze.
-Efthimios Mitropoulos, IMO Secretary General, 2005

1.1 Preamble

Fuel efficiency has never been the key objective within the shipping community due to the relatively low price of fuel oil and the absence of strict environmental regulations. However, the newly adopted mandatory measures to reduce greenhouse gas emissions introduced by the IMO [1] along with the continuous fluctuations in the price of fuel oil [2], have forced ship owners, operators and shipbuilders to explore new possibilities to reduce fuel consumption. It is clear that the room for improvement is vast if one considers the complexity of ships, the variety of the onboard energy systems and the limited effort that has been expended to optimise them.

Contrary to shipping, the building industry has been focusing on improving the efficiency of building energy systems by taking advantage of available numerical techniques and computational power since the 70's. The field of Building Energy Simulation is mature and well established, and is widely used during building design and operation.

This disparity in energy consideration between the building and shipping industries offers opportunities for technology transfer and hence innovation to improve the energy efficiency onboard ships. To this end, the research undertaken in this thesis focuses on improving the energy efficiency of ships by modelling thermal energy flows onboard and utilising knowledge from the building industry in the field of energy simulation.

1.2 Need for energy efficiency in the shipping sector

Today 80% of world's intercontinental trade is transported by ships. Although ships are the most efficient means of trade as shown in Figure 1-1, conventional marine engines operate on extremely low quality cheap fuel, known as bunker or heavy fuel oil, which is the residue from the production of higher grade fuels.

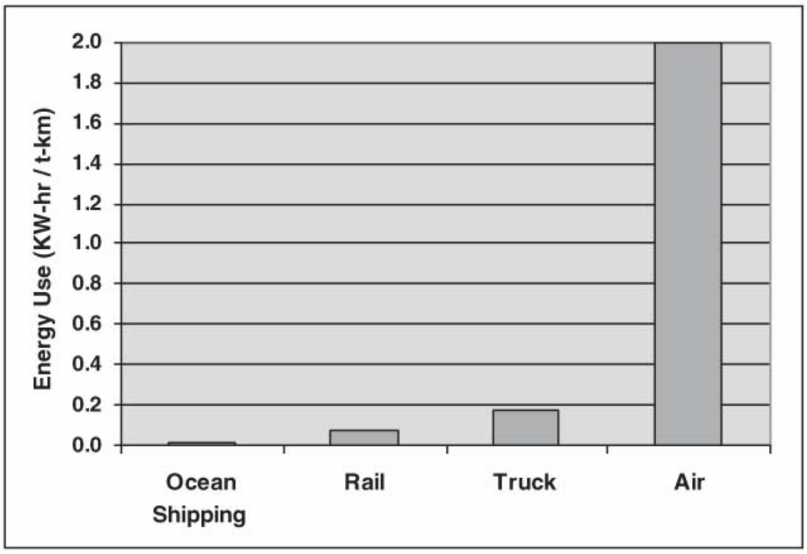


Fig 1-1. "Comparison of energy use between different means of trade"

Bunker oil is the worst grade available and despite the fact that it contains large concentrations of toxic compounds banned from other industries [3], bunker oil complies with marine ISO regulations and is widely used in ships. For every tonne of fuel burnt in a marine diesel engine, 3.19 tonnes of CO_2 are produced from the combustion process along with other sulphur and nitrogen oxides, gases that endanger biological diversity, natural resources, human health and contribute significantly to the greenhouse effect.

According to the third greenhouse gas study published by the IMO in 2014, shipping was estimated to have emitted 949 million tonnes or about 2.7% of the global man-made emissions of CO_2 in 2012 [4]. Yearly statistics for shipping related GHG emissions are shown in Figure 1-2.

Year	Global CO_2[1]	Total shipping	% of global	International shipping	% of global
2007	31,409	1,100	3.5%	885	2.8%
2008	32,204	1,135	3.5%	921	2.9%
2009	32,047	978	3.1%	855	2.7%
2010	33,612	915	2.7%	771	2.3%
2011	34,723	1,022	2.9%	850	2.4%
2012	35,640	949	2.7%	796	2.2%
Average	**33,273**	**1,016**	**3.1%**	**846**	**2.6%**

Fig 1-2. "Estimated CO_2 emissions from shipping from 2007 to 2012", [4]

Apart from CO_2, pollutants produced by shipping include sulphur oxides, nitrogen oxides and particulates. Ships are responsible for 10%-15% of NO_x and 4%-9% of SO_x total anthropogenic emissions [5]. A fraction of those are released far from land but an estimated 70% to 80% is released within 400 km from the shore [3] mostly by coastwise shipping (Figure 1-3). These air pollutants have been proven to cause lung cancer, asthma, cardiovascular diseases, other respiratory diseases and premature mortality to residents of local communities. Shipping-related particulate matter emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths annually, with most deaths occurring near coastlines in Europe, East Asia, and South Asia [6]. It is clear that shipping operations have a direct effect on both human health and the environment.

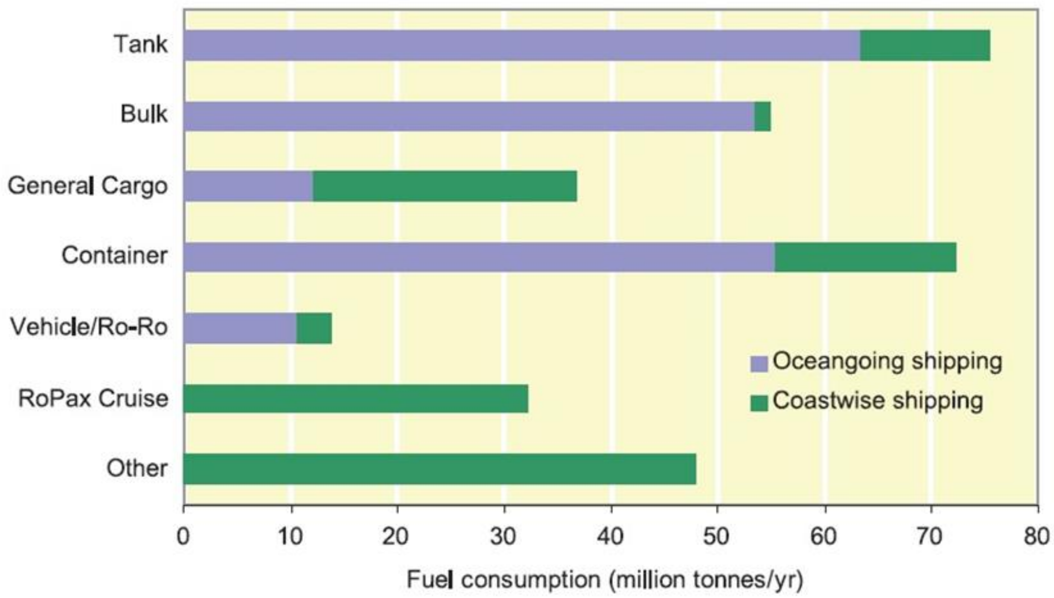


Fig 1-3. "Fuel consumption by vessel types and area of operation", [1]

More than four years after the economic and financial crisis of 2008, the world fleet continued to expand during 2012, reaching more than 1.63 billion deadweight tons in January 2013, an increase of over 50% in ten years [7]. Although a decrease in new orders was reported in 2011, the world fleet continued to grow and as of January 2013 it reached 1.63 billion dwt whilst the current schedule for ordered ships indicates a little less orders for 2014 [7]. To add to the problem the Earth's population is expected to increase in the following years (8 billion by 2030) [8] and citizens of developing countries will most likely seek improved quality of living, which will lead to even higher demand for trade. As shown in Figure 1-4, even with a high uptake of recently introduced environmental measures, shipping related emissions are still expected to increase [8]. All the above are indications that future GHG emissions studies are likely to show even higher levels of air pollution from ships and is a justification why energy efficiency is currently the focal point within the shipping industry and is most likely to remain the primary objective for at least the next two to three decades.

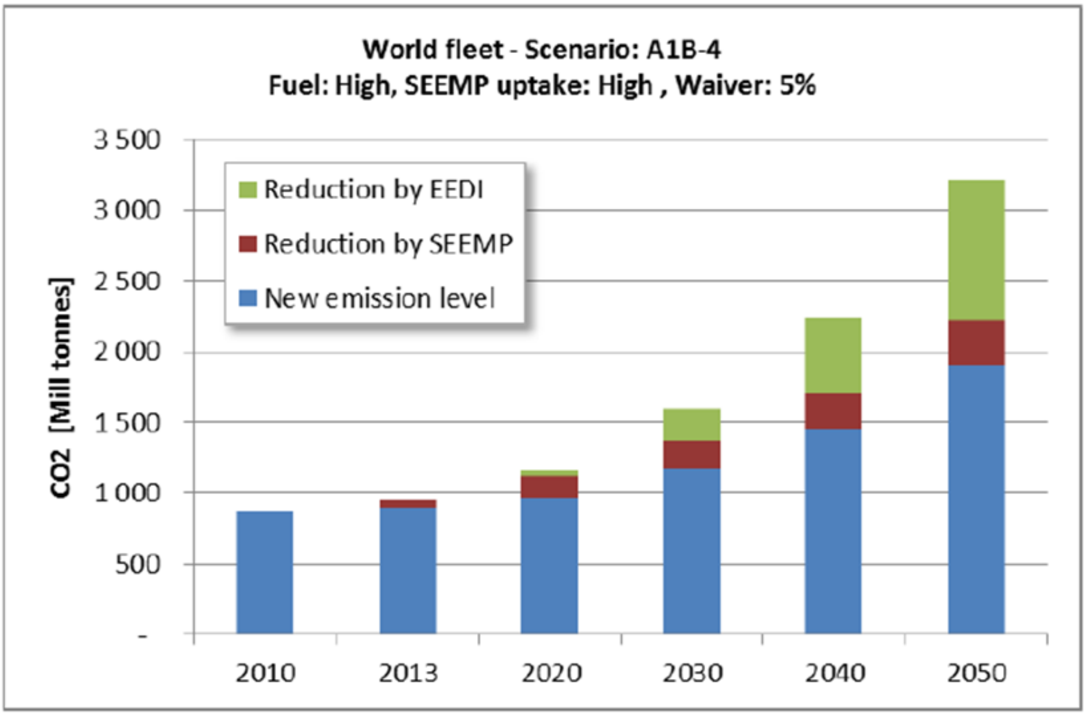


Fig 1-4. "Projection of CO_2 emissions for a high growth scenario with high uptake of EEDI and SEEMP", [8]

1.3 Energy efficiency considerations

Progress to reduce the total environmental impact of maritime transport in the last few decades has been neutralised by the tremendous growth of seaborne trade. In an attempt to reduce air pollution and improve energy efficiency, the Marine Environmental Protection Committee at IMO introduced mandatory efficiency measures, which entered into force January 1st 2013 [1]. The measures were expressed through the amended Marine Pollution Convention Annex VI, which introduced new concepts pertaining to the "Energy Efficiency Design Index" and the "Ship Energy Efficiency Management Plan". Both measures apply only to cargo ships with conventional large 2-stroke and 4-stroke diesel engines. EEDI was the first attempt to quantify the CO_2 efficiency of new ships with the use of a simple formula. The efficiency of the most dominant power consumers on board along with the transportation work are fed to the EEDI formula to give a rating indicative of the ship's environmental efficiency. SEEMP is an operational measure that establishes a mechanism to improve energy efficiency and is mandatory for all cargo ships both new and old. The IMO is currently considering extending the applicability of EEDI and SEEMP to other ship types [9].

The introduction of the aforementioned environmental measures forced the shipping community to reduce GHG emissions. The most prominent ways to achieve this are:

- use of alternative 'greener' fuels,
- integration of renewable energy sources on board ships,
- reduction of the power demand and,
- recovery of wasted heat.

Recent developments in alternative energy sources research, have introduced innovative technologies that can be considered in the shipping sector in order to substitute fuel oil as the main energy source. Those technologies include gas-fuelled [10], bio-fuelled [11], hybrid battery electric, and LNG-fuelled ships [12], nuclear reactors [13] and fuel cells [14]. Concerning renewable energy sources, there have been efforts to assess the feasibility and applicability of harvesting wind energy (Flettner Rotors - Figure 1-5 (a), Fixed Profile Sails - Figure 1-5 (b), Indo Sail Rig and kites) and solar energy (photovoltaic arrays - Figure 1-5 (a)) on board ships [15]. The installation of alternative fuel and renewable technologies is still in an experimental stage and has only been applied in very few cases. It is certain that new technologies will require rules and standards to facilitate their introduction and operation, whereas their economic feasibility is yet to be verified. Consequently, fuel oil is likely to remain the dominant energy source for commercial ships for at least the next 50 years. For this reason the industry is currently focusing on energy efficiency considerations for fuel oil powered vessels.

(a) (b) (c)

Fig 1-5. "(a) Solar panels, (b) wind sails and (c) Flettner Rotors"

Reduction of the power demand in ships can be achieved using a number of operational and technical measures. Some of the most protuberant operational scenarios that have been addressed are weather routing, passage planning, power distribution management, speed management, hull, propeller and rudder management, and trim and ballasting optimisation while technical measures include improvements in the ship hull form, appendages, hull coating, optimisation of the propeller design, electric propulsion and waste heat recovery. An extensive guide of operational and technical measures available today has been published by FATHOM [16].

Conventionally, the effectiveness of those measures has been assessed with small scale experiments and on board monitoring. These methods have been widely applied and are well established. However, the costs involved on new technology installation, on board monitoring and lab experiments have triggered the exploration of innovative and more economic assessment techniques such as computer simulation.

Apart from the hydrodynamics modelling by using of the traditional methods or the more detailed approach of Computational Fluid Dynamics, simulation has also been used to address the performance of onboard mechanical, electrical and hydraulic energy systems. The first attempt to simulate a marine heat and power generation plant was that of Ito and Akagi [17] in 1986. Since then some effort has been spent in the simulation of individual energy systems [18,19]. However, until very recently there have not been any noticeable coordinated attempts to simulate the energy performance of on board systems in a holistic manner. The need for global energy simulation stems from the fact that simulation at a component level ignores the interactions between different energy systems. Therefore, no conclusion can be drawn concerning the total power consumption of the vessel. In an attempt to apply and advance the available knowledge in computer simulation and systems modelling, EU has funded a number of projects (TARGETS, REFRESH, JOULES and RETROFIT), focusing on improving the global energy efficiency of ships by simulating all on board energy systems and their interactions. Holistic energy simulation of ships as visualised in Figure 1-6 is still at infant stage in the shipping sector but contemporary developments are very promising for the future.

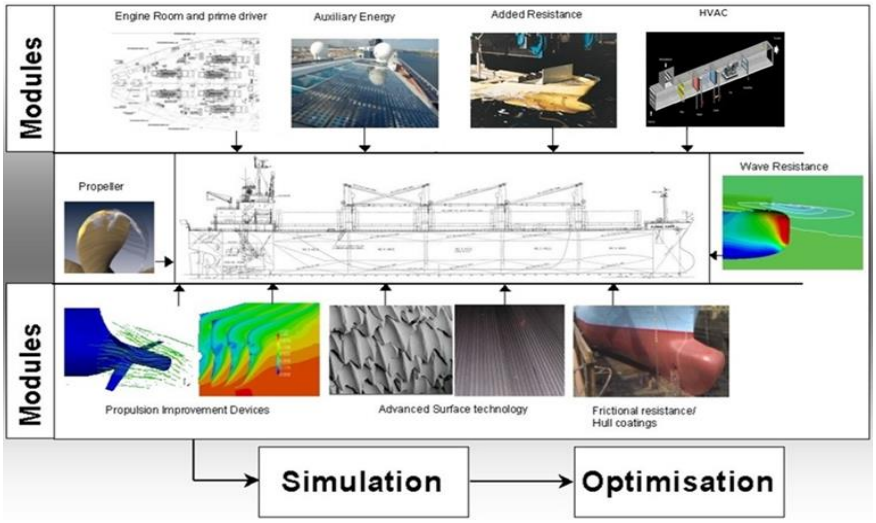


Fig 1-6. "Holistic approach to ship energy systems simulation"

1.4 Current design methodology of on board energy systems

Ship design is a non-trivial task since it encompasses a wide range of engineering disciplines. The final design highly depends on the ship type and its area of operation. The designer has to make sure to account for a range of disciplines including functionality, safety, efficiency and economy, producibility, maintainability, environmental safety and disposability [20], being addressed by a number of contrasting objectives. Notwithstanding this the majority of the ship designs produced today follow the much popularised 'design spiral' methodology.

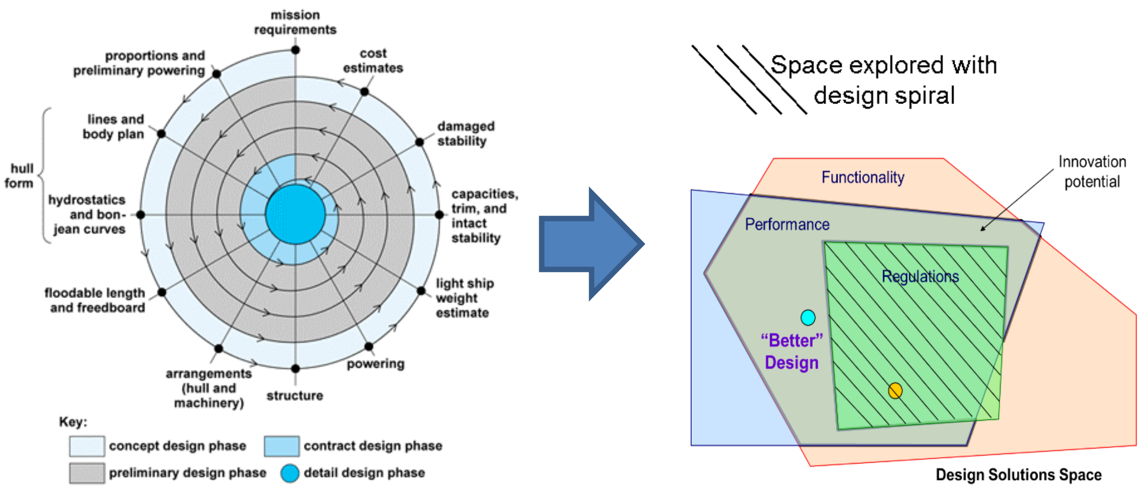


Fig 1-7. "Limitations of design spiral"

'Design spiral' is straightforward and easy to implement and is characterised by a step-wise iterative approach where decisions on the design production are taken in a series of predetermined steps. However, this step-wise approach does not allow for the simultaneous exploration of the design space as shown in Figure 1-7, since a decision in one step acts as a constraint for the next step and will most probably limit the number of feasible designs. This raises the need to adopt a different mind-set targeting holistic simultaneous design methodologies. No attempt is made in this work to establish a new holistic methodology for ship design, but rather demonstrate the applicability of dynamic energy simulation of multiple energy systems during ship design and propose design methodologies of smaller systems, based on dynamic energy modelling.

Given infinite time and resources, a ship designer would ideally explore all different design alternatives based on first principles. However, time and financial restrictions imposed by a very demanding shipping industry, have forced designers to rely on rules and regulations placed by IMO and by independent classification societies. A quick look at the current design methodology of energy systems in ships reveals how design regulations have remained intact over the past decades and only limited effort has been used towards improving the ship system energy efficiency.

The majority of on board energy systems are selected and designed based on rules of thumb and past experience, in order to safeguard against worst case operational conditions and/or scenarios, which are rarely or never met during the ship's lifetime. As a result the involved components mostly operate at off-design conditions away from their optimum efficiency point, and therefore consume an excessive amount of power. The design of marine energy systems today is characterised by:

- extreme design conditions,
- lack of transience in the calculations,
- disregard for important energy flows,
- neglect of interactions between energy systems and,
- simplified representation of energy paths.

The design of the heating ventilation and air conditioning system on board ships is a good reference of an inefficient design. It is selected here for further attention since it can be readily compared to land based HVAC systems and will be often addressed throughout this work.

While in cargo ships the HVAC system accounts roughly for 2%-3% of the total power consumption, in passenger vessels, HVAC may account for up to 40%. Estimating the heat gain and loss of accommodation spaces is the core process in the design of an HVAC system. A good indication of the power demand early in the design stage allows for educated sizing and selection of components. At the moment the design of marine HVAC systems is based on rather antiquated regulations [21] and follows a very simplified methodology [22].

Elaborating on the currently used design methodology, the system is designed in order to safeguard against extreme ambient conditions, which might never be met (35^{o}C and 70% humidity in summer and -20^{o}C in winter). Thermal calculations are based on constant coefficients derived from past experience that do not account for the involved fundamental heat transfer parameters (wind speed, wind direction, etc.). The actual heat transfer processes are omitted with the radiation exchange between surfaces and the external environment being the most indicative. Finally, many simplifications in energy calculations are employed such as heat gains from occupants and lighting that are vaguely taken into consideration in spite of their effect in the heat balance. Since the design of most systems on board is based on similar methodologies [22] the potential for improvement of the energy efficiency of ships is considerable.

1.5 Aim and objectives

The aim of this thesis is to improve the energy efficiency of ships through the dynamic modelling of the thermal processes on board and their interactions, drawing initially from the developments of the established field of "Building Energy Simulation".

To achieve this aim the following objectives should be completed:

- To review the state of the art in Building Energy Simulation.
- To identify the differences between ships and buildings and their effect on energy simulation.
- To examine the compatibility of the geometrical, topological and thermal modelling methodology of BES in ships.
- To propose and develop a modular approach for ship accommodation spaces complete with all pertinent spaces found in ships and use this to simulate the performance of ships in purposely selected case studies.
- To draw conclusions based on the derived results and offer recommendations for future research in the area.

1.6 Structure of the thesis

Chapter 1 (**Introduction)** presents recent developments in the shipping sector in the fields of energy efficiency and environmental impact. The problem of energy efficiency is explained and the past and ongoing developments to address this are listed. The disadvantages of current design methodologies are detailed, giving rise to the need to turn towards computer simulation and performance-based design methodologies, on the basis of which the aim and objectives of this work are laid out.

Chapter 2 (Building Energy Simulation) gives a brief introduction on the building industry, demonstrating how computer-based energy simulation has been used since the 1970's to improve energy efficiency. The energy flows in buildings are described and the building performance simulation tool ESP-r is presented.

Chapter 3 (Ships and Buildings: Differences and effect on Energy Simulation) establishes functional, operational and constructional differences between buildings and ships and elaborates on their effect on energy simulation.

Chapter 4 (Building a ship accommodation energy model) presents the 'marinisation' of the ESP-r software by addressing the main differences between ships and buildings in an energy modelling framework, and renders ESP-r capable to simulate the energy interactions in ship accommodation.

Chapter 5 (Topological decoupling of accommodation spaces) investigates the validity of assuming boundary conditions of conditioned spaces for the most commonly met space connections, in an attempt to simplify thermal modelling.

Chapter 6 (Space grouping during design) examines the possibility to reduce the space discretisation of thermal modelling during design, by merging adjacent thermal zones of selected space configurations in consecutive steps and defining the loss of accuracy at each step.

Chapter 7 (Conceptual design) proposes a design methodology for the accommodation of commercial vessels based on the findings of this work, and demonstrates its application in two case studies.

Chapter 8 (Discussion and recommendations) summarises the contributions of this work and discusses recommendations for future work in the field of ship design with the use of thermal energy modelling.

Chapter 9 (Conclusions) which concludes this work, provides an overview of the need for energy efficiency in the shipping sector and lists the original contributions of this work that address this problem.

1.7 Closure

In this introductory chapter the need for energy efficiency in the shipping sector has been discussed and the up to date developments towards energy efficient shipping have been listed. The current design methodology of on board energy systems has been critically reviewed and the need for life cycle energy management of vessels based on computer modelling has been established. Finally the aim and objectives of this work have been discussed and the structure of the thesis has been laid out.

2 BUILDING ENERGY SIMULATION

It is a strange paradox that we live in an information age and yet information is never in the hands of those who need it to make informed decisions.

-Joe Clarke, Professor of Energy Systems, 2001

2.1 Preamble

Unlike shipping, energy simulation is a mature field in the buildings sector. This chapter gives a brief overview of the buildings industry and presents the history of building energy simulation from the 1950's until today. The main energy flow paths that characterise building physics are discussed, and the capabilities of the building performance simulation tool 'ESP-r' that will be used in later chapters are explained.

2.2 The buildings industry

The buildings sector is comprised by places where people work, reside, and buy goods and services and excludes industrial facilities used for producing, processing, or assembling goods [23]. The primary use for buildings is to protect occupants from the elements and provide comfortable living and working conditions. Indoor comfort is divided in thermal comfort and indoor air quality. Thermal comfort (Figure 2-1) is a function of air temperature, air speed, relative humidity, mean radiant temperature, clothing insulation and metabolic rate [24] while IAQ can be affected by particulates, microbial contaminants and gases [25].

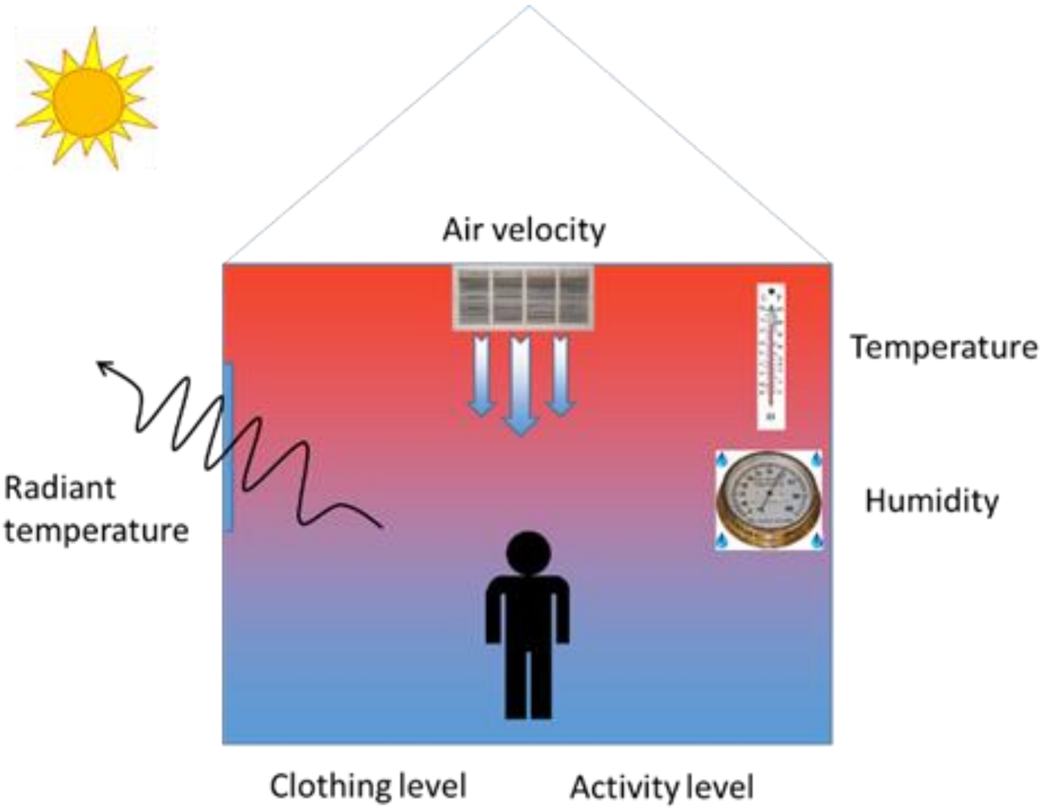


Fig 2-1. "Factors affecting thermal comfort in buildings"

To achieve indoor comfort one might think that a simple box and a boiler or an air conditioning unit would suffice. Unfortunately, the physics involved around buildings make the provision of thermal comfort a challenging and complicated problem. For example, designers had always thought that a very tight building envelope would minimise infiltration from the ambient environment, therefore reduce the power demand for heating and cooling. It came as a surprise when instead of solving a problem a bigger one was created, namely, Sick Building Syndrome: due to lack of fresh air occupants were trapped in a stew of mould, fungi, toxic gases and dust.

Worldwide, 30-40% of all primary energy is used in buildings [26] while increasing demand for housing and office space in developing countries will further push up energy consumption from the buildings sector. According to the Intergovernmental Panel on Climate Change (IPCC), building-related CO_2 emissions could increase from 8.6 billion tonnes in 2004 to 11.4 billion tonnes in 2030 under a low-growth scenario and to 15.6 billion under a high-growth scenario [27]. In both cases, the building sector's 30% share of total CO_2 emissions is expected to remain.

After the Kyoto protocol came into force in 2005, countries committed to reduce GHG emissions started pushing harder towards energy efficiency in the buildings sector. Since about 80%-90% of the energy consumption in the buildings sector is apportioned to the usage of buildings (heating, cooling, ventilation, lighting, appliances, etc.), measures to reduce buildings carbon footprint have refrained from all other stages (materials manufacturing, construction and demolition). According to the "Buildings and Climate Change: Summary for decision makers" UNEP report [28] the five major policy objectives for reducing GHG emissions from buildings are:

- increase energy efficiency of new and existing buildings,
- increase the energy efficiency of appliances,
- encourage energy and distribution companies to support emission reductions in the Buildings Sector,
- change attitudes and behaviour and,
- substitute fossil fuels with renewable energies.

Today energy efficiency is taken under consideration during the design of new buildings, whilst energy rating of new and old buildings is common practice in most countries. In tandem with the rise of software engineering during the second half of the 19^{th} century, computer simulation of the energy performance of buildings has been under development since the seventies by governmental organisations, academia and the industry.

All of the above are indications that unlike ships, the buildings sector has been addressing environmental pollution issues in depth and has been focusing on energy efficiency for several decades. The informational and technological gap between the buildings and shipping industries in the energy sector could not go unnoticed, thus it is only rational to expect improved energy efficiency from the application of knowledge from the buildings to the shipping industry, particularly as shipping is responsible for roughly 4% of the world's GHG emissions and like buildings it is a global industry.

2.3 History of building energy simulation

Simulation is a very powerful 'tool' as it allows the prediction of an outcome based on past observations. It is widely used in engineering, finance, biology, and several other fields. With the advance in computing power and numerical techniques over the years, the energy performance of buildings can now be simulated on personal computers, thus deriving results in reasonable amounts of execution time, ranging from a few minutes to a few hours depending on the building size, and spatial and temporal discretisation. In the building sector simulation can be used to predict the energy, environmental and comfort performance of different design alternatives allowing for more educated decisions concerning construction, equipment and control strategies. Due to the complexity of buildings and the intricate physics involved around them, building energy modelling is not an easy task and should not be treated lightly. This is why building simulation has been evolving since the 1950's to reach its current mature form, as shown in Figure 2-2.

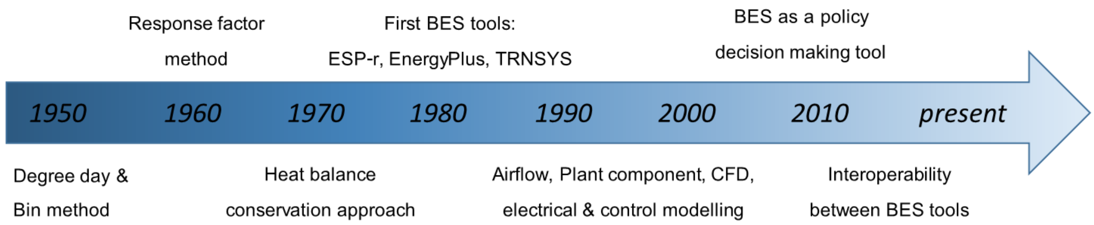


Fig 2-2. "History of building energy simulation"

1950's

During the '50s and '60s, slide rules and desktop calculators were the only tools available to perform engineering calculations. With the absence of computers, two computationally cheap methods were used to calculate buildings energy demand at the time, the degree day method [29] and the bin method [30]. Although state-of-the-art at the time, both methods oversimplified the design problem and neglected the transient nature of buildings physics. They were both used to provide an indication of the performance during design and by no means tried to simulate the occurring energy flows.

1960's

The earliest attempts to apply computer applications to the simulation of buildings behaviour date from the late 1960's [31]. At that time buildings simulation codes dealt with heat flow simulation using semi-numerical approaches such as the heat transfer factor and electric network approach both of which are now extinct.

A big breakthrough was the introduction of the response factor method by Stephenson and Mitalas in 1967 [32]. This method managed to overcome the problem of modelling the complex non-linear heat transfer system by decomposing it into a summation of responses of the component parts. The response factor method, which continues to be the basis of some modern simulation tools, is apt for the solution of systems of linear differential equations possessing time invariant parameters and can handle the dynamic interactions occurring within buildings. However, the invariability and linearity assumptions on which the method is based makes it suitable only for an early indication of performance trends and not for emulating reality.

1970's

A huge step in buildings simulation was made in the 1970's when the heat balance approach was introduced by Kusuda [33]. The method was based on an energy conservation approach that allowed for the formation and calculation of heat balances for discrete time steps. Although weighting factors were dropped a response factor was still used to calculate heat transmission through opaque surfaces.

Along with the evolution of computational power it was Clarke in 1977 [34] who established a simultaneous solution based on numerical discretisation. This approach extended the concept of the heat balance methodology to all relevant building and plant components. A finite volume or finite difference discretisation approach to the conservation of energy is employed to represent the opaque and transparent surfaces, internal air spaces and plant components. This approach does not demand linearity and allows material properties to vary with temperature and time. It also gives the flexibility of allowing a user specified time step.

1980's

Besides response factor and numerical techniques, other approaches were investigated based on regression analysis [35], stochastic modelling [36] and neural networks [37]. With the intention to expand the use of BES beyond their developing teams, considerable effort was expended to validate the existing buildings simulation codes and reform them into versatile and user-friendly tools. Maintenance, ability to be updated and addition of desired features were some of the attributes that made some BES tools stand out from a pool of available buildings energy simulation software. With the industry and more specifically software vendors showing little interest in the buildings simulation area, the developer community started to combine forces in order to stop duplication of efforts. That led to a variety of available tools dominated by the large simulation codes that were generated with research funding, such as DOE-2, ESP-r and TRNSYS.

1990's – 2000's

As new simulation domains came along, these tools tried to expand into these domains and go beyond their traditional energy origin. Firstly, simulation of airflow and plant component simulation was introduced [38] followed by CFD [39] (Figure 2-3), electrical systems [40] and control systems [41]. Today a large number of simulation tools are available [42] based on similar principles but with notable differences [43].

2010's - Present

The buildings energy simulation community is currently focusing on introducing simulation in the early design stages, use BES to support policy decision making [44] and expand the interoperability between different simulation tools [45].

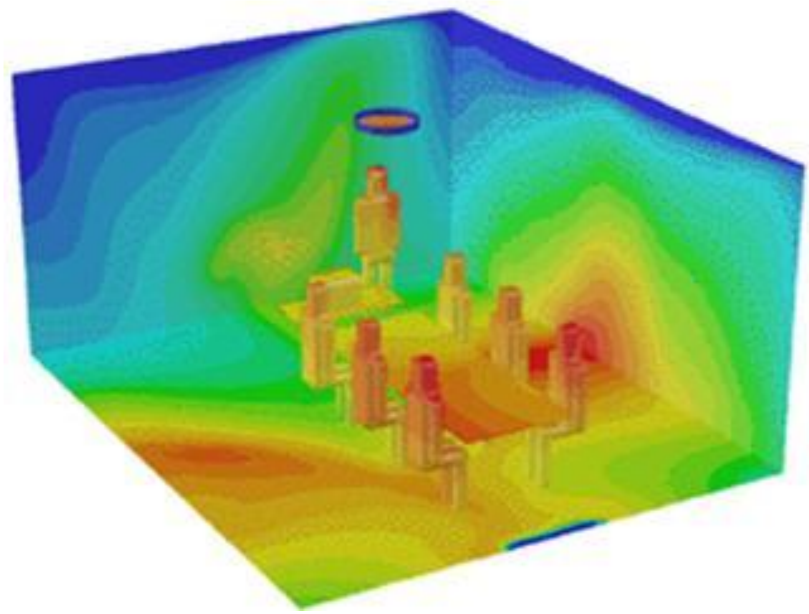


Fig 2-3. "Thermal modelling of an office space with the use of CFD."

2.4 Energy flow paths in buildings

Heat and mass transfer are the two disciplines that govern energy flows in buildings. To understand buildings modelling it is essential to study the underlying mechanisms describing the energy interactions between the ambient environment, the building and the occupants.

2.4.1 Conduction

From a purely theoretical point of view conduction is the transfer of energy from more energetic to less energetic particles due to interactions between the two and appears only in solids. In buildings conduction is encountered inside the buildings fabric (walls, floors, ceilings, doors and windows) and is the process of heat transfer from one side of the structural element to the other due to a temperature gradient. Since materials have thermal inertia, some heat is stored in the buildings fabric, therefore heat flux is reduced when it reaches the other end of the wall. The magnitude of heat transfer and storage highly depends on the thermo-physical properties of the construction materials:

- conductivity k (W/m/K)
- density ρ (kg/m^3) and
- specific heat capacity C_p (J/kg/K)

Conduction is characterised by Fourier's law, which states that the heat transfer rate is proportional to the temperature gradient in the direction of heat flow:

$$q_x = -kA\frac{dT}{dx} \tag{1}$$

The minus sign represents heat transfer towards the direction of decreasing temperature.

In building energy modelling, conduction is of primary importance since it describes the connection between the indoor and the ambient environment. Conventionally and more specifically in steady state calculations, heat storage inside the walls is neglected and heat transfer through walls is characterised by a value indicative of the overall thermal transmittance (overall HTC) of the wall, namely the U-value (W/m^2/K). In more advanced modelling techniques the dynamic behaviour is accounted for and group representations are replaced by dynamic modelling of heat transfer and storage. Mathematically, this is represented by the heat equation which is derived by Fourier's law (1) and the conservation of energy:

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{a}\frac{\partial T(x,t)}{\partial t} - \frac{q}{k} \quad (2)$$

2.4.2 Convection

Convection is a heat transfer mode that is characterised by the collective movement of fluids and can be subdivided into two mechanisms: diffusion and advection. Diffusion is mostly concerned with the heat transfer between a solid and fluid due to their relative movement and temperature difference, while advection is the heat transfer due to a fluid's bulk motion. Both mechanisms have been widely studied [38,46] and their role in buildings simulation is of major importance [47].

Convective diffusion is met in buildings mostly in the form of surface convection. It is the heat exchange between the walls and the adjacent layer of air and can be either buoyancy (natural) or airflow (forced) driven. Newton was the first to give a mathematical equation describing the convection mechanism, 'Newton's law of cooling':

$$q = hAdT \quad (3)$$

The HTC depends on the physical properties of the fluid and the physical situation in which convection occurs. In buildings HTC is highly dependent on air movement, temperature difference and surface area, and is not constant. Extensive studies have been conducted for the correct calculation of HTC and several algorithms have been developed [48,49]. No single algorithm has been found to outmatch all the others, thus different calculation methods are used depending on the physical circumstances [46].

Advection on the other hand occurs due to infiltration from outside through cracks and openings or from adjacent spaces through doors and from mechanical ventilation. Air entering the room is mixed with the air inside to change the indoor conditions and even small quantities of air can affect the thermal balance greatly. Also excessive airflow might create indoor drafts which decrease occupant comfort. The effect in the energy balance is given by:

$$q = \dot{m} C_p dT \tag{4}$$

In BES, indoor airflow is primarily modelled with the nodal network method and computational fluid dynamics. Both methods will be elaborated later in this chapter.

2.4.3 Thermal Radiation

Every object with a temperature greater than absolute zero emits thermal radiation. This is caused due to subatomic movement in matter in solids and liquids. In buildings, thermal radiation is divided in two major types: longwave and shortwave with the former being related to long wave lengths (low energy) and the latter to short wave lengths (high energy). The radiation emitted from a surface is given by the equation:

$$q = \varepsilon A \sigma T_s^4 \tag{5}$$

Longwave radiation is encountered in buildings in two major forms: internal surface and external surface. Internal surface longwave radiation is the exchange of radiation between internal surfaces and is dictated by the emissivity of surfaces, the proportion of radiation transfer between pairs of surfaces (view factor), nature of reflection (diffuse, specular of mixed) and temperature of the surfaces.

External surface longwave radiation is concerned with the radiation exchange between the external side of the building fabric and the surrounding buildings, the ground and sky. Factors that govern external longwave radiation exchange are the sky cloud cover, ambient temperature, the building exposure (urban, rural, isolated etc.) and the ground reflectivity. The net longwave radiation exchange for an external surface is given by equation:

$$q = \varepsilon A_s \sigma (T_e^4 - T_s^4) \tag{6}$$

Shortwave radiation is the exchange of radiation between the building and the sun. Solar radiation can either impinge on an opaque surface or enter indoors through transparent surfaces. Once direct or diffuse radiation hits an opaque surface, it causes a rise in external surface temperature and a subsequent transfer of heat indoors through the mechanisms of conduction and convection. Solar radiation incident on transparent surfaces is partially reflected, absorbed and transmitted. Reflected radiation is lost to the environment, absorbed radiation causes a rise of temperature on the transparent material and transmitted radiation directly impinges on internal walls or occupants. The amount of solar radiation incident on the building depends on the position of the sun and the orientation of the building. For an accurate calculation of the effect of solar radiation, geometrical calculations have to be performed to account for potential shading from buildings, trees or other obstructions and to define the point of application of the radiation to the building. A representation of energy all possible energy flows in a thermal zone is shown in Figure 2-4.

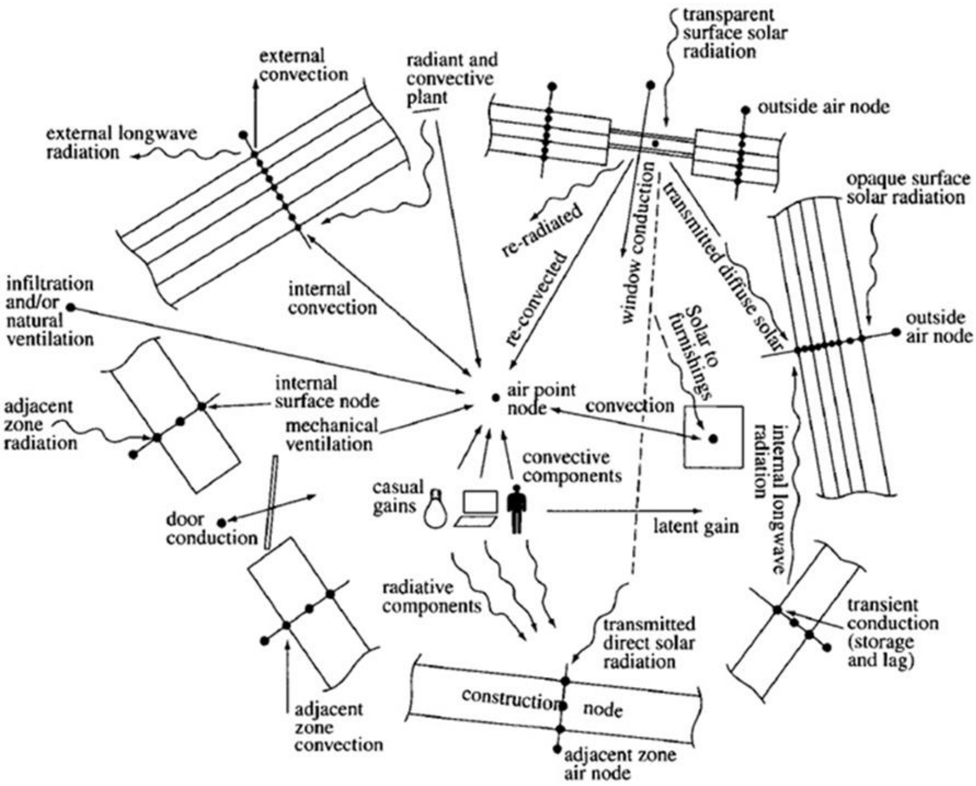


Fig 2-4. "Energy flow paths in buildings", [55]

2.4.4 Casual gains

Heat gains emitted by occupants, lights and equipment constitute casual gains in buildings. All casual gains are transmitted either by surface radiation exchange (radiative component) or by convection to the surrounding air (convective component).

The human body emits heat as dictated by its thermoregulatory system. The amount of heat emitted by humans highly depends on the level of exercise and can range from 70 W while sleeping to 1,000 W while working out. Heat gains from lighting depend on the type of light bulbs used. There are three main types of light bulbs: incandescent emitting from 40 W to 200 W, fluorescent 18 W – 30 W and LED 7 W – 18 W. Equipment includes a wide range of devices such as personal computers, monitors, printers and specific lab equipment. In spaces with a high presence of electronic devices such as offices and labs, heat generated by equipment greatly affects the ventilation requirements.

In building energy modelling, casual gains are included in the heat balance of indoor spaces as a heat source consisting of a radiative and convective component. The estimation of those two components is derived experimentally [50,51]. Information about the heat gains in spaces is crucial since it allows for the integration of heat gains at each time step of the simulation and also signals the presence of occupants and therefore need for indoor comfort. With this information available or estimated, the equipment sizing can be optimised and control techniques can reduce the power consumption for heating and cooling.

2.4.5 Moisture

Moisture is the presence of water in vapour or liquid form, in small amounts. In buildings, excessive moisture in the air might cause dampness and mould growth. Dampness is the unwanted moisture within the building fabric most often caused by indoor condensation, high levels of ambient humidity or rain while mould growth is the reproduction of moulds by spores on moist surfaces. These phenomena can cause structural damage to buildings (rotten wood, plaster and paint deterioration, wall stains etc.) and health problems to occupants (asthma, allergies etc.) mainly due to growth of microbes (moulds, fungi, bacteria) that emit spores, cells and fragments into the indoor air.

Moisture in buildings is dictated by the psychrometric state of air and the moisture flow within constructions. Like heat, moisture is transferred and stored. In buildings, the dominant transport mechanisms for moisture are water vapour diffusion, transport through capillary forces within the construction and airflow exchange between fluid volumes and the environment. Moisture storage can occur in solid, vaporous or liquid form. The intricacy of this physical phenomenon makes the calculation of the moisture content a very complicated task involving the heat and mass balance, airflow calculation and intra-construction modelling. Intra construction moisture flow has been studied in depth [52] and moisture modelling has been integrated in multi-domain simulation tools [53].

2.5 ESP-r: A building energy simulation tool

2.5.1 Overview

ESP-r (Environmental Systems Performance – research) [54] (Figure 2-5) is a dynamic energy modelling tool developed by the "Energy Systems Research Unit" (ESRU) of the University of Strathclyde. It is used to simulate the performance of buildings by modelling the actual physical systems in an in-depth manner. ESP-r was selected as the energy modelling tool in this work for the following reasons:

- it is an open source software, allowing for code addition and in depth understanding of the calculations,
- it is not based on fixed geometries, therefore geometries met in ships can be created from points in the 3D space,
- the variability of model parameters such as site orientation, geographical location, building exposure, material properties, climate

and thermal gains allows for the representation of the marine environment,

- it allows coupling and can be integrated with other software codes,
- all energy domains (thermal, airflow and plant) and their interactions are simultaneously addressed and,
- ESP-r has been extensively validated [55].

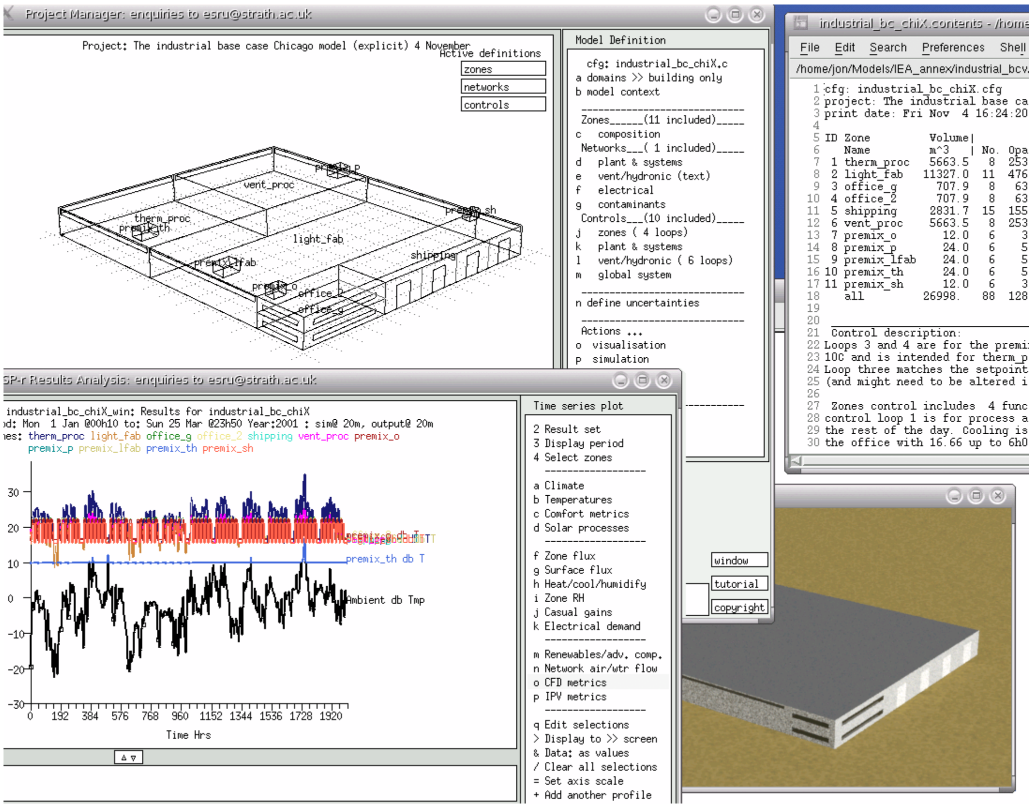


Fig 2-5. "ESP-r graphical user interface", [68]

ESP-r follows a finite volume conservation approach, in which a problem is transformed into a set of conservation equations for energy, mass and momentum. The equation set is then integrated at each time-step in response to the system's boundary conditions, occupant behaviour and control system influences. ESP-r can be used to assess the energy performance of systems during both early and detailed design stage, during retrofitting with selection of different configurations and during operation with varying operational scenarios in existing configurations. During its development ESP-r has always regarded buildings as:

- Dynamic, in the sense that the state variables (temperature, pressure, voltage, moisture concentration, etc.) associated with its parts (constructions, fluid volumes, interface surfaces, plant and control components, electrical networks, etc.) vary at different rates.
- Nonlinear in that parameters within the large number of conservation equations are not constant and depend on the present values of the state variables at each time step.
- Systemic, in that different interacting domains form a building (thermal, airflow, electrical etc.) and the unjustified exclusion of a domain will lead to wrong results.
- Uncertain in that parameters such as occupant behaviour, climate and monitored values vary stochastically.

At this point of development ESP-r has the capability to address heat, air, moisture, electrical loads, light and control signal flows. Of these, the thermal and air flow modelling methodologies are described below, which constitute the heart of building energy modelling, indeed of any environment. A detailed description of modelling of all domains can be found in Clarke (2001) [56].

2.5.2 Thermal modelling

Simulation of thermal flows is the crux of BES. The modelling methodology followed in ESP-r, requires the identification of typical control volumes (nodes) that interact with their adjacent volumes and the system boundaries. Each node is assigned an energy conservation equation, the elements of which depend on the type and the location of the node. With temperature being the unknown variable, a system of conservation equations is formed that is simultaneously solved at successive time steps.

In ESP-r there are three fundamental types of control volumes: solid, surface and fluid nodes. These types are used to model both the building and the plant side. A representation of all thermal node types is shown in Figure 2-6.

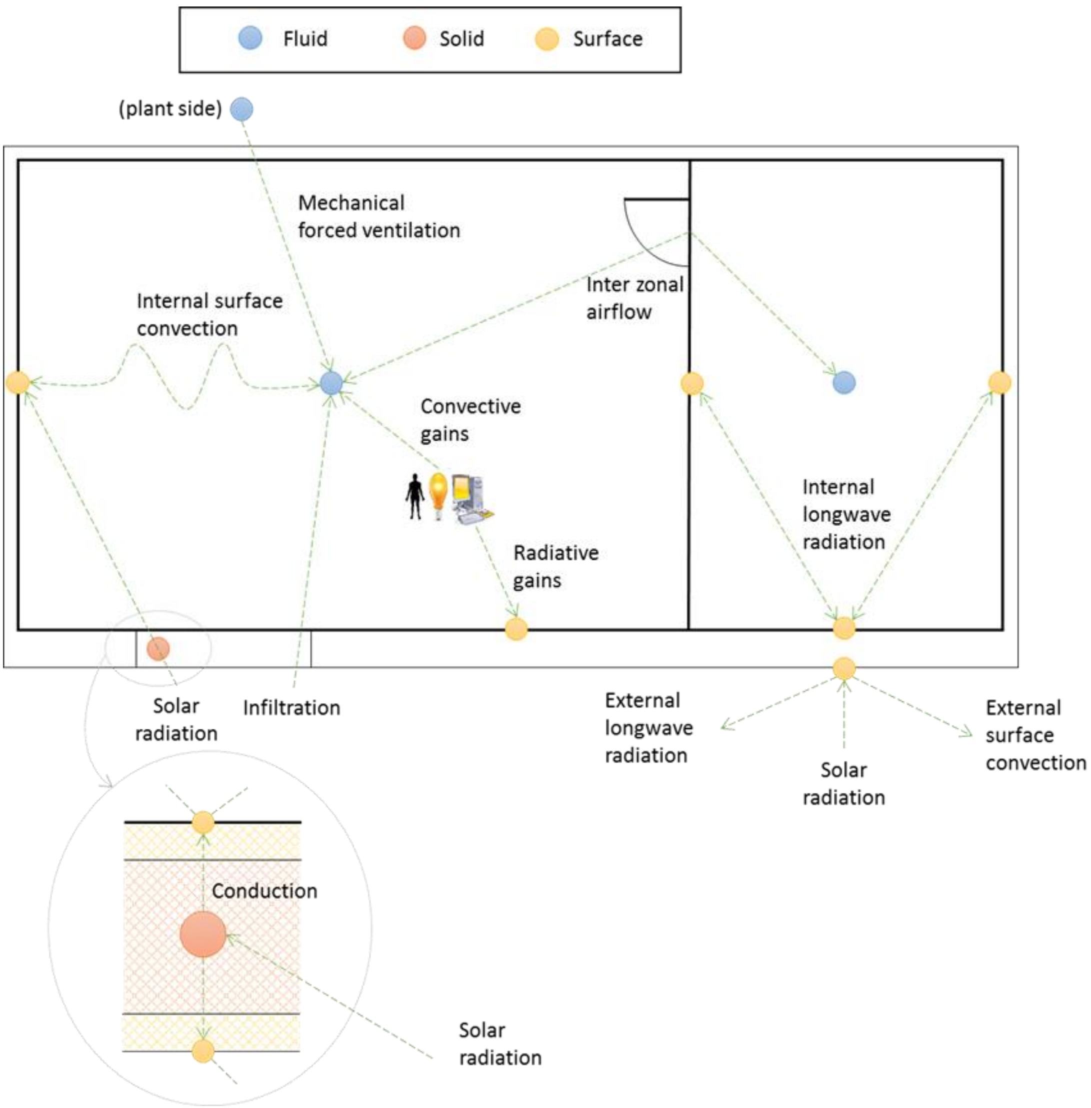


Fig 2-6. "Thermal interactions between different node types."

Solid

Solid nodes are control volumes representing a solid region in contact only with another solid region. Energy is exchanged with the adjacent nodes only by conduction and internal heat generation is allowed to represent heating mechanisms (e.g. underfloor heating) and the absorption of shortwave radiation travelling through transparent solid constructions such as windows. ESP-r treats heat transfer through solids one dimensionally.

Surface

Surface nodes represent solid regions that are in contact with solid and fluid control volumes or the system boundaries. They exchange energy with the adjacent solid node by conduction and with the fluid node and boundaries by convection and radiation. Each solid construction contains $2v+1$ nodes where v is the number of construction layers.

Fluid

Fluid nodes represent fluid regions that exchange energy by surface convection with the surrounding surface nodes and by advection with the ambient environment, adjacent zones and the plant. Like solid nodes, heat sources are allowed to represent casual heat gains.

Depending on its position and interactions, every node in the system is assigned a variation of the Fourier equation for transient heat conduction:

$$\frac{\partial \theta}{\partial t} = \alpha \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} \right) + \frac{q}{\rho C_p} \qquad (7)$$

where, convective and radiative heat transfer are introduced through the heat generation term q as described in 2.3 (equations (3), (4) and (5)). These partial differential equations are brought to an algebraic form by applying a mixed implicit and explicit second order finite difference scheme. This results in the creation of an equation set or two sets if the plant-side is modelled, where the future temperatures at nodes are the unknown variables. This set is solved with a tailored solver comprised by a mix of direct solutions for specific equation sub-sets and an iterative solution between them.

2.5.3 Air flow modelling

ESP-r provides the choice of two modelling approaches for modelling the airflow domain, the nodal network method and computational fluid dynamics.

The nodal network method

This method is used to simulate infiltration, natural ventilation and mechanical ventilation. Fluid volumes are represented by nodes and their connections by components (openings, cracks, ducts etc.). Each component is essentially an equation that relates the pressures on its boundaries with the mass flow rate through the component. Conservation of mass is assigned to each node, which leads to a system of non-linear equations that are solved at each time step to give pressures and mass flow rates for the whole network. Wind induced pressures at the system boundaries along with mechanical ventilation are the driving forces for airflow in the system. Integration between thermal and airflow domains is succeeded with an extra term in the heat conservation equation of the fluid node, in the form of equation (4). A representation of all airflow node types is shown in Figure 2-7.

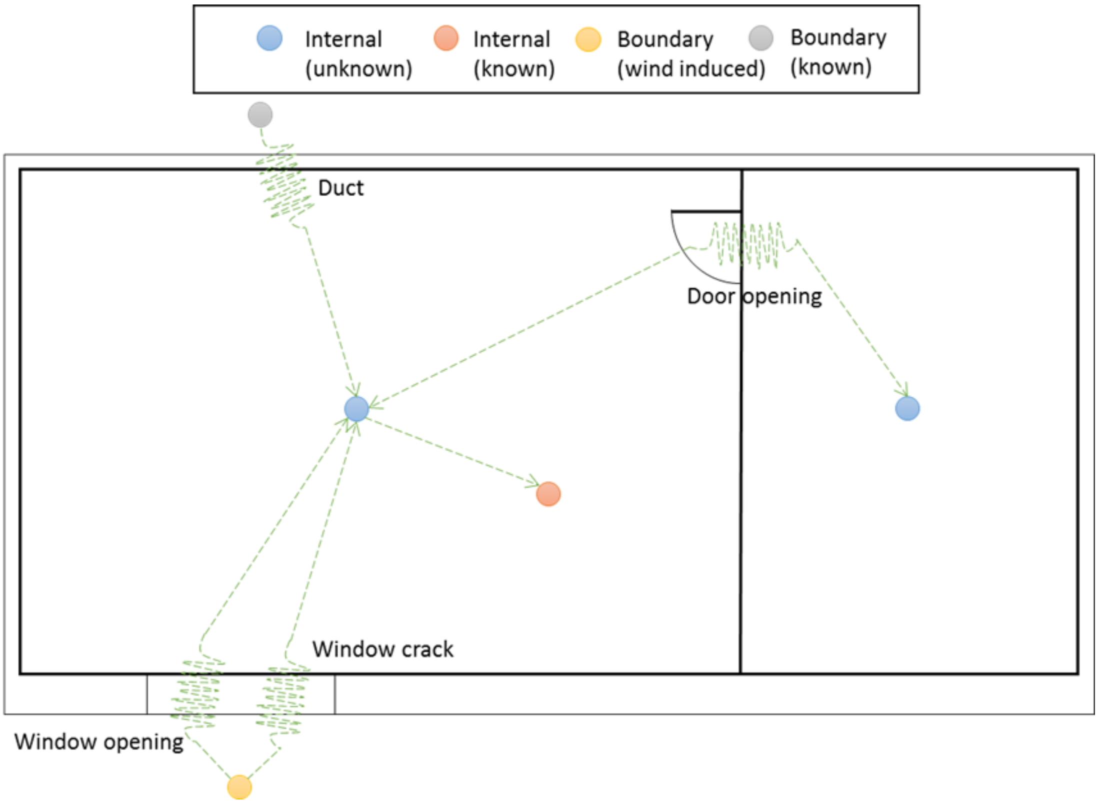


Fig 2-7. "Airflow interactions between nodes"

Computational Fluid Dynamics (CFD)

This method allows for detailed calculations of airflow by applying a finer spatial discretisation to fluid volumes and solving the conservation equations for mass, momentum and heat for each control volume. In ESP-r, CFD can be used in tandem with the nodal network method in cases where detailed calculations are required for specific rooms [57]. CFD is also used for comprehensive calculations of heat transfer coefficients for internal surfaces [46] and for the prediction of the contaminant concentration [58].

2.5.4 Simultaneous solution

ESP-r solution is based on an integrated simultaneous approach. Once modelling of all relevant domains is complete, initial values are assigned to state variables of the domains with a transient solution[1] (heat, moisture, CFD). The equation sets are then solved with domain tailored solvers in the order of domain independence: air, water and electrical flow – building/plant heat flow – moisture flow – and CFD. This order allows for the calculation of dependent source terms of domains later in the chain (e.g. for the calculation of the advective heat transfer term the mass flow rate must be known). Although ESP-r treats common domain variables "one time-step in arrears" by default, sometimes iteration between different domains can be invoked for a more detailed result. Since most source terms are highly non-linear, iterations within a domain might be required for their accurate calculation. To reduce computational effort, the user can differentiate time-steps between domains in order to achieve the desired temporal discretisation, for example control of the plant-side might require time-step in the order of minutes while a building side time-step of one hour might be sufficient for indoor temperature calculations. Figure 2-8 shows the algorithm of ESP-r's global simulator.

[1] To eliminate initialisation errors, ESP-r uses the concept of "start-up days" which is the simulation of the model prior to the beginning of results recording, to ensure a better estimate of the present value of state variables

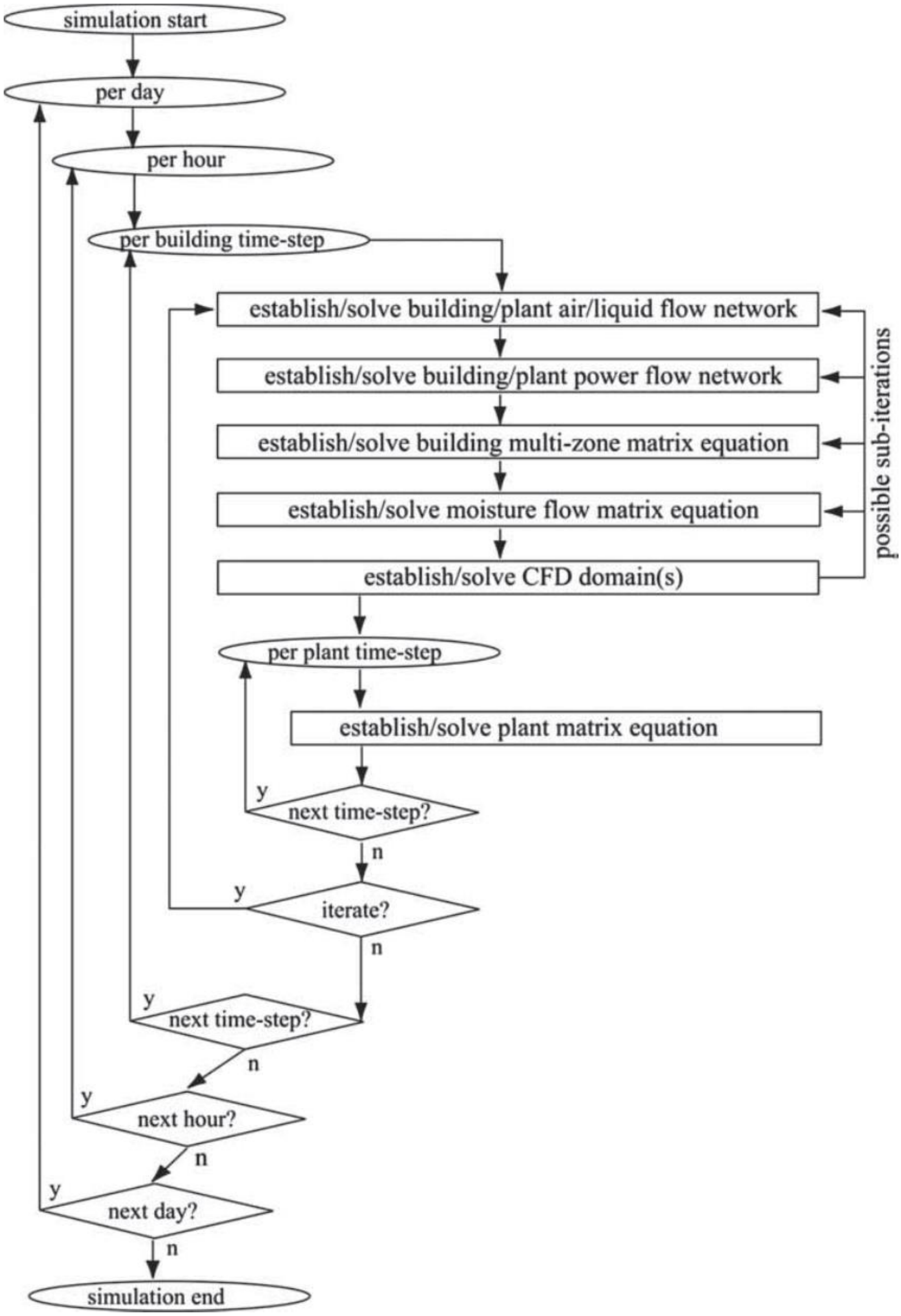


Fig 2-8. "ESP-r simulation flowchart"

2.6 Closure

In this chapter the current state and developments in the buildings industry have been presented, as well as the technological gap between the buildings and shipping sector. A historical background of building energy simulation has been given that showed the advanced stage of computer simulation in building design. The main energy flow paths that characterise building physics have been described and the ESP-r software has been presented and justified as the selected simulation tool in this work.

3 SHIPS AND BUILDINGS: DIFFERENCES AND EFFECT ON ENERGY SIMULATION

All things are the same except for the differences, and different except for the similarities.

-Thomas Sowell, Social Theorist, 1996

3.1 Preamble

While commercial ships are primarily built to transfer goods and passengers, buildings exist to provide occupant comfort and safety. Although very different at first sight, buildings and ships share some similarities in terms of functionality and operability. Those differences and similarities define the transferability of BES to ships.

3.2 Functionality

Ships are categorised based on their function. Cargo ships are built to transfer supplies and goods (food, oil, iron, electronic devices etc.) between countries and continents, Ro-Pax vessels are designed to transport vehicles, goods and passengers and cruise liners are luxury vessels, built to provide pleasure voyages. On the other hand, two main building categories exist: residential (where people live) and commercial (where people work) both of which focus on the provision of indoor comfort and safety.

The common ground between ships and buildings is found in the provision of indoor comfort and safety for their occupants. To carry out their mission, all ships require a crew on board. Crew accommodation can be regarded as a residential building that should cater for acceptable living conditions, potable water, food and safety. Ro-Pax vessels are very similar to hotels as they have to accommodate from several hundreds to thousands of people from hours, to days. Finally, cruise liners can be compared to resorts providing high quality comfort and safety, and a plethora of leisure and entertaining activities (pools, restaurants, cinemas, shops, etc.). These similarities hint that BES might be used to represent energy flows in shipping accommodation in a similar manner.

Although provision of comfort and safety in buildings are the most important functions, this is not always the case for all ships. For cargo vessels the need to deliver undamaged cargo in acceptable delivery times sometimes takes precedence over crew comfort. For example, in container ships and bulk carriers the cargo quality highly depends on the conditions inside the cargo spaces which in turn are affected by external weather, airflow, cargo respiration, time etc. These requirements widen the focus of energy modelling and introduce new objectives such as delivery time and cargo quality.

3.3 Equipment / diversity

Ships are autonomous artefacts and need to operate at sea for several days or weeks. This essential autonomy is what makes ships so unique since the required power for propulsion and auxiliaries has to be generated on board unlike buildings where power is supplied from a central power grid. This necessitates the installation of a wide range of components and systems on board that are not found in buildings.

Main Engine

Large ships are equipped with large diesel engines / turbines with a nominal power ranging from 10 to 40 MW depending on the ship type. The majority of cargo ships have one main engine used exclusively for propulsion, accompanied by smaller diesel generators for auxiliaries while passenger ships use only diesel generators to both propel the ship (electric propulsion) and power auxiliaries. Despite the configuration, all on board energy is supplied by burning fuel oil. From an energy modelling perspective this necessitates the simulation of the combustion process along with the interaction with all the coupled systems (propulsion, cooling, discharge, waste heat recovery, etc.). Several simulation tools exist that are combustion specific such as the zero dimensional "AVL-Boost" and the CFD based "AVL-Fire", "KIVA", "Converge" and "Star CD". However, the suitability of these tools for the development of a holistic modelling tool has not yet been addressed.

Fuel supply system

Since all the energy is produced on board, ships carry all the fuel they burn. Heavy fuel oil is stored in tanks, from where it is pumped, heated, purified and then supplied to the main engine. This process results in a fluid network comprised by tanks, heat exchangers, purifiers and pipes. BES provides the capability to model such networks with water or air, thus the flow and thermal properties of bunker oil need to be investigated before applying BES flow network methodology to represent the fuel oil supply system.

Cooling system

To avoid overheating of the main engine, a cooling system is installed to dissipate heat from the mechanical parts of the engine. The system is comprised by pumps and piping that circulate a cooling liquid (lubricating oil or fresh water) around internal passages within the engine. The cooling liquids are, in turn, cooled by sea water, which is heated and then discharged to the sea. The cooling system is very similar to fluid networks found in buildings (e.g. central heating) and has been addressed by BES along with the ensuing thermal interactions. However, the applicability of BES for marine cooling systems might be limited by the presence of sea water which has different thermal and flow properties than fresh water as well as by the large heat gains present in the network from the main engine.

Exhaust gas emissions

One of the by-products of the combustion process is gas emissions released to the atmosphere. Together with heat dissipation to sea, these two processes constitute the environmental impact of the ship. To date, approximate correlations derived from on board monitoring and statistical analyses exist that connect the amount of fuel burnt with the amount of gas emissions and the concentration of sulphur and carbon oxides. Simulation of the exhaust process would require very detailed chemical modelling of the combustion process followed by thermal along with contaminant simulation.

Waste heat recovery

Exhaust gas emissions contain large amount of heat after leaving the main engine. Some of this heat can be recovered and used around the ship with the use of a waste heat recovery system. The performance of WHR systems has been simulated [19], however like all systems on board it has been addressed in isolation and not as a part of a holistic ship model.

Heat transfer to surroundings from machinery

The heating of mechanical equipment results to radiative and convective heat transfer to the surroundings, which in turn leads to excessive temperatures and unbearable working conditions in engine rooms. Large fans are installed to remove excessive heat, the sizing of which is performed based on simple steady state calculations. Energy modelling of the heat gains of diesel engines and auxiliary equipment coupled with a CFD analysis of airflow and heat in the engine room would lead to more accurate calculations for the large fans that provide combustible air and air for removing excessive heat.

Propeller

All ships are equipped with propellers/thrusters to produce thrust and move the ship. Computer modelling has been widely used for propeller design mostly in the form of CFD. Along with the ship hull and the main engine, it constitutes the propulsion system of the ship. In order to address this system, different types of energy (mechanical, chemical and thermal) require simulation and integration. This hydrodynamic interaction between the sea and the vessel has to be accounted for during the design for the efficient sizing of the ship's main engines.

HVAC

All ships have an HVAC system installed on board. The size and type of the system highly depends on the ship type. Cargo ships have single duct systems with air recirculation, a direct expansion system for cooling, and steam or electric heating. Passenger vessels that might accommodate up to 8,500 people have single duct systems with local fan coil units for crew cabins and twin duct systems for staterooms, both of which are served by an indirect expansion cooling system with one or more central chillers. In both cases, the air supply temperature can be controlled at the cabins by the passengers, either by adjusting the added heat by the reheating coil or by defining the mixture ratio for twin duct systems.

Marine HVAC systems are very similar to their land-based counterparts but have to comply with the following structural and topological criteria imposed by ship characteristics and the marine environment:

- Space limitations for machinery and components
- Dealing with corrosive effects of seawater and salt-laden air
- Should remain operational under ship movement
- High degree of reliability (availability while at sea)
- Noise minimisation due to small indoor spaces
- Prevention of water intake during severe weather conditions
- Prevention of exhaust gases intake
- Higher firefighting requirements

Other

Apart from the essential equipment to sail and accommodate people on board, ships are equipped with mission specific equipment. In cargo ships and more specifically containers, large cranes are installed to load and unload cargo.

3.4 Location / motion / orientation

Location

Unlike buildings, ships constantly change their location, speed and orientation when on sail. In BES the geographical location of a structure defined by longitude and latitude along with the time of year defines the position of the sun relative to the building which is expressed with the zenith and azimuth angles (Figure 3-1) that are calculated at each time step of the simulation. These two angles along with the orientation of a surface are used to calculate the angle of incidence of the direct solar beam for every a surface according to equation:

$$i_{\beta} = cos^{-1}[\sin \beta_s \cos(90 - \beta_f) + \cos a_s \cos(|a_s - a_f|) \sin(90 - \beta_f)] \quad (8)$$

The angle of incidence is then used to define the amount of solar radiation impinging on external and internal surfaces.

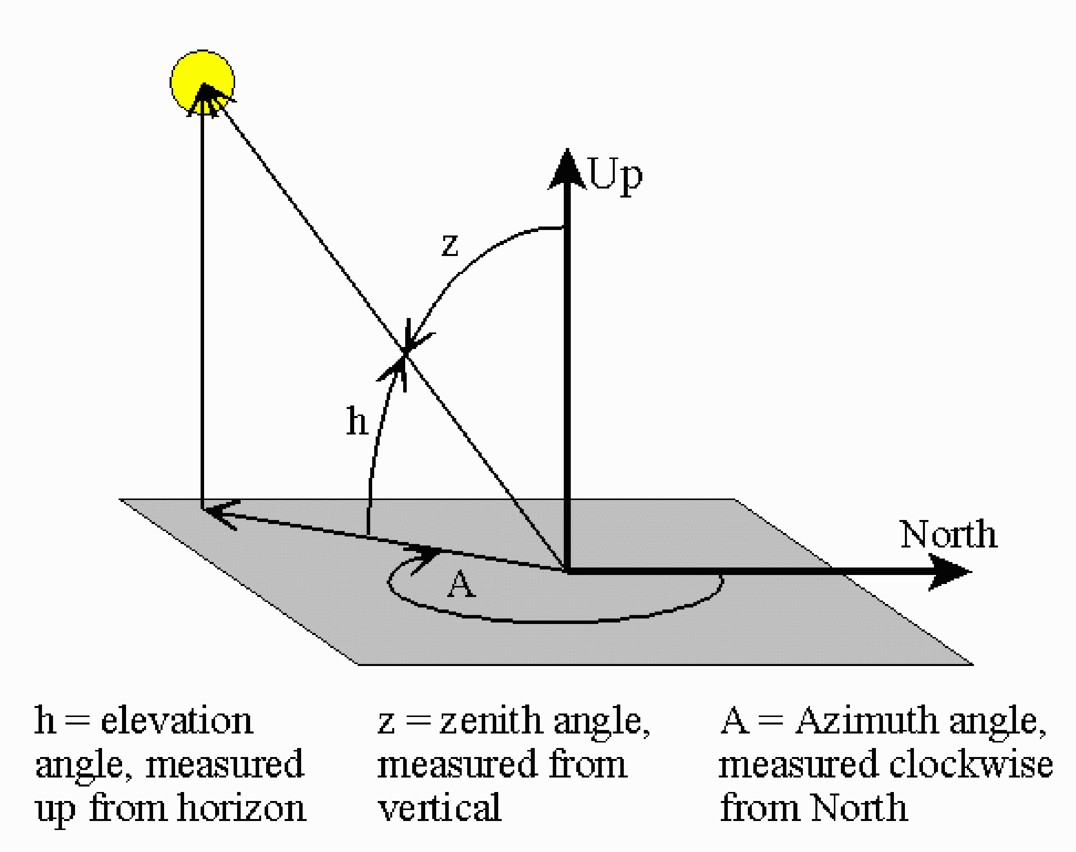


Fig 3-1. "Solar angles"

When a ship is on sail, it constantly changes its geographical location, which means that the latitude, longitude and local solar time change constantly. The change in position during simulation has been addressed [59] and a roaming capability has been added to the ESP-r software, where the user can assign different latitude and longitude during a simulation through a roaming file. However, the effect of the location change on the experienced weather has not yet been addressed.

Motion

Ships sail between ports and spend the majority of their time on the move. This movement has an effect on the way the vessel experiences wind. In BES wind is a first order effect since it determines the external HTC to a large degree and drives natural indoor airflow. When the ship is on sail, it experiences a relative wind speed namely 'apparent wind' that depends on the ship's speed and orientation. This is calculated according to the following equation:

$$\overrightarrow{Vaw} = \overrightarrow{Vw} - \overrightarrow{Vs} \tag{9}$$

Orientation

The change in orientation is responsible for the change of the surface azimuth a_f for all spaces on board the ship, which in turn affects the angle of incidence (eq. 6). Another important factor affected by the orientation change is the calculation of insolation and shading. In BES surrounding objects, buildings and parts of the modelled building that might block the incident solar radiation are taken into consideration during simulation. This is possible with the introduction of geometrical calculations, more specifically with the direct application of vector geometry. When ships are on sail surrounding objects are non-existent and the only source of shading can be the ship itself. A ship would therefore require continuous update of the area blocked by its parts.

3.5 Geometry / topology / complexity

Geometry

The geometrical diversity of ships is limited by their stability requirements. Most ships follow conventional geometrical designs described in “SOLAS Chapter II - Construction” [60] since the adoption of novel geometries requires extensive stability tests and calculations to ensure acceptable safety levels. Spaces on board ships can be divided according to their function in cargo, machinery and accommodation spaces. The geometry of cargo spaces is defined by the type of goods being transferred (fuel oil, containers, grains, cars, etc.) and the stability requirements (space subdivision, weight allocation etc.). Machinery spaces are designed to accommodate large equipment and their geometry mostly depends on the size of the larger piece of equipment inside. The geometry of the engine room depends on the size of the main engine and/or diesel generators and consists of an open plan space with distinctive floors and a separate control room. Since ESP-r allows for volume generation from points, all geometries are possible to generate. However large volumes such as engine rooms might require finer spatial discretisation.

Accommodation spaces range from single cabins to large atria up to three decks high. In every ship type the accommodation block is comprised by the bridge, cabins, mess rooms, offices, sanitary spaces and corridors while more complex configurations can be met in passenger vessels such as large dining rooms, entertainment rooms, entrance spaces, etc. The geometry of accommodation spaces bears great resemblance to their building counterparts as seen in Figure 3-2.

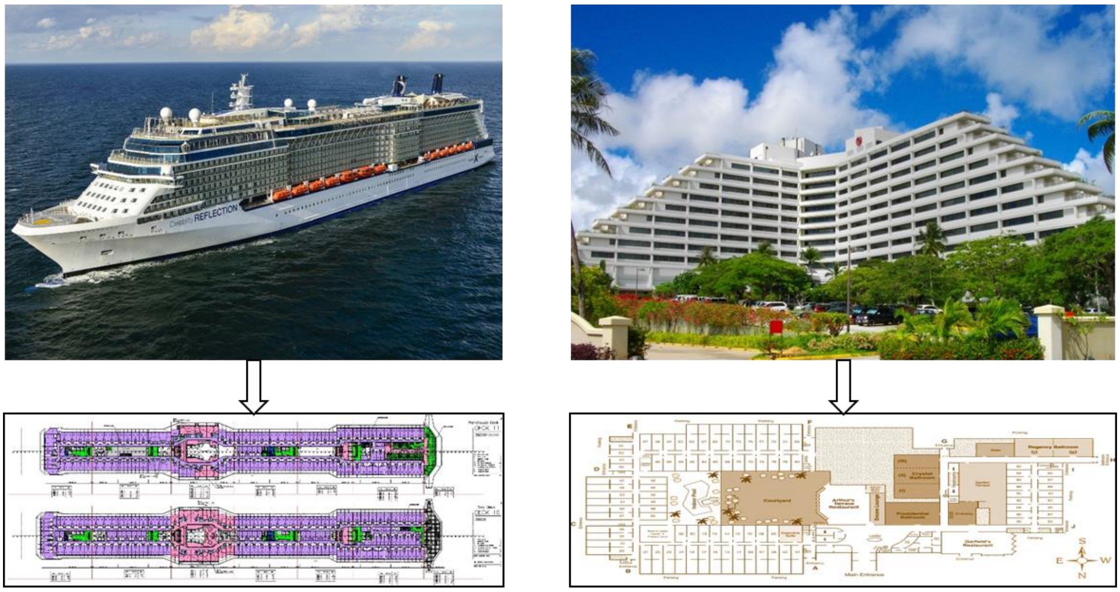


Fig 3-2. "Geometry and plan similarity between a cruise vessel and a resort"

Buildings on the other hand allow for more complex and innovative geometries since stability requirements are not a limiting factor. The freedom in diverse geometries has commenced the study of passive buildings, which focuses on taking advantage of building geometry and construction to passively condition indoor spaces.

Topology

In terms of topology, there are two main differences. Firstly in ships and more specifically in passenger vessels it is common to encounter interior rooms that are not in contact with the environment and cannot be ventilated naturally while in buildings this is extremely rare for living spaces. This is one of the reasons that make mechanical ventilation and therefore an HVAC system mandatory in all passenger vessels.

Secondly, in ships there is a wide variation of adjacent room configurations since cabins, galleys, cinemas and engine rooms might co-exist in a single vessel (Figure 3-3). This has a direct effect in energy simulation since heat gains from adjacent rooms might significantly affect the energy balance. Also spaces in the immersed part of the ship exchange heat with the surrounding sea. To represent that heat exchange, a study of the HTC of seawater in contact with the ship hull is required, which would involve parameters such as water temperature and salinity, relative speed between the ship hull and seawater, wave height, etc.

Fire integrity: Max → Min

Passenger Ships with more than 36 passengers	Passenger ships with 36 passengers or less and Cargo ships except Tankers	Tankers
Control stations	Control stations	Control stations
Stairways	Corridors	Corridors
Corridors	Accommodation spaces	Accommodation spaces
Evacuation stations and external escape routes	Stairways	Stairways
Open deck spaces	Service spaces (low risk)	Service spaces (low risk)
Accommodation spaces of minor fire risk	Machinery spaces of category A	Machinery spaces of category A
Accommodation spaces of moderate fire risk	Other machinery spaces	Other machinery spaces
Accommodation spaces of greater fire risk	Cargo spaces	Cargo Pump Rooms
Sanitary and similar spaces	Service spaces (high risk)	Service spaces (high risk)
Tanks, voids and auxiliary machinery spaces having little or no fire risk	Open decks	Open decks
Auxiliary machinery spaces, cargo spaces, cargo and other oil tanks and other similar spaces of moderate fire risk	Special category and ro-ro spaces	
Machinery spaces and main galleys		
Store room, workshops, pantries, etc.		
Other spaces in which flammable liquids are stowed		

Fig 3-3. "Classification of spaces in different ship types based on their fire integrity according to SOLAS"

Complexity

The capacity of commercial ships ranges from 20 people in cargo vessels to over 8,500 in large cruise ships. This analogy is valid for indoor spaces as well, meaning that excluding cargo holds and corridors, a conventional cargo ship has around 30 to 40 discrete indoor spaces while a cruise ship might exceed 3,000. Although in theory there is no limitation to the number of spaces that can be modelled and simulated with BES tools, if this number is very large the computational expense and modelling effort might be prohibitive. In cargo vessels explicit modelling of all spaces and the involved networks (HVAC, fresh water, etc.) might be feasible, however, when it comes to large passenger vessels this would require months of modelling. Alternative methodologies to model such large accommodations are investigated later in this thesis.

3.6 Construction materials

The selection of construction materials in ships is dictated by stability, structural strength, fire safety, and thermal and sound insulation requirements. Standard calculations have been established by classification societies concerning the thickness of hull and fire propagation time among other objectives [59].

Almost without exception, modern ships are built of mild steel since it is cheap, easily worked (welding and forming) and has high strength to weight ratio. Where required, fire insulation is achieved with the use of rockwool while in cases where only thermal and noise insulation is required glasswool insulation is used. Single glazing is usually used in cargo ships while double glazing is used in most passenger vessels for better thermal and acoustic comfort.

According to SOLAS regulations accommodation spaces should be divided from the remainder of the ship by thermal and structural boundaries. There are three types of divisions: A-class, B-class and C-class. These divisions are characterised by their ability to prevent smoke and flame passage and their insulation level, with A-class being the most secure and C-class the least effective. The divisions used between spaces and the environment are regulated by SOLAS Chapter II-2 [59] and are presented in APPENDIX I along with a detailed description of the A,B and C class divisions.

In buildings, construction materials can be selected from a wider available range. According to Clarke [34], building construction materials are divided in four categories: Impermeable, Non-hygroscopic, Inorganic-Porous and Organic-Hygroscopic. ESP-r comes with an integrated material database with most common materials and their thermal properties and a construction database that includes common material configurations in buildings. The purpose of the construction database is to easily define the materials of a surface during model development. The 'marinasation' of ESP-r requires the integration of common materials and constructional elements met in ships in the existing ESP-r database.

3.7 Climate / Weather / Exposure

Climate

Buildings are designed based on yearly repeated ambient conditions that dictate material, architecture and equipment selection. More specifically, equipment sizing is based on the hottest and coldest season of the year. For the purposes of BES, climate files are available for major locations around the world that contain average hourly weather observations for ambient conditions (temperature, wind, humidity, solar radiation). Unlike buildings, ships do not spend their lives in the same climate since they constantly shift their location. Within a few days, a ship might move from hot humid environments to cold dry ones (Figure 3-4). Some assumptions can be made about liners but for all other ships the climate (in the sense of weather as a function of time of the year) is highly uncertain.

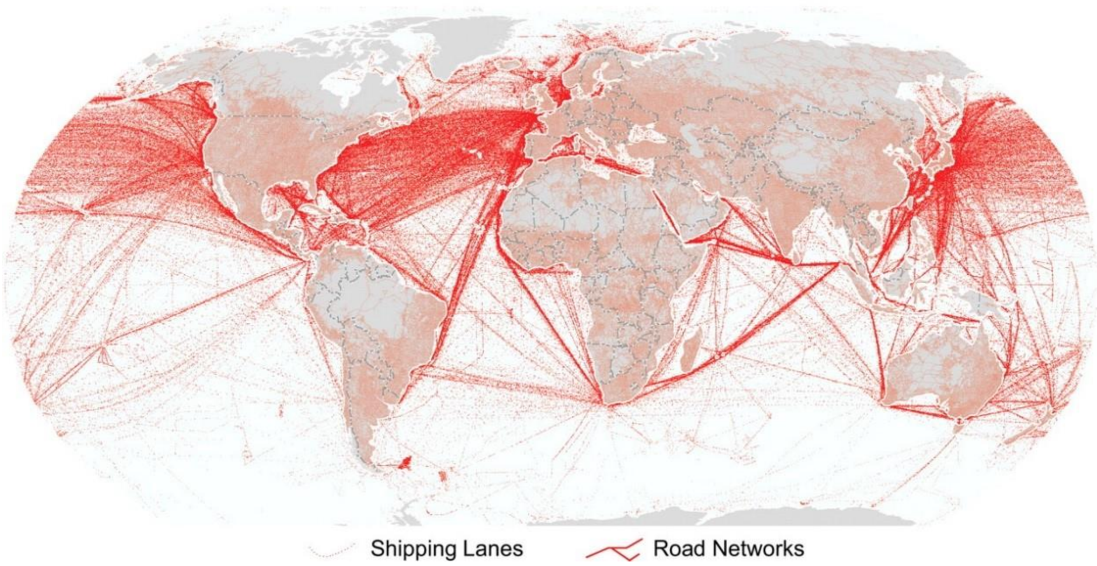


Fig 3-4. "Major Shipping routes"

Weather

Regardless of the climate, weather conditions are more adverse at sea and changes in weather are observed in terms of minutes and not hours as in land. This necessitates faster control methodologies and the installation of more responsive controls on board. In terms of energy modelling this introduces the need for weather files with smaller time discretisation (e.g. 10 minutes instead of 1 hour) and the investigation of the applicability of building control methodologies in a marine environment.

Exposure

Ships sailing at sea are exposed to weather from all directions. On the contrary, buildings might exist in a rural environment surrounded by other structures and plantation. The presence of surrounding obstacles defines how the structure perceives local wind, which in the framework of BES is described by a parameter namely 'site exposure'. For example, if the site is in the middle of an open field then there would be no alteration in the perceived wind. However, in a big city the wind speed might be diminished or increased depending on the surrounding buildings. This has an effect on the definition of boundary pressures for the nodal network method described in 2.4.2, therefore it should be noted that ships will always perceive the real wind speed.

In buildings ground reflected solar radiation is a fraction of the total radiation that impinges on external surfaces. Since ships are surrounded by seawater when on sail, ground reflectivity is replaced by seawater reflectivity which depends on the sea state and the solar position.

3.8 Occupancy

Like most attributes, occupancy is ship type and space specific. In cargo ships, crew schedules bear some resemblance to that of a commercial building. During weekdays the crew works from 9 am to 5 pm, thus working stations are occupied (engine room, ship offices) while accommodation spaces are empty. From 5 pm to 12 am occupancy is uncertain. The crew might spend time in their cabins, recreational spaces, mess rooms and stations that should be manned at all times (e.g., bridge). During night time most of the crew is sleeping in their cabins apart from those in service.

In passenger vessels, occupancy is highly uncertain. More specifically in Ro-Pax and ferries the crew might be comprised by officers, engineers, waiters, cleaners, etc. while in cruise liners the crew is more diverse including actors, entertainers, cooks, lifeguards, etc. With a crew so diverse and so many activities on board, a single conclusion for the occupancy of crew cabins cannot be drawn. Passengers on the other hand have some cohesion in their schedules. During lunch and dinner they are expected to be in one of the ship's restaurants while they are most likely to be asleep during night time. Excluding the above mentioned instances, passengers might occupy a variety of spaces, which follow a specific schedule.

ESP-r includes a module to define hourly schedules for casual gains. For cargo vessels with a crew typically less than 30 people an educated guess for the occupancy of indoor spaces will most probably be acceptable for energy modelling purposes. However, when it comes to passenger vessels where indoor comfort is responsible for 20% - 40% of on board power consumption, uncertainty should be introduced in the calculations.

3.9 Closure

This chapter established the main differences between ships and buildings and their effect on the energy simulation. The comparison showed that several changes must be applied to existing BES tools in order to address the marine environment, mainly due to a wide range of machinery installed on board ships and the ship movement. The most dominant differences established in this chapter are going to be addressed in Chapter 4 in the framework of the 'marinisation' of ESP-r and the development of a working ship accommodation energy model.

4 BUILDING A SHIP ACCOMMODATION ENERGY MODEL

Essentially, all models are wrong but some are useful.
-George E. P. Box, Statistician, 1987

4.1 Preamble

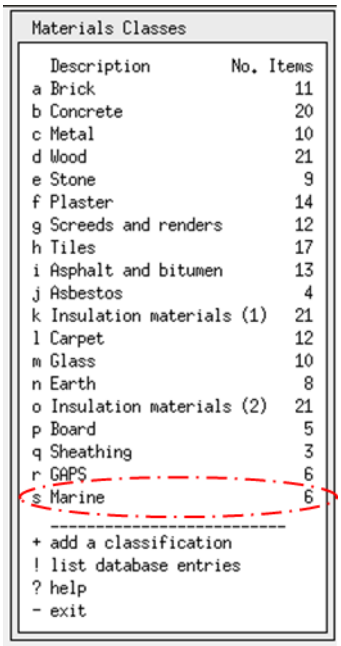
This chapter focuses on the 'marinisation' of ESP-r in order to facilitate the development of a full ship accommodation thermal model. The main differences between buildings and ships that were listed and discussed in Chapter 3 are selected for investigation and the appropriate modifications are made to ESP-r to reflect these. The marinisation process involves updating ESP-r's default material and construction databases, categorising and designing conventional accommodation geometries and HVAC configurations, adopting marine terminology during model design, creating marine climate files, and generating occupancy profiles for major accommodation space types.

4.2 Materials and constructions

As discussed in Chapter 3, the marinisation of ESP-r can be facilitated by enriching the current ESP-r material and construction databases with common materials and construction configurations often met in ships. It has to be noted that there is no intention of introducing and testing novel materials that might improve the energy efficiency of on board thermal systems but rather carefully import materials and constructions so that their thermal properties are properly taken into consideration during simulation.

4.2.1 Materials

Material selection in accommodation spaces is currently based on fire safety and acoustic requirements. Every division is assigned a fire rating according to regulations of Safety of Life at Sea (SOLAS) convention [59]. Bulkheads, ceilings and decks are mainly built from mild steel, galvanised steel sheets, glasswool and rockwool insulation, and polyvinyl chloride. Depending on the space, different types of deck covering may be applied such as carpet in passenger cabins, PVC in crew cabins and tiles in galleys, all of which are glued to the steel deck with a subfloor compound with insulating capabilities. Concerning glazing clear toughened glass is used which might be enhanced with a UV filter to reflect the solar radiation in spaces where extra comfort is required. In the framework of thermal modelling, the material properties that are of interest are conductivity, density, heat capacity, and radiation absorptivity and emissivity. A list of all the materials added to the ESP-r materials database along with their thermal properties is available in APPENDIX II.



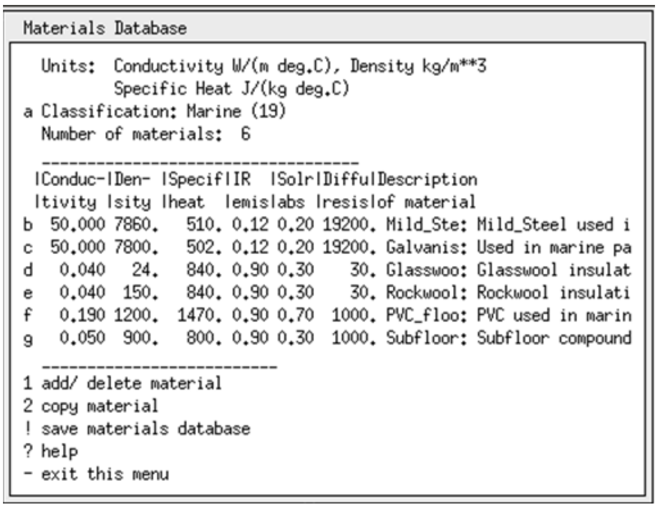


Fig 4-1. "Marine material class added to ESP-r material database"

4.2.2 Constructions

In ESP-r, combinations of the previously described materials assigned with user defined thicknesses, form constructions, the divisions between adjacent spaces and between spaces and the environment. Since there is no thermal classification for these divisions in ships, one is sought here which will expedite the marinisation of ESP-r.

For every thermal zone, ESP-r's modelling methodology necessitates the definition of every construction until the zone boundaries, or in other words until the surface that is exposed to the ambient air or the air of the adjacent zone. As a result, common divisions of adjacent thermal zones will be modelled twice using the same construction. Since every construction has an outer and an inner surface, non-symmetrical constructions require an additional inverted construction for adjacent interior bulkheads.

Following this methodology, the ceiling of a zone, along with the deck of the zone above, are represented by a single construction, comprised of several layers. The complexity and thickness of the ceiling-deck construction raises the need to address it separately. Therefore, constructions are initially divided in horizontal (bulkheads, doors and windows) and vertical (ceilings and decks).

Secondly, constructions are divided according to their topology, in external (exposed to the weather) and internal. Both horizontal and vertical external surfaces require higher thermal insulation and are usually comprised (from the outside to inside) of steel, glasswool insulation, air gap and a panel. Where higher fire insulation is required, glasswool is replaced by rockwool insulation[2]. As for internal divisions, adjacent cabins are separated by 25 mm panels while corridors and cabins are separated by 50 mm panels (Figure 4-2). All panels are comprised of two 0.5 mm sheets of galvanised steel and glasswool or rockwool insulation. Divisions connecting main vertical fire zones are comprised of steel and rockwool insulation (A-60 fire rating). Internal vertical divisions are typically comprised of a ceiling panel, an air gap of around 500 mm to accommodate ducts and pipes, a steel deck, a subfloor compound and the space specific deck covering of the above space.

Fig 4-2. "Typical bulkhead panel used in ships comprised of two sheets of metal and glasswool insulation in the middle"

[2] Although glasswool and rockwool insulations have different fire insulation capabilities, they share the same value for thermal conductivity (0.04 W/m/K) and of all the thermal properties only their densities differ slightly. In the framework of thermal modelling this small difference makes those two materials almost identical therefore, rockwool and glasswool might be commonly referred to as 'insulation'.

Concerning glazing there is a distinction between different ship types. In cargo ships windows are usually single glazed with a thickness of 8 mm to 12 mm depending on the accommodation space. In Ro-Pax ships both single and double glazed windows can be found. In cruise ships cabins are usually equipped with double glazing for maximum comfort and if the room has an accessible balcony, sliding glass doors are installed. Finally doors are constructed much like wall panels with thin metal sheets on each side and insulation in the middle. A list of all the constructions added to the ESP-r constructions database can be found in APPENDIX II.

4.3 Geometry

The geometry of on board spaces highly depends on their usage. Although most space types are common to all ships (cabins, galleys, mess rooms etc.), there are some that are ship type specific (atria, theatres etc.) (Figure 4-3). In this work, the main geometries of accommodation spaces met in ships are listed, classified according to their size and designed with the ESP-r software. Each surface of each room is then assigned a constructional element, in order to develop the fundamental blocks (modules) for the energy modelling of accommodation spaces. Information about the geometry of accommodation spaces was drawn from regulations and several ship libraries available.

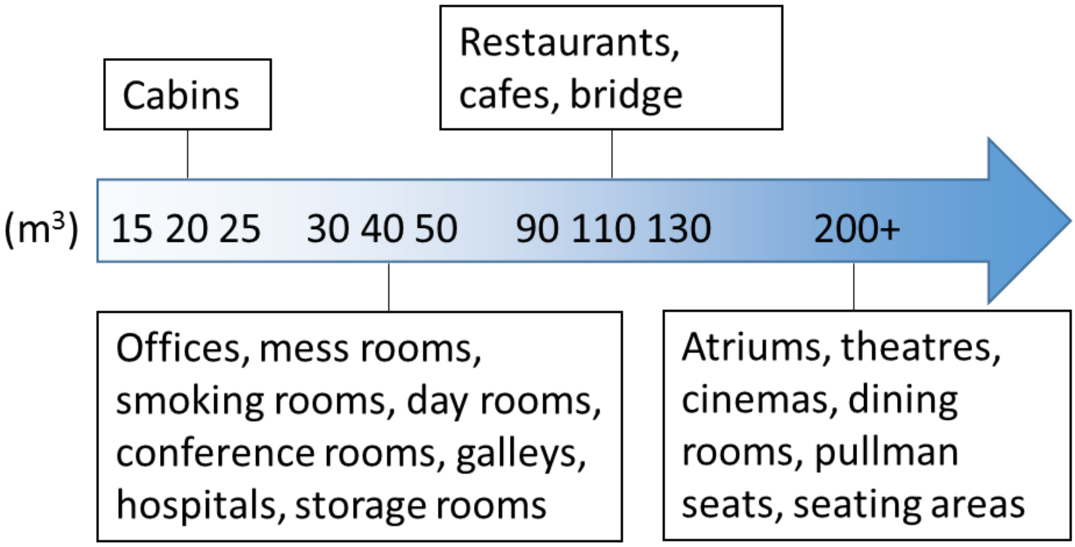


Fig 4-3. "Volume of spaces on board ships"

4.3.1 Cabins

Cargo ships

Cabins occupy the majority of the accommodation spaces in both cargo and passenger vessels. In cargo ships, there are three types of cabins characterised by the ranking of the occupant: lower, medium and higher ranking.

All cabins are parallelepiped volumes. Lower ranking cabins are characterised by their small size and the absence of an en suite bathroom. Occupants are served by common toilets and showers, installed on the same deck. The volume of lower ranking cabins might vary between different ships and is usually within the range of 18 m^3 to 20 m^3. A typical lower ranking cabin is 2.2 m wide, 3.8 m long and 2.2 m high although no regulations exist for the minimum volume or dimensions of a cabin, apart from the height which should be no less than 2.05 m [59]. These cabins can be either external (one surface exposed) or corner (two surfaces exposed).

Windows in cabins of cargo ships are rectangular with rounded edges and although their dimensions may vary between different ships, they are usually 400 mm to 450 mm wide and 500 mm to 600 mm high.

Medium ranking officer cabins are almost identical to lower ranking cabins with the only difference being the presence of an en suite bathroom and the exhaust of air from the sanitary space. The presence of the internal panel separating the bathroom from the cabin and the air exhaust from the bathroom affects the thermal balance. However, in early design when a rough heat load calculation is performed this is negligible and lower and medium ranking cabins need not be addressed separately.

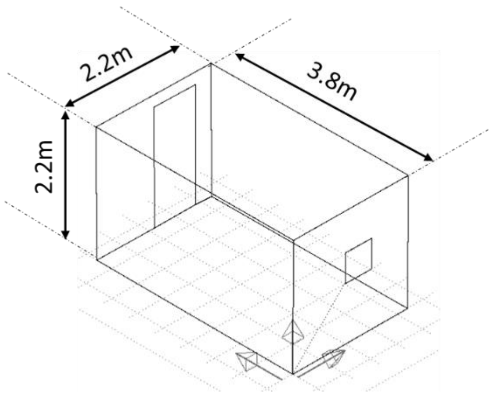
Higher officer cabins (captain and 1st engineer) are comprised of two separate rooms, a day room and a bed room connected with a door. Also, an en suite bathroom is installed in the bedroom. Air is supplied to both day room and bedroom and exhausted from the bathroom. Higher officer bedrooms are similar to medium officer cabins but a bit smaller with roughly 15 m^3 of volume and 2.0 m width, 3.6 m length and 2.2 m height. Day rooms are larger and can be thought off as small living rooms with a volume of 40 m^3 to 45 m^3.

Ferries

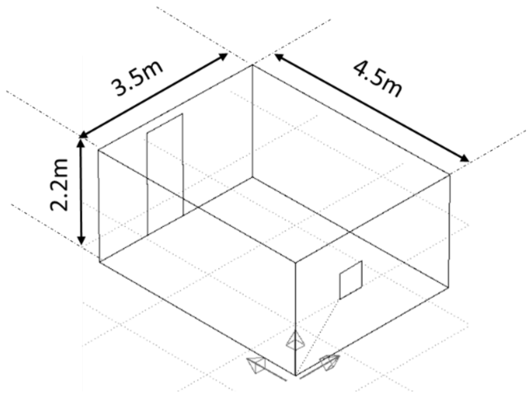
Passenger cabins in ferries are slightly larger than cargo ships since they usually accommodate between 2 to 4 passengers. Their volume is roughly around 30 m^3 with dimensions of 4.5 m length 3.5 m width and 2.2 m height. Since passenger comfort is more demanding than cargo ships double glazing is installed for exterior cabins while larger ships might have internal cabins with no surfaces in contact with the environment.

Cruise ships

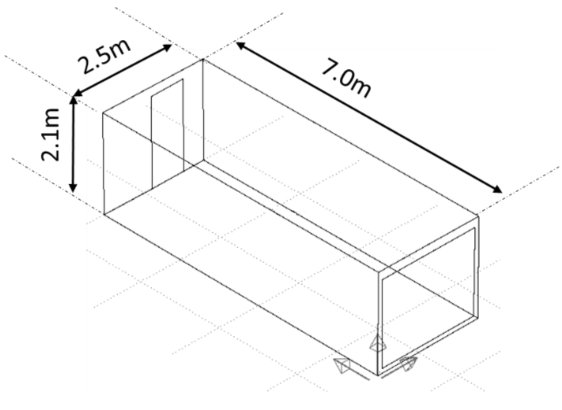
In cruise liners cabins are categorised in staterooms (passenger cabins) and crew cabins. Crew cabins are treated as lower ranking cargo cabins. Staterooms on the other hand can be categorised in external and internal. External staterooms are either equipped with a sliding door that occupies the whole area of the external surface and leads to a private balcony, or a large window with typical dimensions of 1.2 m x 1.3 m. A conventional stateroom is 7.0 m long, 2.5 m wide and 2.1 m high. Internal staterooms are not in contact with the environment and like all staterooms have an en suite bathroom. The ESP-r model of small cabin modules are shown in Figure 4-4.



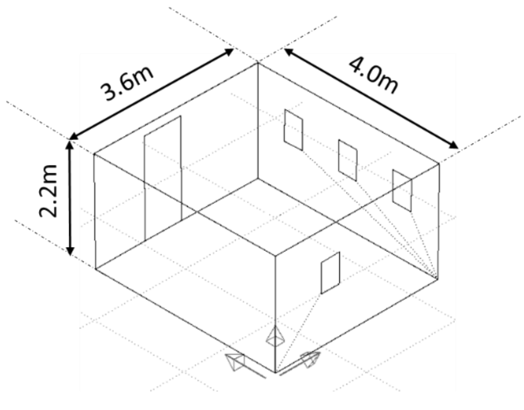
(a)



(b)



(c)



(d)

Fig 4-4. "Geometry of space modules for cabins designed with ESP-r. (a):Low Ranking Cabin, (b):Passenger Cabin, (c):Stateroom, (d):Day Room"

Apart from the previously described types of cabins, special types exist such as luxury cabins and suites that are ship specific and do not fall under any general category. These special types need to be addressed individually.

4.3.2 Medium size spaces

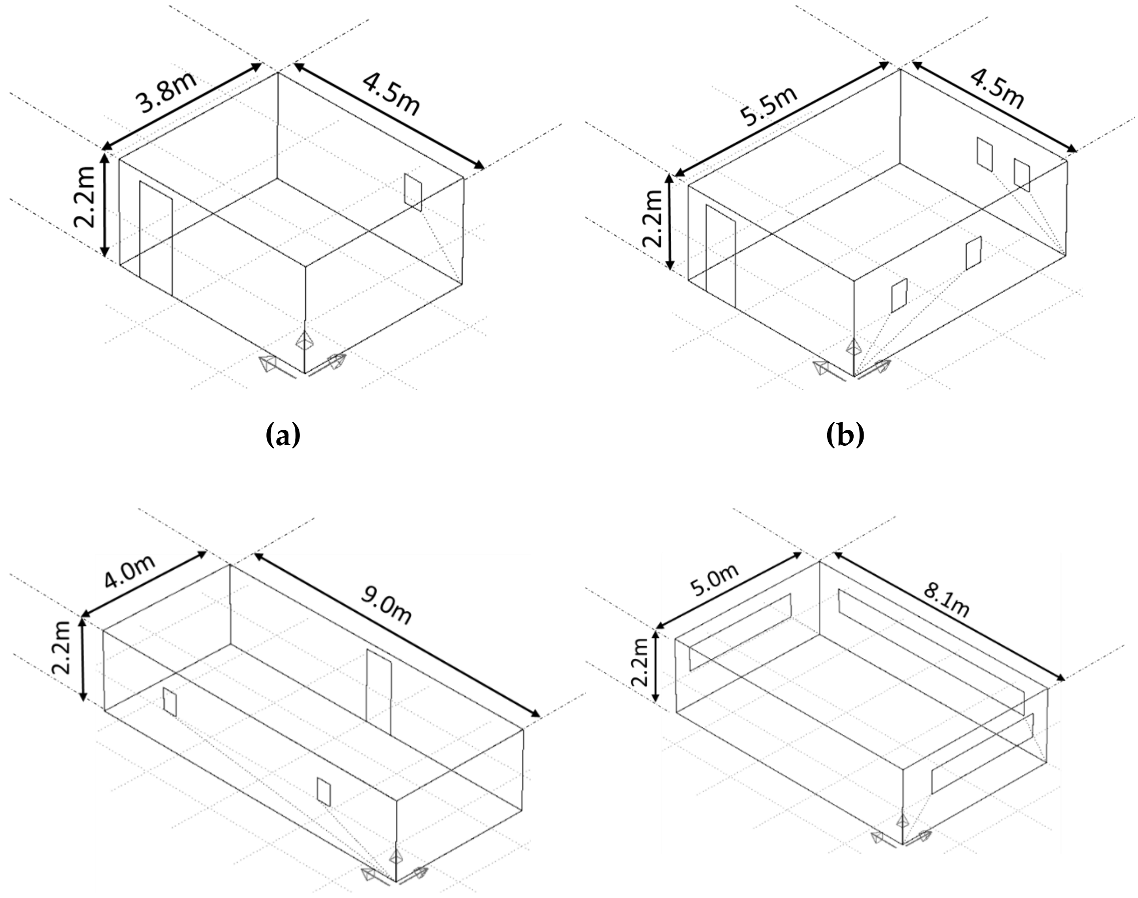
Cargo ships

Offices, mess rooms, smoking rooms and galleys comprise the medium size accommodation spaces in cargo ships. Offices have a size of 30 m^3 to 40 m^3 and their shape can be either rectangular or parallelepiped. Mess and smoking rooms are larger, with size roughly 45 m^3 to 55 m^3 and are usually placed in corners in order to receive more natural lighting and ventilation. Galleys have a volume of around 80 m^3 and are 4 m wide, 10 m long and 2.1 m high.

Passenger ships

As for passenger vessels, offices, mess and smoking rooms for the crew can be assumed to be similar to cargo ships, while several different galleys might exist for smaller restaurants on board. In cruise liners the main galley usually occupies one deck of a main vertical fire zone and is therefore addressed as a large space. Since the size of each smaller galley is restaurant specific, these galleys will either be treated as conventional cargo galleys or if more detail is needed they can be addressed individually.

Finally all ships have a bridge, which is characterised by its wide shape and the presence of additional glazing, enabling adequate visibility for the captain. In cargo ships the bridge is approximately 5 m long and 8 m wide while in passenger vessels the width is similar to the beam of the ship which can be up to 47 m in modern ships. The ESP-r models of medium space cabin modules are shown in Figure 4-5.



(a) **(b)**

(c) **(d)**

Fig 4-5. "Geometry of space modules for medium sized spaces designed with ESP-r. (a):Office, (b):Mess Room, (c):Galley in cargo ships, (d):Bridge in cargo ships"

4.3.3 Large spaces

Seating areas, pullman seats, restaurants and diners are some of the larger spaces that can be found in passenger vessels. Usually, they take up one deck of a MVZ although large restaurants in cruise ships might take up two decks of a MVZ. According to SOLAS, the length and width of main vertical zones does not in general exceed 40 m, which are dimensions assumed for these spaces.

4.3.4 Other

Apart from the previously mentioned spaces that are common to most ships, ship specific accommodation spaces exist such as atria, cinemas, solaria, outdoor promenades, etc. Since they do not fall under a general category, these spaces need to be addressed individually with a dedicated thermal model that will capture their geometrical and thermal complexity.

4.4 Climate

ESP-r's heat conservation approach, regards climate as a known boundary condition during simulation. Hourly averaged values of six climatic parameters for 365 days are stored in weather files in an ESP-r specific format. These six parameters are:

- diffuse solar radiation
- ambient temperature
- direct solar radiation
- wind speed
- wind direction and
- relative humidity.

The user can choose among several climate files for major cities around the world stored in ESP-r's default database, import weather data from available sources [61], or create a weather file from scratch.

Since ships constantly change their geographic location when on sail, the existing land based weather files are not indicative of the weather met by ships. In the framework of marinisation of ESP-r, a methodology to create marine weather files for specific routes was developed, based on available ocean weather data. The "International Comprehensive Ocean-Atmosphere Data Set" (ICOADS) [62] was used for the construction of the marine weather files. ICOADS is a global ocean marine meteorological and surface ocean dataset that is formed by merging many international data sources that contain measurements and visual observations from ships (merchant, navy and research), moored and drifting buoys, coastal stations, and other marine platforms.

The methodology to develop marine weather files is comprised of two phases:

- development of weather files for major marine locations and,
- development of weather files for a specific route.

In the initial phase, ocean weather data from 2000 to 2012 with a geographical step of 0.5 degrees was downloaded for major shipping routes. The downloaded datasets included hourly values for ambient temperature, wind speed and direction, and relative humidity. At the time, information about solar radiation was not available, therefore values from nearby land locations were used for the construction of marine weather files. Since on board measurement of solar radiation has already been implemented for research purposes [63], it is likely to become a standard process in the future to facilitate the assessment of the energy performance of solar panels on board ships. The downloaded dataset was sorted according to geographical location and year. Then for each specific location, an average climate file was developed, by averaging hourly values of all years.

Based on the available marine climate files for major geographic locations, the second phase included the development of a climate file for specific journeys. Given a specific route, and the time of the beginning and end of the voyage, a route specific climate is generated by copying weather data in a single file, for certain days from the previously created weather files. This means that the 2nd phase needs to be repeated for every route, while the first phase was carried out only once.

Microsoft Excel and "Visual Basic for Applications" (VBA) programming language were used to draw information from the large datasets, perform calculations and create the marine weather files, while ESP-r climate module was used to convert text files to ESP-r readable binary files.

4.5 Boundary conditions

4.5.1 Heat transfer between seawater and ship hull

Spaces in decks below the sea surface are surrounded by seawater. In cargo ships, no accommodation space is in direct contact with sea water, as accommodation sunken decks are usually surrounded by fuel oil tanks. Apart from the accommodation, cargo spaces and the engine room are in contact with sea water. In passenger vessels, and more often cruise ships, crew cabins are located in decks below the sea surface. In the framework of detailed thermal modelling, modelling of the heat transfer between seawater and the ship was investigated and integrated in ESP-r.

Another choice for the calculation of the external convection coefficient of surfaces was added to ESP-r, representing forced convection (ship on sail) between the sea and ship hull. Since the temperature of seawater does not change considerably during a voyage, a fixed temperature can be assigned by the user at this time. Ideally, a profile of the seawater temperature should be applied during the ship route. However, this has been left for future work. For the calculation of the HTC between the ship hull and seawater at each time step, the equation of Zukauskas & Slanciauskas [64] was used. According to Zukauskas the HTC is calculated as a function of the ship speed, ship length, and seawater thermal properties.

$$HTC = \frac{NuSWk}{SL} \tag{10}$$

$$Nu = \left(0.037Re^{\frac{4}{5}} - Trans\right)Pr^{\frac{1}{3}} \tag{11}$$

$$Pr = \frac{SWvSWcp}{SWk} \tag{12}$$

$$Trans = 0.037R_{crit}^{\frac{4}{5}} - 0.664R_{crit}^{\frac{1}{2}} \tag{13}$$

$$Re = \frac{SW\rho SLSS}{SWv} \tag{14}$$

$$R_{crit} = 350000 \tag{15}$$

The properties of seawater are calculated as a function of seawater temperature and salinity using the equations by Sharqawy [65].

4.5.2 Seawater reflectivity

An additional option for ground reflectivity has been added to ESP-r for the calculation of the radiation reflected by the sea surface. Sea reflectivity can be calculated at each time step as a function of wind speed and the incident angle of solar radiation as investigated by Haltrin [66] (Figure 4-6). The equations are derived from regression of experimental data. The FORTRAN code added to ESP-r for the calculation of seawater HTC and seawater reflectivity can be found in Appendix III.

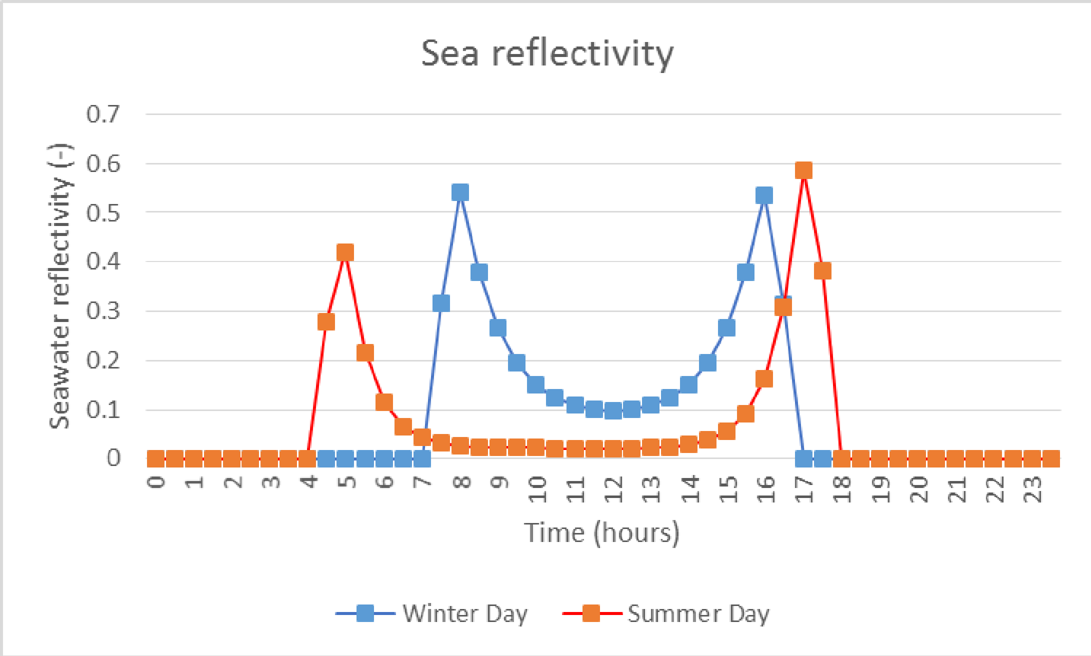


Fig 4-6. "Seawater reflectivity calculated by ESP-r on a winter and a summer day"

4.6 Casual gains

The presence of occupants, lighting and other sources of heat are treated as sources of heat in ESP-r's heat conservation approach. ESP-r allows for the creation of occupancy files where several schedules can be defined and assigned to one or multiple different spaces. Also ESP-r allows the definition of different day types during simulation runtime, which means that occupancy profiles can be created when the ship is on sail, docked, loading, etc. Development of indicative occupancy files for typical accommodation spaces is sought here. Information about occupancy of spaces in ships was drawn from classification society regulations, on board schedules and observations, and evacuation guidelines.

4.6.1 Cargo ships

Cargo ships follow a strict schedule when on sail. The crew works from 9 am to 5 pm. Although after that time the schedule is uncertain, a good assumption would be that the crew spends time in smoking and mess rooms until 10 pm. Then they return to their cabins to sleep until next morning. Offices are assigned one occupant during working hours. Spaces that need to be manned at all times such as the bridge have dedicated occupancy files. Other non-habitable spaces such as provision stores, hospitals and gyms are assumed to have no internal heat gains.

4.6.2 Ferries

Passengers in ferries are assumed to be asleep during night time from 12 am to 8 am and spend the rest of the time in common areas. Of course this assumption is very rough and the occupancy of cabins depends on the route, time of departure and arrival, and duration of the trip. A schedule of the crew is assumed taking into consideration the evacuation guidelines issued by the IMO [67] according to which one third of the crew is not working from 12 am to 7 am. For this reason two different occupancy files are created for crew cabins, one for crew in service at night and one for those working during the day. If dining areas exist they are assumed to have 75% occupancy during lunch (1 pm to 3 pm) and diner (7 pm to 9 pm). Other common areas such as seating areas are assumed to have 75% occupancy from 3 pm to 7 pm and 9 pm to 12 am.

4.6.3 Cruise liners

Although cruise liners follow a strict schedule, the large selection of activities for passengers makes it hard to accurately predict occupancy of spaces.

Concerning staterooms, a safe assumption would be to have full occupancy during night from 12 am to 8 am. Then breakfast is served in two batches, therefore the dining room is assumed to be occupied by half of the passengers from 8 am to 10 am. After breakfast and until lunch at 1 pm to 3 pm when the dining room is full, there is a plethora of choices for passengers. Then the dining room is assumed to be full from 7 pm to 9 pm when dinner is served. Dinner is followed by entertainment which comes in the form of theatrical plays, clubs, casinos and other ship specific areas. Since those spaces do not fall under the general categorisation previously established, no occupancy files are created for these spaces.

Crew cabins follow a similar schedule as in ferries, with one third of occupancy during night. Therefore, the same occupancy files created for ferries can be used.

4.7 Orientation

Since buildings do not rotate, the orientation of external surfaces in ESP-r is based on the four cardinal points, north, east, south and west. However, this convention is not valid for ships since accommodation spaces often undergo rotations when the ship is on sail or manoeuvring. Therefore, a new convention is adopted to depict the orientation of the external surfaces of accommodation spaces during thermal modelling.

The bow of the ship is to be facing the north. Following this convention, when designing accommodation geometry in ESP-r, external surfaces that face the bow of the ship, face the north. Similarly, surfaces that face the aft, port and starboard of the ship, will face the south, east and west in ESP-r, respectively. This way, a reference point is created that allows the designer to be consistent between different models.

The change of orientation when on sail is addressed with ESP-r's roaming capability. This allows the global transformation of the model by a user specified value during simulation. This is accomplished with the definition of a roaming file in which the user defines when (month, day and hour) and by how many degrees the ship rotates. The change in orientation is expressed in degrees clockwise.

4.8 HVAC

Current design methodology of on board HVAC systems prerequisites a heat load calculation which gives the amount of thermal energy that is lost or gained in extreme conditions. Then based on this value and following a design technique that depends on the psychrometric chart, the sizing of the heating, cooling and humidifying components is performed. Although straightforward and easy to implement, this technique is based on steady state calculations, it is over simplified and neglects the dynamic interactions between the HVAC equipment, the ambient environment and the accommodation spaces. For detailed calculations concerning the sizing of conditioning equipment, HVAC component modelling is required.

ESP-r offers the capability to model the HVAC components using a dedicated plant component network that interacts with the thermal network of spaces. The air handling unit along with other components are modelled independently and can be coupled with the existing model. This gives an integrated approach to system sizing and minimises the assumptions of the current design methodology. Real time control of the HVAC components is also available, with the use of different control strategies (on/off, PID, optimum start, etc.). ESP-r allows for the definition of different time steps for the plant and thermal networks, ranging from one hour to one minute, to address the higher sensitivity of state variables in the plant network. Although most HVAC systems are comprised by similar components, different configurations can be found, depending on the application.

4.8.1 Cargo ships

Conventional cargo ships are equipped with single duct HVAC systems. The main components of the system modelled in ESP-r are:

- Fan, to supply air to spaces
- Cooler, to remove heat and moisture from the air
- Heater, to add heat to the air
- Humidifier, to add moisture to the air
- Mixing box, to mix fresh with recirculated air and
- Ducts to move air to and from the conditioned spaces.

Of these components, the fan, cooler, heater and humidifier are power consumers. Fans are rotated by electric motors powered by the main diesel generator. Usually the AHU contains one fan, however, if more static pressure is required another fan might be installed to recirculate air from the spaces. Coolers consume electrical power required by the compressor to circulate the refrigerant through the cooling fins and remove heat from the air. Most heaters use steam as the heating medium, however, there are applications where electric heaters are used. In terms of holistic energy modelling, this would mean that in the former case the heater would be coupled with the steam network while in the latter with the electric network. Finally, humidifiers use steam as well, which is directly injected to the supplied air.

In the framework of holistic ship energy modelling, all these components would ideally be coupled to an integrated ship energy model where heating and cooling demands of the accommodation would directly affect electrical power and steam generation. Although, developing a holistic ship energy model is not in the scope of this work, the marinisation of ESP-r and the simplification of the design of thermal systems which is attempted later in the thesis, are crucial steps towards the integration of different energy types in a single model. The configuration of a single duct system is shown in Figure 4-7.

Using ESP-r's plant component library, the single-duct HVAC system configuration was modelled. Since ESP-r saves the plant network information in a separate text file, the designed system can be easily connected to any ship accommodation model. To do that, the parameters determining the components capacity need to be adjusted to each model and the connections between the HVAC and the thermal zones need to be generated according to ESP-r's modelling methodology.

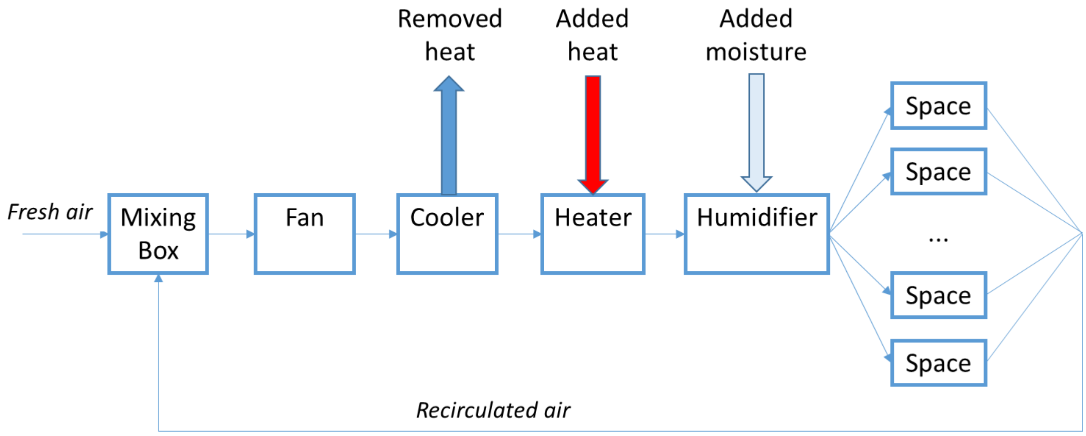


Fig 4-7. "Line diagram of a single duct HVAC system"

4.8.2 Passenger vessels

Passenger vessels usually have more than one AHUs serving the accommodation spaces. Air cooling is based on an indirect expansion method where the cooling medium (fresh water) is cooled in one or more, large chiller units located in the engine room and circulated to all coolers on board. The chillers are equipped with a control system that maintains the water temperature to a certain set point and allow for variable water flow, dictated by the requirements of the coolers in the network. Fans in each AHU force fresh air through the cooling coils, which is then directed to conditioned spaces equipped with local reheating or fan coil units, controlled by the occupants. When heating is required, the chiller stops operating and fresh air is heated by heaters in AHUs and the local re-heating units (Figure 4-8).

In terms of energy consumption this configuration might not be optimal since air is cooled below the supply temperature and reheated locally. However, due to subjective guest comfort levels, maintenance, and availability, this decentralisation is necessary.

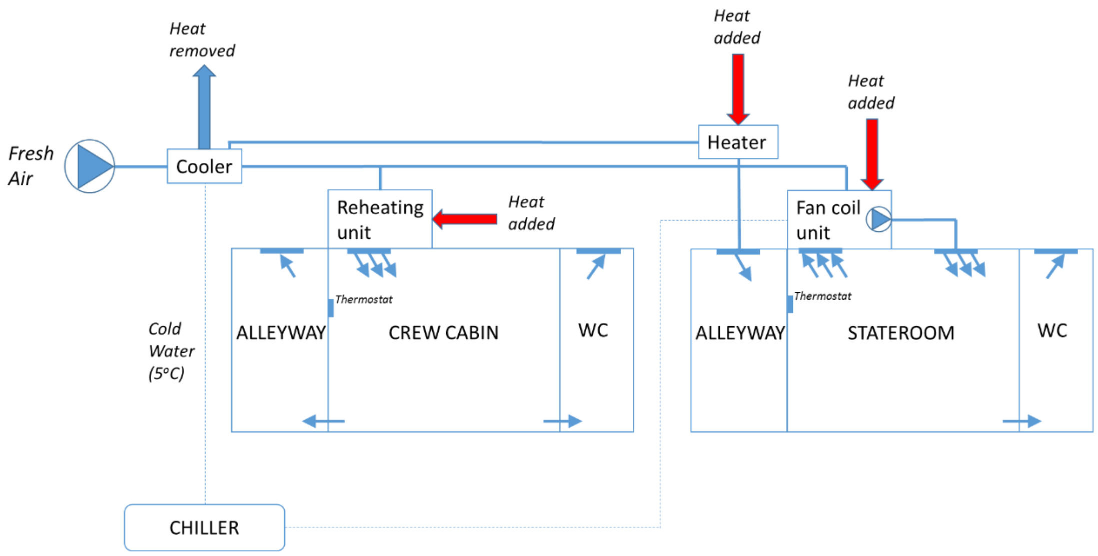


Fig 4-8. "Representation of a modern HVAC system in a cruise liner"

Using ESP-r's plant network modelling capability, sizing of the power consuming components can be achieved by modelling the equipment and the served spaces. Since the system configuration may vary between different passenger ships, the development of a generic plant network is non-applicable. Explicit modelling of all areas and equipment seems an impossible task and a simplified methodology to achieve this based on space grouping is discussed in later chapters.

4.9 Closure

In this chapter 'marinisation' of ESP-r was carried out and a modular approach for the development of a dynamic thermal ship accommodation model with the ESP-r software for all ship types has been described. Different levels of modelling detail have been presented that can be used during different stages of the design process to calculate the heating and cooling requirements of accommodation spaces.

5 TOPOLOGICAL DECOUPLING OF ACCOMMODATION SPACES

5.1 Preamble

With the 'marinisation' of ESP-r the detailed thermal modelling of accommodation spaces and HVAC systems of both cargo and passenger vessels is now feasible. However, the development and modification of such detailed models for whole accommodation blocks is time consuming and susceptible to modelling errors, especially for large vessels. In order to reduce modelling effort for design, retrofitting and operation studies, this chapter focuses on the investigation of the topological decoupling of accommodation spaces that will drop the requirements for exact topological representation of whole accommodation spaces in the 3D space and will allow the examination of smaller parts of the accommodation, individually.

5.2 Need for topological decoupling

In order to accurately model the thermal interactions between indoor spaces and the environment, all spaces need to be included and be thermally coupled in the same model. A thermally correct model would essentially be bounded only by the environment. Although modelling the simple geometry of ship accommodation spaces is quite straightforward with ESP-r, large models are susceptible to modelling errors that can be time consuming to correct. For example, if after defining 80 thermal zones the user realises that a zone has been misplaced or the dimensions have not been properly defined, all other zones might be affected and need to be redefined, model topology would have to be reconstructed and connections between zones re-established. Correcting such a large model can be very time consuming to the extent that it might be easier to build it from the beginning.

Apart from technical modelling issues, exact thermal modelling raises computational problems when specific spaces of the accommodation are being investigated. For example sizing an AHU in a ship with more than one units, would ideally require building and running a full accommodation thermal model, the boundaries of which would be the environment. This means that even if 15 to 20 spaces would be of interest, the model would in fact include hundreds, which would result in large simulation times, lots of useless simulation results and inconvenience in model error checking.

Since ESP-r's multi-domain solver has been extensively optimised, computational effort is generally not a problem when conventional spatial and temporal discretisation is used (one thermal zone per space, one hour time step for thermal solver and 15 min time step for plant side). An annual simulation of the accommodation of a cruise ship is typically carried out in 5 to 10 minutes in a modern computer. However, in sensitivity, uncertainty and optimisation studies where a model might need to be simulated a few hundred times, computational time might pose a problem.

In an attempt to reduce modelling effort and computational requirements, thermal decoupling of on board spaces was investigated. By assuming the boundary conditions of the most common spaces met on board, the need for exact 3D geometrical modelling is sought to be dropped.

5.2.1 Modelling topology with ESP-r

ESP-r allows the user to select among different boundary conditions for the surfaces of a thermal zone. The basic choices are:

- external
- adjacent
- similar
- adiabatic
- fixed (user defined temperature, heat transfer coefficient and/or radiation)

In a model representing reality as closely as possible all external surfaces of thermal zones will be either 'external' (exposed to the weather) or 'adjacent' (exposed to the condition of the adjacent space). 'Similar' boundary condition is used when the adjacent space is not modelled but it is assumed that the conditions are similar to the modelled space (the conditions of the modelled space one time step in arrears are used). If very thick insulation is used the boundary condition can be assumed as 'adiabatic' (no heat transfer is allowed) and finally in cases where a surface is exposed to fixed conditions (e.g. to model an experimental setup) 'fixed' boundary conditions are used.

Here the focus is on the replacement of 'adjacent' (real) with 'similar' (assumed) boundary conditions. In the cases where this assumption if proven valid, thermal modelling of the adjacent zone can be skipped.

5.2.2 Construction type selection

During design, all decks and bulkheads are built according to SOLAS fire regulations. Based on the classification of spaces according to their fire integrity (Figure 3-3), the type of construction for all divisions is selected from SOLAS 'fire protection tables' [59], which regulate the fire rating for the division between every possible space combination. The tables are divided in four categories:

- Passenger ships with more than 36 passengers
- Passenger ships with 36 or less passengers
- Cargo ships except tankers
- Tankers

Each category is assigned two tables, one for horizontal (bulkheads) and one for vertical (decks) connections.

5.3 Verification methodology setup

The main idea behind topological decoupling is to model two adjacent spaces and investigate the loss of accuracy when the boundary condition of the connecting bulkhead or deck is switched from 'adjacent' to 'similar'. All models were developed using the 'ESP-r marine' software, following the methodology presented in Chapter 4. All conditioned spaces are supplied with 30% fresh and 70% recirculated air with a volume flow rate of 8 ac/h per zone, as instructed by regulations based on minimum fresh breathable air for occupants [21]. The supplied air is conditioned to 24^{o}C before entering the spaces, as at this set point all conditioned spaces are maintained within the acceptable comfort range of indoor temperature (22^{o}C - 27^{o}C). Although real systems use PID or more advanced controllers for the operation of heating and cooling components, here the supplied air was conditioned using ESP-r's ideal controller which calculates the power requirements to keep the temperature of the supplied air in the user defined set point. In late stages of design where the performance of specific components and control loops are tested, modelling of the PID controller with ESP-r's plant simulator is necessary. To add to the complexity, the cabins designed for higher comfort levels, are equipped with a separate fan coil unit that can be controlled by the occupant. This introduces a stochastic parameter during design namely 'passenger comfort level', which might lead to different temperatures of supplied air for adjacent cabins. However, since topological decoupling during early stages of design is considered at this point, the possibility of slightly different air supply temperature between adjacent zones is not taken into consideration.

Simulations are carried out for the 'adjacent' and 'similar' cases and the power consumed to condition the air is used as the comparison measure between the different cases. As the effect of boundary conditions on power consumption is investigated, relative humidity of spaces and the supplied air was not taken into consideration since wall panels contain steel which has a very high vapour resistance value in the order of 600,000 GNs/kg/m. For each case simulations are performed for three different climatic conditions, 'cold', 'mild' and 'hot' in order to verify the assumption in extreme and mild conditions. Details for the climate files used are shown in Table 5.1. The specified files can be found in DoE's online weather database [61]. The simulations use a time step of half an hour and have a duration of one week.

Table 5-1: Weather data used in simulations.

Season	Location	Duration	File name
Cold	Ottawa, CAN	January 24-30	CAN_ON_Ottawa.716280_CWEC.zip
Mild	Firenze, ITA	April 16-22	ITA_Firenze-Peretola.161700_IGDG.zip
Hot	Guantanamo, CUB	July 21-27	CUB_Guantanamo.Bay.NAS.783670_TMY.zip

Results were compared using the coefficient of determination / R squared method. The coefficient of determination (CoD) is given by

$$R^2 = 1 - \frac{SS_{res}}{SS_{tot}} \tag{16}$$

where SS_{res} is the 'residual sum squares' which is given by

$$SS_{res} = \sum_i (y_i - f_i)^2 \tag{17}$$

In this case y_i is the power consumption to condition the cabins using the 'adjacent' boundary conditions and f_i the power consumption for the 'similar' boundary conditions. SS_{tot} is the 'total sum of squares' which is given by

$$SS_{tot} = \sum_i (y_i - \bar{y})^2 \tag{18}$$

where $\bar{y}$ is the mean power consumption for the 'adjacent' case. Values of the coefficient of determination closer to 1, show better agreement between the two sets of data which in this case means validation of the assumed boundary conditions.

In the framework of topological decoupling, connections in accommodation were initially classified according to the presence of air conditioning in the adjacent space. Therefore, the connections are divided in two wider categories: 'conditioned' and 'non-conditioned'. This division is of primary importance during the decoupling process, since assuming 'similar' boundary conditions when the adjacent space is served by the same AHU, is expected to better represent the actual systems response.

5.4 Conditioned adjacent spaces

To examine the feasibility of topological decoupling between conditioned spaces, three basic connections were considered:

- cabin – cabin in the same MVZ
- cabin – cabin in different MVZs
- cabin – corner cabin

Cabins were selected as the connected spaces for all calculations since small spaces are more sensitive to changes. More specifically, in all cases a typical exterior stateroom with a balcony was used, as specified in Chapter 4, in terms of geometry, occupancy and constructional elements.

5.4.1 Cabin – Cabin (same MVZ)

Adjacent cabins is the most common space connection found in ship accommodation and more specifically in cruise liners where usually half of the decks are cabin decks. Figure 5-1 presents the model configuration used in this methodology to check the validity of the 'similar' assumption of two adjacent cabins.

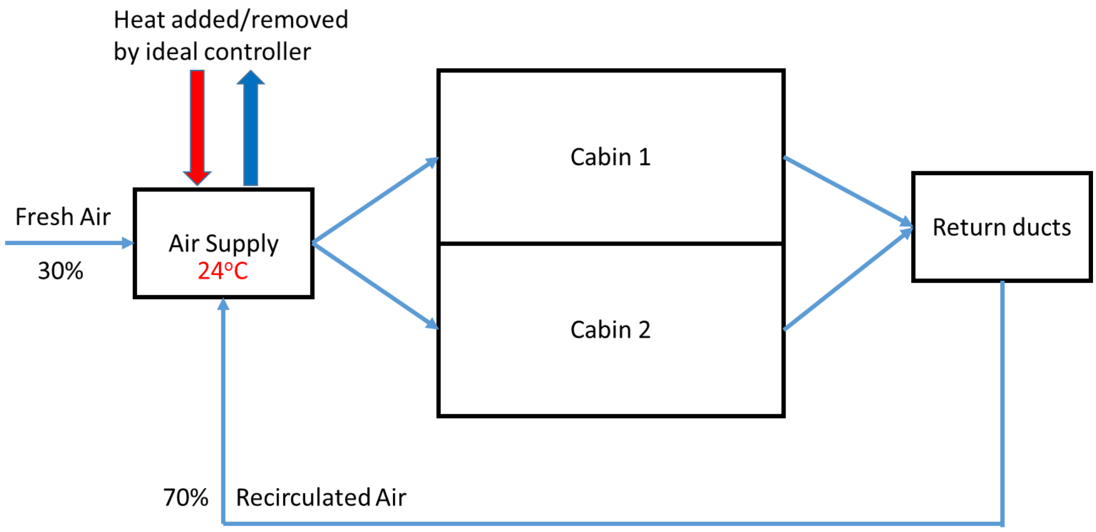


Fig 5-1. "Cabin-Cabin model configuration"

Since connected cabins can be located either on the same deck (horizontal connection) or on different decks (vertical connection) proving that cabins can be thermally decoupled during design, requires the examination of both cases, as vertical and horizontal divisions are comprised of different construction materials.

Vertical connection

In the case of vertical connection, cabins are separated by the 'ceiling internal' (or the inverted 'deck internal' for the upper cabin) construction as defined in Chapter 4 and seen in APPENDIX II. Both sliding doors leading to the balcony were assumed closed. Exhaust air from the bathroom was not modelled since exhausted non-recirculated air does not affect the thermal balance. The wireframe of the ESP-r model for this case can be seen in Figure 5-2.

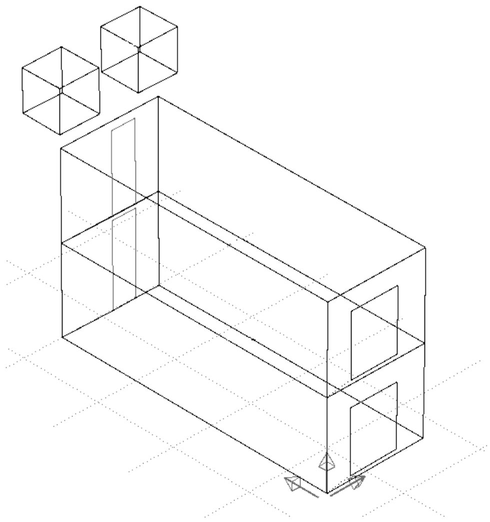


Fig 5-2. "ESP-r model of two staterooms vertically connected"

The results of the simulations are shown in Figure 5-3 below. All values of the CoD are very close to 1 therefore it can be safely assumed that cabins vertically connected can be modelled with 'similar' boundary conditions for their top and bottom surfaces.

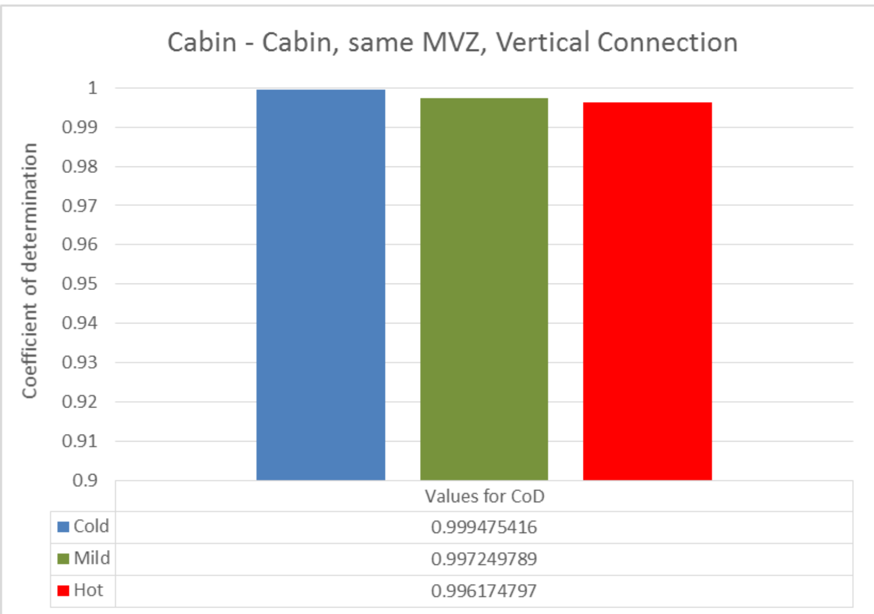


Fig 5-3. "Results for vertically connected cabins"

Horizontal connection

In this case, the staterooms are connected with the ‘Bulkhead Internal’ construction. The results as seen in Figure 5-5 show that for all periods the CoD value is very close to 1. From the two cases examined so far it can be concluded that if both adjacent cabins are conditioned, the ‘similar’ boundary condition assumption is valid and ‘similar’ boundary conditions can be assumed for thermal modelling. The wireframe of the ESP-r model for this case can be seen in Figure 5-4.

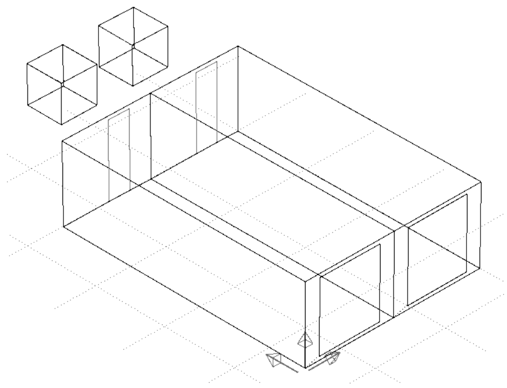


Fig 5-4. "ESP-r model of two staterooms horizontally connected"

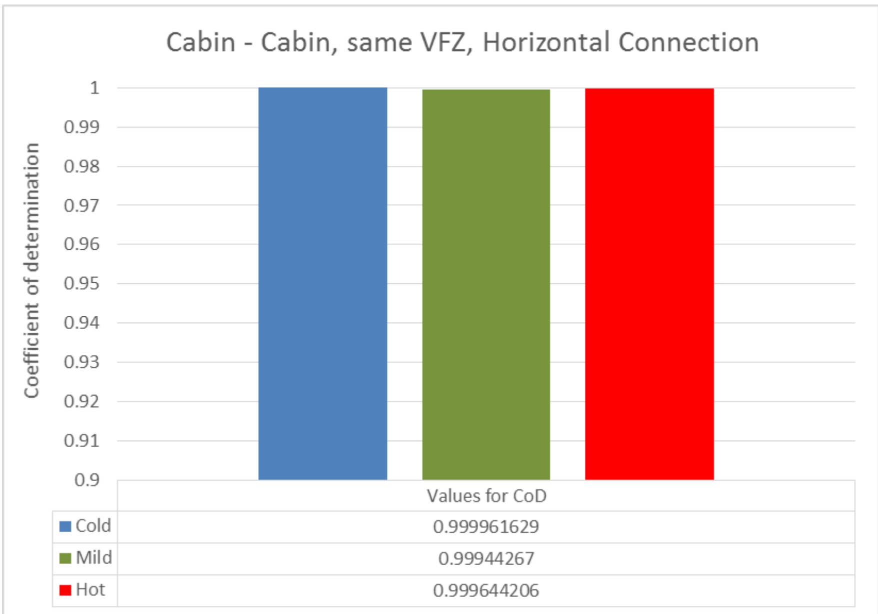


Fig 5-5. "Results for horizontally-connected cabins"

5.4.2 Cabin – Cabin (different MVZs)

Since ships are divided in vertical fire zones, several on board spaces are separated by A-60 fire rating bulkheads. To test the validity of the 'similar' boundary conditions assumption, two adjacent staterooms in different MVZs were selected as the test spaces. The ESP-r model wireframe, and modelling and simulation configuration are similar to the horizontal cabin – cabin model seen in Figure 5-4. The results presented in Figure 5-6 show values of the CoD very close to 1, which validates the replacement of 'adjacent' to 'similar' boundary conditions assumption for this case.

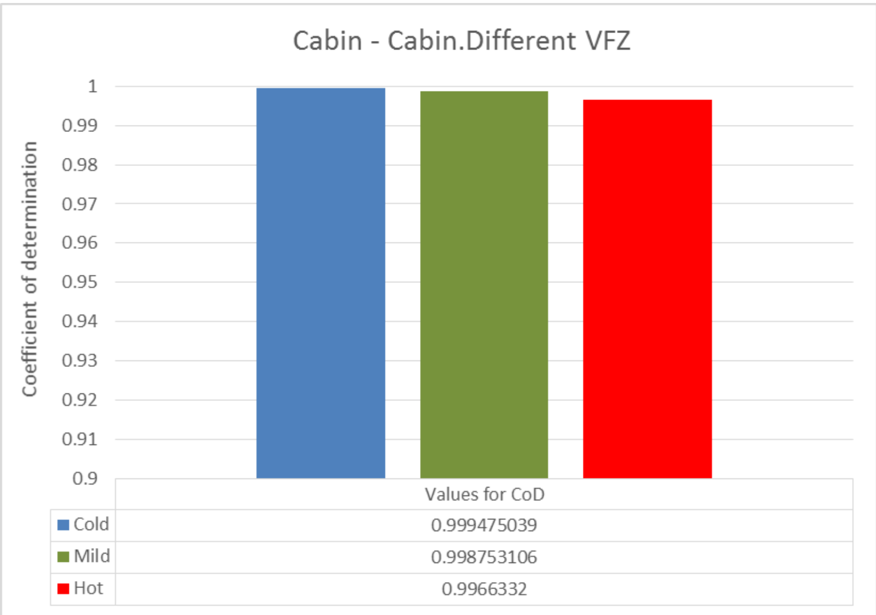


Fig 5-6. "Results for adjacent spaces in different MVZ"

5.4.3 Cabin – Corner cabin

In the framework of space topology, corner spaces show particular interest as they have two external surfaces and are therefore more sensitive to ambient conditions. Here two adjacent staterooms are selected for investigation, one of which is a corner cabin. Since ESP-r's graphical user interface does not differentiate surfaces according to their boundary condition, the ESP-r model for this case is similar to the one shown in Figure 5-4. The results of the simulations are shown in Figure 5-7 where it is clear that for this case the assumed 'similar' boundary condition is again valid.

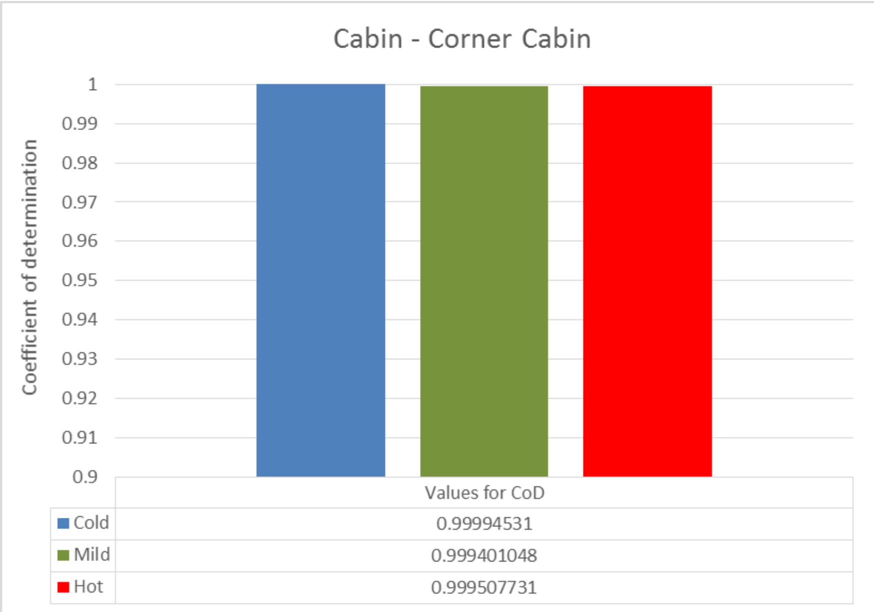


Fig 5-7. "Results for Stateroom – Corner Stateroom connection"

5.5 Conditioned – Non-conditioned spaces

Apart from living and recreational spaces that require high levels of indoor comfort, other spaces like corridors, storage spaces, laundry and drying rooms, and machinery rooms are might not be supplied with conditioned air. As a result these spaces are likely to have great temperature differences with adjacent conditioned cabins, especially in extreme ambient conditions. Non-conditioned spaces are divided in three main categories according to their usage:

- corridors
- storage/utility spaces
- engine room

5.5.1 Cabin – Corridor

Since most corridors are not directly supplied with conditioned air, they are conditioned by the supplied air from the cabins after it has been exhausted through the door grill or undercut. A typical airflow configuration for cabins and corridors is shown in Figure 5-8. Conditioned air is supplied to the cabins where its temperature is either raised or reduced and is then directed to the corridor. Air is then recirculated, mixed with fresh air and subsequently supplied to the accommodation block.

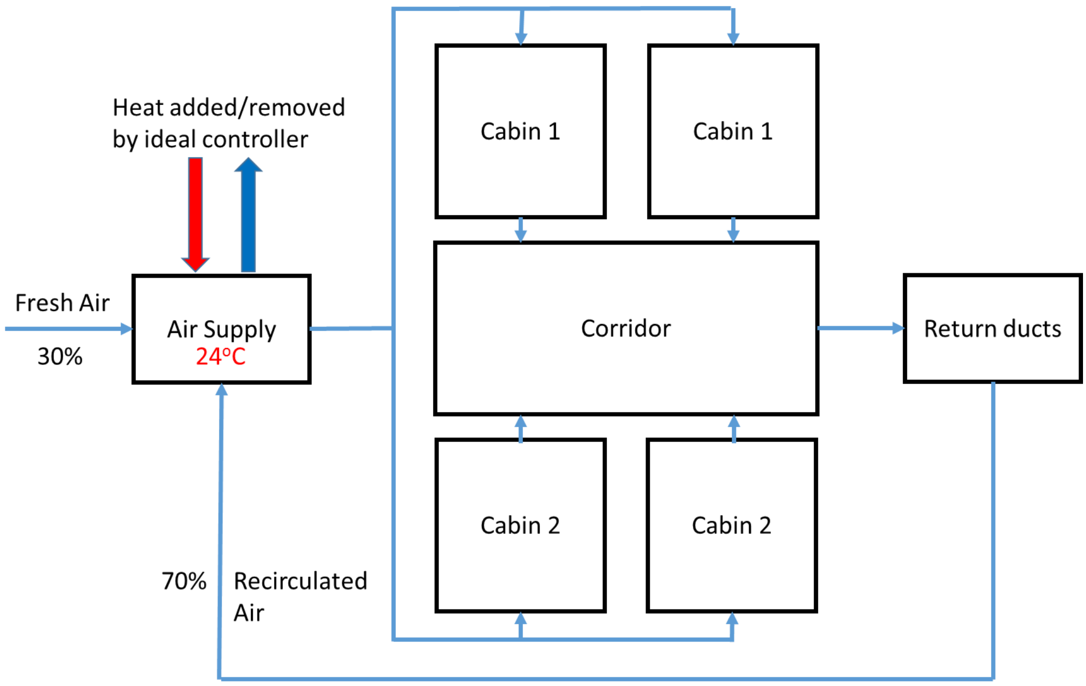


Fig 5-8. "Cabin – Corridor model configuration"

The ESP-r model for the aforementioned configuration was developed, the wireframe of which can be seen in Figure 5-9. The volume flow rate to the cabins is again 8 ac/h and the top, bottom and side surface boundaries have been assumed similar.

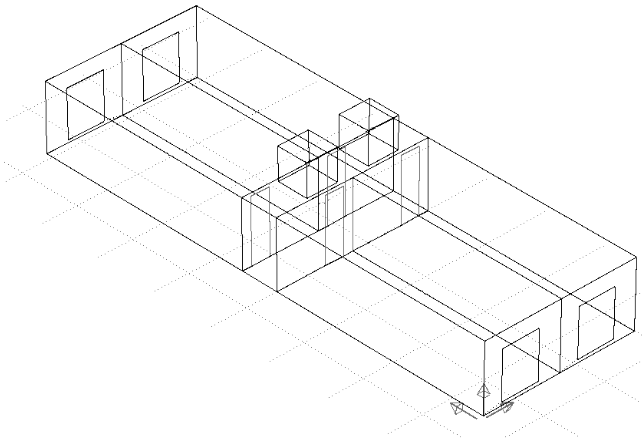


Fig 5-9. "ESP-r model of Cabin – Corridor connection"

The simulation results presented in Figure 5-10, show values of CoD very close to 1. As a result boundary conditions of the connecting surfaces between cabins and corridors can be confidently replaced with 'similar'.

Taking a closer look at the results of the simulation, Figure 5-11 shows that the temperature of the south facing cabins is higher due to solar radiation, and that the temperature in the corridor has a value very close to the average temperature of cabins. The effect of the recirculated air from the cabins to the corridor helps to condition the corridor and validates the 'similar' assumption in this case.

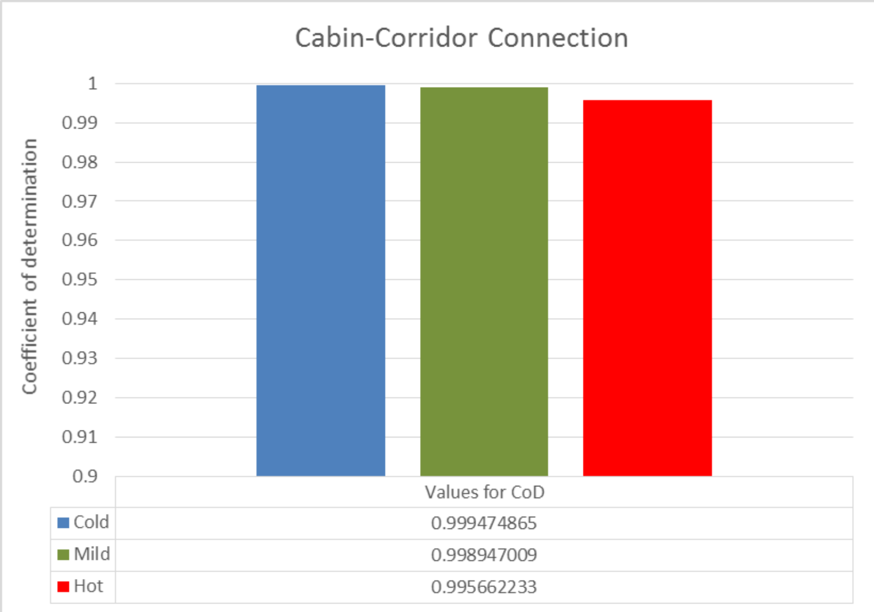


Fig 5-10. "Results for Cabin – Corridor connection"

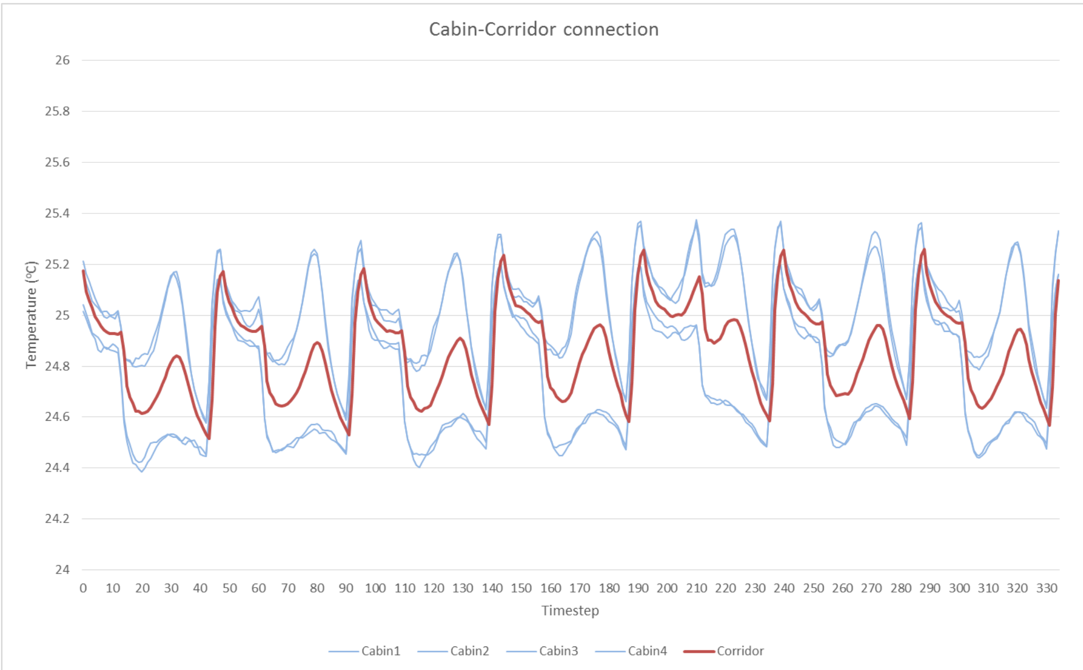


Fig 5-11. "Comparison of corridor and cabin temperature"

5.5.2 Cabin – Storage/Utility Space

Since indoor conditions of storage spaces are not of great importance, bulkheads in such spaces are not thermally insulated and no glazing is present. The cabin – storage room connection is most likely to be found in cargo ship superstructures. Therefore, a cargo cabin is selected as the conditioned space and an adjacent corner storage space as the non-conditioned. A topological representation of the configuration is shown in Figure 5-12.

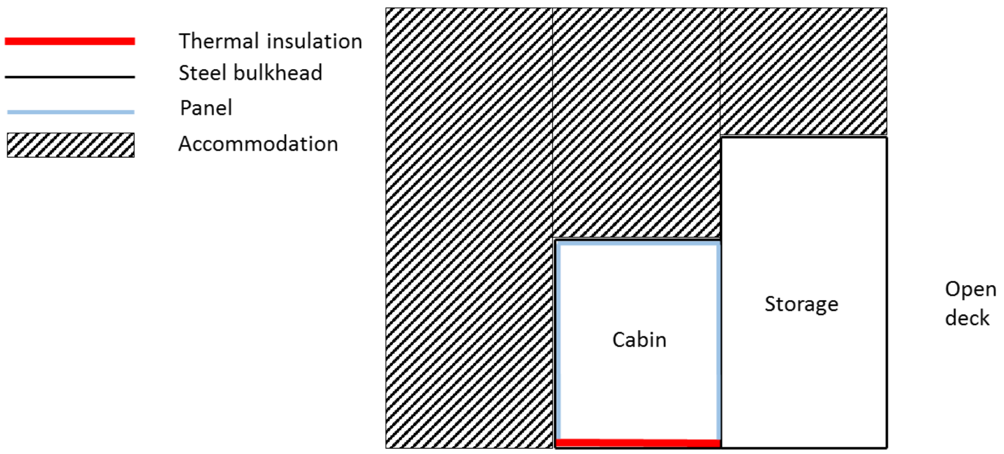


Fig 5-12. "Insulation in Cabin – storage space connection"

The CoD presented in Figure 5-13 shows considerable differences especially for winter extreme conditions. Comparing the temperatures of the storage space with the conditioned cabin in Figure 5-14 it is obvious that replacement of adjacent conditions with similar in this case is not acceptable, and uninsulated, non-conditioned spaces should always be modelled explicitly.

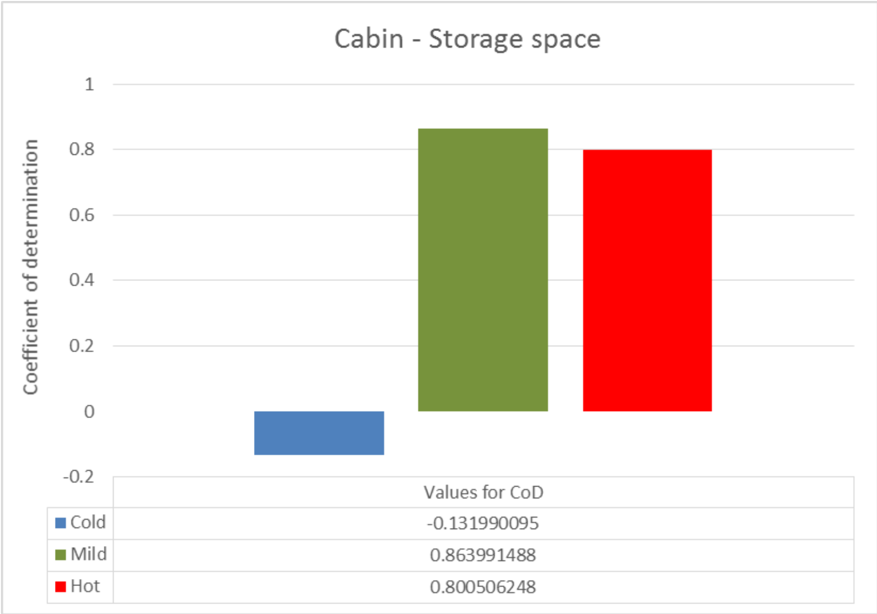


Fig 5-13. "CoD for Cabin – Storage space connection"

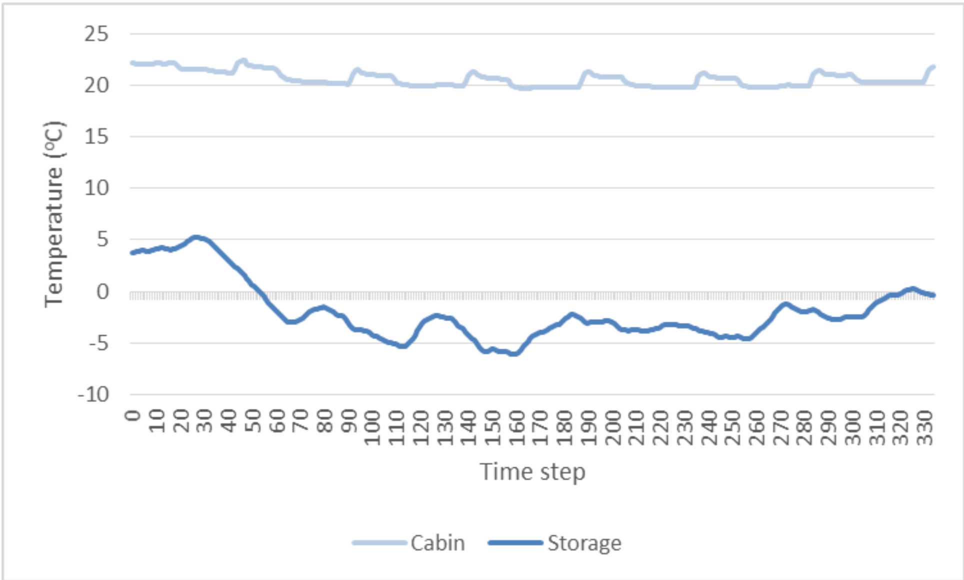


Fig 5-14. "Comparison of temperatures of cabin and non-conditioned storage space"

5.5.3 Cabin – Engine Room

Conditions in engine rooms of diesel powered vessels are dictated by the heat radiation from machinery. Classification society rules often specify an engine room air temperature range of 0°C - 55°C as the basis for the design of the engine room components. Although conditioned air is not supplied, engine rooms are ventilated with fresh ambient air at a rate of 20 to 40 ac/h. As a result, the average temperatures in engine rooms range from 40°C -45°C. Spaces in contact with the engine room are usually be found on the deck above the engine room. Therefore, to check the validity of the 'similar' boundary conditions, an interior cabin was modelled and its floor was exposed to constant temperature of 45°C to represent engine room temperature. The results of the simulations were then compared with the 'similar' boundary assumption for the same surface. According to regulations, the deck separating the machinery spaces with accommodation needs to be an A-60 class construction, therefore 'Deck Internal A60 Fire rating' construction was used.

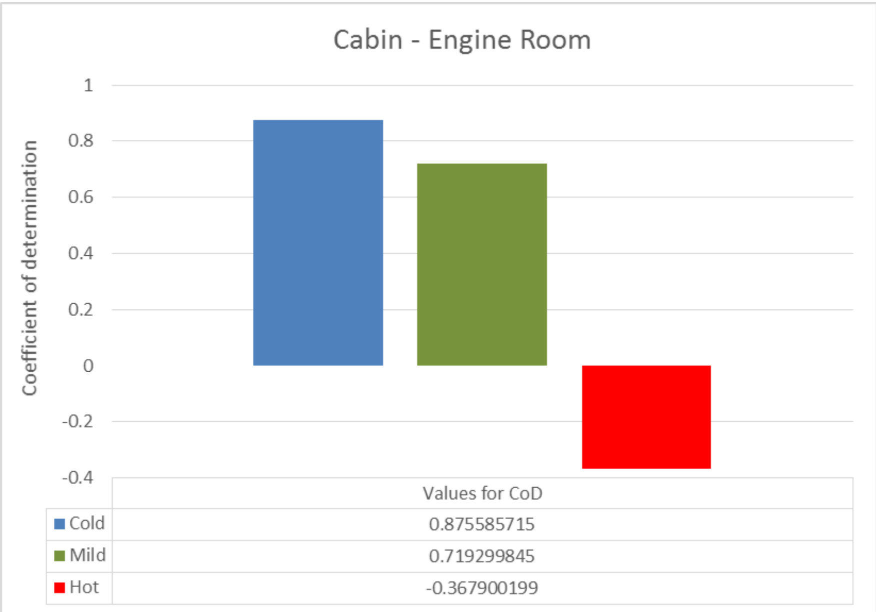


Fig 5-15. "CoD for Cabin – Engine Room space connection"

The results presented in Figure 5-15 show considerable differences, especially for the cooling period. Therefore, 'similar' boundary conditions are not to be used in this connection type.

5.6 Boundary condition modelling guidelines

A very detailed thermal model with uncertain boundaries is bound to derive uncertain results. Taking a look at the results in this chapter, it is obvious that arbitrary assumptions about boundary conditions of spaces during thermal modelling are not recommended and might lead to wrong conclusions about heat transfer through the bounding surfaces. This in turn, would lead to wrong design decisions concerning equipment sizing and occupant comfort. In an attempt to formalise the assumptions about boundary conditions, general guidelines were developed based on the results of the investigation of topological decoupling. The following guidelines will serve as a reference for ship accommodation design.

1) *When the outermost side of a surface of a conditioned space is exposed to an adjacent conditioned space, the boundary condition of this surface can be safely assumed similar to the conditions of the modelled space.*

This statement encompasses all pairs of adjacent conditioned accommodation spaces and is valid regardless of the topology of the adjacent space and the material that divides the two spaces. This allows for the investigation of individual spaces or groups of spaces. Single space modelling can be used in local FCU sizing and CFD calculations for the vertical temperature difference and maximum air velocity that is required by comfort class regulations [67].

2) *When the outermost side of a surface of a conditioned space is exposed to a corridor, the boundary condition of this surface can be safely assumed similar to the conditions of the modelled space.*

The combination of statement 1 and 2 allows the individual investigation of blocks of cabins, and limits the requirements to model the corridor and the airflow from the spaces towards it. This will also facilitate the investigation of space grouping in the next chapter that will further simplify the design process.

3) *When the outermost side of a surface of a conditioned space is exposed to a non-conditioned space, no safe assumption can be made for its boundary condition and the adjacent space should be modeled explicitly.*

Since non-conditioned spaces are not insulated their thermal conditions highly depend on their topology (sides exposed to the weather), size (area of the sides exposed) and use (presence of machinery, personnel and lighting). The variety of non-conditioned spaces does not favour their categorisation, therefore each connection with such a space should be treated separately. As for spaces in contact with the engine room, a static boundary condition at a temperature between 37°C – 40°C might be acceptable, however, the engine room should be modelled to acquire average temperatures during operation. Modelling the mechanical equipment along with the dissipated heat during operation is out of the scope of this work and has been left for future work.

The above statements summarise the findings of this chapter and will be used in the course of the thesis to facilitate further calculations and case studies.

5.7 Closure

This chapter focused on the simplification of the thermal modelling with the investigation of the validity of assumed boundary conditions for the most commonly met space configurations in ships. Calculations for conditioned spaces showed that modelling of adjacent conditioned spaces and corridors can be skipped by assuming boundary conditions. On the contrary, boundary conditions of common surfaces of cabins with non-conditioned storage spaces and engine rooms cannot be assumed 'similar' since the loss in accuracy is significant. Findings of this chapter are formalised in three statements that act as a reference for future designs and are a necessary step for the group representation of areas in the accommodation which is considered in the next chapter.

6 SPACE GROUPING DURING DESIGN

6.1 Preamble

In an attempt to further simplify thermal modelling, especially during design, this chapter focuses on the group representation of ship accommodation spaces. Representative groups of spaces of cargo and passenger vessels are modelled with 'ESP-r marine', and thermal zones of each model are merged in consecutive steps until the whole area of interest is represented by a single thermal zone. The uncertainty during the reduction process is calculated at each discrete step of the process, quantifying the loss of accuracy and the extent to which grouping can be performed.

6.2 Merging of thermal zones

In the framework of the simplification of accommodation modelling especially during concept design, the possibility to reduce the number of zones in a thermal model while maintaining its total volume was investigated. Reducing the number of zones, would lead to reduced modelling effort and faster simulation execution times. Apart from the obvious simplification of the design process and sizing of HVAC systems, space grouping would make consideration of the HVAC system within an integrated ship energy model more straightforward and easier to implement. To test the feasibility of such an assumption, the loss of accuracy during space merging has to be investigated first.

6.2.1 Loss of accuracy

In this work, merging two zones is regarded as removing the connecting division between them and representing them as a single zone with the same perimeter geometry, initial constructions, boundaries and an air volume equal to the sum of their original volumes. When two thermal zones are merged into one, accuracy is lost for a number of reasons. Firstly, since the internal division connecting the zones is not modelled, the heat that was to be stored in the material of the division, is supplied to the merged zone and increases the power demand to condition the air. The impact of this effect depends on the thickness of the removed bulkhead, the heat capacity of the materials and the ambient conditions. During hot months more heat will be released to the air, therefore more accuracy is expected to be lost. This is why space grouping is investigated in cold, mild and hot climates.

Apart from heat storage issues, the absence of connecting bulkheads affects the internal long wave and external short wave radiation exchange in the model. By removing a connecting bulkhead, new pairs of surfaces are formed which leads to new radiation view factors between internal surfaces. Concerning short wave processes, solar radiation that entered the space and impinged on the connecting bulkhead, will now continue to travel until it hits the next opaque surface.

Finally merging of a conditioned with a non-conditioned zone, leads to unwanted conditioning of air which, in turn, results in excessive calculated power consumption. This phenomenon is expected to be more severe if the non-conditioned space in not thermally insulated and heat is lost or gained at higher rates.

6.2.2 Methodology

The uncertainty during the reduction process was investigated by merging adjacent spaces in consecutive steps until an area was represented by a single thermal zone. At each step of the process a simulation was performed and the results were compared with the fully detailed model. The comparison measure selected was again the power to condition the zones and the derived results at each step of the processes were compared using the previously described 'coefficient of determination' method. In this case, y_i is the power consumption of the first fully detailed model and f_i is the power consumption at each step of the reduction process. A representation of the reduction process is shown in Figure 6-1.

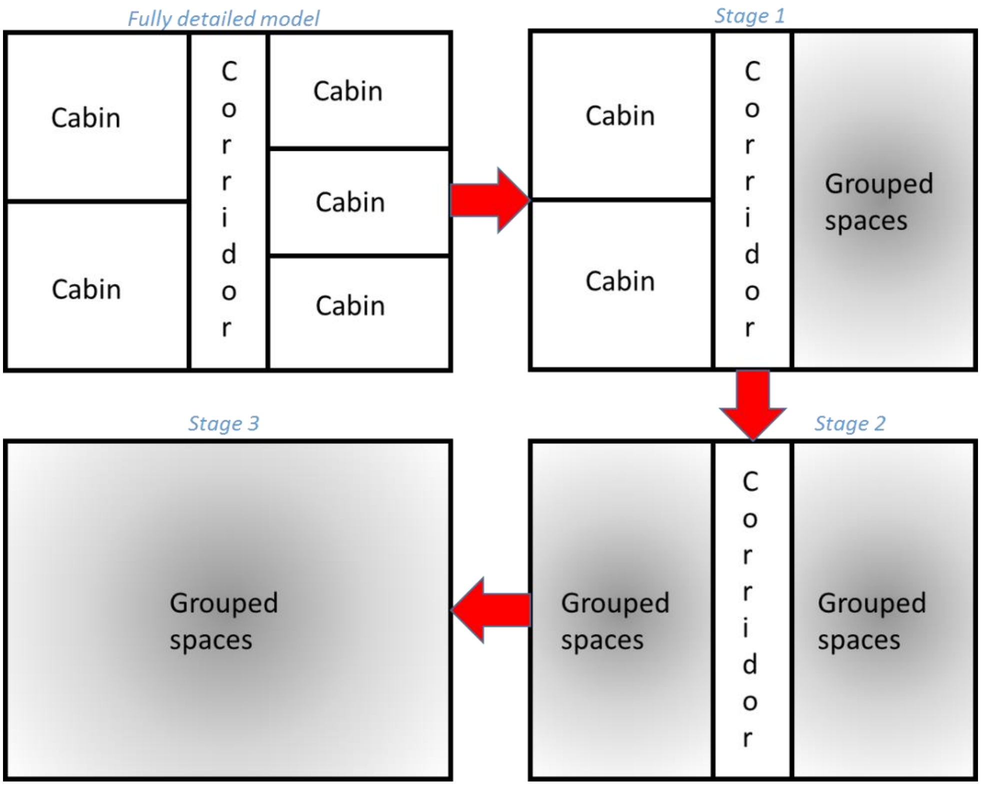


Fig 6-1. "Representation of space grouping methodology"

Like in topological decoupling, all the conditioned zones are supplied with air conditioned to 24°C and the total supplied air flow is determined using 8 ac/h for each conditioned space. The feasibility of the space grouping was examined for cargo and passenger ships. For each case, typical deck configurations were selected and investigated.

Boundary conditions of top and bottom surfaces (ceilings and decks) of all zones were assumed 'similar', based on the results of the previous chapter. When spaces were merged the sum of the individual supply and exhaust flow rates, and heat gains were assigned to the merged zone. Regarding construction materials, the outer bulkheads of the final single zone model are identical to the original construction materials. At each step of the reduction process, simulations were performed for cold, mild and hot climates and the CoD in reference to the fully detailed model (Stage 1) was calculated.

6.3 Cargo ship

Classifying decks by their size, the accommodation block of cargo ships is comprised of 3 different types of decks:

- decks on the bottom of the superstructure containing lower ranking cabins, the galleys, and utility and recreational spaces,
- higher ranking cabin decks, and
- the bridge.

Since the bridge is usually a single space, to allow for 360° of vision around the ship, it cannot be further simplified. For the remaining deck types a typical deck found in conventional cargo ships was selected and the simplification process was performed.

6.3.1 Utility and recreational spaces, and lower ranking cabin decks

After reviewing several accommodation blocks of cargo ships, the configuration shown in Figure 6-3 was selected for investigation. The ventilation line diagram of the selected deck can be seen in Figure 6-2 below.

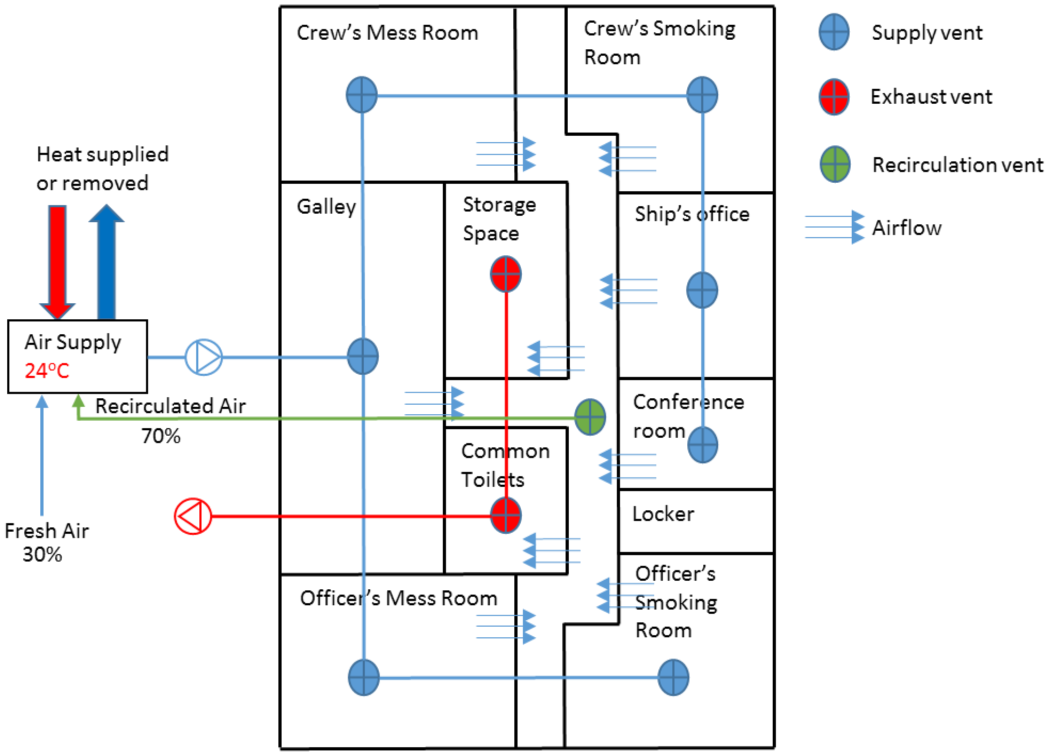
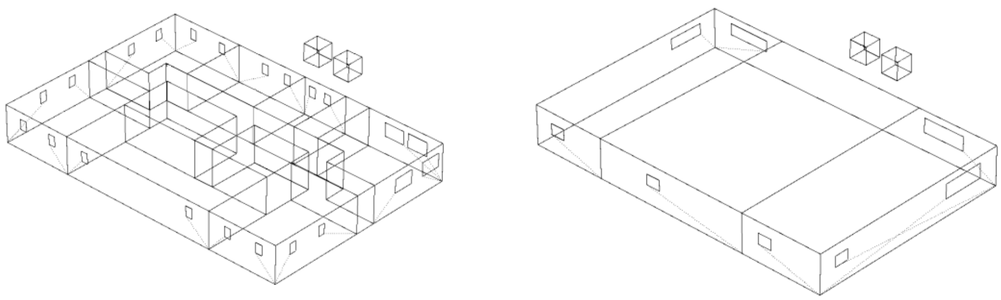


Fig 6-2. "Ventilation diagram for utility deck"



(a) (b)

Fig 6-3. "ESP-r model of utility spaces (a) stage1 (b) stage 10"

In this case the reduction process was performed in 10 stages.

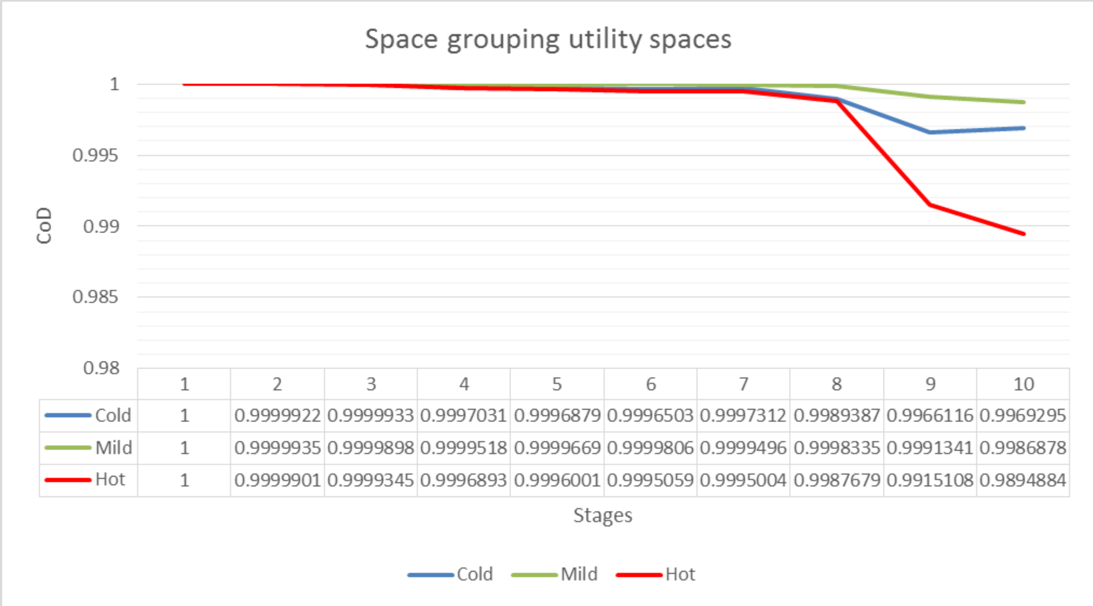


Fig 6-4. "CoD in different stages of space grouping for utility deck"

The results presented in Figure 6-4, show very high CoD values for all climates. For mild and cold ambient conditions there is barely any accuracy lost while for the hot climate the results are less accurate in the last stages of the simplification process. This is due to the fact that as material is removed, the heat that was to be stored in the divisions is released to the air, thus increasing the indoor temperature. As seen in Table 6-1 more cooling power is required for hot ambient conditions, as the reduction process is progressing. However, a CoD value of 0.989 is an acceptable value, therefore space grouping is recommended both for cooling and heating calculations.

Table 6-1: Total cooling power of deck for hot climate.

Stage	1	2	3	4	5	6	7	8	9	10
Cooling power (W)	-4104	-4106	-4117	-4137	-4144	-4145	-4147	-4175	-4210	-4229

6.3.2 Higher ranking cabin decks

The ventilation diagram of the selected deck for the reduction process can be seen in Figure 6-5.

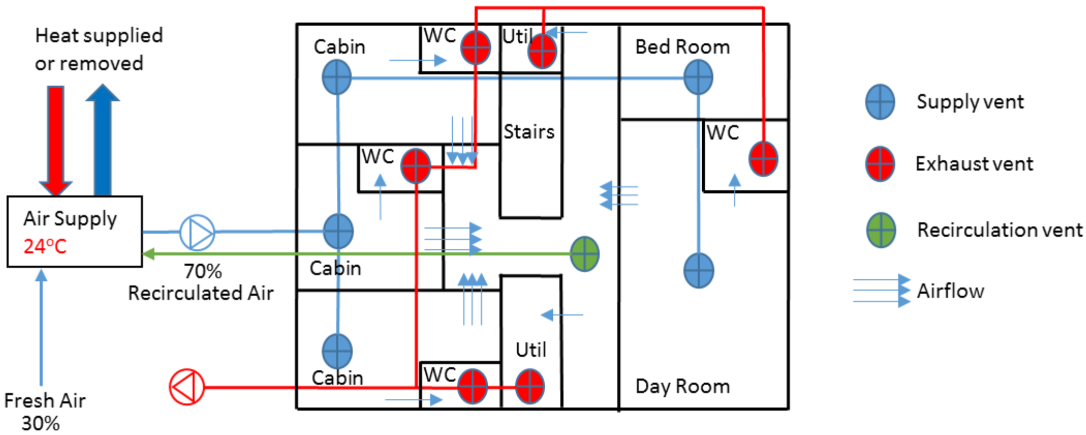


Fig 6-5. "Ventilation diagram for typical accommodation deck"

In this case space grouping was performed in 12 stages. The results of the simulations are shown in Figure 6-6 below.

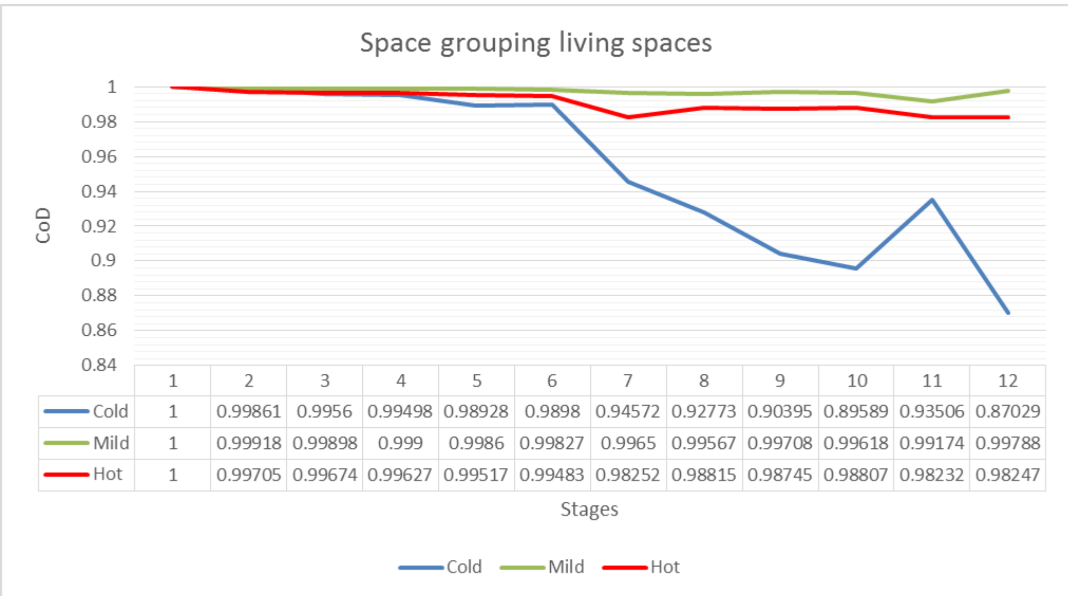


Fig 6-6. "CoD in different stages of space grouping for living spaces deck"

Although space grouping shows good results for warm and mild ambient conditions the results for the cold period are not equally encouraging. The transition from the 6th to the 7th stage and onwards reduces the accuracy of the results considerably, up to 4.4%. As shown in Figure 6-7 during this transition a cabin is merged with a small utility space.

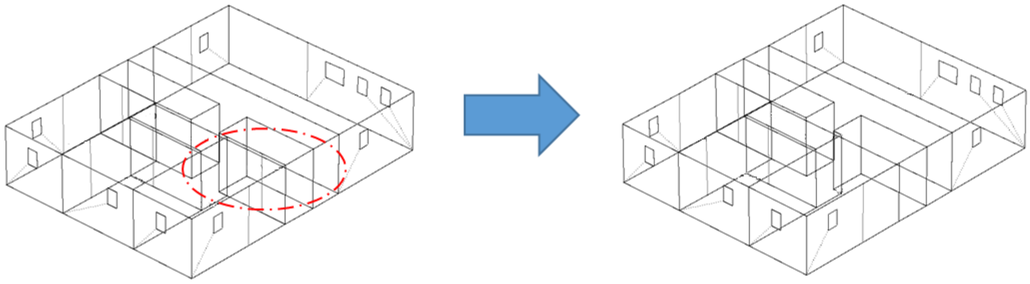


Fig 6-7. "Transition from Stage 6 to Stage 7"

The steep loss of accuracy is caused due to two reasons. Firstly, the utility space is not supplied with conditioned air. Therefore, its indoor conditions are analogous to the ambient temperature. Secondly, the external bulkhead of the space is not insulated, which magnifies the effect of the climate on the indoor conditions. This excessive heat that is either lost or gained increases the power demand to condition the air. The loss in accuracy is more severe for cold conditions since the temperature difference between living spaces and the environment is higher as shown in Figure 6-8.

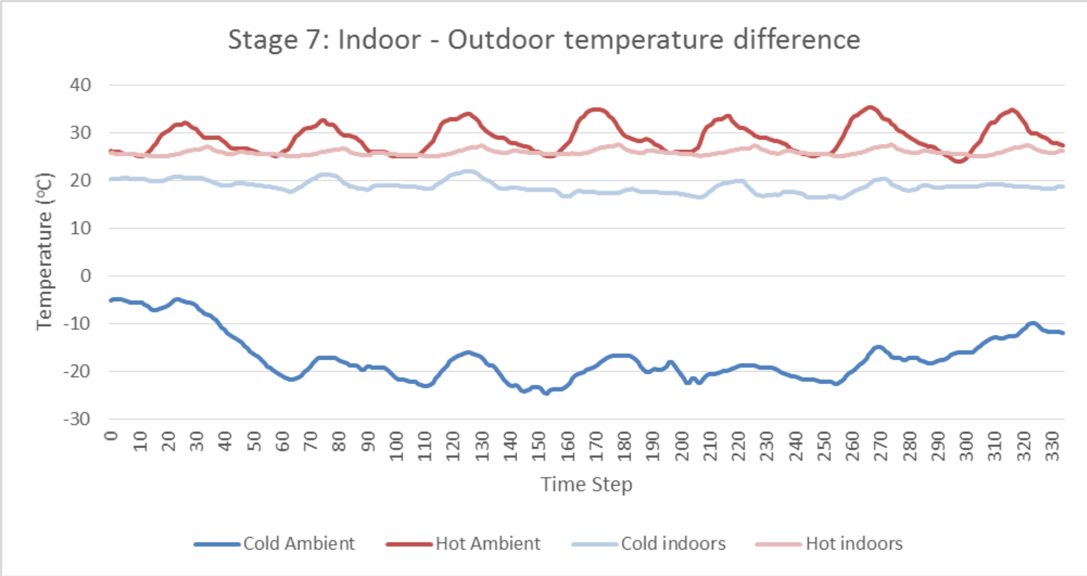


Fig 6-8. "Outdoor and indoor temperatures for living and utility merged space"

To investigate the effect of non-insulated external surfaces during the reduction process, a simulation was carried out where all the external surfaces were thermally insulated. Comparing a 'box' model insulated throughout its perimeter with the fully detailed model (stage 1), gives CoD values very close to 1 as shown in Table 6-2.

Table 6-2: CoD for fully detailed and fully insulated box model.

Cold	Mild	Hot
0.998267248	0.994633873	0.992996736

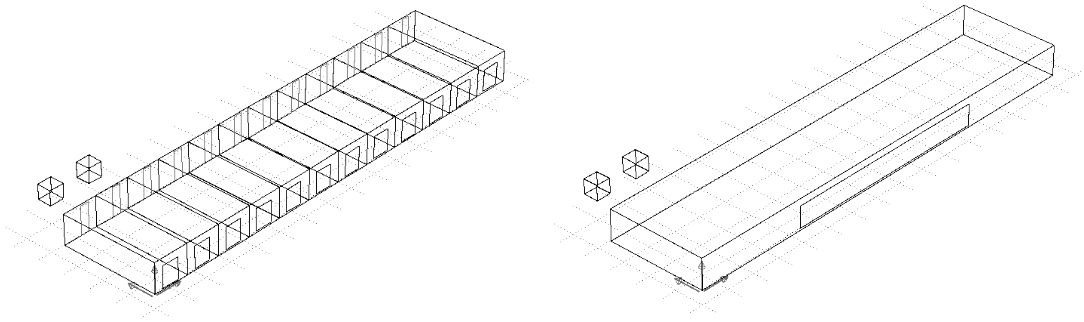
Although further investigation might be necessary to quantify the effect of the size, level of insulation and area of exposed surfaces of the non-conditioned space, at this stage it is safe to assume that conventional accommodation decks in cargo ships can be represented as single spaces during concept design as long as non-insulated external constructions of non-conditioned zones are replaced by the 'Bulkhead External Thermal Insulation' construction.

6.4 Passenger Ship

Although there is a wide range of spaces in the accommodation of passenger vessels and especially in cruise ships, in this work investigation of space grouping is restricted to cabin decks. The reason is twofold: firstly the majority of spaces found in passenger vessels are cabins, and, secondly, cabin decks have a high zone density. Two spaces were selected for investigation. A set of exterior adjacent cabins and a cabin deck of a MVZ.

6.4.1 Group of exterior cabins

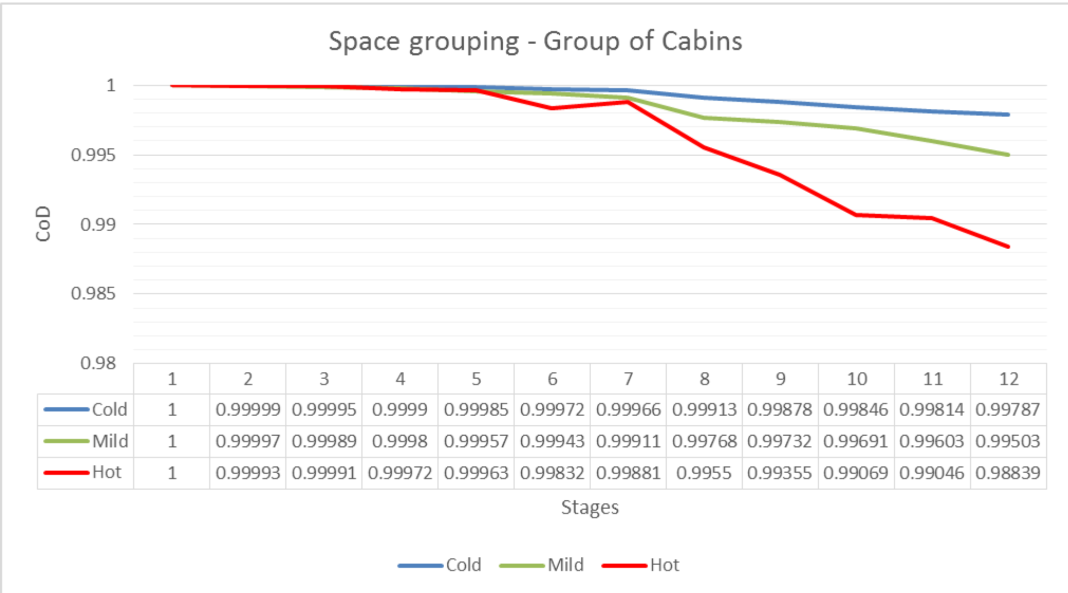
For this case, a group of 12 exterior adjacent cabins occupying one deck of a MVZ were selected. All staterooms are bounded by a corridor from one side, therefore boundary conditions for the internal surfaces can be assumed 'similar'. The side surfaces of the first and last cabin of the group were assumed to be in contact with another conditioned cabin on a different MVZ therefore 'similar' boundary conditions were also assumed. Finally top and bottom surfaces were also assumed 'similar' as they are in contact with other conditioned staterooms. The wireframe of the ESP-r model is shown in Figure 6-9.



(a) (b)

Fig 6-9. "ESP-r model of group of cabins (a) stage1 (b) stage 12"

As shown in Figure 6-10 results of the simulations are promising. The least accuracy is lost during the cooling period, as removing material reduces heat storage and increases heat that is released in spaces. Loss of accuracy is not linear which is most likely caused due to the merging of glazing during the reduction process and the newly formed radiation view factors of surfaces. In any case, the high values of CoD imply that grouping representation of adjacent cabins in the same MVZ yields to minor loss of accuracy.

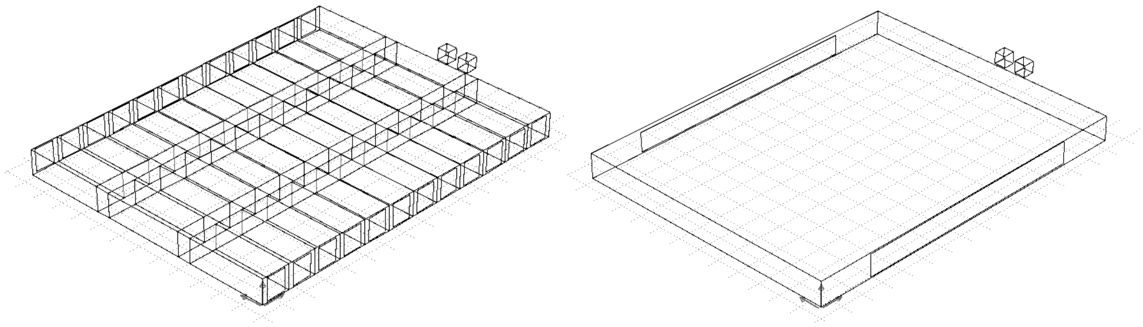


	1	2	3	4	5	6	7	8	9	10	11	12
Cold	1	0.99999	0.99995	0.9999	0.99985	0.99972	0.99966	0.99913	0.99878	0.99846	0.99814	0.99787
Mild	1	0.99997	0.99989	0.9998	0.99957	0.99943	0.99911	0.99768	0.99732	0.99691	0.99603	0.99503
Hot	1	0.99993	0.99991	0.99972	0.99963	0.99832	0.99881	0.9955	0.99355	0.99069	0.99046	0.98839

Fig 6-10. "CoD in different stages of space grouping for group of cabins "

6.4.2 Cabin deck

Based on the confident results of the group of cabins, the simplification process was applied to a whole section of a cabin deck comprised of three rows of cabins. Two of the cabin rows are external and are assumed to be facing north and south respectively, and one row is internal. The north and internal cabin rows exhaust the air to the corridor between them, which is then recirculated to a return duct and mixed with the air exhausted from the south cabin row. The wireframe of the ESP-r model is shown in Figure 6-11.



(a) (b)

Fig 6-11. "ESP-r model of cabin deck (a) stage1 (b) stage 8"

In this case, there seems to be a great difference for different climates as shown in Figure 6-12. Although for cold and mild conditions there is a slight loss of accuracy, during hot periods the CoD is reduced to 0.96 which might still be a reasonable value for concept design. However, a more detailed model might be required in the final stages of design of cooling equipment.

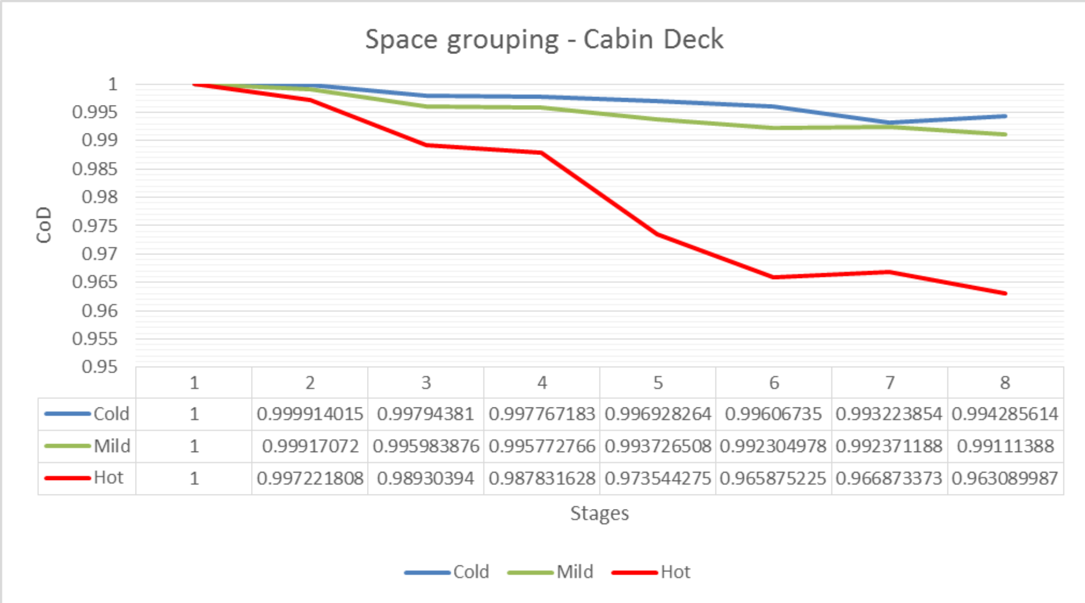


Fig 6-12. "CoD in different stages of space grouping for cabin deck"

6.5 Space grouping guidelines

Similarly to topological decoupling in the previous chapter, space grouping is acceptable under conditions and should not be arbitrarily applied to accommodation spaces during thermal modelling. Care should be taken when space grouping is used for cooling calculations, since simulation results showed a greater loss of accuracy for hot ambient conditions. The findings of this chapter are compiled in the two following formalised statements that will serve as guidelines for accommodation design.

<u>*Cargo ships*</u>

It is acceptable to model an accommodation deck of a cargo ship as a single space for heat load calculation and component sizing purposes providing that:

- *The volume of the single space model is equal to the total volume of the individual spaces.*

- *The supply airflow volume flow rate of the single space model is equal to the sum of the supply volume flow rate of the individual spaces.*
- *The heat gains of the single space model is equal to the sum of the heat gains of the individual spaces.*
- *The total glazing area at each surface of the single space model is equal to the total glazing area of each side of the original model.*
- *Uninsulated external surfaces must be modelled as external insulated constructions.*

Although the accommodation decks in cargo ships are comprised by similar spaces, the layout of each deck may vary between different ships. The decks selected for investigation in this work are indicative of most ships, however, if further quantification of accuracy is required, the same calculations can be performed for different accommodation layouts with alternative total supply airflow, occupancy, lighting, infiltration, etc.

<u>Passenger ships</u>

It is acceptable to model a MVZ of a cabin deck of a passenger ship as a single space for heat load and component sizing purposes providing that:

- *The volume of the single space model is equal to the total volume of the individual spaces.*
- *The supply airflow volume flow rate of the single space model is equal to the sum of the supply volume flow rate of the individual spaces.*
- *The heat gains of the single space model is equal to the sum of the heat gains of the individual spaces.*
- *The total glazing area at each surface of the single space model is equal to the total glazing area of each side of the original model.*

It has to be noted that the previous statement only applies to cabin decks. Although dining rooms usually occupy one MVZ of a deck, thermal modelling of these spaces might require further spatial discretisation due to the complex dynamics created by heavy occupancy, lighting and HVAC equipment.

6.6 Closure

Following the mind set of simplifying the thermal modelling of accommodation spaces, this chapter demonstrated to what extent selected groups of spaces can be modelled as single thermal zones. External conditions were found to significantly affect the loss of accuracy during space grouping and more specifically care should be taken when merging conditioned with non-conditioned spaces during the heating period and removing material during the cooling period. Results showed that space grouping can be used to size HVAC components and the findings were compiled in the form of two formalised statements that will serve as design guidelines.

7 CONCEPTUAL DESIGN

7.1 Preamble

The aim of this chapter is to propose a design methodology for the accommodation of commercial ships based on dynamic energy modelling and demonstrate its application. Two fictional design scenarios are created, which serve as the basis for the development of two accommodation models. All calculations are performed with 'ESP-r marine'. Simulation results are presented and decisions are made for the sizing of the installed components.

7.2 Design methodology

With the marinised ESP-r modelling tool at hand and modelling guidelines available, the design of commercial ship accommodation with the use of dynamic energy simulation is now feasible. In an attempt to facilitate its application, a design methodology is proposed here that is demonstrated in two case studies later in the chapter. Design for both vessels follows a similar methodology and is initially divided in two stages: early and detailed design.

7.2.1 Early design

During early design, the primary objective is to acquire rough estimations about the power requirements for the provision of comfort in conditioned spaces. Changes in materials and constructions cannot be currently considered since they are dictated by fire safety, stability and structural requirements. All accommodation spaces are modelled with 'ESP-r marine', following the topological decoupling and space grouping guidelines of

Chapters 5 and 6. Once the geometry, constructions and heat gains have been modelled, an airflow network is defined that represents the HVAC system. Components of the HVAC network are represented by thermal zones that condition the air according to an ideal controller that keeps the temperature at 24^{o}C. Each zone is supplied with a mix of fresh and recirculated air at a 30% - 70% ratio, the volume flow rate of which, is defined by the 8 air changes per hour rule. Since ESP-r's airflow network does not allow modelling of the air as a two-phase fluid, condensation of air vapour in cold temperatures cannot be represented. Therefore, humidity control is not considered at this stage. This will be included later during detailed design.

Once the model is set up, simulations are performed for extreme hot and cold conditions. Even when the area of operation of the vessel is very well defined, these calculations offer an initial range for the power demand of the system and allow the designer to quantify the power requirements to safeguard against any external conditions. The next step is to develop indicative yearly climate profiles of the expected route and simulate the energy performance for the anticipated ambient conditions. Results of the simulations derive indicative variations for the power demand of HVAC components during extreme and expected weather. These will serve as initial estimations during the detailed design stage.

It should be noted that when all spaces are served by a single AHU and no local air conditioning is available, which is the case for most cargo ships, it is necessary to maintain similar temperatures in all conditioned zones. Failure to achieve this, leads to corrective actions by the occupants (e.g. change of the local supply diffuser area, complaints for discomfort and change of the central heating/cooling set point) that will change the balance of the system and force it to operate sub-optimally.

7.2.2 Detailed design

During this stage, the airflow network and ideal controls are replaced by plant component modelling and real control strategies. The plant component network is comprised of HVAC components (fan, heater, cooler, humidifier and ducts) that are controlled individually and are initially sized, based on the findings of the early design stage. Both during early and detailed design, the actual length of the ductwork along with the flow resistance in the HVAC system are not modelled. Instead, the supply and return airflow are imposed by modelling fans as constant volume flow rate components. Exact airflow modelling would necessitate modelling the resistance from ducts and junctions, infiltration/leaks from cracks and openings, and representation of the fan as a pressure / flow rate curve. This, in turn, would derive the volume flow rate and pressure in different parts of the system after a balance has been achieved. Although this is feasible with ESP-r's airflow network, design and optimisation of the HVAC duct system and airflow speed, are out of the scope of this work and have been left for future research.

7.2.3 Control

HVAC components can be controlled by a variety of controllers ranging from simple (e.g. on/off, outside compensation temperature) to more intelligent (e.g. PID, optimum start). Due to its large application in the HVAC industry, a recursive[3] PID controller is selected here. Different control strategies can be investigated, since ESP-r comes with built-in control functions. Detailed information about control modelling in ESP-r can be found in MacQueen [41].

In order for a PID controller to function, the following parameters must be set:

- Maximum and minimum power output of the controlled component.
- Set point, which depending on the controlled component can be temperature, flow rate, or a percentage of relative humidity.
- The proportional gain constant 'Kp', which multiplies the current error value between the sensed value and the set point.
- The integral gain 'Ki', which multiplies the contribution of the magnitude of the error and the duration of the error.
- The derivative gain 'Kd', which multiplies the derivative term calculated by determining the slope of the error over time, and gives the accumulated offset that should have been corrected previously.

Tuning a PID controller is a non-trivial task and has been a research subject for several years. PID controls are very sensitive to small changes that can easily lead to instabilities of the controlled parameters, such as consecutive extremes that might, in turn, create errors and terminate the simulation. Correct selection of the controller parameters requires some sort of optimisation. The optimisation objectives in this case would be the

[3] Recursive algorithms are characterized by the calculation of the current manipulated variable u(k) based on the previous manipulated variable u(k-1), and correction terms.

minimisation of power consumption and maximisation of occupant comfort in accommodation spaces. ESP-r does not currently have an integrated optimiser for the parameters of the controller, therefore the simple method of Ziegler–Nichols was used to define the parameters while achieving stability and indoor comfort. Fine tuning and optimisation of the controllers is out of the scope of this work.

7.2.4 Design decisions

In the framework of performance-based design, this methodology does not set thresholds that define a good or acceptable design. On the contrary, based on the results of the detailed simulation, the designer can make decisions depending on ship specific objectives. One of the decisions that have to be made is whether or not to size equipment in order to safeguard against extreme weather conditions. For example, if a ship operates in a very well-defined area of operation, decisions based on extreme weather simulations, will result in oversized components. However if the area of operation is uncertain and high level of comfort is of primary importance, then adopting extreme design conditions might be appropriate.

A very important decision-making tool produced by energy simulation is the identification of peaks in the power - time variation. Assuming that the simulation of the ship accommodation of a cargo ship produces the power consumption - time variation in Figure 7-1 for the heater. The peaks in this graph can be easily identified. If sizing of the heater is based on the highest value (16 kW) then it is bound to operate in less than half of its capacity for the majority of its life. This is where the designer can make a decision and sacrifice a couple of uncomfortable days during the year, and install a smaller and cheaper component with a capacity of 12 kW. It is noteworthy that today, most ship energy systems are designed based on a single extreme operating condition.

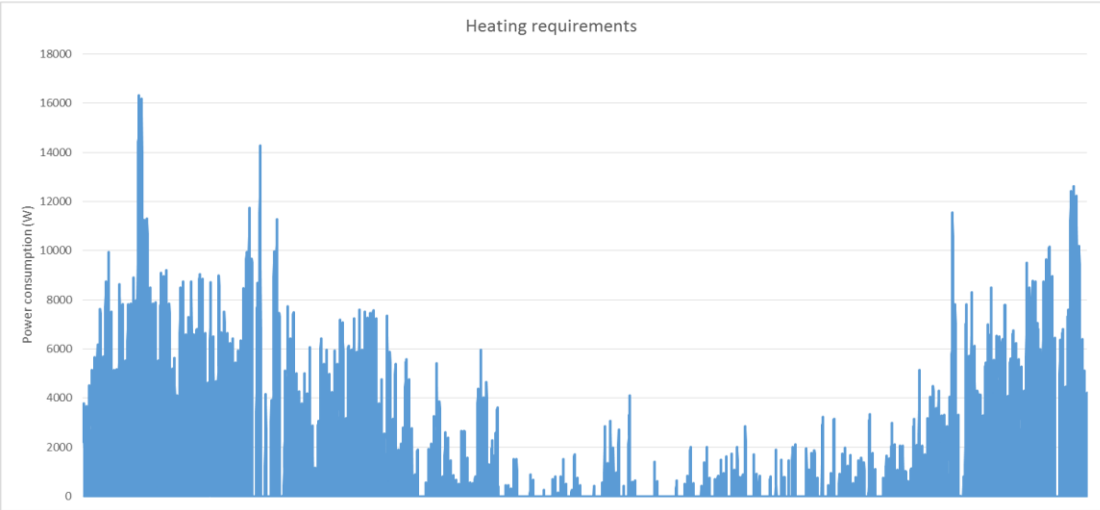


Fig 7-1. "Yearly power consumption of a heater"

Following the described methodology, the accommodation of a conventional cargo and passenger vessel are modelled in the next section and their energy performance is assessed. This does not in any way imply that dynamic thermal modelling is limited to the simulation of existing designs, since its foundation, based on first principles, makes it equally applicable to the investigation of novel ideas and innovative concepts.

7.3 Cargo ship

An accommodation block of a cargo ship with seven decks and a crew of 28 was selected for investigation. Design specifications were generated after reviewing the libraries of multiple conventional cargo ships. For this design scenario the ship was assumed to transfer goods from China to the US, traversing the Pacific Ocean. The connections between the thermal zones were modelled explicitly, meaning that no ‘similar’ boundary conditions assumptions were made for this case. As the lowest deck of the accommodation is in contact with the engine room, boundary conditions for its floor were assumed static at 38^{o}C. The mechanical drawings generated for this case study along with all pertinent model information concerning additional thermal gains, supply and exhaust airflow etc. can be found in APPENDIX IV.

7.3.1 Early design

Initially, the geometry, constructions and casual thermal gains of the accommodation were modelled. The wireframe of the accommodation model is shown in Figure 7-2.

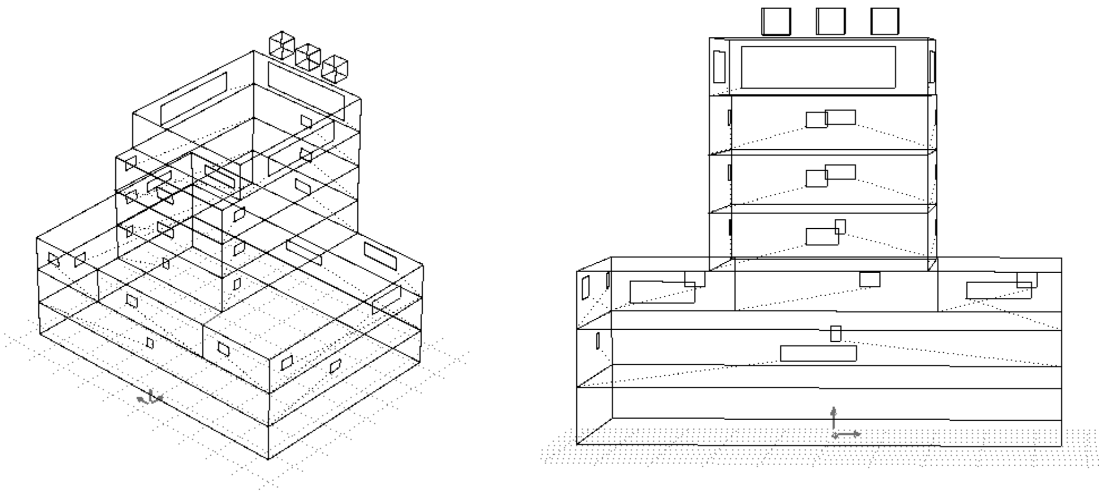


Fig 7-2. "ESP-r model for cargo superstructure"

Following the design methodology for early design, the HVAC system was modelled as an airflow network with ideal temperature control. Air is supplied to each deck at a temperature of 24^{o}C as shown in the block diagram in Figure 7-3.

Two weekly simulations were carried out for extreme cold and hot weather conditions (same climate files used in Chapter 5 and 6, and found in APPENDIX IV). The simulations produced the heat demand - time variation shown in Figure 7-4, which constitutes the first rough estimation for the heating and cooling requirements of the HVAC components.

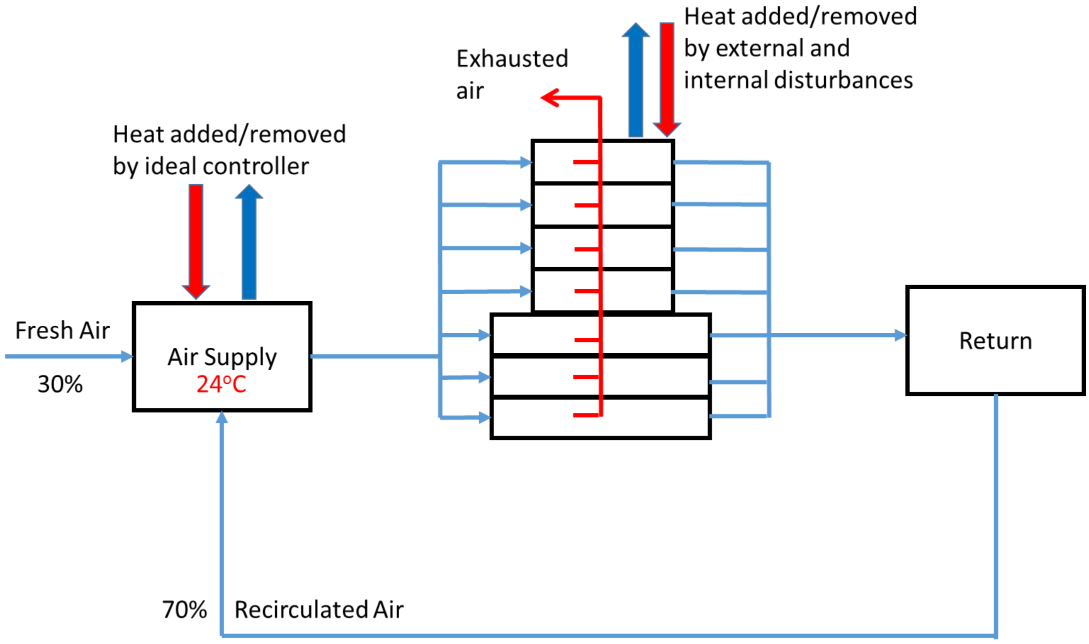


Fig 7-3. "HVAC system configuration for cargo ship accommodation during early design"

The heating and cooling load variation should be always viewed along with the respective internal temperatures variation of the zones, to ascertain that conditioned zones are within acceptable comfort levels. As shown in Figure 7-5, the temperature of the navigation bridge is considerably below the comfort temperature range during the heating period and most of the decks demonstrate temperatures below 22°C at some point during the simulation. This is an indication that a higher temperature set point is required and that corrective action has to be taken, so that all spaces exhibit similar temperatures.

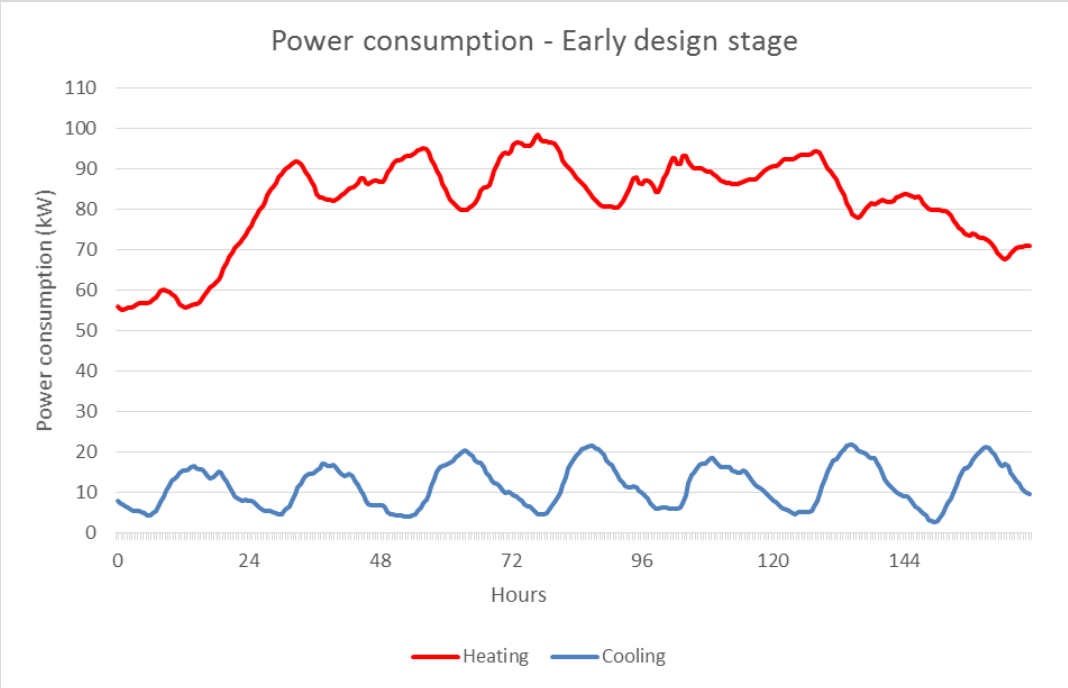


Fig 7-4. "Heating/cooling demand for cargo accommodation during early design for extreme cold and hot conditions"

During extreme hot ambient conditions all zones but the bridge are in the 22°C – 27°C acceptable temperature range. The bridge exhibits temperatures beyond the recommended passenger comfort levels, due to its high level of exposure to the weather and the presence of large glazing area that allows high levels of incoming solar radiation. Simulation results are shown in Figures 7-5 and 7-6.

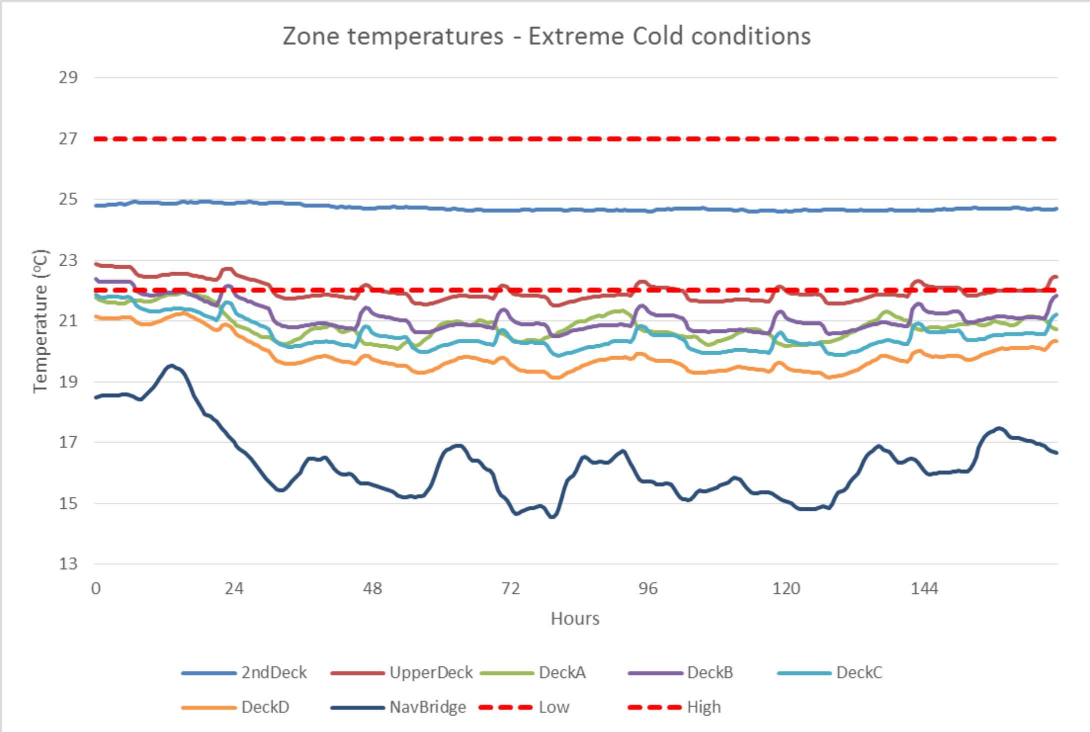


Fig 7-5. "Zone temperatures during extreme cold conditions with 24ºC set point"

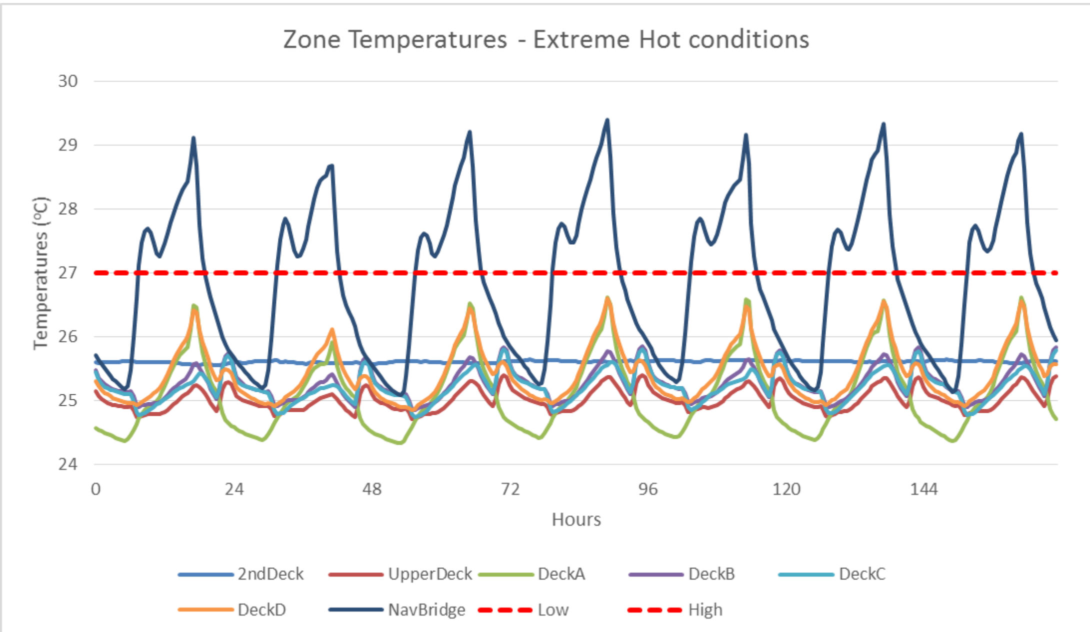


Fig 7-6. "Temperatures during extreme hot conditions with 24ºC set point"

Before making any design decisions, the severity of the problem was examined for the expected climatic conditions. Following the methodology described in Chapter 4, a yearly climate file for the operating area was generated, and an annual simulation was performed. Results shown in Figure 7-7, indicate that temperatures in all decks but the bridge show little deviation. Also the temperature in every zone falls below the comfort range at some point during winter. Based on all previous results, it is clear that the heating set point during winter conditions has to be increased and the temperature extremes in the bridge need to be controlled.

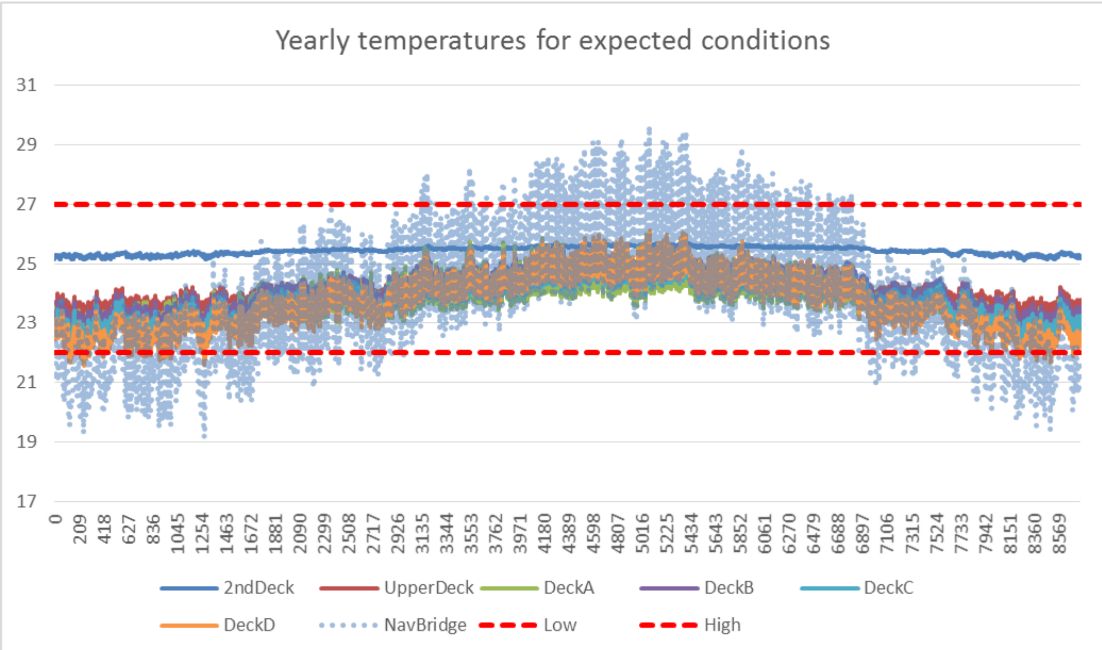


Fig 7-7. "Yearly zone temperatures for expected conditions"

Corrective action

As seen in Figure 7-5, deviation of indoor temperatures is higher for the heating period. This is primarily due to the great indoor – outdoor temperature difference (-20°C – 24°C), which causes excessive heat loss.

One way to reduce the temperature deviation between zones is to increase the air flow in the "problematic" zones. This would require the installation of a more powerful fan, which would in turn mean increased heating and cooling requirements since more air would have to be conditioned. Another approach would be to install local reheating units in spaces in higher decks so that the temperature of the supply air can be corrected according to the liking of the occupants. Although a cost analysis is required to proceed with the selection of a solution, it is assumed here that the first option is cheaper and more effective. Simulation results for the new design conditions with increased airflow to the higher decks are shown in Figures 7-8, 7-9 and 7-10, and Table 7-1.

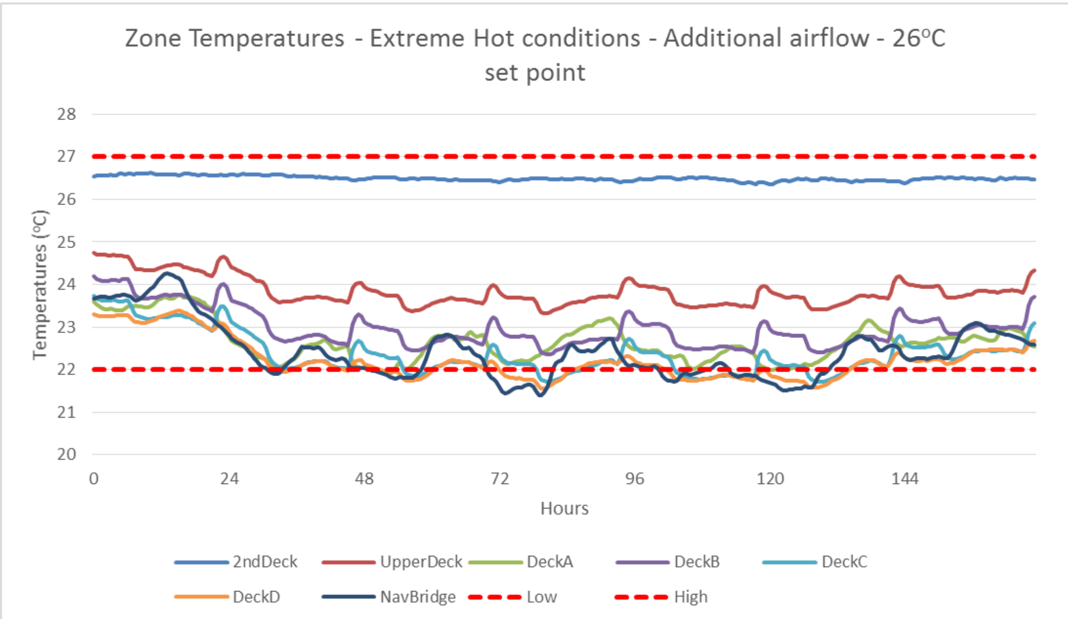


Fig 7-8. "Temperatures in extreme cold conditions with 26°C set point"

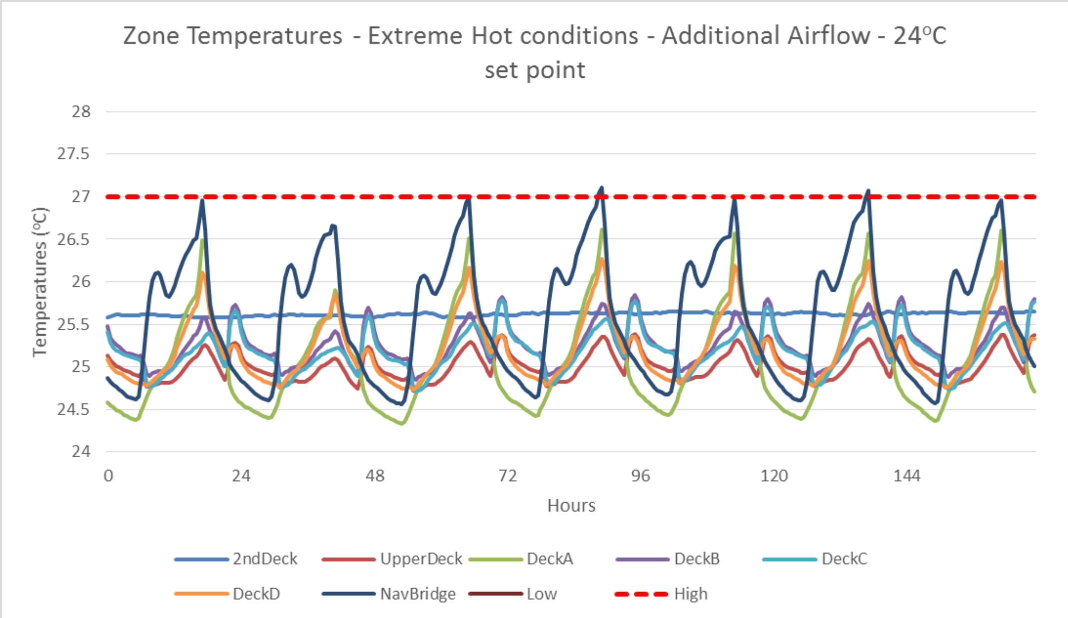


Fig 7-9. "Temperatures in extreme cold conditions with 26°C set point"

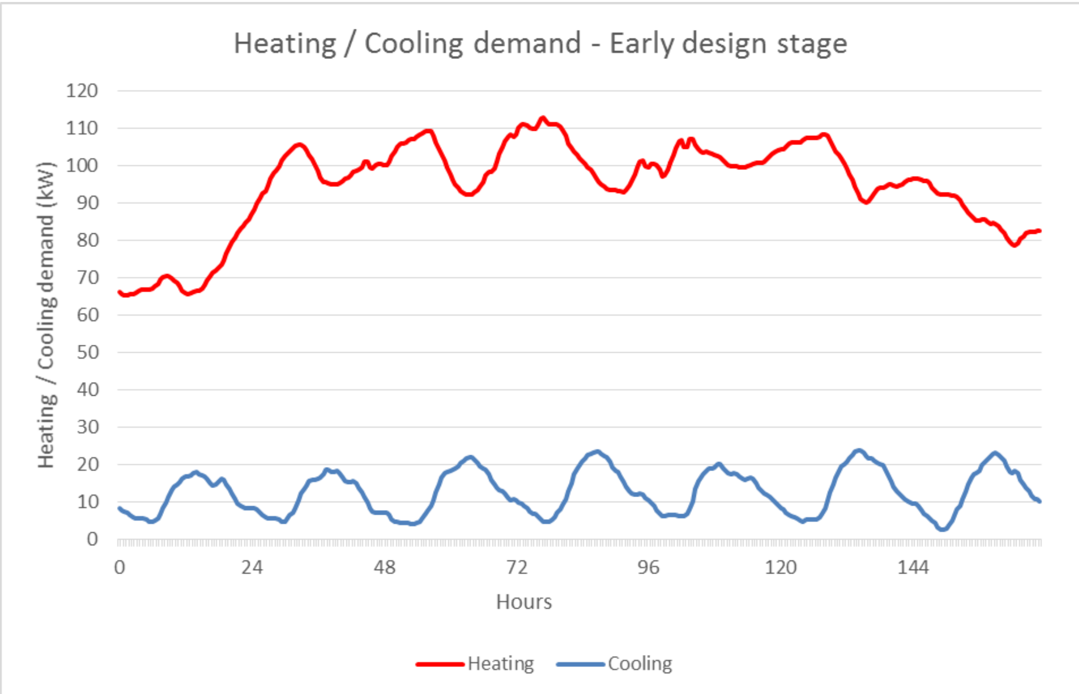


Fig 7-10. "Heating / cooling demand for extreme conditions with corrected airflow and set points"

Table 7-1: Initial and corrected airflow to zones.

	Bridge	D Deck	C Deck	B Deck	A Deck	Upper	2nd	Total
Initial Airflow (m3/h)	1405	1322	1105	1323	5783	3185	965	15088
Corrected Airflow (m3/h)	3405	1522	1105	1323	5783	3185	965	17288

At this point the early design stage is over. Values for the airflow and, heating and cooling demand, will be used as initial values for the component models in detailed design.

7.3.2 Detailed design

In this step of the design process, explicit HVAC component modelling is introduced to produce more detailed information about the power demand and control of the components. Ideal control laws are dropped and replaced by real control strategies for the heater, cooler and humidifier. As a variable time step is allowed, a time step of 1 min is selected for the plant component network.

At this stage, air is modelled as a two-phase fluid, which allows for the calculation of condensation during the cooling process of the air. This is necessary for humidity calculations in the system, where possible condensation of air vapour has to be compensated for by the humidifier. The HVAC plant network developed in section 4.8.2 was used for this case study the block diagram of which is shown in Figure 7-11.

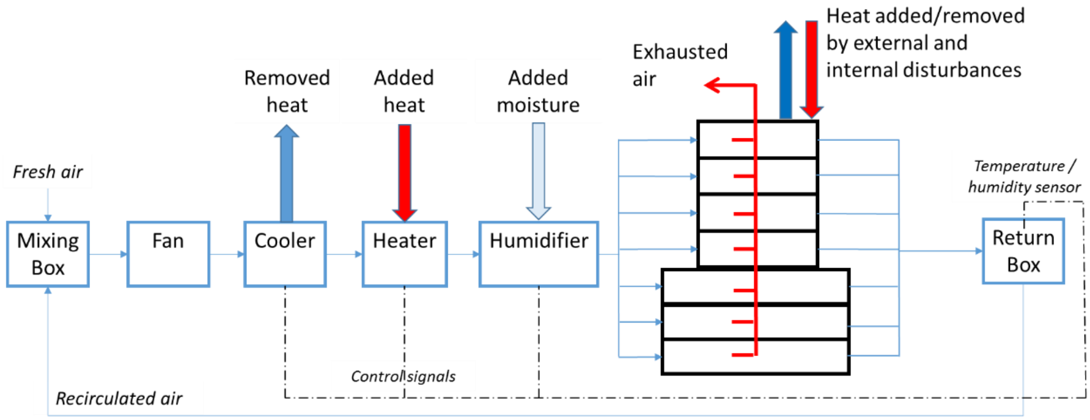


Fig 7-11. "HVAC plant component network for detailed design of Cargo accommodation"

To set the controllers, initial values from early design were used for the maximum heating and cooling capacity of the components. After applying the Ziegler-Nichols method, the PID parameters that provided stable and acceptable results for extreme weather climate files were identified and are shown in Table 7-2. It is worth mentioning that for large components with a wide range of possible output gains, it is difficult to find a unique set of parameters that provides optimum control for the whole operational range. In HVAC modelling this is usually confronted with the change of the set point either manually (different simulations and PID parameters for different climates) or automatically (algorithm to dynamically change the set point during simulation).

Table 7-2: Initial and corrected PID control parameters for cargo ship accommodation during extreme weather.

	Max flux/flow	Min flux/flow	Setpoint	Proportional	Derivative	Integral
	Initial values					
Heater	120000 W	0	26°C	5	0	0
Cooler	27000 W	0	26°C	5	0	0
Humidifier	0.020 kg/s	0	50%	5	0	0
	Corrected values after Ziegler-Nichols method					
Heater	140000 W	0	27°C	11	0	300
Cooler	27000 W	0	26°C	2	0	200
Humidifier	0.013 kg/s	0	50%	50	0	200

Simulations were initially carried out for extreme weather conditions. As seen in Figures 7-12 and 7-13, the zone temperatures and humidity are within the acceptable range in both cases. All the results can be found in APPENDIX IV. With an indication for the components behaviour in extreme weather conditions, simulations were performed for the expected conditions to be met by the ship. The hottest and coldest months of the previously generated yearly climate file indicative of the ship route were selected, and two simulations were carried out. Since the heat gain for the heater and cooler was lower, the control parameters were re-set for optimum operation as shown in Table 7-3.

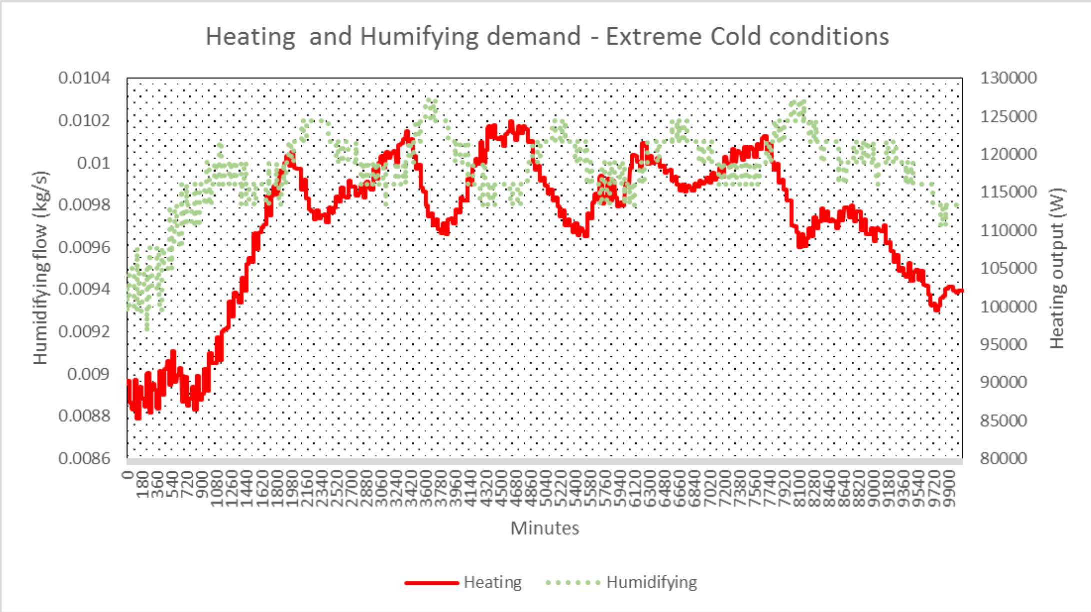


Fig 7-12. "Heating demand in extreme cold conditions with PID control"

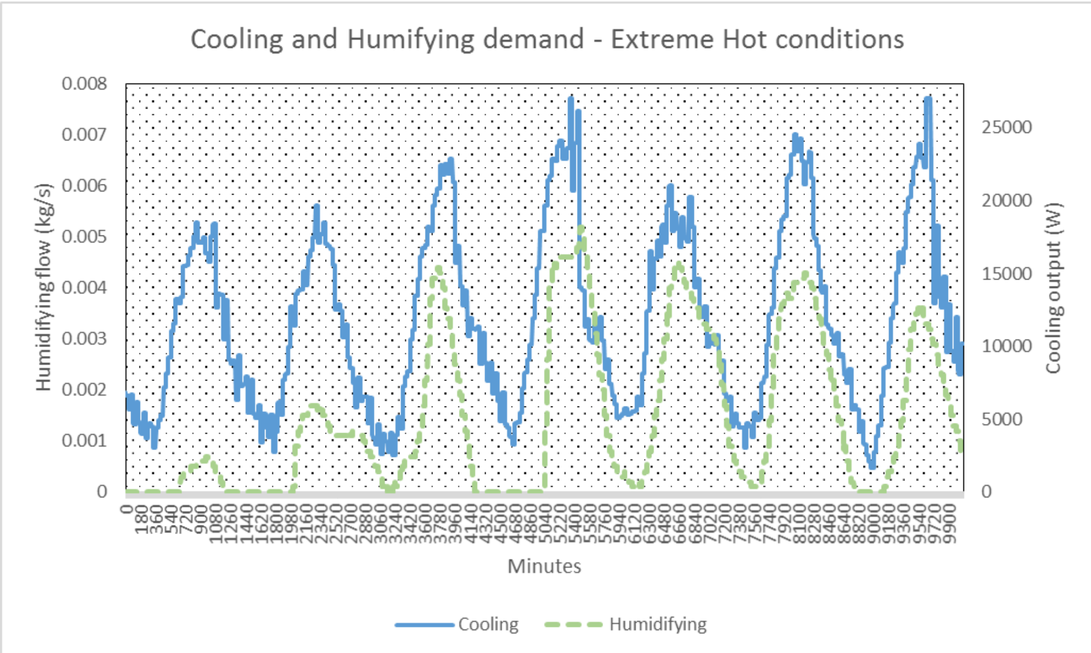


Fig 7-13. "Cooling demand in extreme cold conditions with PID control"

Table 7-3: PID control parameters for cargo ship accommodation for expected weather.

	Max flux/flow	Min flux/flow	Setpoint	Proportional	Derivative	Integral
	Expected climatic conditions					
Heater	85000W	0	26degC	8	0	300
Cooler	20000W	0	26degC	4	0	200
Humidifier	0.013kg/s	0	50%	50	0	200

Results in Figures 7-14 and 7-15 show that for the expected conditions, the heating and cooling demand are significantly lower than for extreme conditions. At this point all the information necessary to make a decision is available. The results are presented in Table 7-4.

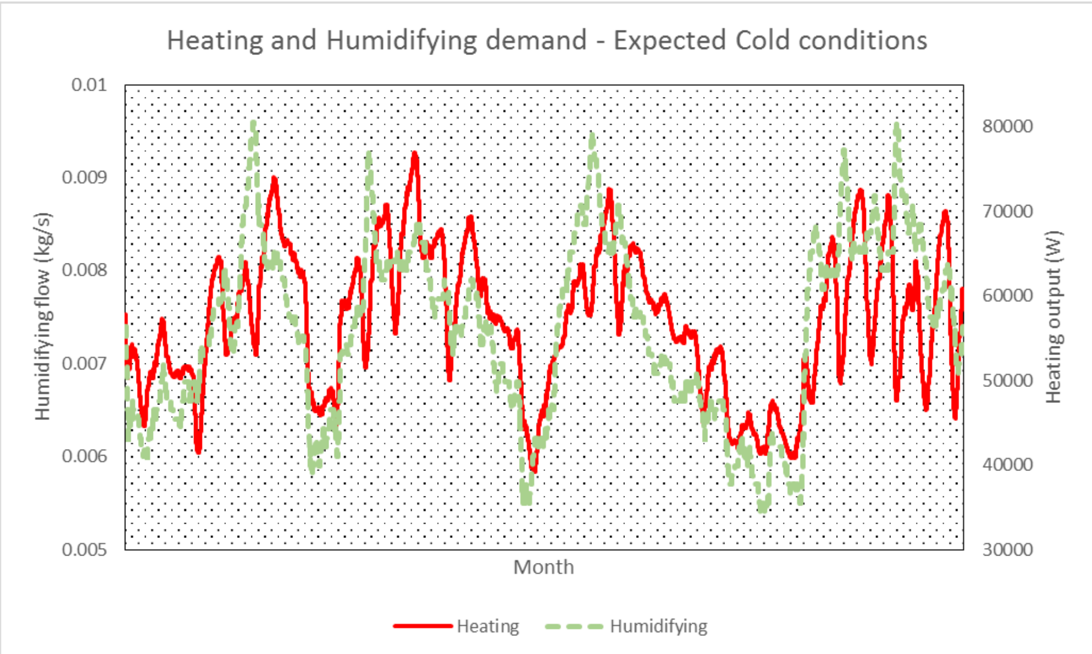


Fig 7-14. "Heating demand for expected cold conditions with PID control"

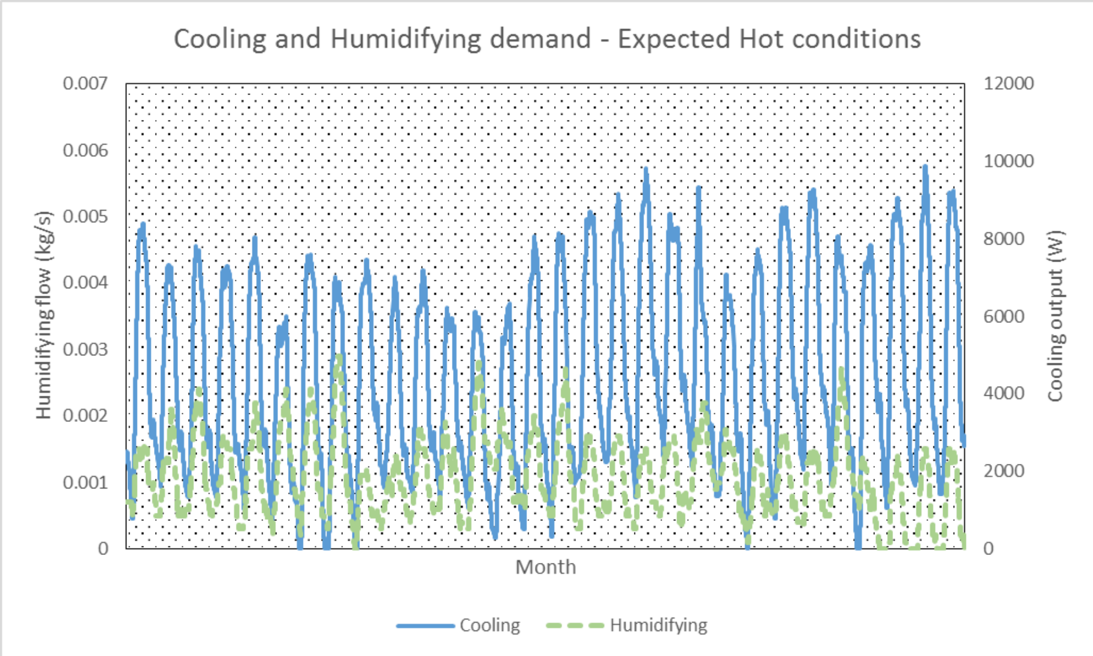


Fig 7-15. "Cooling demand for expected hot conditions with PID control"

Table 7-4: Component sizing recommendation for extreme and expected weather.

	Cooler (kW)	Heater (kW)	Humidifier (kg/s)	Fan (m3/h)
Extreme	27	130	0.011	17288
Expected	10	80	0.010	17288

7.4 Passenger ship

As discussed in Chapter 4, HVAC system configurations may vary between different passenger ships. For this case, 2 passenger decks of a cruise ship were selected for investigation that are divided in 4 MVZ. The decks are served by an indirect expansion HVAC system with central cooling and heating that takes place in two separate air handling units (AHU) and local reheating for each stateroom. Water is used as the cooling medium which leaves the chiller at a temperature of 5°C and is circulated to the AHUs where it enters the coolers and cools the air at 15°C during the cooling period. The cooled air is then directed to the staterooms, where it is heated by the re-heaters, according to locally defined set points. During the heating period, fresh air is heated at 21ºC and supplied to the accommodation. Both central heating and local reheating use electrical resistances to heat the air. The block diagram of the system is shown in Figure 7-16.

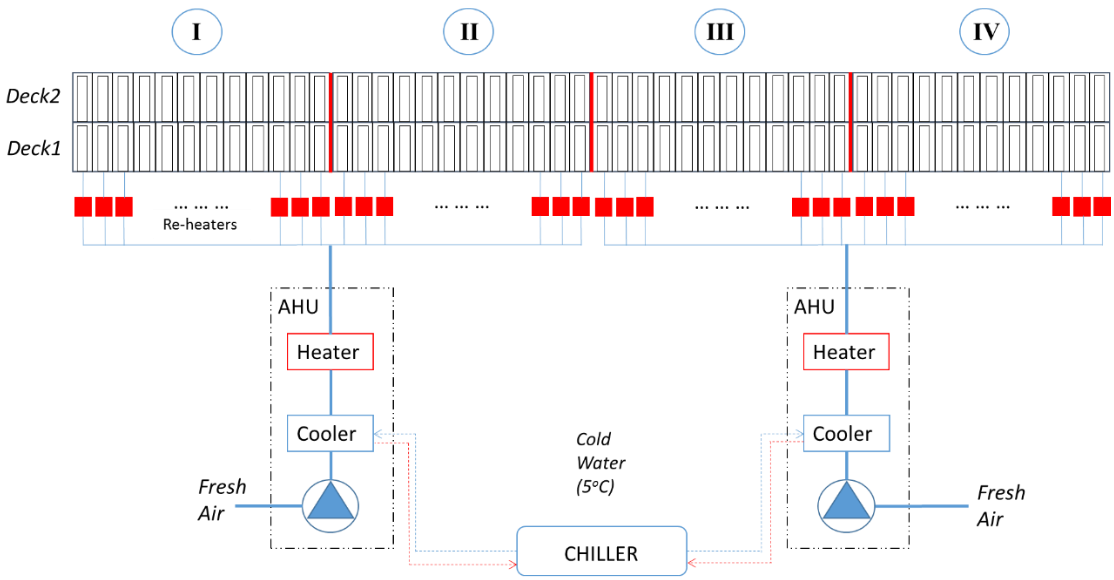


Fig 7-16. "HVAC configuration for passenger ship"

Each MVZ of each passenger deck, is comprised of 3 rows of 12 cabins, totalling 24 exterior and 12 interior cabins. The ESP-r wireframe of the model is shown in Figure 7-17. Like in most passenger ships, central recirculation of air is not allowed due to health issues (spreading of germs, pathogens etc.), therefore air is recirculated locally. This means that the required 30% of fresh air is supplied by the AHU, which is mixed in the re-heater with recirculated air before being conditioned and supplied to the zone. Detail of this configuration is shown in Figure 7-18.

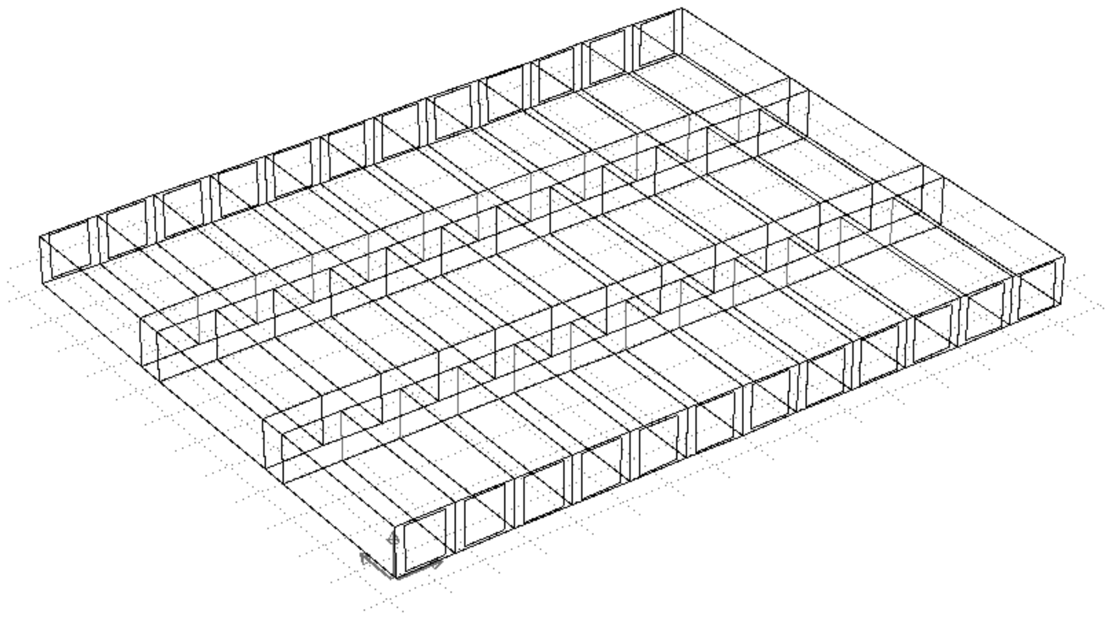


Fig 7-17. "Geometry of a passenger deck of one MVZ comprised of 36 cabins"

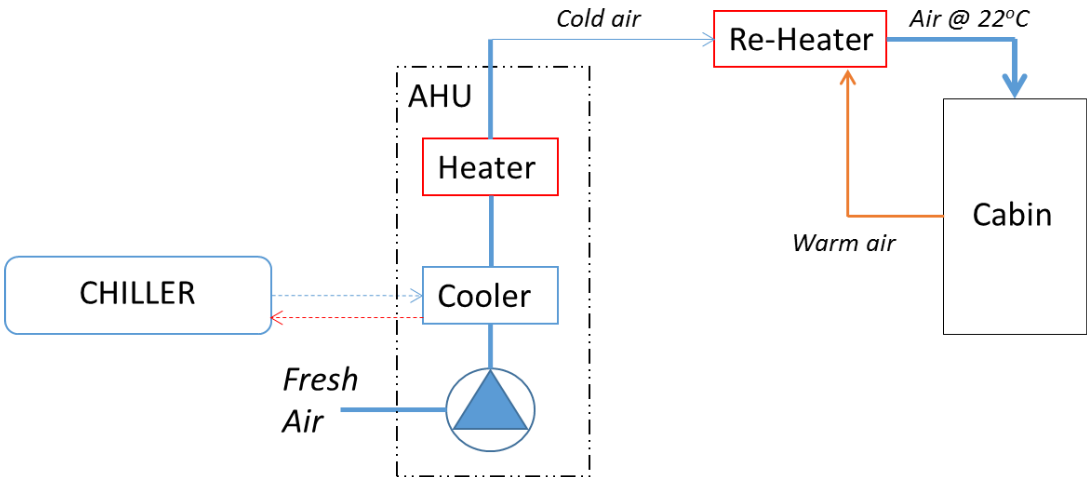


Fig 7-18. "Detail of supply airflow in a cabin"

The ship under consideration has a well-defined area of operation located in the east Caribbean and follows a weekly itinerary presented in Figure 7-19.

Fig 7-19. "Area of operation for the ship under investigation"

7.4.1 Early design

Following the modelling guidelines of Chapter 6, staterooms are grouped per deck per MVZ, totaling eight thermal zones. Top surfaces of the upper deck, and bottom surfaces of the lower deck are assumed to be in contact with conditioned spaces, therefore, their boundary conditions are assumed similar. Modelling of the chiller unit is not considered at this stage, and air coolers, heaters, and re-heaters are modelled as ideal temperature controllers within an airflow network. Since spaces are grouped, local reheating units are represented as one unit per grouped space. This means that calculations will yield the total heating demand of all the re-heaters in each thermal zone. The size of each separate reheating unit can be then estimated by dividing the total deck power demand by the number of staterooms. It has to be pointed out that the power demand of each re-heater depends on the topology of the stateroom, orientation of the vessel, and the individual occupant preferences, however it is unlikely that components of different size will be installed in different staterooms due to economic reasons. Therefore, since occupant comfort is of primary importance in passenger vessels, sizing of the re-heating units will be based on the highest calculated demand. The wireframe of the related ESP-r model is shown in Figure 7-20.

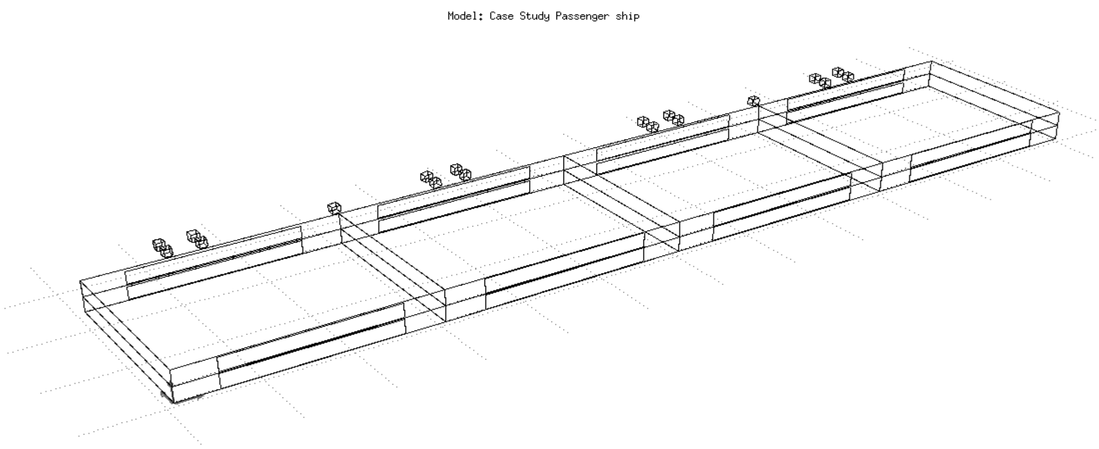


Fig 7-20. "ESP-r model geometry for passenger decks"

Following the previously defined design methodology, the power demand for cooling and heating was calculated for extreme heating and cooling conditions, respectively.

Cooling period

Since the two AHUs cool the same volume of air and are not affected by other parameters, their cooling demand is identical and is shown in Figure 7-21. The re-heaters demonstrate different power demands as seen in Figure 7-22, which are dictated by the topology of the served spaces. Thermal zones that are more exposed to the weather require less reheating as the return air from the zone that is mixed with fresh air, is warmer.

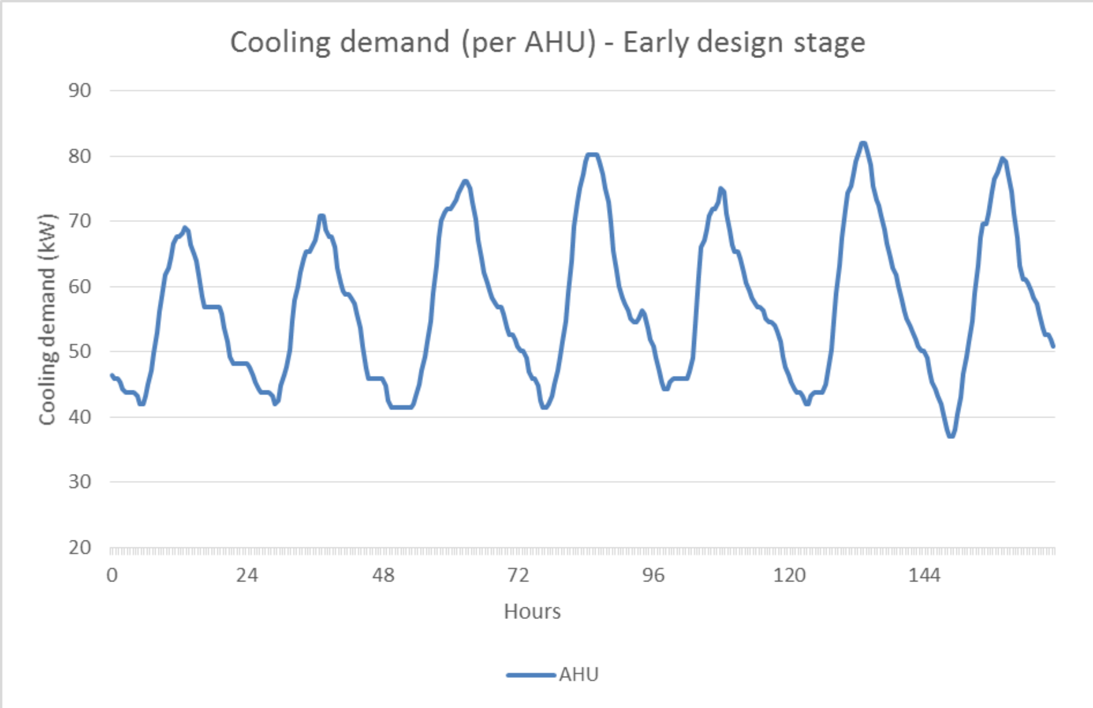


Fig 7-21. "Cooling demand for AHU1&2 for extreme hot conditions"

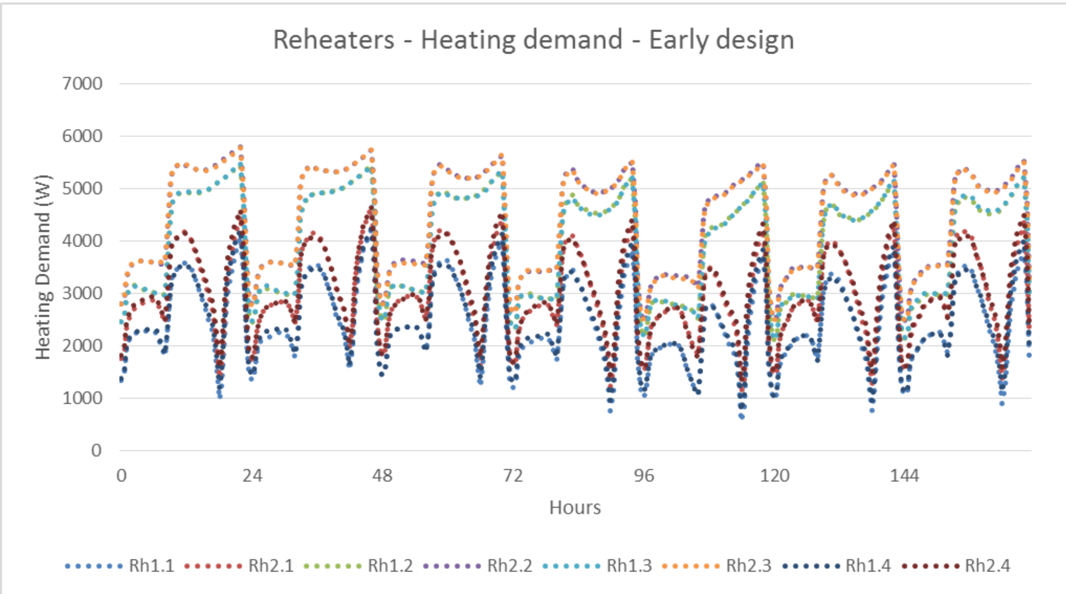


Fig 7-22. "Heating demand for re-heaters in extreme hot conditions"

Figure 7-23 below, shows that temperatures in thermal zones are kept within the acceptable range during simulation.

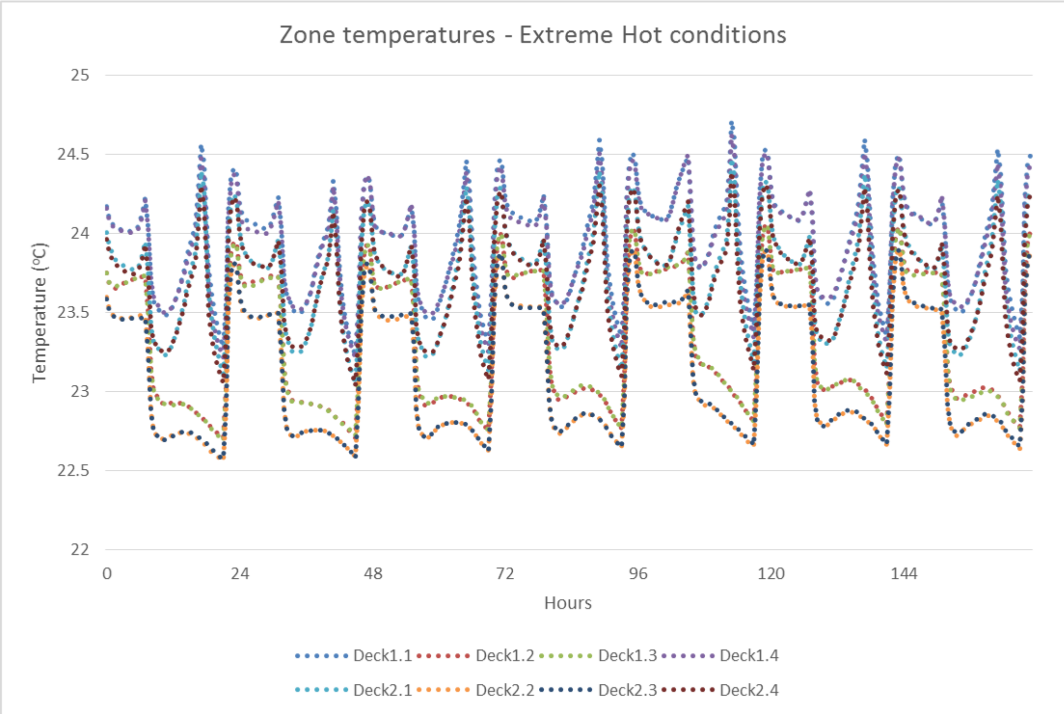


Fig 7-23. "Zone temperatures for extreme hot conditions"

Heating period

During cold ambient conditions, circulation of cold water stops, and heaters in the AHUs are activated and heat the air at 21°C. Then air is directed to the re-heaters where it is brought to the required supply temperature of 24°C. Results of the simulations are shown in Figures 7-24, 7-25 and 7-26 below.

Unlike cargo ships, temperatures in passenger ship accommodation are not likely to deviate due to the presence of local conditioning units. With rough estimations available, detailed design can commence.

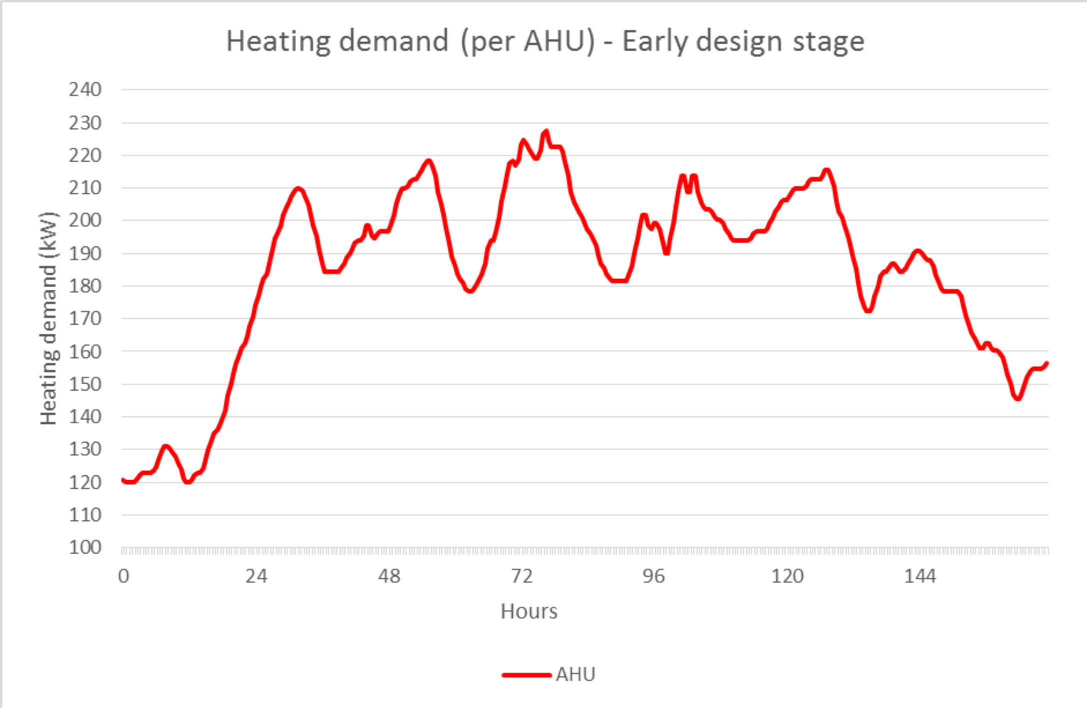


Fig 7-24. "Heating demand for AHUs during extreme cold conditions"

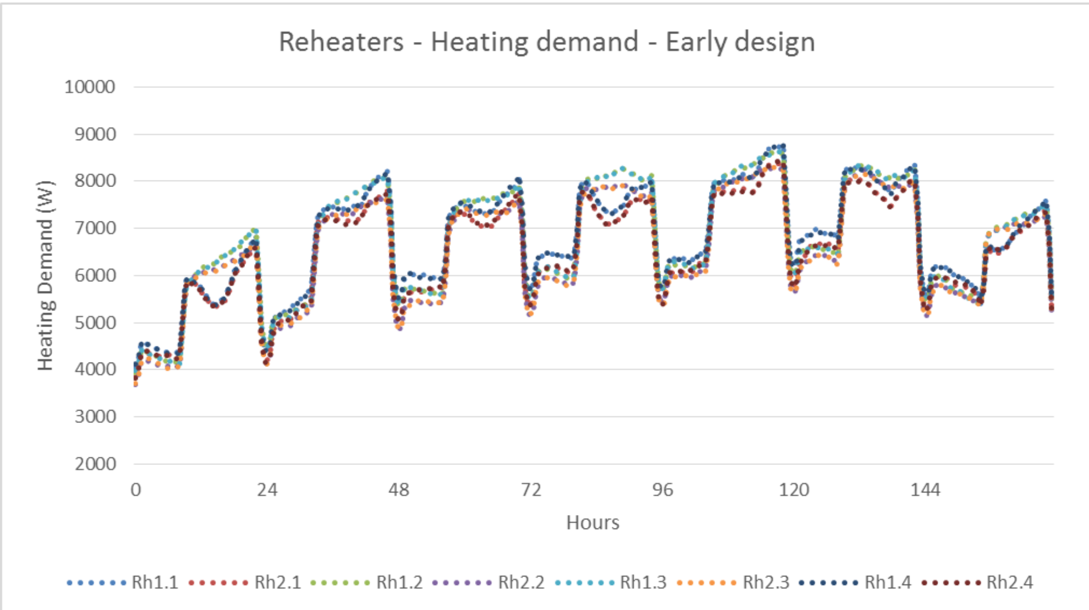


Fig 7-25. "Heating demand for re-heaters during extreme cold conditions"

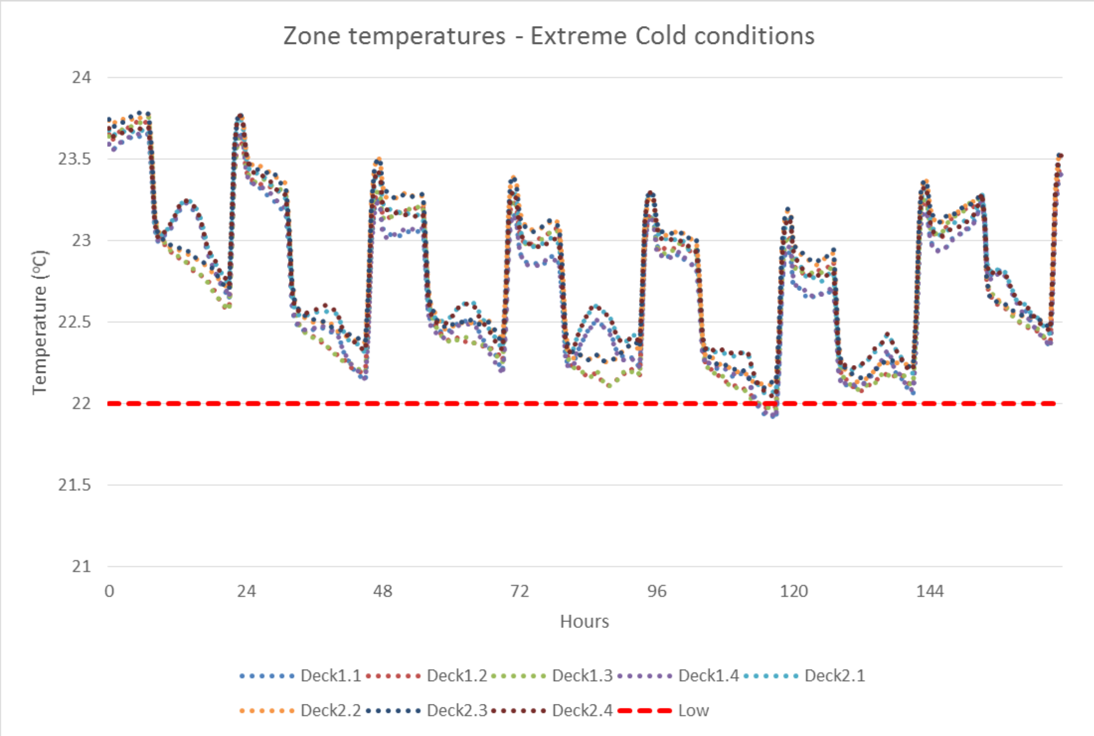


Fig 7-26. "Zone temperatures for extreme cold conditions"

7.4.2 Detailed design

At this point, a plant component network is introduced and control is assigned to each modelled component.

Cooling period

Initial and corrected values of the PID control parameters are shown in Table 7-5 and results for cooling during extreme hot conditions are presented in Figures 7-27, 7-28 and 7-29 below.

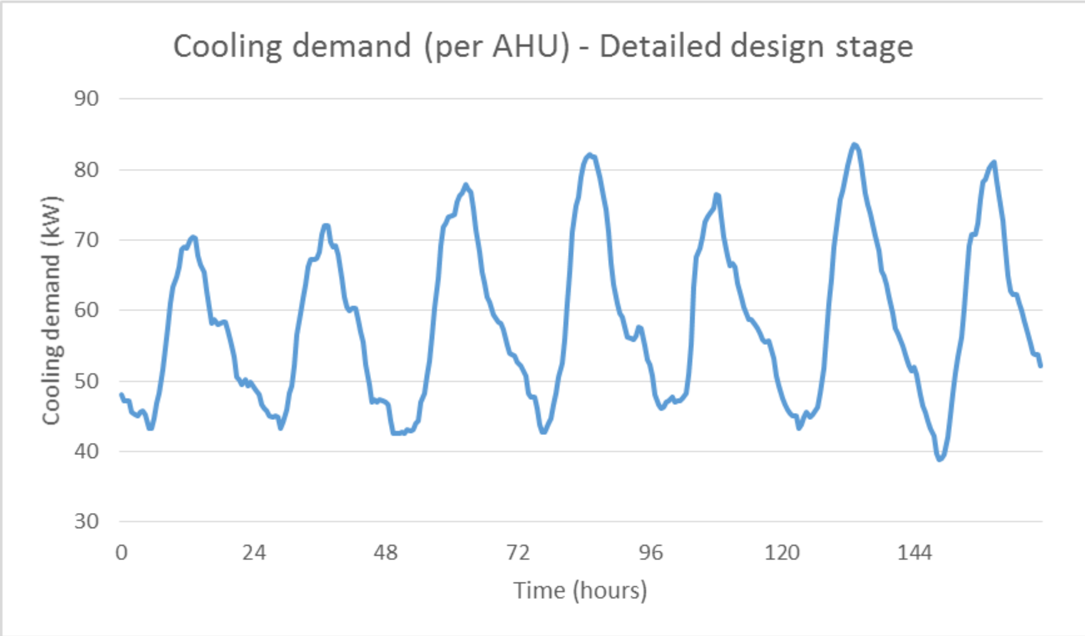


Fig 7-27. "Cooling demand for AHUs during detailed design"

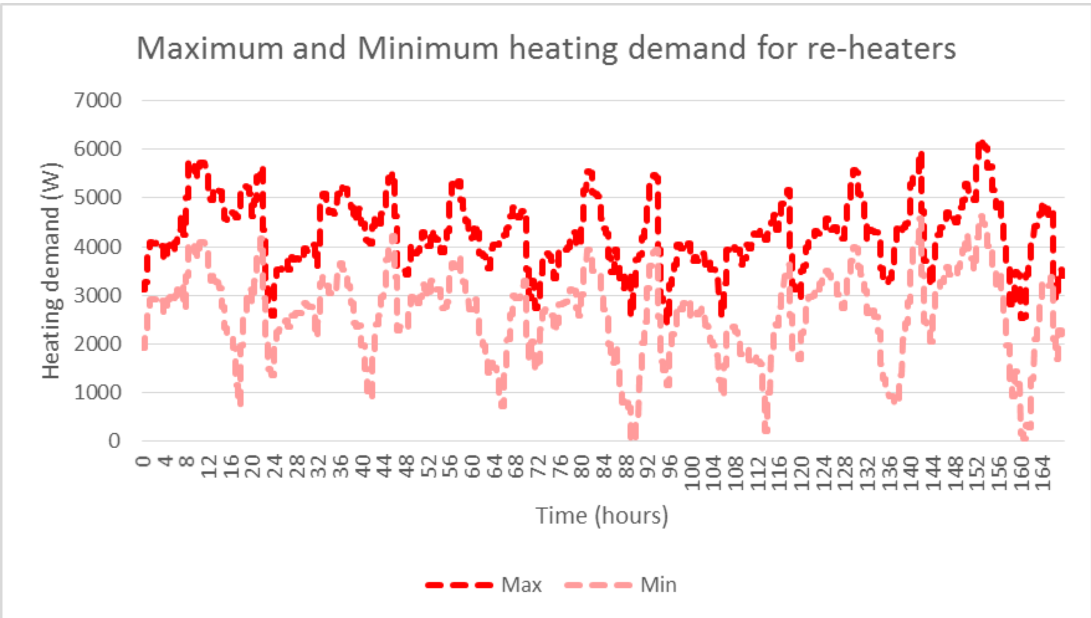


Fig 7-28. "Maximum and minimum heating demand for re-heaters during extreme hot weather"

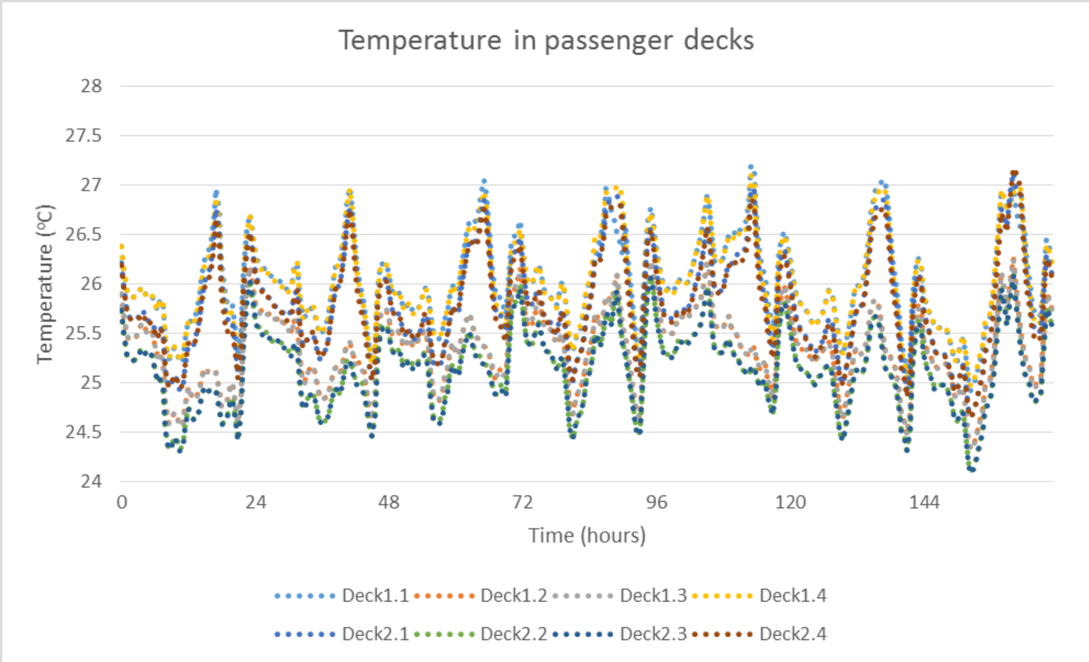


Fig 7-29. "Temperature of grouped cabins during extreme cold conditions"

Table 7-5: Tuning PID parameters for Passenger ship

	Max flux	Min flux	Setpoint	Proportional	Derivative	Integral
	Initial values					
Cooler	82000 W	40000 W	15ºC	5	0	0
Heater	230000 W	100000 W	21ºC	5	0	0
Reheaters	9000 W	0	25ºC	5	0	0
	Corrected values after Ziegler-Nichols method					
Cooler	87000 W	20000 W	15ºC	10	200	500
Heater	200000 W	100000 W	21ºC	22	500	900
Reheaters	9000 W	0	25ºC	5	0	0

Heating period

Using the Ziegler-Nichols method the control parameters were defined (shown in Table 7-5) and results were derived for the heating demand of the central and local heaters. Simulation results are shown in Figures 7-30, 7-31 and 7-32 below.

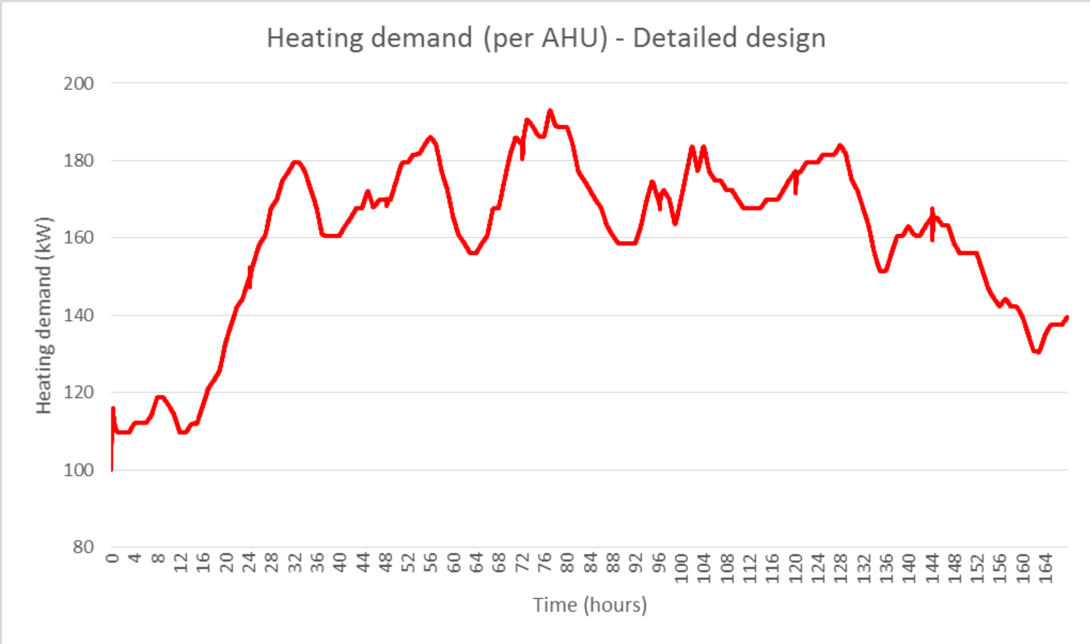


Fig 7-30. "Power demand of central heater"

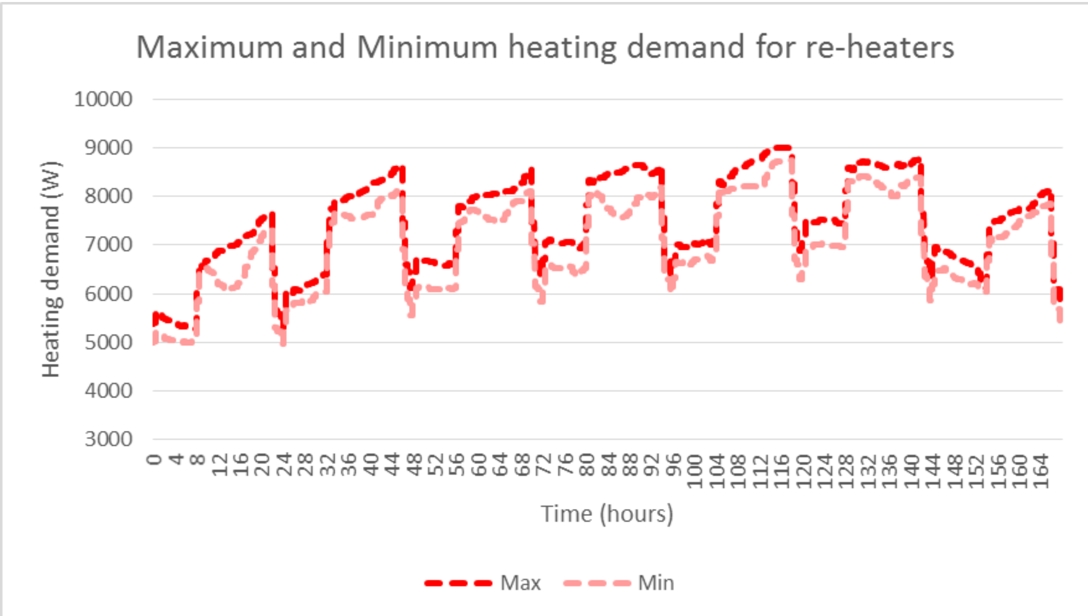


Fig 7-31. "Maximum and minimum heating demand for re-heaters"

The zone temperature variation in Figure 7-32, shows that the temperature in every zone is within the acceptable range.

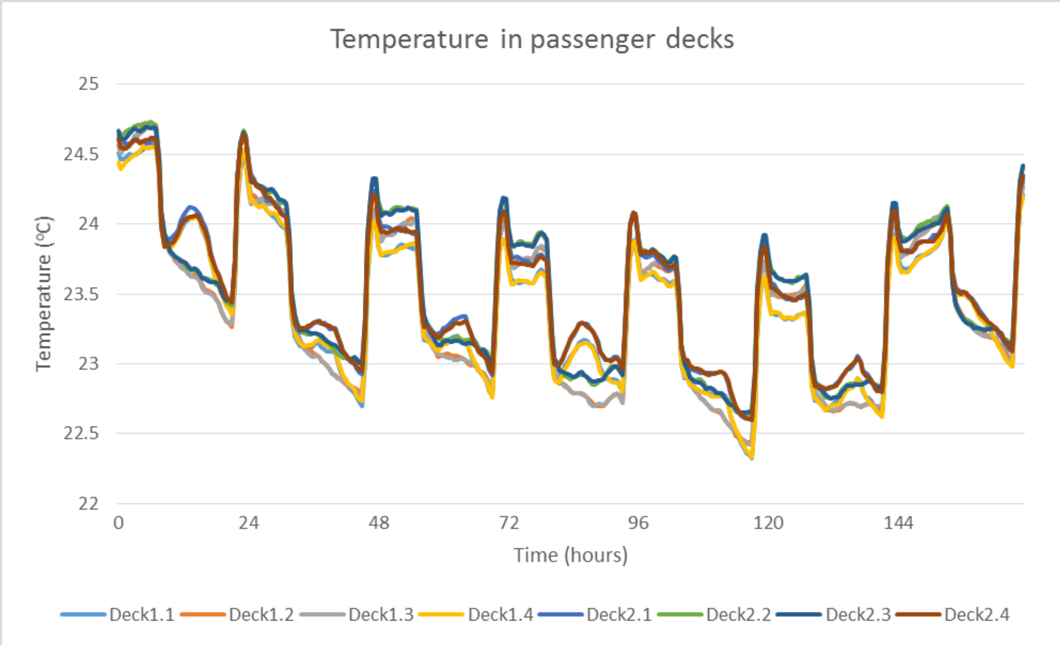


Fig 7-32. "Temperature of grouped cabins during extreme cold conditions"

Expected conditions

Since the ship operates on a strict schedule and within a very well-defined area of operation, the roaming capability is used to accurately model the energy interactions between the ship and the environment during the trip. The roaming file is generated according to the trip information presented in Table 7.6. A climate file is generated following the methodology presented in Chapter 4, indicative of the route of the ship.

Since the east Caribbean region does not demonstrate cold weather throughout the year, calculations for the central heater were not carried out for expected conditions. A simulation was performed for the warmest week of the expected conditions and results are shown in Figure 7-33 and 7-34.

Table 7-6: Roaming information data for passenger ship

Hour	Day	Month	Orientation	Speed (knots)	Location
1:00	30	7	90	0	Fort Lauderdale
16:00	30	7	100	21	Cruising
7:00	31	7	100	0	Nassau
14:00	31	7	125	21	Cruising
10:00	2	8	125	0	Charrlotte Amalie
19:00	2	8	110	21	Cruising
8:00	3	8	110	0	Philipsburg
17:00	3	8	300	21	Cruising
6:15	6	8	90	0	Fort Lauderdale

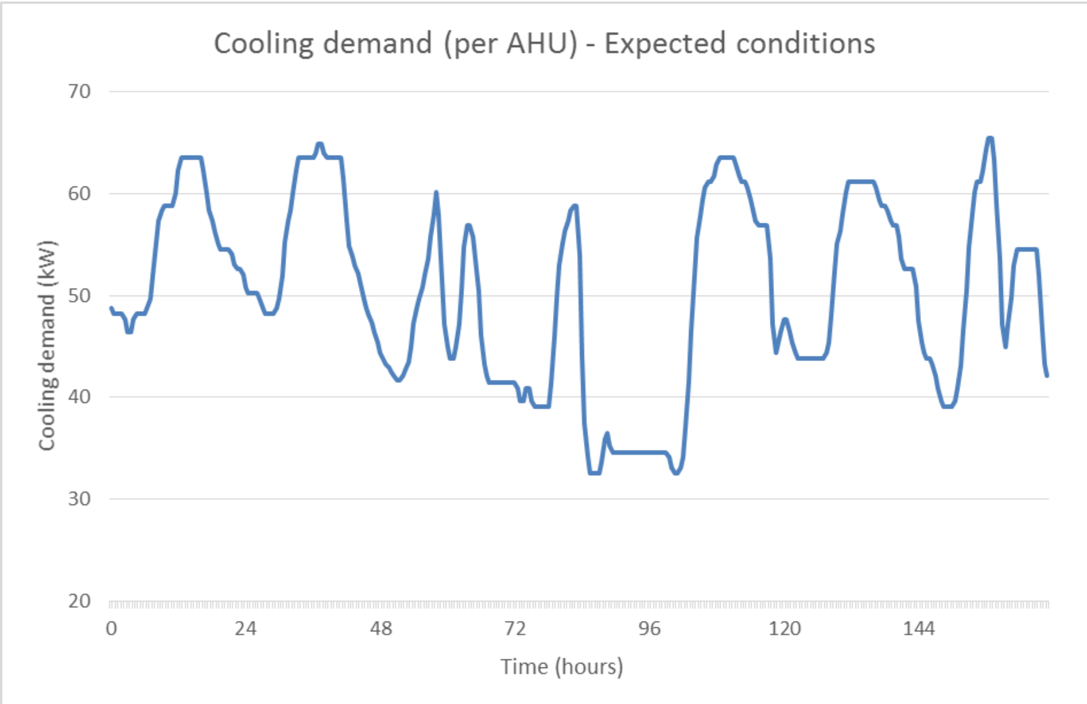


Fig 7-33. "Cooling demand per AHU for expected temperate conditions"

Summarising the results of all calculations, Table 7-7 presents all the information necessary for an informed decision concerning the sizing of the HVAC components.

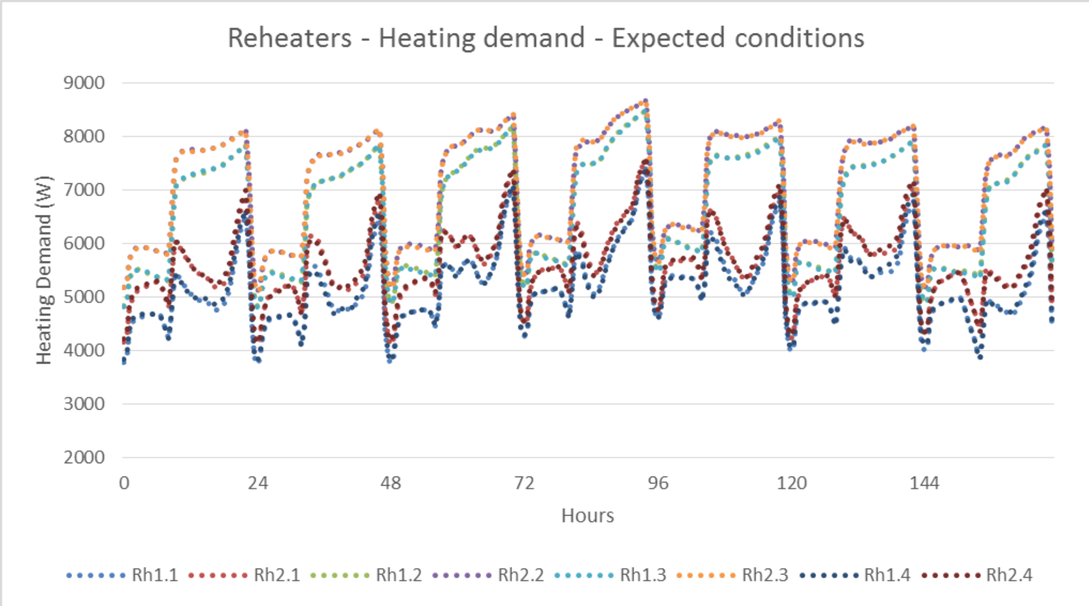


Fig 7-34. "Heating demand for re-heaters during expected conditions"

Table 7-7: Component sizing recommendation for extreme and expected weather.

	Cooler – per AHU (kW)	Heater – per AHU (kW)	Re-heater - per stateroom (W)	Fan – per AHU (m3/h)
Extreme	90	200	300	12700
Expected	70	-	250	12700

7.5 Closure

In this chapter a design methodology was proposed based on dynamic thermal modelling and the use of 'ESP-r marine', which is comprised of different levels of modelling. The methodology was demonstrated in two case studies where the sizing of HVAC components was performed. This chapter closes the work of this thesis and is followed by discussion and recommendations.

8 DISCUSSION AND RECOMMENDATIONS

8.1 Preamble

This chapter summarises the contributions of this thesis in the field of energy efficiency during ship design and operation, and proposes areas for future work that were not investigated in this research. Contributions to the field include the critical review of current design regulations, the introduction of dynamic energy modelling as an energy efficiency assessment tool, the investigation of the applicability of BES in the shipping sector and subsequent update of the BES tool ESP-r, the simplification of the design process for ship accommodation, and the development of a design methodology for on board spaces and its demonstration in two case studies. Further work is then proposed that includes recommendations for the improvement of accuracy and performance of energy calculations in ships, the development of an integrated holistic ship energy modelling tool, and the introduction of energy simulation as an integral part of the life-cycle energy assessment of ships.

8.2 Contributions to the field

This work started four years ago in an attempt to address the ever-growing need for energy efficiency in the shipping sector, primarily caused by the uncertainty of fuel prices and the introduction of mandatory environmental regulations targeting the increasing carbon footprint of shipping. Until recently, fuel efficiency had never been the key objective during ship design.

The first contribution of this work was the critical review of current design regulations of on-board energy systems. Critical review is not normally cited among the contributions of a PhD dissertation but this constitutes the first such review, at least from the perspective of dynamic energy modelling. As such, it revealed many deficiencies of existing regulations such as the use of extreme design conditions for component and system sizing, the lack of transient calculations (use of a static approach instead a dynamic one), the disregard for important energy flows for most energy systems, the simplified representation of energy paths, and lastly the neglect of interaction between energy systems. The drawbacks of regulations-based design were also pointed out, and the need for multi-objective performance-based design was justified.

The second contribution, original in many ways, particularly in the detailed implementation in ship design, was the introduction of dynamic energy modelling as a platform to assess and improve the performance of ship energy systems. Stemming from the remarkable absence of technology in the design calculations of new ships, design practices of related fields were explored. Developments in the established field of BES were reviewed, the technological gap between the buildings and shipping industry was unveiled, and thermal energy modelling was proposed as an assessment tool for the performance of on board energy systems.

The third original contribution was the transfer of technology from the buildings to the shipping industry. This started with the identification of similarities and differences between ships and buildings and their effect on the energy simulation. Centred on these differences, BES tool 'ESP-r' was upgraded to include the capability to model the energy paths present in a marine environment. To cater for the expected weather met by ships, a methodology was developed to generate route specific climate files, based on historical oceanic weather data (ICOADS data sets). Finally to facilitate geometrical and thermal modelling of ship accommodation, geometrical modules and occupancy profiles were generated for the most common spaces found on commercial ships.

The fourth original contribution was the reduction (simplification) of the modelling process for ship accommodation, which was achieved in two steps: topological decoupling and space grouping. Topological decoupling, dropped the requirements for explicit 3D geometrical modelling of the accommodation while space grouping significantly decreased the required spatial discretisation of accommodation models. Both exercises led to the development of modelling guidelines for cargo and passenger ship accommodations.

Finally a design methodology based on the dynamic energy modelling of thermal energy flows was proposed for commercial ship accommodations, which was demonstrated in two case studies.

The research undertaken for the completion of this thesis, produced three conference papers [69,70,71] that were presented in one international and two national conferences, in the framework of getting feedback from the academic and industrial community, and promoting this work.

8.3 Recommendations for future work

Time limitations did not allow the investigation of some topics that might have improved the energy efficiency and simulation of on board thermal systems. These are discussed below.

Extensive detailed validation

Although ESP-r has been extensively validated, this is not the case for 'ESP-r marine' developed in this work. Several calculations in this thesis have been compared with on board measurements in the framework of EU projects, however, due to the large number of inputs required by ESP-r and the lack of resources, no systematic and thorough comparisons were performed. Validation of an energy modelling tool requires extensive on board monitoring that would give values of thermal parameters over time. Since the energy balance in the accommodation is sensitive to many stochastic parameters, validation studies would need to include accurate and frequent observations for external weather, occupancy profiles, materials and constructions, HVAC components and ship operational profile.

Integration with ship energy model

In the framework of two EU projects, accommodation models were developed based on this work, which were used for the estimation of the total power consumption of cargo and passenger vessels. In these holistic models, results of the power demand of the accommodation, were used as boundary conditions for the electrical and steam systems, disregarding the interaction between those systems and the accommodation. To accurately model this interaction, more effort should be spent towards the integration of all energy systems under a holistic ship energy model, which necessitates the identification of points of connection and exchange of information between two different modelling environments. The development of a modelling tool and the simplification and reduction of the design process achieved in this thesis play a major role in this integration since fast simulation and modelling times are vital in a holistic model.

Airflow network design

Throughout this work, explicit modelling of the duct network was bypassed and airflow was imposed by constant flow rate components. However, in real systems the correct airflow is achieved once the resistance of the network has been calculated and an appropriate fan (pressure / flow rate curve) is selected. Minimisation of the duct network is of primary importance due to spatial and economic reasons and an early indication of the system resistance can facilitate the selection of a specific fan. ESP-r's airflow network allows the user to import specific fan curves and model the resistance of the network with the definition of the actual length of ducts, junctions and components and due to the interaction of thermal and airflow systems its impact on indoor comfort can be assessed.

Cabin comfort rating assessment

Apart from design regulations for the central HVAC system, classification societies rate accommodation spaces according to the level of indoor comfort provided [68]. Parameters that define indoor comfort are the maximum cabin air velocity, vertical air temperature difference, relative humidity level and the temperature range. Assessment of comfort is based on measurements taken once the ship has been built. With the use of energy modelling and the coupled CFD capability within ESP-r, very early indications about the comfort rating can be achieved. Once a model has been developed and all the parameters have been assigned, ESP-r allows for the detailed representation of a thermal zone in the model with the use of CFD. The spatial discretisation is user-defined and results about the air velocity and local temperature can be acquired.

Alternative topological considerations

With the ability to assess the energy performance of individual spaces and model the environmental conditions and operational profile of the ship, the connection between the topology of on board spaces and the efficiency of the HVAC system can be investigated.

Optimisation of HVAC system operation

This work has focused mainly on the development of a modelling tool and methodology for the design of ship accommodation. Optimisation was only performed in a very informal manner while fine tuning the PID parameters. Further optimisation can be investigated taking into consideration the installation of variable air volume fans, the adjustment of the fresh / recirculation air ratio, definition of the number of AHUs on board, length of ductwork, great levels of indoor comfort etc.

Use for life-cycle energy management

In this work energy modelling has been demonstrated as a design tool. However, with a holistic energy modelling tool at hand, the power consumption of a vessel can be estimated during her life-cycle from very early stages in the design with rough assumptions about the ship's operational profile.

8.4 Closure

This chapter summarised the contributions of this thesis in the field of energy modelling during ship design and operation and discussed further developments that would improve the application of energy modelling during the assessment of the life-cycle energy performance of ships.

9 CONCLUSIONS

Energy efficiency and environmental pollution are most likely to remain the major problems within the shipping community for the next couple of decades to say the least. With the introduction of MARPOL Annex XI and the mandatory implementation of EEDI and SEEMP in 2013, the need to reduce shipping's carbon footprint is pushing for the improvement of energy efficiency.

Since energy efficiency was never of primary importance, the design of ship energy systems is characterised by antiquated calculations and rules-based deterministic procedures. It is clear that available technology is disregarded while in other industries detailed design with use of energy simulation is well established.

Dynamic energy simulation in the buildings industry has been developing since the 1960's and is now at a very mature stage. Available tools are able to capture almost every energy interaction between mechanical equipment, construction, occupants and the environment. Stemming from several obvious similarities between ships and buildings, this work investigated the applicability of building energy simulation in ships.

Initially the differences and similarities between ships and buildings were listed and their effect on the energy simulation of ship energy systems was discussed. This led to the development of 'ESP-r marine', an energy modelling tool capable of modelling the accommodation and HVAC systems of cargo and passenger ships. However, the large number of accommodation spaces especially in passenger ships required some form of simplification during the modelling process. For this reason the work focused on the possibility to investigate single or groups of spaces separately and the space grouping of adjacent spaces. Results showed that accommodation spaces in cargo ships can be represented by one thermal zone per deck in most cases, with only a slight loss of accuracy in the energy calculations. For passenger vessels, results indicated that each MFZ of each cabin deck can be represented by one thermal zone in the model, and that the loss of accuracy is minimal in this case as well. Based on these results, design guidelines were generated that simplify the modelling process.

At this point a modelling methodology for the design of accommodation in commercial ships was proposed, and its use was demonstrated in two case studies. Results showed how environmental (temperature, wind, solar radiation), operational (orientation and location of the ship) and control parameters affect the power consumption and dictate the energy performance of accommodation systems in cargo and passenger ships. Further recommendations for future work were made that are expected to improve the validity, accuracy and performance of thermal energy modelling in the marine environment.

From a practical point of view, 'ESP-r marine' along with the proposed design methodologies, has introduced an informed way to develop more energy efficient accommodation designs. The effect of alternative and non-conventional designs on the power consumption of the accommodation can now be quantified in detail during the design phase, in a straightforward and relatively quick manner.

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APPENDIX I – FIRE RATING OF DIVISIONS ACCORDING TO SOLAS

- A-class divisions that are so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test and are insulated with approved materials such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature, at any point, including any joint, rise more than 180°C above the original temperature with 60 mins for class "A-60", 30 mins for class "A-30", 15 mins for class "A-15" and 0 mins for class "A-0".

- B-Class divisions that are so constructed as to be capable of preventing the passage of flame to the end of the first half hour of the standard fire test they have an insulation value such that the average temperature of the unexposed side will not rise more than 140°C above the original temperature, nor will the temperature at any one point, including any joint, rise more than 225°C above the original temperature, within 15 mins for class "B-15" and 0 mins for class "B-0".

- C-Class divisions need meet neither requirements relative to the passage of smoke and flame nor limitations relative to the temperature rise.

APPENDIX II – LIST OF MATERIALS AND CONSTRUCTIONS ADDED TO ESP-R DATABASES

Although thermal properties are temperature dependent, their values do not change considerably within the temperature range of -20°C to 40°C met in ship accommodation systems, therefore constant values can be assumed for thermal modelling purposes.

Table II-1: List of materials added to ESP-r's material database.

Material	Conductivity	Density	Specific Heat	Emissivity	Absorptivity
Units	W/m/K	kg/m3	J/kg/K	(-)	(-)
Mild steel	50	7860	510	0.12	0.2
Galvanised steel	50	7800	500	0.12	0.2
Glasswool	0.04	24	840	0.9	0.3
Rockwool	0.04	120	840	0.9	0.3
PVC	0.19	1200	1470	0.9	0.7
Subfloor compound	0.05	900	800	0.9	0.3
Plate glass	0.76	2710	837	0.83	0.05

Table II-2: List of constructions added to ESP-r's construction database.

Construction	Material	Thickness (mm)
Bulkhead External A60 Fire rating	Mild Steel	10
	Rockwool	75
	Air	100
	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
Bulkhead External Thermal insulation	Mild Steel	10
	Glasswool	50
	Air	100
	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
Bulkhead External No insulation	Mild Steel	10
Bulkhead Internal 25mm	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5

Bulkhead Internal 50mm	Galvanised steel	0.5
	Rockwool	49
	Galvanised steel	0.5
Bulkhead Internal A60 fire rating	Mild Steel	10
	Rockwool	75
Ceiling Internal	PVC	3
	Subfloor compound	20
	Mild Steel	10
	Air	500
	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
Ceiling External Thermal insulation	Mild Steel	10
	Glasswool	50
	Air	500
	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
Ceiling External A60 Fire rating	Mild Steel	10
	Glasswool	50
	Air	500
	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
Deck Internal	Galvanised steel	0.5
	Rockwool	24
	Galvanised steel	0.5
	Air	500
	Mild Steel	10
	Subfloor compound	20
	PVC	3
Deck Internal A60 Fire rating	Mild Steel	10
	Rockwool	75
	Subfloor compound	20
	PVC	3
Window Single glazing	Plate glass	10
Window Double glazing	Plate glass	14
	Air	10
	Plate glass	14

APPENDIX III – FORTRAN CODE ADDED TO ESP-R SOURCE CODE

External HTC calculation for seawater.

```
ELSEIF(ICOR.EQ.20)THEN

C Fored convection model for turbulent flow, using correlations as found in 'Heat transfer in turbulent fluid flows,
C Zukauskas & Slanciauskas, 1987' and cited in Lienhard & Lienhard, 'Heat transfer textbook, 2011', when the fluid is
C seawater. SWSAL=salinity of water. Boundary conditions are superimposed in the model using the 'internal/specified
C constant' boundary conditions. The assigned constant temperature 'ATF(ICOMP,ISUR)' represents the sea temperature.

      SWSAL=35.0
      SWTMP=ATF(ICOMP,ISUR)
      LENGTH=300
      SPEED=10.289
      RCRIT=3.5*(10**5)

C Calculation of seawater density
      CALL SWDENSITY(SWTMP,SWSAL,SWRHO)
C Calculation of Cp for Sea Water
      CALL SWCAPACITY(SWTMP,SWSAL,SWCP)
C Calculation of dynamic viscosity of seawater
      CALL SWVISCOSITY(SWTMP,SWSAL,SWMU)
C Calculation of conductivity of seawater
      CALL SWCONDUCTIVITY(SWTMP,SWSAL,SWCON)
C Calculation of Reynolds Number, Transition coefficient, Prandtl Number, Nusselt Number

      REY=SWRHO*LENGTH*SPEED/SWMU
      TRANS=0.037*(RCRIT**(4.0/5.0))-0.664*(RCRIT**(1.0/2.0))
      PRANDTL=SWMU*SWCP/SWCON
      NUSSELT=(0.037*REY**(4.0/5.0)-TRANS)*PRANDTL**(1.0/3.0)

      HC=NUSSELT*SWCON/LENGTH

      if(dotrace)then
          write(outs,'(A,4F9.3)')
     &    ' Zukauskas & Slanciauskas: HC & ATF',
     &    HC,ATF(ICOMP,ISUR)
          call edisp(itu,outs)
        endif

      ELSEIF(ICOR.EQ.21)THEN

C Natural convection model from a verical surface, using the 'Churchill and Chu (1975)' correlations
C as given at 'Incropera et al (2007)'. Primary purpose of this calculation is the heat transfer from
C the fuel tanks of the ship to the engine room.

C       All properties are calculated at an average (film) temperature between the surface and the tank.
      FOTMP=(ATF(ICOMP,ISUR)+TFS(ICOMP,ISUR))/2.0+273.0
C     Specific gravity of fuel oil fraction
      SG=0.96
C     Boiling point of fraction
      TBOIL=(300.0+273.0)*9.0/5.0
C     Watson characterization number. Denotes the parafinicity of the fraction.
      WA=TBOIL**(1.0/3.0)/SG
C     Expansion coefficient.
      FOEXP=950E-06
C     Temperature difference between the surface and the tank.
      DELTAT=ABS(ATF(ICOMP,ISUR)-TFS(ICOMP,ISUR))

      CALL FODENSITY(FOTMP,SG,WA,FODEN)
      CALL FOCAPACITY(FODEN,FOTMP,FOCP)
      CALL FOCONDUCTIVITY(SG,FOTMP,FOCON)
      CALL FOVISCOSITY(SG,FOTMP,FOVIS)
```

```
      PRANDTL=FOVIS*FOCP/FOCON
      GRASHOF=(HEIGHT**3)*(FODEN**2)*9.81*
     +(DELTAT)*FOEXP/FOVIS**2
      RAY=GRASHOF*PRANDTL
      NUSSELT=(0.825+(0.387*RAY**(1.0/6.0))/(1+(0.492/PRANDTL)
     +**(9.0/16.0))**(8.0/27.0))**2.0

      HC=NUSSELT*FOCON/HEIGHT

      if(dotrace)then
          write(outs,'(A,2F9.3)')'Churchill and Chu: HC & DT',HC,DT
          call edisp(itu,outs)
        endif
```

Calculation of seawater properties

```
C *************SWDENSITY************************************
C Subroutine that calculates and returns the density of seawater SWDEN as
C a function of its temperature SWTMP and salinity SWSAL.

      SUBROUTINE SWDENSITY(SWTMP,SWSAL,SWDEN)

      DOUBLE PRECISION A(1:5),B(1:5),SWSAL1,RHOW,RHOD,SWTMP,SWSAL,SWDEN

      SWSAL1=SWSAL/1000.0
      A(1)=9.9992293295E+02
      A(2)=2.0341179217E-02
      A(3)=-6.1624591598E-03
      A(4)=2.2614664708E-05
      A(5)=-4.6570659168E-08
      B(1)=8.0200240891E+02
      B(2)=-2.0005183488E+00
      B(3)=1.6771024982E-02
      B(4)=-3.0600536746E-05
      B(5)=-1.6132224742E-05

      RHOW=A(1)+A(2)*SWTMP+A(3)*(SWTMP**2)+A(4)*(SWTMP**3)+A(5)*
     +(SWTMP**4)
      RHOD=B(1)*SWSAL1+B(2)*SWSAL1*SWTMP+B(3)*SWSAL1*(SWTMP**2)+
     +B(4)*SWSAL1*(SWTMP**3)+B(5)*(SWSAL1**2)*(SWTMP**2)

      SWDEN=RHOW+RHOD

      RETURN
      END

C ***************SWCAPACITY************************
C Subroutine that calculates and returns the specific heat capacity of seawater
C SWCAP as a function of its temperature SWTMP and salinity SWSAL.

      SUBROUTINE SWCAPACITY(SWTMP,SWSAL,SWCAP)

      DOUBLE PRECISION A(1:4),SWTMP,SWTMP1,SWSAL,SWSAL1,SWCAP

      SWTMP1=1.00024*SWTMP
      SWSAL1=SWSAL/1.00472

      A(1)=4206.8-(6.6197*SWSAL1)+1.2288E-2*(SWSAL1**2)
      A(2)=-1.1262 +5.4178E-2*SWSAL1-2.2719E-4*(SWSAL1**2)
      A(3)=1.2026E-2-5.3566E-4*SWSAL1+1.8906E-6*(SWSAL1**2)
      A(4)=6.8777E-7+1.517E-6*SWSAL1-4.4268E-9*(SWSAL1**2)

      SWCAP=(A(1)+A(2)*SWTMP1+A(3)*SWTMP1**2+A(4)*SWTMP1**3)

      RETURN
      END

C***************SWVISCOSITY*************************
C Subroutine that calculates and returns the dynamic viscosity of seawater SWVIS,
C as a function of its temperature SWTMP and salinity SWSAL

      SUBROUTINE SWVISCOSITY(SWTMP,SWSAL,SWVIS)

      DOUBLE PRECISION A(1:11),B,SWSAL1,WMU,SWVIS,SWTMP,SWSAL

      SWSAL1=SWSAL/1000.0
```

```
      A(1) = 1.5700386464E-01
      A(2) = 6.4992620050E+01
      A(3) = -9.1296496657E+01
      A(4) = 4.2844324477E-05
      WMU=A(4)+1.0/(A(1)*(SWTMP+A(2))**2+A(3))
      A(5) = 1.5409136040E+00
      A(6) = 1.9981117208E-02
      A(7) = -9.5203865864E-05
      A(8) = 7.9739318223E+00
      A(9) = -7.5614568881E-02
      A(10) = 4.7237011074E-04
      A(11)=A(5)+A(6)*SWTMP+A(7)*(SWTMP**2)
      B=A(8)+A(9)*SWTMP+A(10)*(SWTMP**2)

      SWVIS=WMU*(1+A(11)*SWSAL1+B*SWSAL1**2)

      RETURN
      END

C**********SWCONDUCTIVITY***************************
C Subroutine that calculates and returns the dynamic viscosity of seawater SWCON,
C as a function of its temperature SWTMP and salinity SWSAL

      SUBROUTINE SWCONDUCTIVITY(SWTMP,SWSAL,SWCON)

      DOUBLE PRECISION SWTMP,SWSAL,SWCON,SWTMP1,SWSAL1

      SWTMP1=1.00024*SWTMP
      SWSAL1=SWSAL/1.00472

      SWCON=0.001*(10**(DLOG10(240.0+0.0002*SWSAL1)+0.434*(2.3-
     +(343.5+0.037*SWSAL1)/(SWTMP1+273.15))*((1-(SWTMP1+273.15)
     +/(647.3+0.03*SWSAL1)))**(1.0/3.0)))

      RETURN
      END
```

Calculation of seawater reflectivity

```
C CASE 4: SEAWATER MODEL
C In this model the reflectivity of seawater is calculated as a function of the
position
C of the sun (solar zenith angle) and prevailing wind speed. The equation to
calculate
C the seawater albedo comes from the paper "Spectral approach to calculate specular
C reflection of light from wavy water surface, Haltrin 2001".

      ELSEIF (groundreflmodel.EQ.4) THEN    !New ground reflectivity type seawater
DSFAKIANAKIS

          IF (ISUNUP .EQ. 1) THEN   !Check if sun is up
          thet=90.0-SALT            !Calculate solar zenith angle from solar altitude
C          print*,thet, ISUNUP
          u=VF                      !Use future wind speed
          nWat=1.341                !Water refraction index

          a0 = ATAN(1.0)/45.0       ! = p/180
          phi =  a0*thet            ! converts angles to radians

C Calculate Fresnel reflection coefficient for calm water
          if (phi .ne. 0.) then
          aRef = ASIN(SIN(phi)/nWat)
          aDif = phi-aRef
          aSum = phi+aRef
          Rpar = TAN(aDif)/TAN(aSum)
          Rper = SIN(aDif)/SIN(aSum)
          fresnel = 0.5*(Rpar*Rpar+Rper*Rper)
          else
          aSum = (nWat-1.)/(nWat+1.)
          fresnel = aSum*aSum
          end if

C Calculate Fresnel coefficient with wind effect
          fr0 = fresnel
          a0 = 0.001*(6.944831+u*(-1.912076+0.03654833*u))
          a1 = 0.7431368+u*(0.0679787-0.0007171*u)
          a2 = 0.5650262+u*(0.0061502+u*(-0.023981+0.0010695*u))
          a3 = -0.4128083+u*(-0.1271037+u*(0.0283907-0.0011706*u))
```

```
         FresnWind = a0+fr0*(a1+fr0*(a2+a3*fr0))
C       print*,FresnWind
         groundrefl=FresnWind

         ENDIF

         IF (ISUNUP .EQ. 0) THEN
           groundrefl=0
         ENDIF
```

APPENDIX IV – MODEL SPECIFICATION AND RESULTS FOR CASE STUDIES

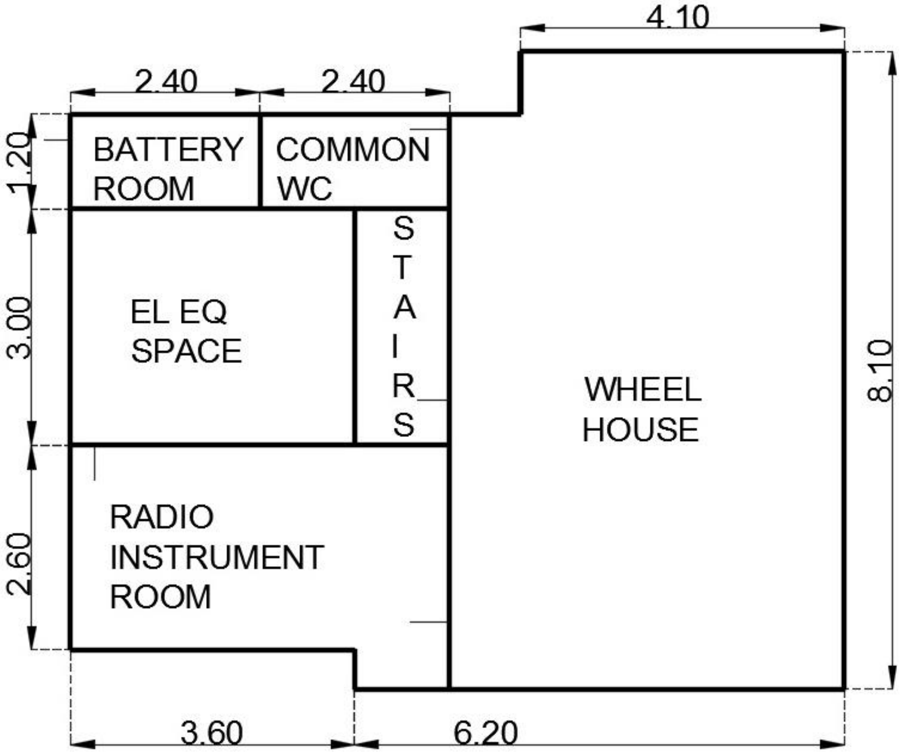

Fig V-1. "Navigation bridge deck plan for cargo ship"

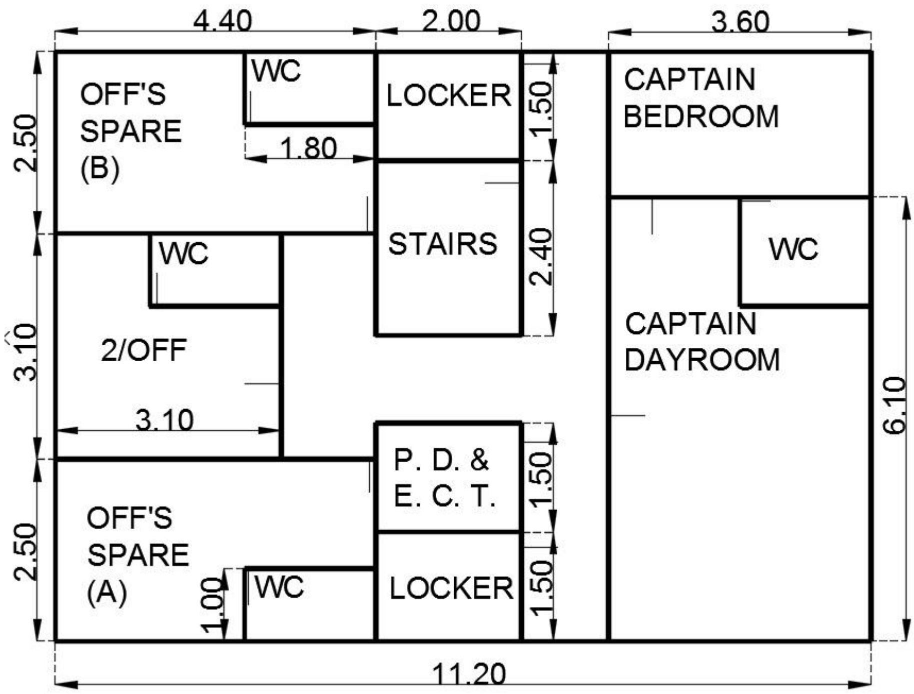

Fig V-2. "Deck D plan"

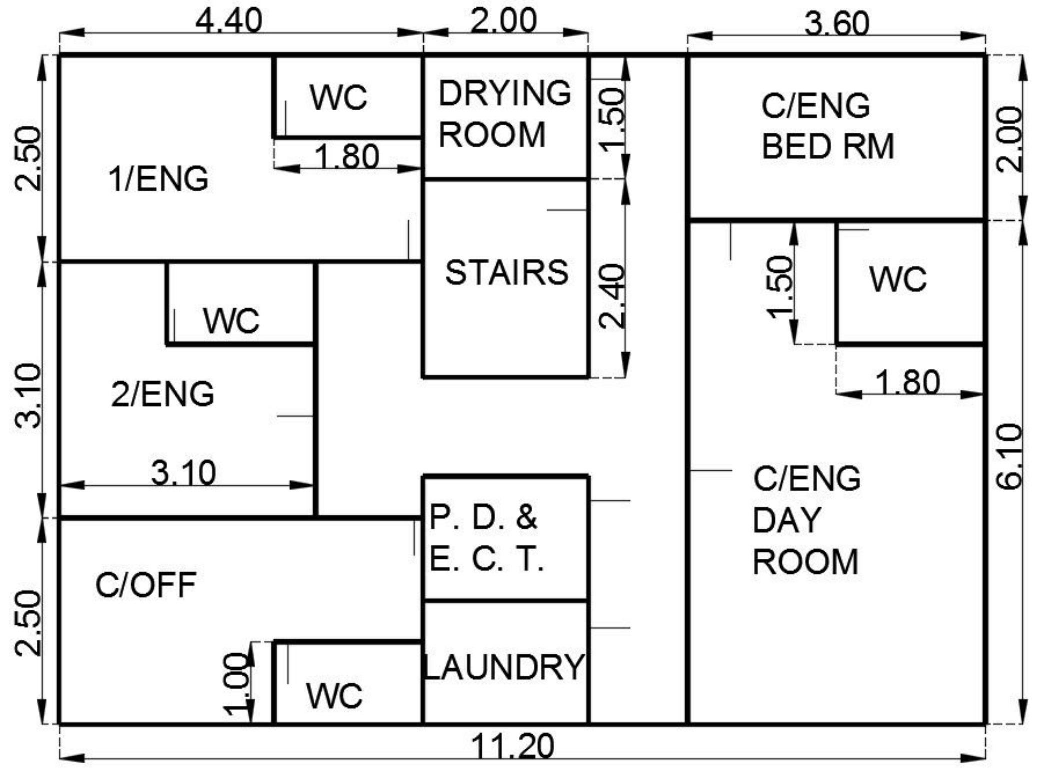

Fig V-3. "Deck C plan"

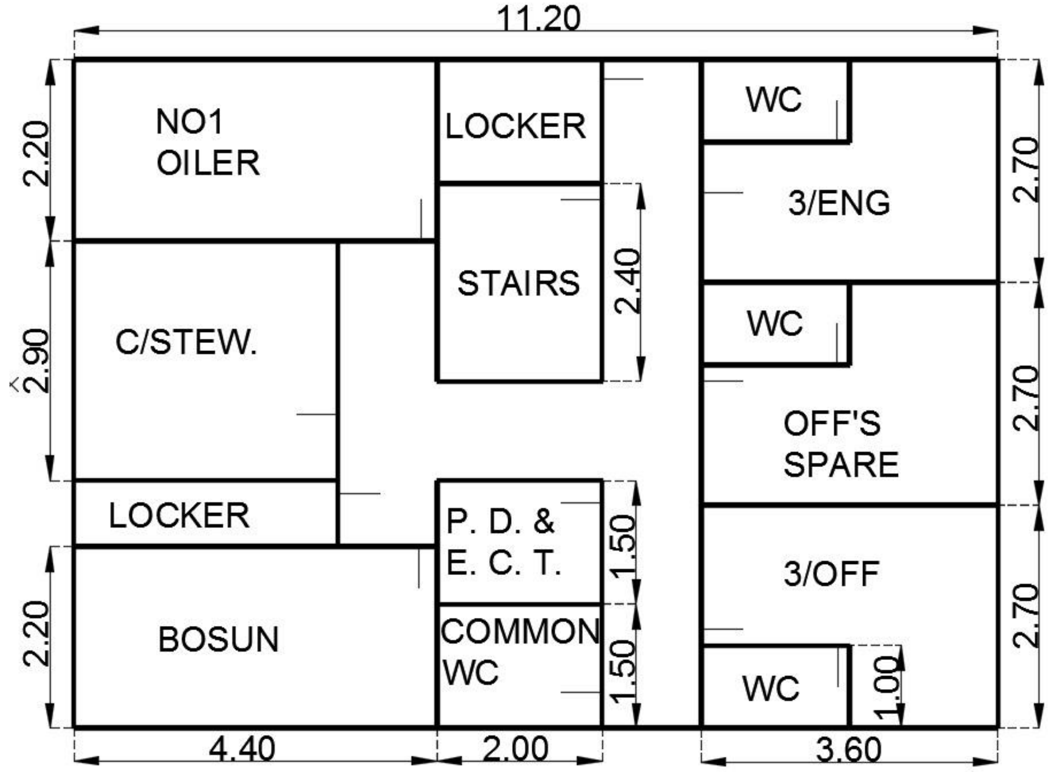

Fig V-4. "Deck B plan"

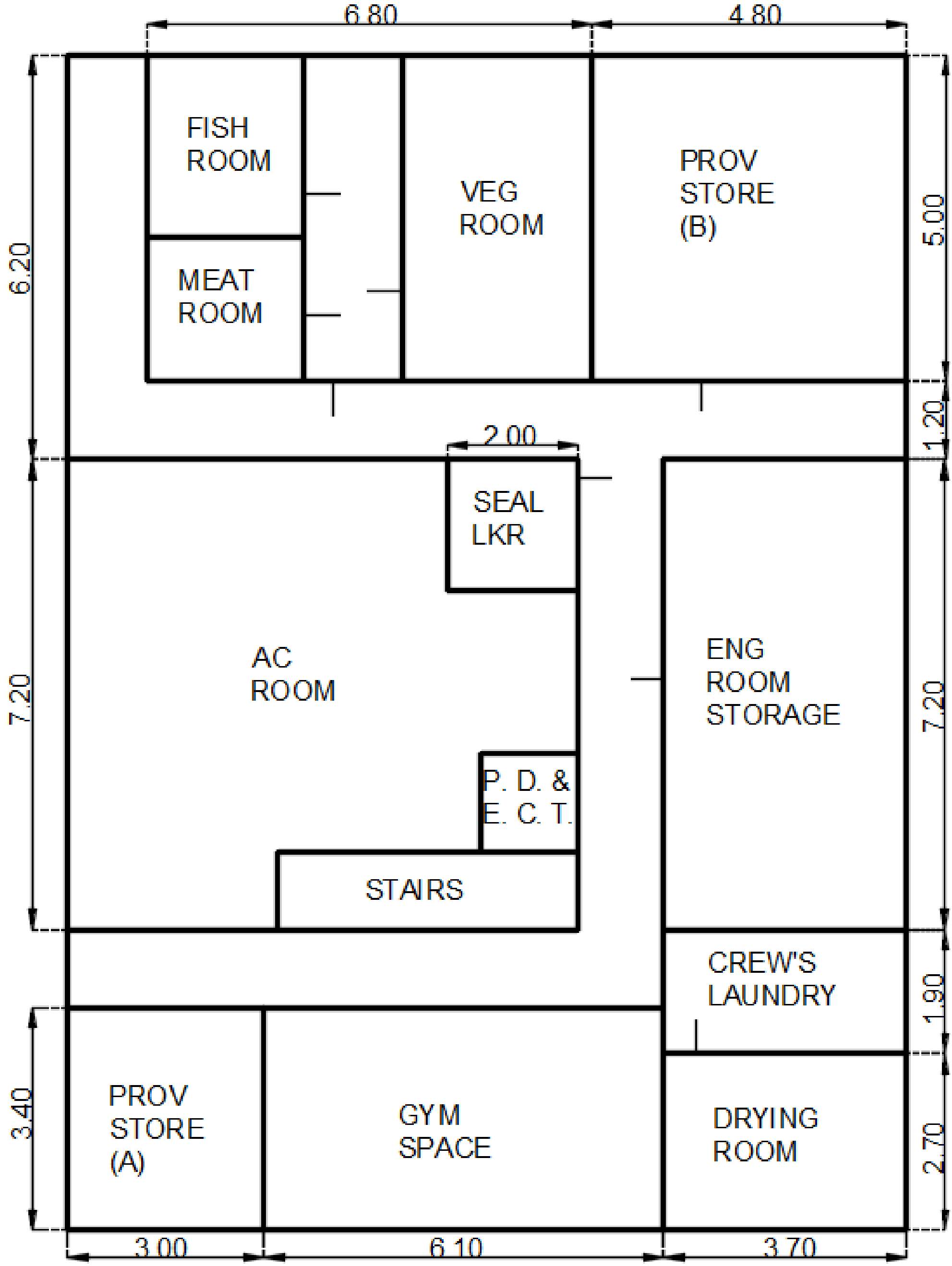

Fig V-5. "Deck A plan"

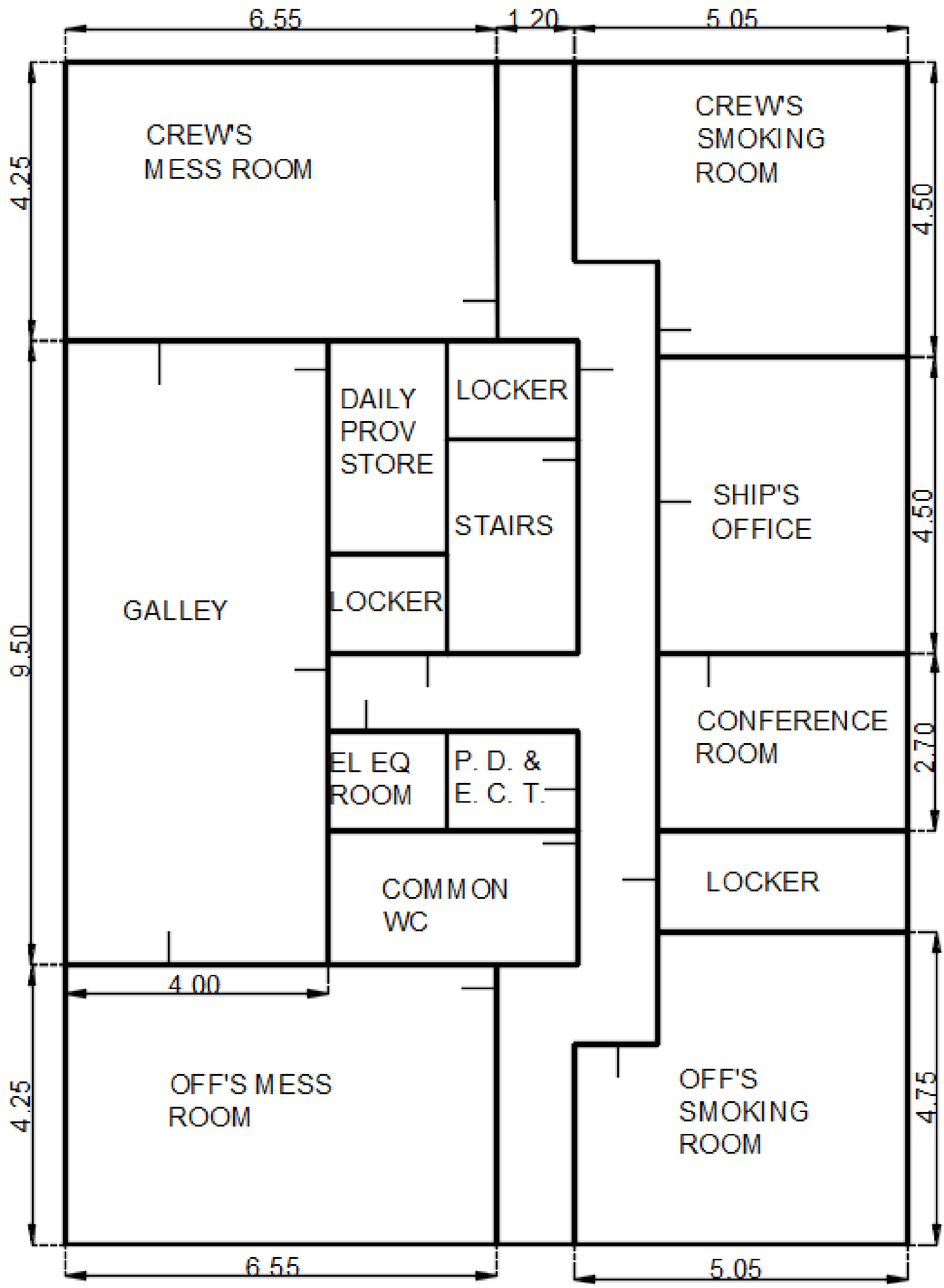

Fig V-6. "Upper deck plan"

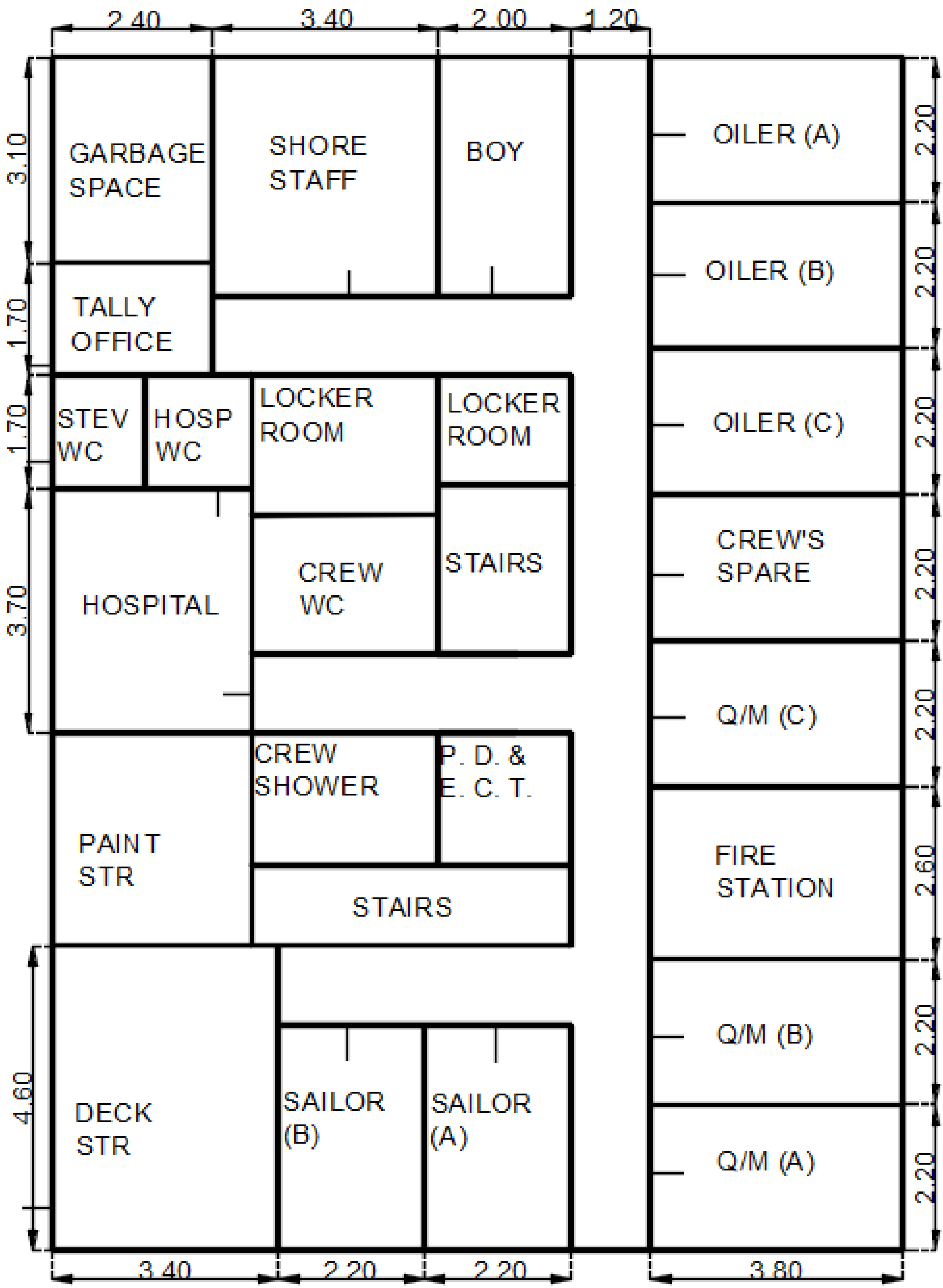

Fig V-7. “2nd deck plan”

Heat Gains		0-7		7-22		22-24	
		Sensible	Latent	Sensible	Latent	Sensible	Latent
Navigation Bridge Deck		200	100	300	150	200	100
Nav.WheelHo	*Wheel House*	200	100	300	150	200	100
Nav.RadioRm	*Radio Instrument Room*	0	0	0	0	0	0
Nav.Pilot	*Pilot*	0	0	0	0	0	0
D Deck		160	80	0	0	462	100
D.CptBedRm	*Captain Bedroom*	80	40	0	0	0	0
D.CptDayRm	*Captain Day room*	0	0	0	0	262	50
D.OffSpA	*Officer's Spare (A)*		0	0	0	0	0
D.2Off	*2nd Officer*	80	40	0	0	200	50
D.OffSpB	*Officer's Spare (B)*	0	0	0	0	0	0
C Deck		320	160	0	0	762	200
C.CengBedRm	*Chief Engineer Bedroom*	80	40	0	0	0	0
C.CengDayRm	*Chief Engineer Day room*	0	0	0	0	262	50
C.Coff	*Chief Officer*	80	40	0	0	100	50
C.2ndEng	*2nd Engineer*	80	40	0	0	200	50
C.1stEng	*1st Engineer*	80	40	0	0	200	50
B Deck		400	200	0	0	1000	250
B.3rdEng	*3rd Engineer*	80	40	0	0	200	50
B.OffSpC	*Officer's spare (C)*	0	0	0	0	0	0
B.3rdOff	*3rd Officer*	80	40	0	0	200	50
B.Bosun	*Bosun*	80	40	0	0	200	50
B.Cstew	*C Stew*	80	40	0	0	200	50
B.No1Oiler	*No1 Oiler*	80	40	0	0	200	50
		17-22		6-18			
		Sensible	Latent	Sensible	Latent		
A Deck		1400	500	300	100		
A.CrewMsRm	*Crew's mess room*	0	0	0	0		
A.CrewSmRm	*Crew's Smoking room*	700	250	0	0		
A.ShipOffic	*Ship's Office*	0	0	0	0		
A.ConfRmc	*Conference Room*	0	0	0	0		
A.OffsSmRm	*Officer's smoking room*	700	250	0	0		
A.OffMessRm	*Officer's mess room*	0	0	0	0		
A.Galley	*Galley*	0	0	300	100		
A.ElEq	*Electrical equipment room*	0	0	0	0		
		0-7		7-22		22-24	
		Sensible	Latent	Sensible	Latent	Sensible	Latent
Upper		720	360	0	0	1530	450
Up.OilerA	*Oiler (A)*	80	40	0	0	170	50
Up.OilerB	*Oiler (B)*	80	40	0	0	170	50
Up.OilerC	*Oiler (C)*	80	40	0	0	170	50
Up.CrewSpar	*Crew's spare*	0	0	0	0	0	0
Up.QMC	*Q/M (C)*	80	40	0	0	170	50
Up.QMB	*Q/M (B)*	80	40	0	0	170	50
Up.QMA	*Q/M (A)*	80	40	0	0	170	50
Up.SailorA	*Sailor (A)*	80	40	0	0	170	50
Up.SailorB	*Sailor (B)*	80	40	0	0	170	50
Up.Hospital	*Hospital*	0	0	0	0	0	0
Up.TallyOf	*Tally office*	0	0	0	0	0	0
Up.ShoreSt	*Shore Staff (4P)*	0	0	0	0	0	0
Up.Boy	*Boy*	80	40	0	0	170	50
2nd		0	0	0	0	0	0
2nd.ProvStB	*Provision Store (B)*	0	0	0	0	0	0
2nd.SeallLkr	*Seal Locker*	0	0	0	0	0	0
2nd.Gym	*Gym Space*	0	0	0	0	0	0
2nd.ProvStA	*Provision Store (A)*	0	0	0	0	0	0

Fig V-8. "Heat gains of within cargo accommodation"

Supply airflow		Designed Air Flow (m3/h)	Designed Air Flow (%)	Desgned Air Flow (% rounded)
Navigation Bridge Deck		1405	0.093120361	0.093
Nav.WheelHo	*Wheel House*	934	0.062	0.062
Nav.RadioRm	*Radio Instrument Room*	346	0.023	0.023
Nav.Pilot	*Pilot*	125	0.008	0.008
D Deck		1322	0.0876193	0.087
D.CptBedRm	*Captain Bedroom*	268	0.018	0.018
D.CptDayRm	*Captain Day room*	366	0.024	0.024
D.OffSpA	*Officer's Spare (A)*	247	0.016	0.016
D.2Off	*2nd Officer*	193	0.013	0.013
D.OffSpB	*Officer's Spare (B)*	248	0.016	0.016
C Deck		1105	0.07323701	0.074
C.CengBedRm	*Chief Engineer Bedroom*	249	0.017	0.017
C.CengDayRm	*Chief Engineer Day room*	323	0.021	0.021
C.Coff	*Chief Officer*	194	0.013	0.013
C.2ndEng	*2nd Engineer*	160	0.011	0.011
C.1stEng	*1st Engineer*	179	0.012	0.012
B Deck		1323	0.087685578	0.087
B.3rdEng	*3rd Engineer*	168	0.011	0.011
B.OffSpC	*Officer's spare (C)*	140	0.009	0.009
B.3rdOff	*3rd Officer*	161	0.011	0.011
B.Bosun	*Bosun*	332	0.022	0.022
B.Cstew	*C Stew*	229	0.015	0.015
B.No1Oiler	*No1 Oiler*	293	0.019	0.019
A Deck		5783	0.38328473	0.383
A.CrewMsRm	*Crew's mess room*	927	0.061	0.061
A.CrewSmRm	*Crew's Smoking room*	707	0.047	0.047
A.ShipOffic	*Ship's Office*	453	0.030	0.030
A.ConfRmc	*Conference Room*	227	0.015	0.015
A.OffsSmRm	*Officer's smoking room*	804	0.053	0.053
A.OffMessRm	*Officer's mess room*	985	0.065	0.065
A.Galley	*Galley*	1640	0.109	0.109
A.ElEq	*Electrical equipment room*	40	0.003	0.003
Upper		3185	0.21109491	0.21
Up.OilerA	*Oiler (A)*	220	0.015	0.015
Up.OilerB	*Oiler (B)*	142	0.009	0.009
Up.OilerC	*Oiler (C)*	208	0.014	0.014
Up.CrewSpar	*Crew's spare*	187	0.012	0.012
Up.QMC	*Q/M (C)*	258	0.017	0.017
Up.QMB	*Q/M (B)*	255	0.017	0.017
Up.QMA	*Q/M (A)*	246	0.016	0.016
Up.SailorA	*Sailor (A)*	212	0.014	0.014
Up.SailorB	*Sailor (B)*	179	0.012	0.012
Up.Hospital	*Hospital*	468	0.031	0.031
Up.TallyOf	*Tally office*	227	0.015	0.015
Up.ShoreSt	*Shore Staff (4P)*	306	0.020	0.020
Up.Boy	*Boy*	277	0.018	0.018
2nd		965	0.063958112	0.064
2nd.ProvStB	*Provision Store (B)*	165	0.011	0.011
2nd.SeallLkr	*Seal Locker*	63	0.004	0.004
2nd.Gym	*Gym Space*	509	0.034	0.034
2nd.ProvStA	*Provision Store (A)*	228	0.015	0.015
	Total	15088	1	0.998

Fig V-9. "Supply airflows for cargo accommodation"

Exhaust airflow		Designed Air Flow (m3/h)	Designed Air Flow (%)	Desgned Air Flow (% rounded)
Navigation Bridge Deck		62	0.026552463	0.027
Common.WC	Wheel House	62	0.027	0.027
D Deck		179	0.076659529	0.076
D.CptBedRm WC	Captain Bedroom	59	0.025	0.025
D.OffSpA WC	Officer's Spare (A)	40	0.017	0.017
D.2Off WC	2nd Officer	40	0.017	0.017
D.OffSpB WC	Officer's Spare (B)	40	0.017	0.017
C Deck		345	0.147751606	0.147
C.CengDayRm WC	Chief Engineer Day room	59	0.025	0.025
C.Coff	Chief Officer	40	0.017	0.017
C.2ndEng	2nd Engineer	40	0.017	0.017
C.1stEng	1st Engineer	40	0.017	0.017
C.OffLaundry	Officers' laundry room	94	0.040	0.040
C.OffDrying	Officers' drying room	72	0.031	0.031
B Deck		212	0.090792291	0.09
B.3rdEng WC	3rd Engineer	40	0.017	0.017
B.OffSpC WC	Officer's spare (C)	40	0.017	0.017
B.3rdOff WC	3rd Officer	40	0.017	0.017
B.CommonWC	Common WC	92	0.039	0.039
A Deck		92	0.039400428	0.039
A.Common WC	Common WC	92	0.039	0.039
Upper		493	0.211134904	0.211
Up.CrewShower	Crew's shower	161	0.069	0.069
Up.CrewWC	Crew's WC	222	0.095	0.095
Up.HospWC	Hospital WC	58	0.025	0.025
Up.StevWC	Stev WC	52	0.022	0.022
2nd		952	0.407708779	0.409
2nd.ProvStB	Provision Store (B)	275	0.118	0.118
2nd.ProvStA	Provision Store (A)	275	0.118	0.118
2nd.CrewLaundry	Crew Laundry	188	0.081	0.081
2nd.DryingRm	Crew Drying room	214	0.092	0.092
	Total	2335	1	0.999

Fig V-10. “Exhaust airflows for cargo accommodation”

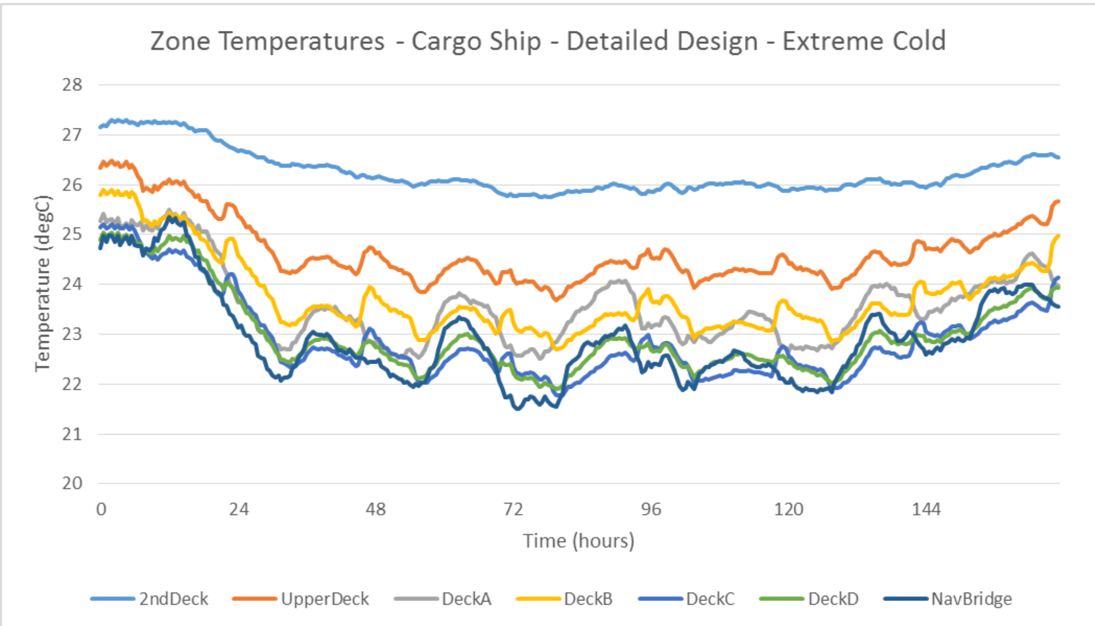

Fig V-11. “Zone temperatures during detail design”

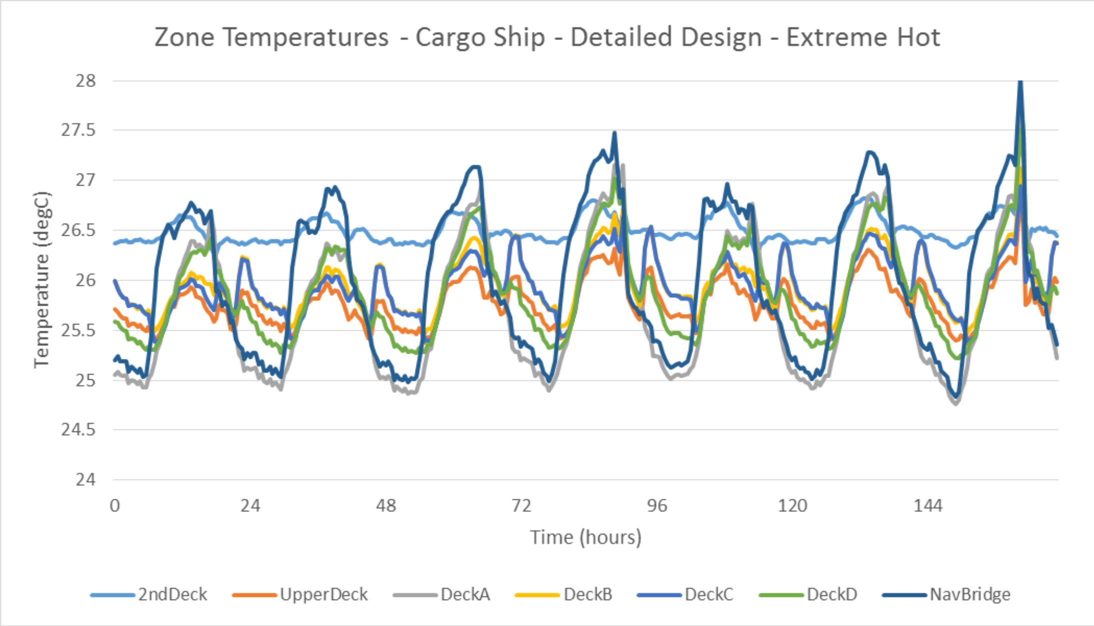

Fig V-12. "Zone temperatures during detail design"

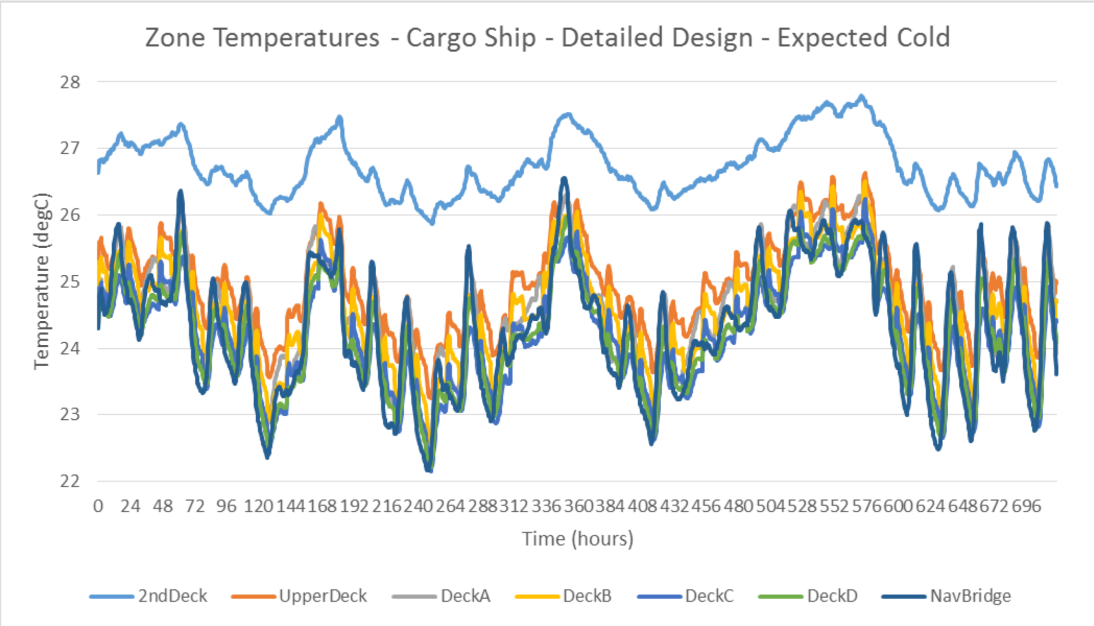

Fig V-13. "Zone temperatures during detail design"

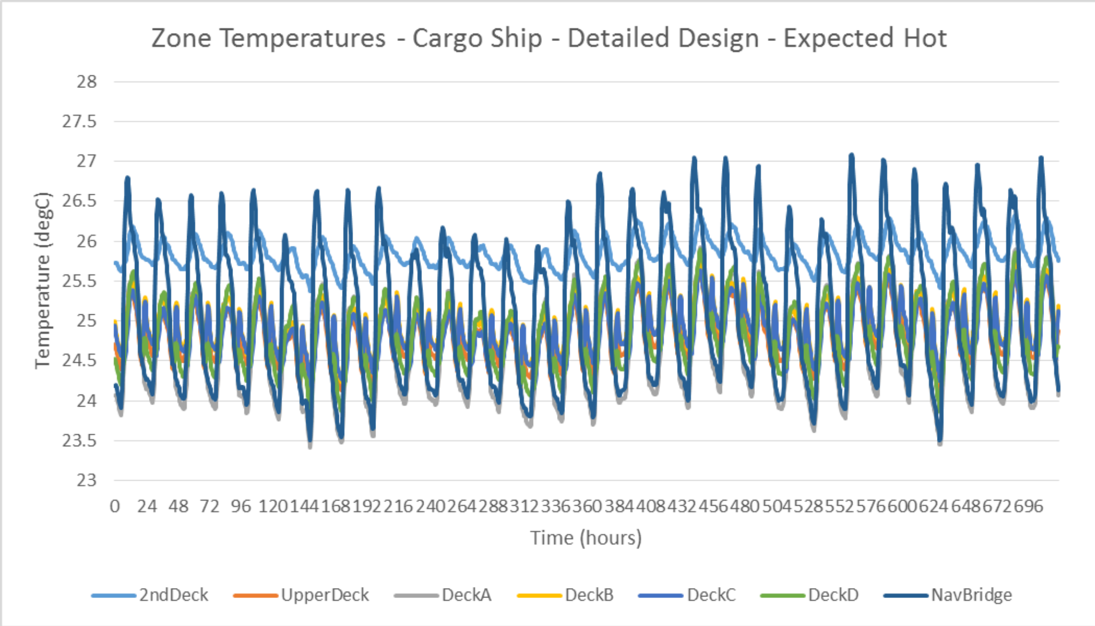

Fig V-14. "Zone temperatures during detail design"

APPENDIX V – NOMENCLATURE

3D	Three dimensional
A	area (m^2)
ac/h	air changes per hour
AHU	Air Handling Unit
BES	Building Energy Simulation
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
C_p	specific heat capacity (J/K/Kg)
Dwt	Deadweight tonnage
ε	emissivity
EEDI	Energy Efficiency Design Index
ESP-r	Environmental Systems Performance - research
ESRU	Energy Systems Research Unit
EU	European Union
FORTRAN	Formula translating system
GHG	Greenhouse Gas
h	heat transfer coefficient ($W/m^2/K$)
HTC	Heat transfer coefficient
HVAC	Heating, Ventilation and Air Conditioning

IAQ	Indoor Air Quality
ICOADS	International Comprehensive Ocean-Atmosphere Data Set
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
i_β	angle between the incident beam and the surface's normal vector
k	thermal conductivity (W/m/k)
K_d	derivative gain
K_i	integral gain
K_p	proportional gain
LNG	Liquefied Natural Gas
MARPOL	Marine Pollution (International convention for the prevention of pollution from ships)
MEPC	Marine Environmental Pollution Committee
MFZ	Main Fire Zone
MVZ	Main Vertical Zone
NO_x	Oxides of nitrogen
Nu	Nusselt number
PID	Proportional Integral Derivative

Pr	Prandtl number
PVC	Polyvinyl chloride
q	Heat (J)
q_x	heat transfer in the direction of 'x' (J)
R_{crit}	Critical Reynolds number
Ro-Pax	Roll-on/Roll-off Passenger
SEEMP	Ship Energy Efficiency Management Plan
SL	ship length (m)
SOLAS	Safety of Life at sea
SO_x	Oxides of sulphur
SS	Ship Speed (m/s)
Ssres	Residual Sum of squares
Sstot	Total sum of squares
SW_k	Conductivity of seawater (W/m/K)
SW_{cp}	Specific heat capacity of seawater (J/kg/K)
SW_v	viscosity of seawater (kg/s/m)
t	time (s)
T_e	equivalent temperature (K)
Trans	Transition number
T_s	surface temperature (K)

UNEP	United Nations Environment Programme
UV	Ultra violet
V_{aw}	apparent wind speed (m/s)
VBA	Visual Basic
V_s	ship speed
V_w	wind speed (m/s)
WHR	Waste Heat Recovery
x	length (m)
α	themal diffusivity (m^2/s)
α_f	surface azimuth
α_s	solar azimuth angle
βf	surface elevation
ϱ	density (kg/m3)
σ	Stefan-Boltzmann constant