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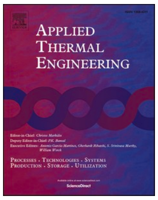

Research Paper

# Advancing sustainability in the maritime sector: energy design and optimization of large ships through information modelling and dynamic simulation

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ABSTRACT

This paper deals with a new energy design approach for ships to reduce the fuel consumption and the related environmental impact. The proposed method is based on the application of the Building Information Modeling (BIM) to Building Energy Modeling (BEM) technique. Specifically, by a BIM model of the ship a 3D physics-based model (BEM) can be suitably created. Then, by BEM the ship energy performance is simulated under real and dynamic operating conditions. By the presented method the whole design-to-delivery process of the ship can be simplified and speeded up with respect to traditional approaches, without losing reliability. As an example, HVAC systems design is easier through BIM since a high number of thermal zones can be effectively handled. Due to BEM, also the optimal design for exploiting waste heat recoveries of on-board combustion engines is easier and faster.

To show the capability of the proposed approach a suitable case study was developed. Basically, it concerns the energy performance analysis of the Allure of the Seas, a 6000-passenger cruise ship operating in the Caribbean Sea. Two different scenarios for recovering the waste heat of the ship diesel generators are investigated. Simulation results highlight that significant primary energy saving can be obtained by optimizing the strategy to recover the available thermal energies (up to 600 MWh per trip), with a remarkable amount of avoided pollutant emissions (58, 0.06, 4.0, 0.2, 2.0 kg/km of $CO_2$, PM2.5, NOx, HC, SOx, respectively).The presented new approach can be easily adopted to design and optimize the energy system of any new or existing ships, with the twofold aim to achieve economic savings and to fulfil environmental sustainability standards.

## 1. Introduction

Environmental issues linked to climate change are of great concern also for the maritime sector. According to new regulations, the emission of pollutants into the atmosphere must be limited to certain values. Along with other major organizations, the International Maritime Organisation (IMO) has issued various regulations over the years to align its policy with the actions adopted worldwide and to reduce pollution from ships [1]. MARPOL is the main international convention that cover regulations aimed at preventing and minimizing pollution from ships including garbage management, energy efficiency and emission of pollutants into the atmosphere, as prescribed in the IMO MARPOL Annex IV, V, and VI. In this context, sustainability has become one of the priorities for the shipping sector [2] and port authorities [3,4]. Ship owners and shipyards are encouraged to improve the energy efficiency of new ships as well as the existing fleet. GHG emissions are increasing, so, legislations for decarbonization are becoming more stringent in sea transport as well. From 1st of January 2020, maximum allowed sulphur content in the fuel oil was reduced from 3.50% to 0.50% [5]. These regulations also concern cruise ships that have high energy demands due to their large size. Cruise ships not only require a huge amount of fuel for propulsion or production of potable water, but also need air-conditioning for indoor spaces which can be responsible alone for about 30% of the total energy use [6].

Several solutions have been analysed for compliance with maritime regulations, starting from the substitution of highly polluting fuels with lower-sulphur ones, such as Liquefied Natural Gas (LNG) [7]. Due to

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**Nomenclature**

| | |
|---|---|
| AC | Air Conditioning |
| AEC | Architecture Engineering and Construction |
| BEM | Building Energy Modeling |
| BIM | Building Information Modeling |
| CAD | Computer Aided Design |
| CHP | Combined Heat and Power generator |
| COP | Coefficient of Performance |
| DHW | Domestic Hot Water |
| EEDI | Energy Efficiency Design Index |
| EEDI | Energy Efficiency Design Indexes |
| EGB | Exhaust Gas Boiler |
| GHG | Greenhouse gas |
| GT | Gas Turbine |
| HFO | Heavy Fuel Oil |
| HT | High Temperature |
| HVAC | Heating, Ventilation and Air Conditioning |
| ICE | Internal Combustion Engine |
| IMO | International Maritime Organisation |
| ISO | International Organization for Standardization |
| KPI | Key Performance Parameters |
| LHV | Lower Heating Value |
| LNG | Liquefied Natural Gas |
| MSF | Multi-Stage Flash evaporator |
| OFB | Oil Fired Boiler |
| PCM | Phase Change Materials |
| VEM | Volume Element Model |

*Symbols*

| | |
|---|---|
| $\dot{m}_{s,EGB}$ | EGB steam production $kg/s$ |
| $\dot{Q}_{EGB}$ | EGB thermal power demand $kW$ |
| $\dot{m}_{f,OFB}$ | OFB fuel consumption $kg/s$ |
| $\dot{m}_{in,st}$ | storage inlet flow rate $kg/s$ |
| $\dot{m}_{out,st}$ | storage outlet flow rate $kg/s$ |
| $\dot{m}_{s,nd,OFB}$ | OFB steam demand $kg/s$ |
| $\dot{Q}_{g,EGB}$ | Thermal power required by EGB $kW$ |
| $\dot{m}_{f,CHP}$ | CHP fuel consumption $kg/s$ |
| $\dot{m}_{fw,MSF}$ | freshwater production $kg/s$ |
| $\dot{m}_{HT}$ | HT loop mass flow rate $kg/s$ |
| $\dot{Q}_{MSF}$ | MSF thermal power demand $kW$ |
| $c$ | conversion factor $kW/kg/h$ |
| $c_{€}$ | cost of energy $€$ |
| $C_{MSF}$ | capacity of activated MSFs $kg/s$ |
| $e_p$ | primary energy $kWh$ |
| $f$ | emission factor $kg/kWh$ |
| $g_{ee}$ | electrical equipment power load intensity $W/\ m^2$ |
| $g_l$ | lighting power load intensity $W/\ m^2$ |
| $g_{l,p}$ | latent heat gain per person $W/person$ |
| $g_{s,p}$ | sensible heat gain per person $W/person$ |
| $LHV_f$ | fuel lower heat value $kWh$ |
| $N_{MSF}$ | number of activated MSFs |
| $p$ | total equivalent amount of pollutants $kg$ |
| $P_{el}$ | power demand $kW$ |
| $plr$ | part load ratio |
| $pr$ | price of fuel $€/kg$ |
| $P_{r,CHP}$ | CHP rated power $kW$ |
| $SOC$ | state of charge |
| $T_{HT,\ in,\ MSF}$ | HT loop MSF inlet temperature $^{\circ}C$ |
| $T_{HT,\ out,\ MSF}$ | HT loop MSF outlet temperature $^{\circ}C$ |
| $V_{st}$ | storage capacity $m^3$ |
| $\eta_{CHP}$ | CHP overall conversion efficiency |
| $\eta_{OFP}$ | OFB overall conversion efficiency |

even more stringent environmental constraints and related penalties, alternative fuels such as hydrogen, biodiesel, biogas, ammonia, and methanol, are being considered for future implementations [8,9]. For example, Wärtsilä and Norwegian ship owner Eidesvik Offshore ASA are collaborating on converting an offshore supply ship to run on 70% of ammonia blend [10]. The treatment of the engine exhaust gases by means of scrubbers [11], or the use of post-combustion carbon capture with the use of amine as a method to reduce the $CO_2$ emissions [12] are considered valuable solutions too. Furthermore, the simultaneous use of an Internal Combustion Engine (ICE) and a Gas Turbine (GT) was analysed obtaining promising results [13].

The exploitation of waste heat from the main engines to power the thermally activated technologies and the optimization of the energy management of the use of heat in the best possible way are now becoming the standard for shipowners. The electrical production can be improved considering the implementation of new hybrid turbochargers considering marine dual-fuel engines [14] or considering a turbogenerator fed with steam produced from waste heat recovery of exhaust gases [15]. Replacing conventional compressor chillers with absorption chillers significantly reduces HVAC electricity consumption. Organic or standard steam turbine systems, and Stirling engines may increase electricity production avoiding the consumption of fuel [16,17]. Additionally, existing plants equipped with energy storage including Phase Change Materials (PCM) may help to increase thermal storage capacity up to 30% thanks to the latent storage share [18]. Such technology contributes to balance variable heat production and demand.

The use of battery energy storage systems (BESS) within ships operating in dynamic conditions increase the ship performance: for RoRo ships a reduction up to 257.5 tons of $CO_2$ per year has been achieved [19]. A life-cycle cost assessment instead pointed out that lower emissions, as well as total cost, can be achieved for a battery-powered ship compared to a diesel engine-powered ship or a battery-powered ship with PV cells [20]. Similarly, power management, renewable energies and fuel cells technologies are increasingly considered to enhance ship energy efficiency [21]. Specifically, effective power management strategies have the potential to reach substantial savings in terms of primary energy and fuel consumption. It is important to consider not only the direct impact on electrical energy production but also the thermal production required to meet heating or cooling needs of passengers [22].

As heating, ventilation, and air conditioning (HVAC) system is one of the largest power consumers after propulsion, a reduction of polluting emissions should start from an optimization of the plants serving the ships. To do so, a careful analysis of the passengers and crew needs in terms of indoor comfort is necessary to correctly assess all energy consumption due to ship operation, thus avoiding unnecessary dissipation of energy and excessive pollutants emissions into the atmosphere. This can be achieved through dynamic analysis that takes into account the real operating conditions and the variability of the various boundary conditions [23]. However, the tool of dynamic simulation applied to ships design and operation verification has not been properly addressed in the past years. The interest in assessing in detail the energy-environmental impact of the various design choices with advanced tools is quite recent and few research works are available in the literature. A steady-state simulation model to assess the temperature distribution of different zones has been developed through the use of a Volume Element Model (VEM) that discretizes the ship volume [24]. Instead, another research [25] focused on a ship thermal analysis, also using a VEM method, based on FORTRAN routines and CAD geometry to obtain the final ship mesh for a notional all-electric ship. The study considers 43 thermal loads with solar irradiation imposed on the top ship boundary. However internal gains due to the people activities are not described in the paper. The modelling of a ship with "Environmental Systems Performance – research edition" (Esp-r), a software used to simulate the building behaviour through a finite volume conservation approach has also been explored [6]; the main problem encountered by the authors is the amount of time needed to model the ship geometry. The study reported in [26] analysed three operating conditions of a naval ship: shore, cruise, and battle mode. The analysis considered average monthly outdoor air and sea water temperatures for two different locations: the East Gulf of Mexico and the Gulf of Alaska. The primary focus of the study was to assess the cooling capacity required to ensure that all equipment stays within their design limits in terms of temperature variation during battle mode. Additionally, the study explored the possibility of pre-cooling deionized fresh water before it reaches the chillers, using seawater heat exchangers, which resulted in fuel savings. The simulation was conducted using the VEM method to implement the ship model.

Also, the synergy between SketchUp and TRNSYS3d plug-in to model the ship geometry and simulate two cruise trips in the Mediterranean and in the Caribbean seas has been exploited [17]. The authors optimized the waste heat recovery system, achieving several energy and financial improvements, eg.fuel savings, minor electricity need and operating cost, low standard Energy Efficiency Design Indexes (EEDI). The model developed in TRNSYS considered the HVAC needs through a dynamical weather data file and, parameters and scheduling obtained from regulations.

The model was also applied in the case of a cruise in the Norwegian fjords with different energy saving devices implemented, obtaining a reduction in the pollutant emissions and primary energy needs, with a simple payback of less than 1 year [27].

Apros, a dynamic simulation software, has also been investigated to simulate the energy systems of a cruise ferry with the purpose of optimizing the waste heat recovery and the chilled water systems. The climate conditions of the Baltic Sea and the ship energy needs were considered to simulate the ship systems. According to the authors, the model proved to be an excellent alternative for simulating the operation of the ship plants, as confirmed by the measured data, providing substantial benefits in the design of new ships and the optimization of the existing ones [28].

Several measures to enhance the energy efficiency of a cruise ship operating in the Nordic climate was investigated by means of IDA ICE energy modelling software. The implementation of a heat pump and variable air volume ventilation proved to be the most efficient solutions, respectively 38% and 24% reduction in energy use, significantly reducing the ship reliance on auxiliary boilers and waste heat from the engines [29].

### 1.1. *BIM in the ship environment*

In recent years, Building Information Modeling (BIM) is playing a key role in the Architecture Engineering and Construction (AEC) sector, thanks to introduction of numerous improvements in the management of the entire building production cycle, with a lot of benefits cited in literature. This has led to the interest in BIM by the shipbuilding industry, where there are similar productivity and lifecycle challenges as the AEC industry [30].

Also, a large organization such as Royal Caribbean International has started to incorporate BIM into the corporate shipbuilding department. Whilst the overall naval attributes may prove difficult to incorporate into BIM, the building-like elements of passenger ships could be introduced into the BIM environment. Typically, tools such as SolidWorks have been used for master planning naval architecture and provided better features than 2D CAD. In addition, the coordination of specialist teams needs improvement and almost welcomes the collaborative advantages of BIM – to overall improve the design and construction phases [31].

### 1.2. *The BIM to BEM approach*

It is fundamental that energy efficiency experts are involved from the concept design phase of ships to ensure that sustainability and efficiency principles are incorporated into design as early as possible. To this aim, practitioners need advanced modelling tools to both manage the project complexity and analyse the energy performance of the ships. While Building Information Modeling (BIM) is a standard methodology in civil engineering, the shipbuilding industry only recently have started integrating it within the design workflow. Energy modelling via a Building Energy Modeling (BEM) approach of the whole ship (envelope and power plants) is even less used except in research projects, despite both BEM and BIM may strongly improve the sustainability of ships and streamline the design-to-delivery process.

Currently, in the field of buildings, the BIM to BEM, also known as BIM2BEM, methodology is increasingly considered for energy simulation, and software based on BIM methodology like Revit, ArchiCAD, or similar BIM authoring software, along with BEM tools such as EnergyPlus, OpenStudio, TRNSYS are more and more used to improve projects' management and energy efficiency [32]. The dynamic profile consumption is obtained thanks to input data files describing location, geometry, construction materials, weather data and HVAC systems [33,34].

### 1.3. *Aims and contribution of the study*

Even if the use of the BIM and BEM is so attractive from different points of view, in the scientific literature, at the best of authors' knowledge, there are no available papers or reports investigating this approach as a design and analysis tool for ships. In addition, very few studies demonstrated how dynamic simulation may benefit the energy design of new ships or the refurbishment of existing ones.

As highlighted in the literature review, other works introduced ship HVAC thermal modelling adopting state-of-the-art tools for building energy performance simulation such as ESP-r or TRNSYS.

The design approach based on dynamic simulation allows one to overcome the issues of the steady-state calculation method (Standard ISO 7547 [35]), which can lead to higher costs due to oversizing energy plant equipment and inefficiency due to frequent partial load operations. Despite the significant advantages that dynamic simulation introduces, the development of reliable building energy models, or in this case ship energy models, is a challenging task that requires time and expertise [36]. It is necessary to implement a 3D model separated from the typical digital model used in the ship design. This limits the integration of such tools in the industrial process and may discourage their adoption.

Therefore, this paper proposes a novel technique based on the BIM to BEM approach to model and analyse the main ship arrangement from an energy, economic and environmental point of view. A suitable novel workflow was developed in order to simulate the real ship operations. Specifically, a simplified BIM model of an existing large cruise ship, the Allure of the Seas, was developed in order to obtain a simulation model for assessing the energy and the environmental impact. Furthermore, the results obtained by means of the simulation tool are described with the aim to show the capability of the proposed approach which represents a step forward in the modern early design of onboard ship energy systems, useful for ship designers, manufacturers, owners, and operators.

It is proven that BEM tools adopted in the AEC industry allow to reduce the energy demand and the environmental impact of building-plant systems, by aiding the design of new buildings and retrofits by facilitating future innovation and technological building progress, with a significant enhancement of occupants' comfort. This article is proposed for demonstrating the potential of this novel methodology for constructions of large modern ships such as cruise ships. Particularly, it is a novel contribution to the current literature since:

- Identifies a suitable modelling and simulation framework based on BIM that allows better integration of energy performance assessment within the shipbuilding industry.
- Develops a specific data exchange routines and modelling features to suit the needs of ship-system behaviour simulations.
- Demonstrates the BIM2BEM methodology allowing simplification and automation in ship energy model generation and information management.

By this approach new design criteria for achieving energy sustainable ships can be obtained by also comparing different energy saving technologies and strategies.

Hopefully, this study represents a kick-off for a productive activity research on the implementation of both BIM and BEM in the shipbuilding industry which is expected to bring the same benefits achieved in the building construction sector.

## 2. Method

This section provides the overall description of the adopted approach for analysing the ship energy needs and system performance by means of the dynamic simulation approach. The next paragraphs focus on the workflow developed to obtain an accurate physics-based energy model of the ship starting from a BIM model of a real case study: the Allure of the Seas, one of the largest cruise ships in the world. The aim of this paper is to validate the BIM to BEM methodology to obtain detailed energy performance data to support the design and operation of large ships such as cruise ships, cargo ships, etc.

The dynamic simulation approach for the early design and renovation of the on-board energy system is expected to substitute the static methods typically adopted for the assessment of the thermal and electrical behaviour of a ship, providing more reliable and accurate results. From this point of view, the workflow developed to achieve the objectives of this paper is summarized in Fig. 1 and further described in the following paragraphs. The accurate and reliable ship energy performance simulation requires three main steps:

i) *Modelling of the ship*. A 3D ship model is developed to calculate the space heating and cooling, and electricity requirements according to the indoor and outdoor conditions,i.e. space occupation, marine weather data. The modelling process can be briefly subdivided in several sub-steps: i) ship geometry analysis, ii) thermal zoning and surfaces identification, iii) 3D physics-based model of the ship.
ii) *Modelling of the existing ship energy system*. The ship power, heat and cool generation plant model is developed to assess the actual performance of the system in meeting the load profiles calculated in the first step of the analysis, namely *Modelling of the ship*.
iii) *Economic and environmental assessment.* The indicators to assess the sustainability in terms of costs and pollutant emissions are identified.

Accordingly, this section is divided in three subsections: subsection 2.1, the modelling of the ship; subsection 2.2, the modelling of the on-board power generation system; and subsection 2.3, the identification of the main indicators to assess the sustainability of the ship from an economic and environmental point of view.

### 2.1. Ship modelling

The methodology proposed to carry out the dynamic simulation of the cruise ship starting from a BIM model is based on the standard information transfer format named *gbxml* which contains all the information to create a BEM model. Therefore, it is required that the software involved in the process are capable of inputting and outputting *gbxml* text files [37].

In this study, the model implementation involves the use of *Autodesk Revit*, *OpenStudio* and *EnergyPlus* in order to perform the modelling of the ship thermal zones. *Autodesk Revit* was used to recreate the geometry of the ship, defining the thermal properties of the materials and the characteristics of the ship, such as occupation, lighting, and equipment scheduling, resulting in a simplified model that suits the demonstrative purpose of the study. A more complex and detailed BIM model might be

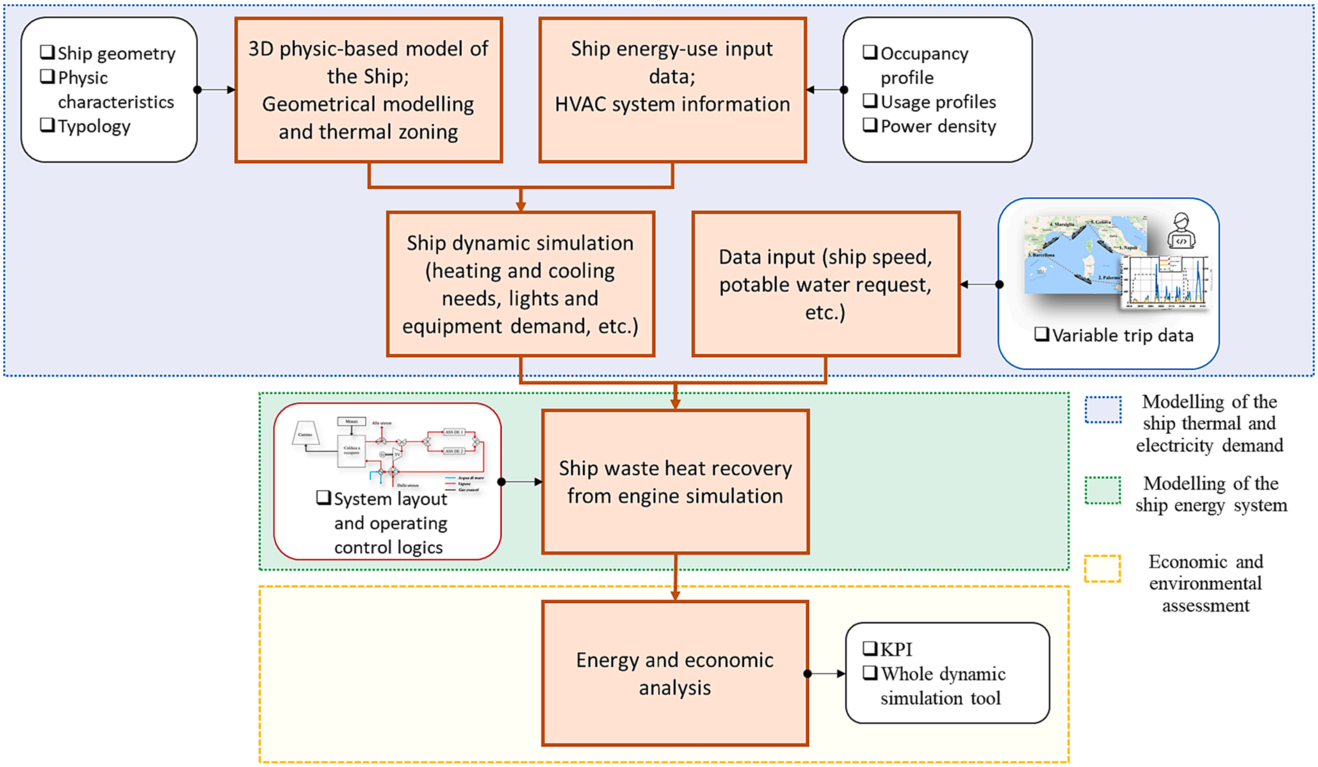

**Fig. 1.** General description of the methodology adopted to carry out the study.

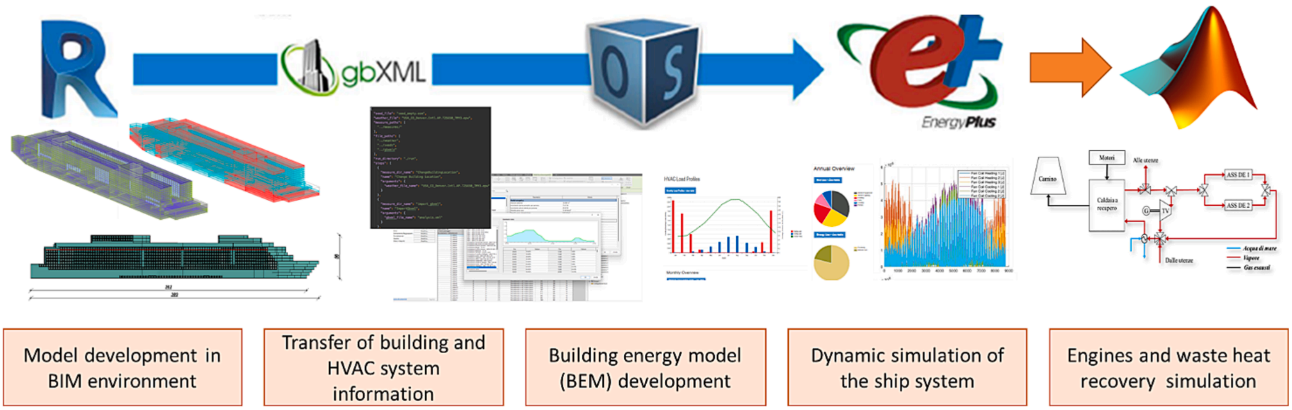

**Fig. 2.** Description of the process developed to obtain the ship's energy model starting from the BIM model; tool-chain representation.

used within the actual application of the methodology in the ship design process.

Fig. 2 summarizes the steps taken to obtain detailed simulation outputs from a BIM model, passing through the *gbxml* format and the *OpenStudio* and *EnergyPlus* energy modelling and simulation software. The figure also depicts the flow of information involved in the entire process: the data collected throughout the design by engineers, energy-related data exploited by energy modellers, and simulation outputs supporting the project optimization.

The data transfer into *OpenStudio* was carried out by means of the automated BIM-to-gbxml-to-OpenStudio import routine of *Autodesk Revit*, *Revit Systems Analysis*. However, the default workflow was purposely modified to customize HVAC systems, include different simulation settings, and collect specific outputs. *OpenStudio* leverages the powerful calculation engine *EnergyPlus* which was adopted to perform multiple simulations.

The multi-zone ship energy model is comprised of both conditioned and non-conditioned thermal zones, each of them is assumed as well-mixed air node zone.

The ship is equipped with several air systems capable to provide the required amount of mixed air airflow to the zone and the necessary thermal energy to keep the temperature setpoints. The HVAC system also guarantees the minimum specified outdoor airflow rate.

The influence of people, lighting and electrical equipment on the heat balance algorithm is accounted by means of characteristic heat gains parameters such as sensible and latent heat fraction per person ($g_{s,p}$ and $g_{l,p}$, $W/person$), lighting power load intensity ($g_l$, $W/m^2$) and electrical equipment power load intensity ($g_{ee}$, $W/m^2$). The appropriate schedules complete the model to take into account the actual operating regime of the ship under investigation.

The selected existing ship is described in section 3. Details on modelling and simulation assumption can be found on the complete *EnergyPlus* documentation [38].

### 2.2. *Waste heat recovery system modelling*

As regard the modelling of the existing ship energy system, the electricity, heating and cooling load profiles obtained by the ship model were processed to simulate the behaviour of the waste heat recovery system coupled with the ship engines, and the heat integration of boilers. This was carried out by means of a script developed on purpose in Matlab, simulating the operation of all components of the existing

**Table 1**
Main technologies included in the calculation routine of waste heat recovery system.

| Technology | Governing equations | | Variable and parameter description |
|---|---|---|---|
| Engine set – Combined Heat and Power generators | $plr = \frac{P_{el}}{P_{r,CHP}}$ | (1) | $plr$ part load ratio |
| | $\dot{m}_{f,CHP} = \frac{P_{el}}{\eta_{CHP} \cdot LHV_f}$ | (2) | $P_{el}$ power demand |
| | | | $P_{r,CHP}$ CHP rated power |
| | | | $\dot{m}_{f,CHP}$ CHP fuel consumption |
| | | | $LHV_f$ fuel lower heat value |
| | | | $\eta_{CHP}$ CHP overall conversion efficiency |
| Multi-stage flash evaporator | $\dot{m}_{fw,MSF} = N_{MSF} \cdot C_{MSF}$ | (3) | $\dot{m}_{fw,MSF}$ fresh water production |
| | $T_{HT,out,MSF} = T_{HT,in,MSF} - \frac{\dot{Q}_{MSF}}{c_p \cdot \dot{m}_{HT}}$ | (4) | $N_{MSF}$ number of activated MSFs |
| | | | $C_{MSF}$ capacity of activated MSFs |
| | | | $T_{HT,\ out,\ MSF}$ HT loop MSF outlet temperature |
| | | | $T_{HT,\ in,\ MSF}$ HT loop MSF inlet temperature |
| | | | $\dot{Q}_{MSF}$ MSF thermal power demand |
| | | | $\dot{m}_{HT}$ HT loop mass flow rate |
| Exhaust gas boiler | $\dot{m}_{s,EGB} = \frac{\dot{Q}_g}{c}$ | (5) | $\dot{m}_{s,EGB}$ EGB steam production |
| | | | $\dot{Q}_{g,EGB}$ Thermal power required by EGB |
| | | | $c$ conversion factor ($kW/kg/h$) |
| Oil fired boiler | $\dot{Q}_{OFB} = \dot{m}_{s,nd,OFB} \cdot c$ | (6) | $\dot{Q}_{OFB}$ OFB thermal power demand |
| | $\dot{m}_{f,OFB} = \frac{\dot{Q}_{OFB}}{\eta_{OFB} \cdot LHV_f} w$ | (7) | $\dot{m}_{s,nd,OFB}$ OFB steam demand |
| | | | $\dot{m}_{f,OFB}$ OFB fuel consumption |
| | | | $\eta_{OFP}$ OFB overall conversion efficiency |
| Fresh/Hot water storage | $SOC_t = SOC_{t-1} + \frac{(\dot{m}_{in,st} - \dot{m}_{out,st}) \cdot \Delta t}{V_{st} \cdot \rho}$ | (8) | $SOC$ state of charge |
| | | | $\dot{m}_{in,st}$ storage inlet flow rate |
| | | | $\dot{m}_{out,st}$ storage outlet flow rate |
| | | | $V_{st}$ storage capacity |
| | | | $\Delta t$ time interval |
| | | | $\rho$ density |

ship generation plant. As shown in Fig. 2, the Matlab routine takes as inputs the detailed EnergyPlus simulation results, as well as the information retrieved by the ship model developed in the BIM environment.

The main technologies implemented in the simulation script such as the engine set for combined heat and power generation (CHP), multi-stage flash evaporators (MSF), exhaust gas boiler (EGB), oil fired boiler (OFB), and fresh/hot water storage are briefly described in Table 1. The equations reported below also involve variable coefficients such as CHP or OFB conversion efficiencies to account for all the operating conditions; performance curves provided by manufacturers are used to solve them [39,40]. The rule-based control logic implemented in the simulation script is reported in section 3.

### 2.3. Economic and environmental model

To assess the economic and environmental performance of the ship power plant, as well as to highlight the advantages of the proposed methodology, the simulation outputs were post-processed. Specifically, the various parameters, coefficients and equations involved in the calculation are introduced below.

The total fuel consumption is estimated by means of equations reported in Table 1. It depends on both fuel burnt by engines and oil fired boilers on board.

From fuel consumption, the primary energy $e_p$ is calculated, then the emissions of carbon dioxide and other pollutants into the atmosphere are calculated by means of equation (9).

$$p_i = f_i \cdot e_{p,i} \tag{9}$$

$p_i$ and $f_i$ are the total equivalent amount of pollutants and the emission factor related to the $i^{th}$ fuel.

The cost related to the fuel consumption is evaluated by equation (10).

$$c_{€,i} = \frac{e_{p,i} \cdot pr_i}{LHV_i} \tag{10}$$

Where $pr_i$ is the price of the fuel per mass unit and $LHV_i$ is the fuel Lower Heating Value.

Furthermore, several parameters that may be of interest to shipowners, such as electricity and thermal energy consumption per passenger ($e_{i,pass}$) or per travelled distance are evaluated. Therefore, the amount of both electricity or thermal energy consumed per passenger is calculated as:

$$e_{i,pass} = \frac{e_i}{n_{pass}} \tag{11}$$

Where $e_i$ is the electrical or thermal energy and $n_{pass}$ is the number of passengers. Also the amount of pollutants emitted into the atmosphere per passenger is evaluated considering the quantity of each pollutant $p_i$ and $n_{pass}$:

$$p_{i,pass} = \frac{p_i}{n_{pass}} \tag{12}$$

Similarly, total equivalent electrical or thermal energy consumed and pollutant emitted per distance travelled are calculated.

$$e_{i,km} = \frac{e_i}{n_{km}} \tag{13}$$

$$p_{i,km} = \frac{p_i}{n_{km}} \tag{14}$$

With $n_{km}$, distance travelled during the cruise.

## 3. Selected ship and modelling assumptions

The selected ship is the Allure of the Seas of the Royal Caribbean. Schematic drawings and data used to develop the ship model are provided by the shipowner and retrieved by public repositories [41,42]. When no information were available, the assumption related to ship plants typology were made by comparison with typical existing cruise ships [17,27]. The energy analysis of the ship was carried out in order to demonstrate the validity of the proposed design methodology. A view of the ship is reported in Fig. 3, while the main characteristics of the ship are summarized in Table 2.

The ship was designed to accommodate 5492–6314 passengers and 2150 crew members and offering the best services to its guests: restaurants and casinos, theatres and pubs, gyms and spas, clubs and sports fields.

The modelling of the ship was carried out by starting from the real ship geometry with the aim of assessing the thermal behaviour of the Allure of the Seas. The obtained model is a representation of reality, with due simplifications. A thermal zoning procedure was conducted for dividing the ship in multiple zones characterized by the same thermo-hygrometric conditions and thermal behaviour. As it occurs in buildings, a thermal zone is the portion of a building – or a deck - that is controlled and maintained by a single thermostat sensor that has its own setpoint and schedule.

Therefore, for the selected ship, different spaces were grouped based on their expected thermal behaviour as well as the same temperature and humidity controls. The typologies of thermal zones identified are reported in Table 3.

For the thermal zoning procedure of the investigated ship, spaces characterized by the same air temperature and humidity set-points and external solicitations are grouped in a single thermal zone. As an example, in Fig. 4, relative to the thermal zoning of the Deck 3, the accommodation compartment (indicated with a blue square) includes only internal cabins, whereas external cabins that are subjected to

**Table 2**
Characteristic of the cruise ship.

| Characteristic | Size |
|---|---|
| Propulsion power | 82 MW |
| Number of decks | 17 |
| Length overall | 362 *m* |
| Beam (width) | 47 *m* |
| Cabins | 2745 |

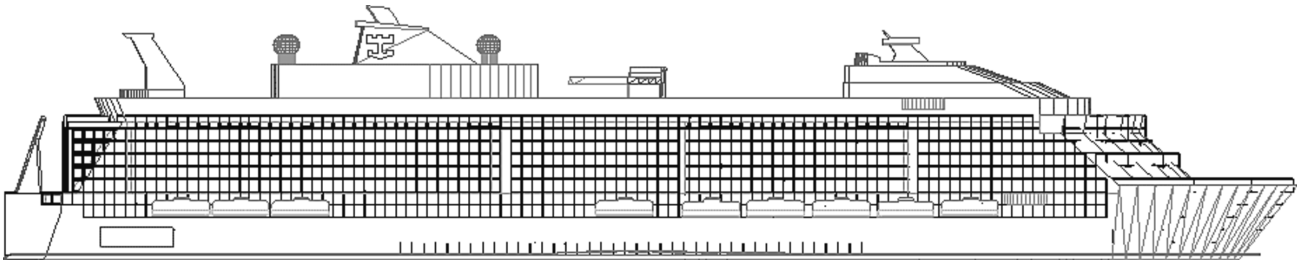

**Fig. 3.** 3D model of the ship. Gathered from public repository [42].

**Table 3**
Classification of the thermal zones.

| Name | Number of thermal zones | Volume [m$^3$] | Area [m$^2$] |
|---|---|---|---|
| 1-Technical rooms | 48 | 203283 | 46870 |
| 2-Cabins | 175 | 322931 | 115731 |
| 3-Casino | 1 | 7630 | 2733 |
| 4-Restaurant | 19 | 61912 | 22175 |
| 5-Entertainment | 12 | 29303 | 10495 |
| 6-Theatre | 3 | 33216 | 6505 |
| 7-Gym and SPA | 7 | 22550 | 8077 |
| 8-Various | 6 | 7909 | 2833 |
| **Total** | **271** | **688734** | **215418** |

diverse solicitations, e.g., external envelope exposure andsolar gains, are grouped in different and multiple thermal zones.

All ship decks are divided into a number of thermal zones that aggregate several spaces, the thermal zones identified for Deck 3 to Deck 6 are depicted in Fig. 5. The temperature set-point is set to 23 °C both in heating and cooling mode according to design specifications. Each thermal zone is characterized by the increase in latent and sensible heat caused by people, power and lighting density, and air exchange rates to be guaranteed per person and per area, temperature and humidity set point values. When no information regarding the zone specifications is available, to define the energy model, the typical parameters suggested by ASHRAE Standard 90.1 were adopted [43]. In addition, an example of the occupation scheduling imposed for cabins is reported in Fig. 6,

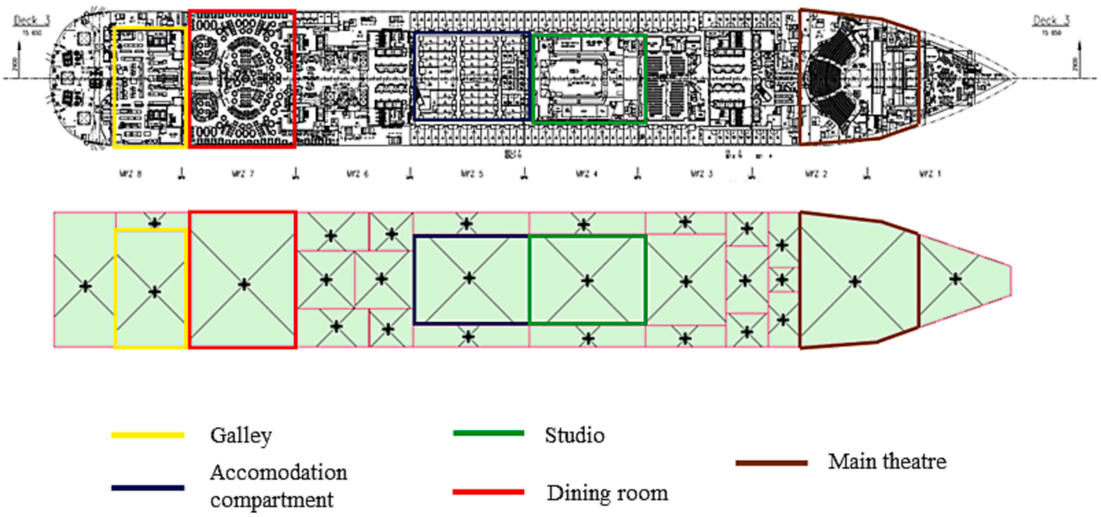

**Fig. 4.** Definition of the thermal zones on Deck 3.

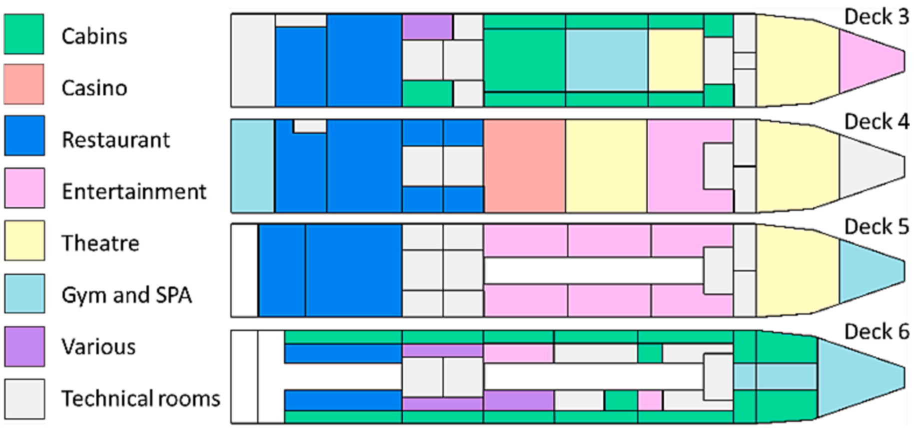

**Fig. 5.** Identification of the thermal zones for the intermediate ship decks [44].

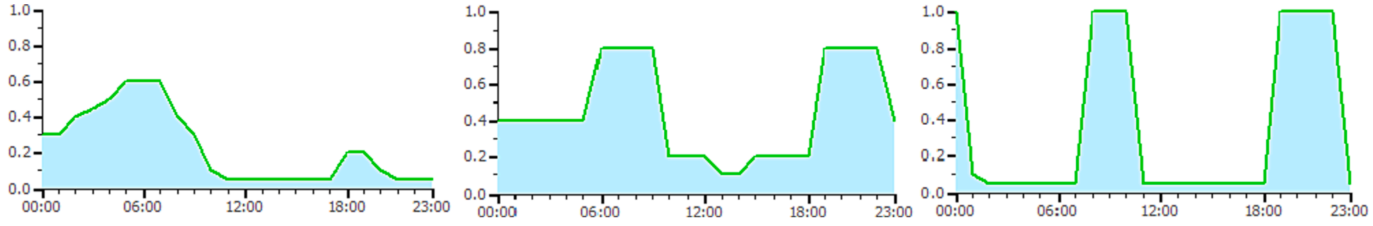

**Fig. 6.** Occupancy, lighting, and equipment scheduling for passenger cabins.

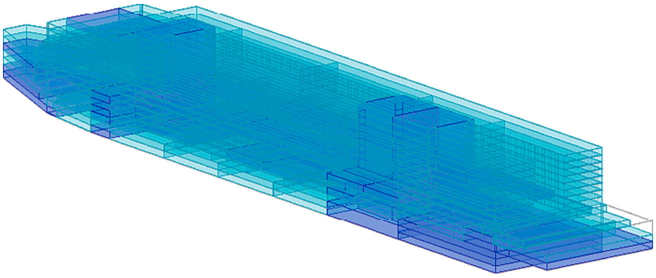

**Fig. 7.** Energy model of the Allure of the Seas cruise ship.

similarly the specific schedules are applied to all spaces.

Fig. 7 shows the 3D energy model of the whole ship which resulted from the thermal zoning procedure described above. The model is comprised of a number of surfaces encapsulating all the conditioned (light blue coloured spaces) and the technical compartments (blue coloured spaces) of the cruise ship. It is required to calculate the thermal loads and the actual indoor temperatures of spaces, taking into account the variability of external and internal conditions.

The reference system is composed by 6 main engines and two Emergency Diesel Generators powered with Heavy Fuel Oil (HFO) to satisfy the electrical needs for propulsion, lighting and appliances on the ship.

Each main engine is equipped with independent high temperature (HT) cooling water circuit and a recovery system that is used for freshwater production (MSF), domestic hot water (DHW), and air conditioning (AC) equipment requirement.

The exhaust gases are used to satisfy the request of steam at the pressure of 8 bar for different consumer, e.g., galleys, evaporators, laundries, etc. The remaining heat demand is satisfied through the use of back-up boilers also powered by HFO. The cooling energy is produced through water-to-water compressor chillers. The system works at different load conditions according to the control logic depicted in Fig. 8. The waste heat recovery system behaves differently depending on whether the ship is at sea or in port ($w_{ship} < w_m$). Whenever the ship is moored or in manoeuvring, freshwater production is limited so that only hot water and thermal energy for air-conditioning is provided by HT recovery or oil-fired boiler (OFB). Two different recovery strategies (RS) are applied in case of ship is sailing instead (RSa or RSb). Specifically, the RSa consists in the exploitation of HT waste heat for MSFs, DHW, and air-conditioning, while the RSb provides for the exploitation of engine exhaust gas through the exhaust gas boilers (EGB) to supply MSFs. OFBs meet the remaining demand if further thermal energy is required. The different strategies are investigated for comparison purpose and

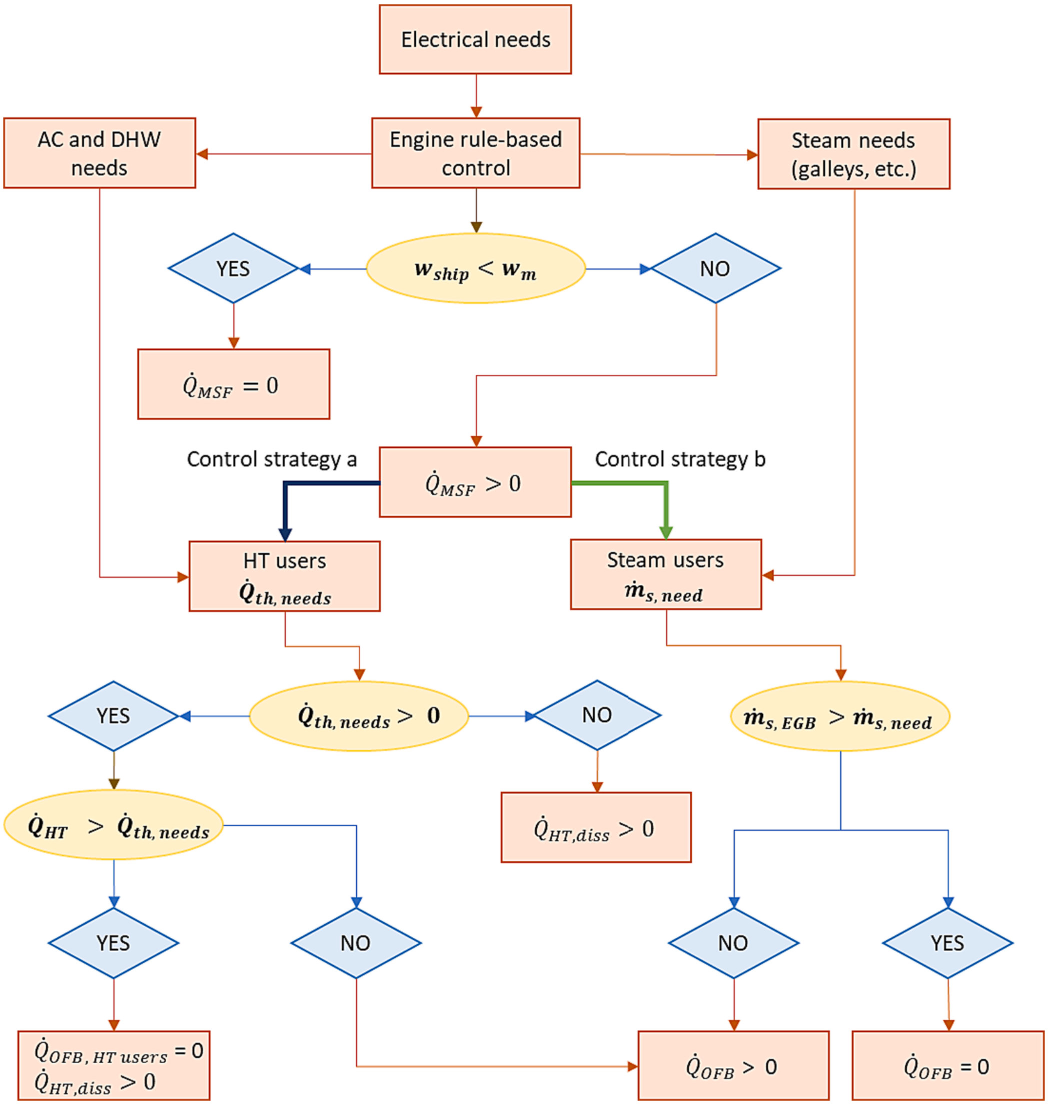

**Fig. 8.** Control logic of the engine waste heat recovery system.

**Table 4**

Emission factors for HFO combustion process [45].

| Pollutant | Emission factor [g/kWh] |
|---|---|
| $NO_x$ | 17.0 |
| $SO_x$ | 10.0 |
| HC | 1.00 |
| PM | 0.25 |
| $CO_2$ | 268 |

demonstrating the capability of the model-based design approach proposed in this study.

The rated engine efficiency is equal to ∼ 0.5, while the boiler efficiency at nominal condition is as high as 0.9. The Coefficient of Performance (COP) of chillers is assumed equal to 4.7 instead. Different operating condition far from nominal operation are taken into account by performance curves.

The emission factor $f_i$ of each pollutants considered to assess the environmental impact of the ship through equation (9) are reported in Table 4.

For the economic analysis, a price for HFO was considered equal to 0.81 k€/t [46].

The cruise ship under investigation operates in the Caribbean Sea. The trip selected for simulation is the June 6-days round-trip of the Western Caribbean Cruise with the following stops:

- Departing from Fort Lauderdale, Port Everglades, Florida.
- Cozumel, Quintana Roo Mexico, Riviera Maya.
- Coco Cay, Bahamas, Royal Caribbean.
- Nassau, Bahamas, New Providence Island.
- Arriving in Fort Lauderdale, Port Everglades, Florida.

From the cruise trip details, the ship speed was calculated according to cruise schedules. Furthermore, the weather of Havana was used in order to assess the energy needs of the cruise ship, the primary energy requirements and the emissions of pollutants into the atmosphere for the specified operating conditions. Fig. 9 summarizes the site information of the selected case study such as outdoor air temperature, direct and diffuse solar radiation of the site, and the cruise speed. During the selected 6-days itinerary the average port-to-port cruise speeds are 14.1, 17.8, 4.52 and 13.9 knots, respectively. Sea water temperature is recorded in the range 27–29 °C in the period 19th − 25th of June.

## 4. Results and discussion

Simulations are performed with the operating conditions described so far. The different thermal needs are obtained through a dynamic analysis that takes into account the variability of solar and temperature conditions, as well as the incidence of people and loads due to lighting and equipment. The ship energy model was verified through comparison with actual measurements collected by the ship's monitoring systems and simulation results obtained using historical data of outdoor temperature, humidity and solar irradiance, referring to the same period as the cruise ship being analysed. The comparison between the measured and calculated chiller energy demand is shown in Fig. 10 for each day of the analysed cruise trip. The simulated chiller energy demand falls outside the ± 5% confidence interval only for day 4 and day 5, due to differences recorded between real outdoor hygro-thermal conditions and historical data adopted for simulations. Although the boundary conditions in the historical data may not perfectly match the actual conditions, the comparison showed that the overall electricity consumption due to chillers predicted by the model over a cruise trip differs by less than 2% from the actual measurement. The total electricity demand is 4.05 GWh, 1% higher than the one predicted by the model. This highlights the robustness and accuracy of the model, despite the uncertainties in using historical data. The verification process provides confidence in the model's ability to be a valuable tool for designing and optimizing ship energy systems. Validating the use of the BIM2BEM approach in this specific context was also essential. As discussed in the previous sections, the design phase plays a pivotal role in reducing energy consumption. Currently, the maritime industry is placing significant emphasis on the adoption of green fuels as the way forward for a sustainable future. However, the availability of these fuels in the quantities required to meet industry demands remains limited. Therefore, achieving the stringent targets at national and international levels in the transition toward zero-energy scenarios necessitates a focus on enhancing the efficiency of ships through advanced modelling techniques. The results presented in this section aim to demonstrate the modelling capabilities of the developed tool and the effectiveness of the adopted approach.

Given the external weather conditions for the site and the analysed period, HVAC system only provides cooling. It is evident in Fig. 11 where the dynamic cooling loads (blue area) of the Casino thermal zone, as well as the outdoor (blue line) and indoor temperature (red line) variation are reported for the considered trip. As observed, the thermal loads calculated have high variability since extreme variability of internal gain and external conditions. The thermal loads consistently

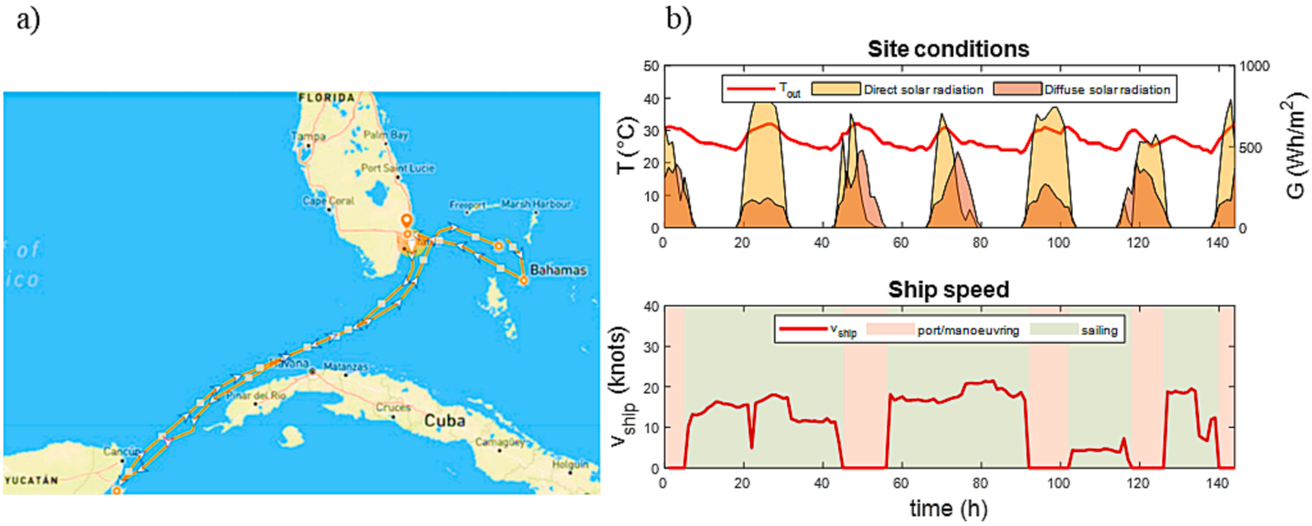

**Fig. 9.** a) details of Western Caribbean Cruise; b) weather conditions considered for the cruise trip; c) cruise speed.

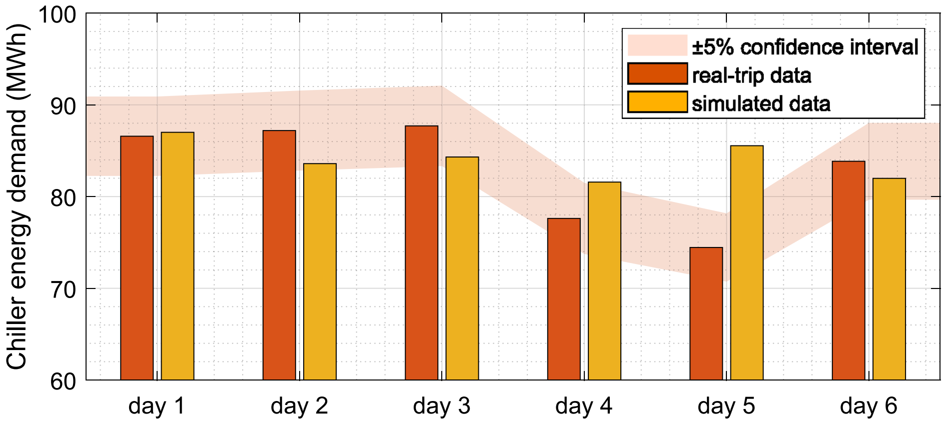

**Fig. 10.** Model accuracy verification. Measured and simulated chiller energy demand.

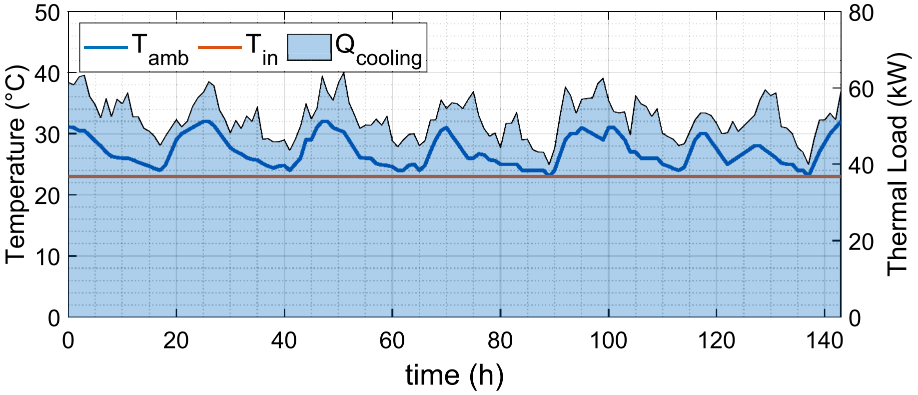

**Fig. 11.** Dynamic cooling load of the Casino thermal zone. Period 19–25 June, Western Caribbean Cruise.

exceed 40 kW and can peak at 63 kW when outside temperature and solar radiation are high. The Casino thermal zone, which remains occupied 24 h a day, requires continuous ventilation and conditioning. The figure shows an excellent example, demonstrating how dynamic loads and temperature profiles might be advanced tools for ship plant designers, improving their understanding of the thermal behaviour of the ship spaces in any operating conditions and the identification of energy-saving solutions.

The strength of the dynamic energy modelling and simulation approach is also evident in Figure; the figure shows cumulated results of different outputs of ship simulation, such as sensible thermal needs due to: lighting, equipment, people, heat loss, heat gains, ventilation, and air infiltration. The figure reveals that an internal accommodation (Core zone, in red) performs differently with respect to an external one (Perimetral zone, in blue). Specifically, the aggregated results reported in Figure shows the cruise trip sensible needs for cooling of two cabins of the ship, normalised by the area of each space for the sake of comparison.

It is possible to appreciate that the external cabin is influenced by the solar radiation on the ship envelope and the heat loss from external surfaces (purple bar), and the air infiltration losses (light blue bar). This variation might be particularly evident in case of severe winter conditions. On the other hand, cooling energy demands of core zones may be affected by internal gains due to their higher lighting requirements.

By the analysis of the shares of energy requirement for HVAC system reported in Fig. 12, the ventilation resulted to be the major contribution to thermal loads (green bar), followed by the contributions of lighting (blue bar), equipment and people (orange and yellow bars). This information can be essential to identify the major energy-consuming services, thereby facilitating improvements in HVAC system design, equipment optimization, heat loss reduction from the ship, and ultimately enhancing passengers' comfort.

Through the assessment of the simulation results obtained using the implemented ship model, it becomes feasible to estimate the ship's annual electrical demand. This comprehensive evaluation provides a holistic understanding of the ship's energy consumption throughout the

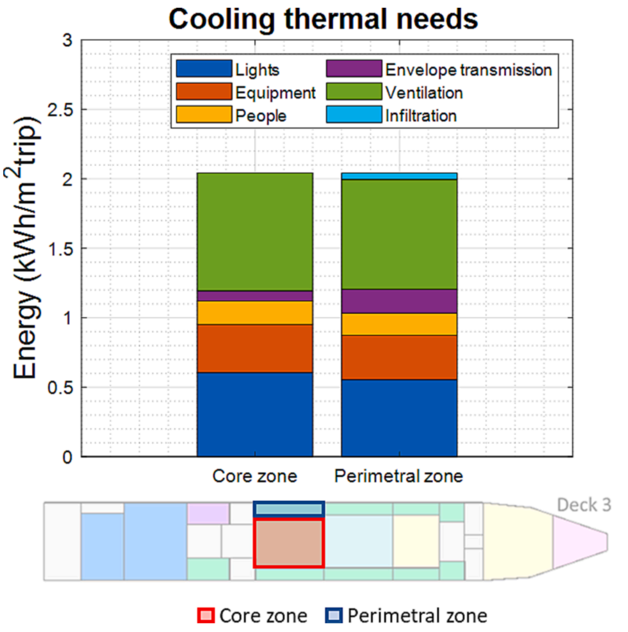

**Fig. 12.** Cruise cooling thermal needs for core and perimetral accommodation zones, and deck view of the ship.

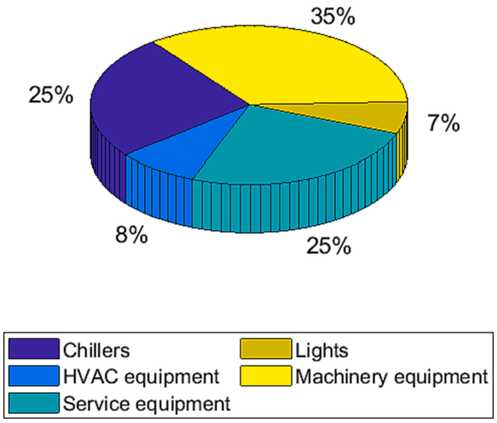

**Fig. 13.** Electricity consumption due to HVAC systems and other on-board services.

cruise trip. The pie chart reported in Fig. 13 shows how electricity needs are subdivided among different on-board services, such as chillers, HVAC equipment (e.g. fans, pumps), machinery equipment (e.g. laundry, sewage treatment), lighting, and hoteling. Excluding the propulsion, the weight contribution of chillers should not be underestimated, as it plays a significant role in meeting the high cooling demands onboard the ship. Additionally, when considering the combined weight of chillers and HVAC equipment, the resulting percentage closely approaches that of the highest electricity user, which is attributed to machinery equipment. While reducing the energy consumption of users such as lights, machinery, and hotel services may be challenging, the energy consumption of chillers can potentially be further reduced by utilizing recovered energy from other on-board processes. Gathering this information during the design phase provides opportunities for improvements and allows for accurate calculations of potential savings, which would not be possible using simplified calculation methods. *How much potential savings can be achieved by optimizing a specific user? What would be the corresponding impact on the overall energy consumption of the ship?* These are inquiries that designers contemplate on a daily basis to ensure compliance with emissions regulations established by diverse regulatory bodies.

The contribution due to the lights and on-board service equipment per space typology are provided in Table 5 and Table 6, respectively. The tables show that the passengers' accommodation is the most energy-consuming service as it is the most important share of occupied spaces on the ships, followed by hoteling services such as restaurants and entertainment. Various spaces - comprising medical facilities, offices, crew relax areas, etc. - require 11% of electricity consumptions due to lights and 14% due to other equipment. Restaurants are also important electricity consumers with 13% and 17% for lights and equipment respectively.

Power and thermal energy required by propulsion and all the on-board services are supplied by the ship engines that are activated according to the actual power demand. As shown in Fig. 14a, the propulsion is the highest electricity consumer when the cruise ship is at sea, up to 70% of the power demand, while chillers and machinery absorb the larger shares of power in port, respectively 32% and 35%. The remaining power is absorbed by HVAC systems, equipment, and lighting when the ship is docked at port. The thermal energy required for DHW, MSFs and steam production for general users is partially balanced by the heat recovered from engines. Its dynamic profile is shown in Fig. 14b which refer to the recovery strategy RSa that use high temperature heat recovery, described in section 3. As observed, the HT waste heat is mostly used to power evaporators (MSF), as long as this is available. When the HT waste heat is not enough, the MSFs are fed through steam, provided by EGBs or by integration of the OFBs (see red area in Fig. 14b). During sailing periods, MSF are frequently powered by steam to meet peak heat demand.

**Table 5**
Summary of electricity consumption of the ship lighting system.

| Thermal zone | Lights | |
|---|---|---|
| | **Electricity consumption** [MWh] | **Share on lights needs** (%) |
| Cabins | 67.3 | 56 |
| Casino | 3.53 | 3 |
| Restaurants | 15.9 | 13 |
| Entertainment | 9.62 | 8 |
| Various | 12.8 | 11 |
| Spa – gym | 4.37 | 4 |
| Theatre | 7.19 | 6 |

**Table 6**
Summary of electricity consumption of on-board service equipment.

| Thermal zone | Service equipment | |
|---|---|---|
| | **Electricity consumption** [MWh] | **Share on service equipment** (%) |
| Cabins | 233 | 48 |
| Casino | 28.1 | 6 |
| Restaurants | 80.6 | 17 |
| Entertainment | 51.6 | 11 |
| Various | 67.1 | 14 |
| Spa – gym | 15.6 | 3 |
| Theatre | 6.66 | 1 |

The RSa strategy is compared to the RSb one in terms of primary energy, electricity usage, and thermal energy consumed. The results are reported in Fig. 15a and Fig. 15b.

The charts provide information on all the energy fluxes within the power and heat generation plant of the ship, all the primary energy shares that are dissipated since not directly used are highlighted in yellow. It is clear from this analysis that the advanced and detailed modelling of the entire ship power plant and all the on-board equipment allow immediate visualization and gathering useful insights that both designers and shipowners may use to improve the overall ship energy efficiency. As concern the two energy management strategies investigated (i.e. RSa and RSb), it is shown in the figure that the overall primary energy used is higher for RSb due to the increased use of auxiliary boilers. Indeed, the HT heat recovery is not fully employed as in the RSa strategy due to the different control logic. When MSFs are powered only by steam, EGBs do not provide enough thermal energy for all steam users which entails higher production of steam by OFBs. As expected, the heat recovery strategy RSb lead to higher primary energy use, thus fuel consumption, up to 9.31 GWh (about 600 MWh higher than RSa strategy). This is due to higher share of dumped HT and LT heat recovery, passing from 15% of the RSa strategy to 22% of the RSb one.

As observed by the shares of the on-board thermal users, adopting the RSa strategy the 49% of the thermal users on the ship is characterized by evaporators powered by HT heat recovery while RSb strategy entails a higher use of steam for evaporators, as high as 79% of all the thermal energy used on-board.

The produced electrical energy accounts for percentages of 46% and 43%, in line with the implemented electrical efficiencies of the engines. As the electrical consumption remains unchanged between the two scenarios, the differing percentage weights are attributed to the increased utilization of boilers in the second strategy, leading to a higher demand for primary energy.

In Fig. 16 the main pollutants released during the considered cruise itinerary are reported for the control strategies analysed RSa (Fig. 16a) and RSb (Fig. 16b). Note that the amount of PM, $NO_x$, HC, $SO_x$ and $CO_2$ are evaluated by means of coefficient reported in Table 4 which not take into account any technologies for the abatement of polluting emissions. The two investigated energy management strategies only differ in terms of $CO_2$ and pollutants emissions due to the higher use of primary energy from OFBs, leading to 7.5% higher emissions.

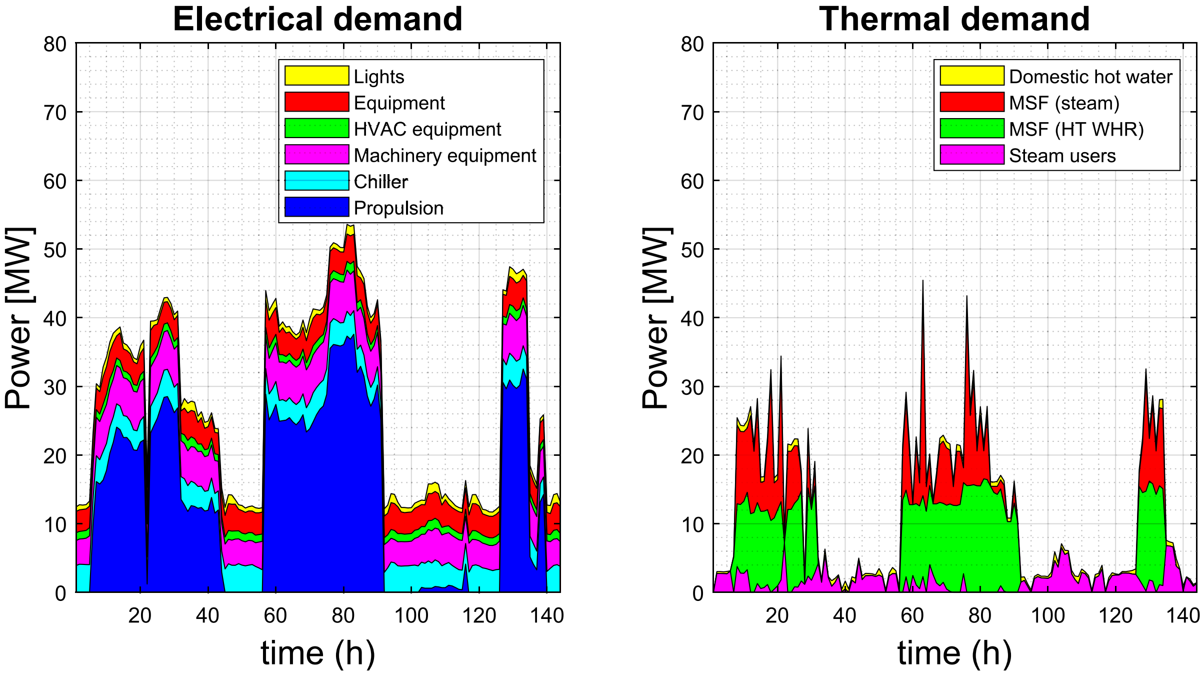

**Fig. 14.** a)engine power supplied to users; b) thermal energy supplied to users.

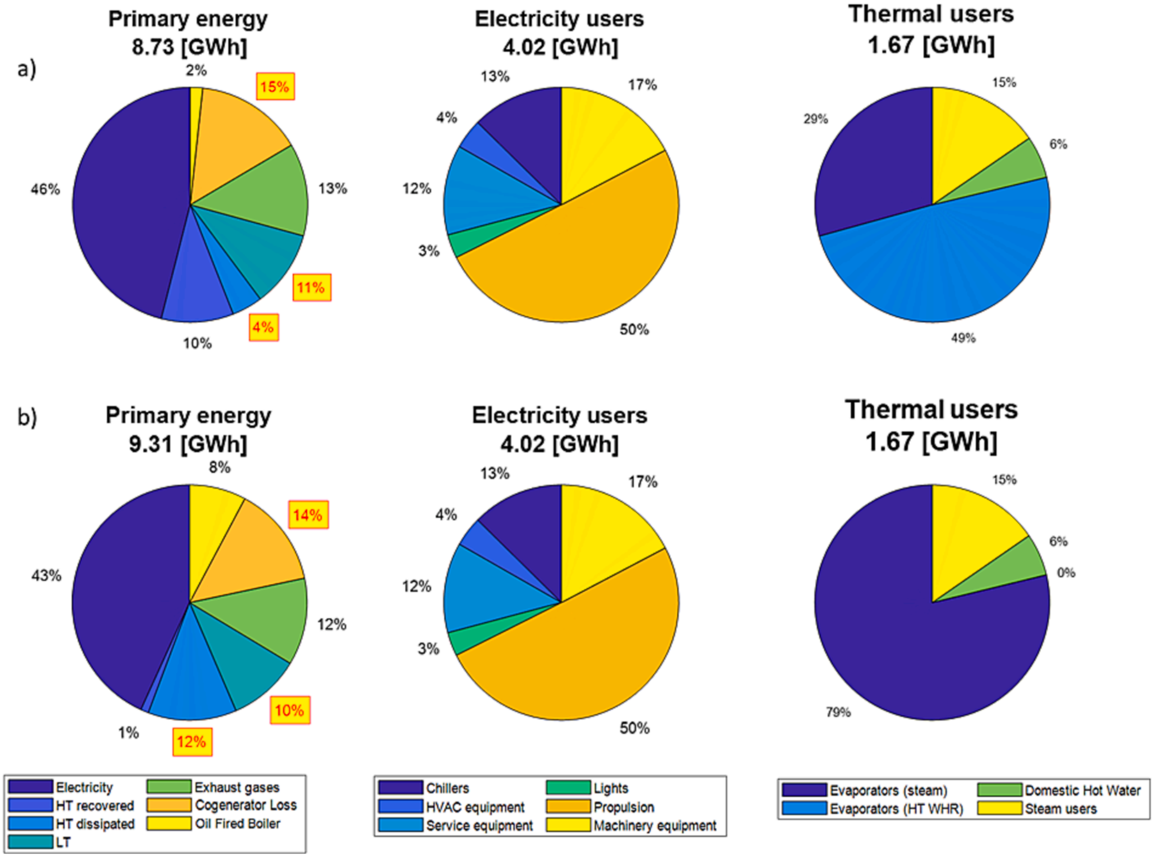

**Fig. 15.** Primary energy, electricity, and thermal energy comparison between RSa (figure a) and RSb (figure b) strategies.

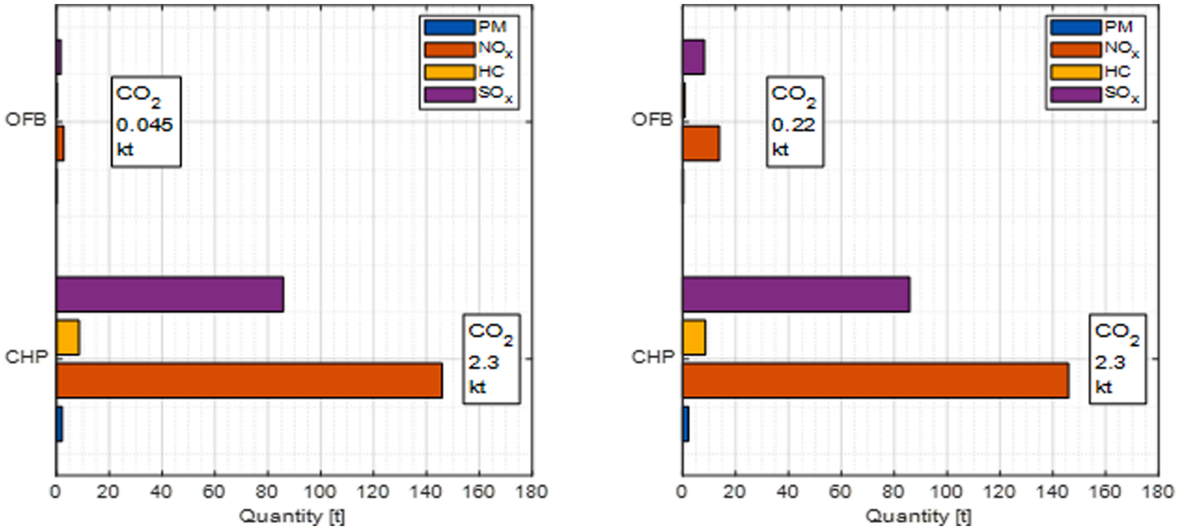

**Fig. 16.** Overall $CO_2$ and pollutants emissions per cruise trip for recovery strategy RSa (figure a) and RSb (figure b).

Finally, in order to estimate the footprint of each passenger from an energy, environmental and economic point of view, the normalized indices described in section 2.3 are summarized in Table 8 for the considered itinerary. These results show overall sustainability performance and can serve as valuable benchmarks for comparison with other ships and provide a basis for future research and optimization initiatives.

As highlighted in this section, the detailed outputs and indicators obtained by a model-based analysis of the ship main arrangement are powerful tools for the value engineering in the ship design process. Implementing the proposed methodology, the most important outcome is the availability of two different models: the BIM model which is an information cloud for stakeholders involved in the ship project, and the BEM model which turns out to be a useful tool supporting the choices concerning the ship energy efficiency or the passenger and crew well-being. The use of such advanced design tools is widely recognized as a fundamental instrument in the modern construction and engineering processes. Software implementing features to exploit BIM methodology has the potential to streamline the design-to-delivery process and significantly reduce overall costs, as well as to facilitate the transition to the model-based design, also applied to continuous improvement processes [47].

Compared to other researches (e.g. references [6,27,47]) underlining the high effort to develop complex ship energy models, the methodology here proposed allows for the simplification of the design process, avoiding redundant model definition and automation in energy model generation. Indeed, designers need to produce drawings and geometrical models for construction anyway. The implementation of a dynamic simulation model would require the development of a separate 3D model with different tools, which can be very time-consuming. The methodology of extrapolating BEM models from BIM suits well the increasing interest in the recent years of the shipbuilding industry and shipowners in BIM adoption to improve project management and costs. Therefore, BIM models should be exploited not only for energy analyses like the one proposed in this study.

In the authors' opinion, further research needs to focus on the automatic generation of BEM model geometry since the information transfer between BIM and BEM software may result in data loss, leading to inaccuracies in simulation outputs. Moreover, the methodology needs to be further investigated by developing new modelling capabilities to simulate different waste heat recovery system layouts or the ship navigation to account for outdoor condition variability. The model developed in this study is based on many assumptions that may affect the accuracy of the results. However, the investigated system presents similar trends compared to the results provided in other studies conducted on different cruise ships and sailing in different locations [17,27,29,48]. These works also focus on the energy analysis of cruise ships operating on real trips, considering both sailing, manoeuvring and periods of berthing. Taking into account the differences among the investigated case studies, it is possible to observe good agreement between the shares of energy consumptions related to propulsion (35–46%), HVAC systems (13%), and other on-board equipment (27–50%). In addition, according to the study reported in reference [29], a 1.05 MWh energy use per passenger was assessed for a cruise trip of one week, which closely aligns with the values obtained in the proposed model: 0.64 $MWh_e$/pass and 0.26 $MWh_t$/pass for the considered cruise itinerary, as reported in Table 7. The comparison between the findings of this study and the aforementioned indicators from the works of other authors is summarized in Table 8, which also presents the actual electricity consumption measured from the cruise ship considered in the case study. As discussed, the BIM2BEM methodology and dynamic energy analysis can be regarded as valuable tools for ship design. It is demonstrated that a well-calibrated model, based on realistic assumptions, can provide accurate and valuable insights for designing an energy-efficient ship, which is the ultimate objective of this research work.

To increase the validity and the applicability of the proposed methodology, the developed model will be improved in future works in

**Table 7**
Summary of main key performance indicators.

| **Indicator** | **CS a)** | **CS b)** | |
|---|---|---|---|
| Electricity per passenger | 0.64 | 0.64 | [$MWh_e$/pass] |
| Cost to produce electricity per passenger | 95 | 95 | [€/pass] |
| Thermal energy per passenger | 0.26 | 0.26 | [$MWh_t$/pass] |
| Cost to produce thermal energy per passenger (OFB) | 1.8 | 9.0 | [€/pass] |
| PM emitted into the atmosphere per passenger | 0.35 | 0.37 | [kg/pass] |
| $NO_x$ emitted into the atmosphere per passenger | 24 | 25 | [kg/pass] |
| HC emitted into the atmosphere per passenger | 1.4 | 1.5 | [kg/pass] |
| $SO_x$ emitted into the atmosphere per passenger | 14 | 15 | [kg/pass] |
| $CO_2$ emitted into the atmosphere per passenger | 371 | 399 | [kg/pass] |
| PM emitted into the atmosphere per km | 0.74 | 0.80 | [kg/km] |
| $NO_x$ emitted into the atmosphere per km | 50 | 54 | [kg/km] |
| HC emitted into the atmosphere per km | 3.0 | 3.2 | [kg/km] |
| $SO_x$ emitted into the atmosphere per km | 30 | 32 | [kg/km] |
| $CO_2$ emitted into the atmosphere per km | 796 | 854 | [kg/km] |

**Table 8**
Comparison between main ship energy indicators and results from literature.

| Reference | Indicator | Value | Verification | Value |
|---|---|---|---|---|
| Brækken et al. [29] | Energy use per passenger | 1.05 MWh/pass | Electricity per passenger, Thermal energy per passenger | 0.64 $MWh_e$/pass, 0.26 $MWh_t$/pass |
| Baldi et al [48] | Propulsion energy share | 46% | Propulsion energy share | 43 – 46 % |
| Actual measured data | Engines total electricity | 4.05 GWh | Engines total electricity | 4.02 GWh |

order to research new energy-saving solutions such as highly efficient thermally activated technologies (absorption chillers, etc.) or new control logic that allow reaching the goal to limit GHG emissions in the next years.

## 5. Conclusions

In this paper, a novel method for modelling and dynamically simulating the energy performance of large ships is presented. Through this approach the benefits of the advanced Building Information Modeling (BIM) are combined to those of the Building Energy Modeling (BEM) technique. Details of the developed design workflow are reported in the paper. Here, the validity of the proposed method for assessing the loads/demands and the potential energy savings of ships is also proved. Strengths of this method are showed through a novel case study concerning the energy analysis and optimization of the Allure of the Seas, an existing large cruise ship. The related 3D model, consisting of 271 different thermal zones, was developed through Autodesk Revit. Specifically, each thermal zone is defined by taking into account as input: occupancy index, loads and schedules of lighting and equipment, ventilation rate, setpoint of temperature and humidity, etc.. Then, the developed BIM model was exploited to generate a BEM model, for the ship energy analysis, obtained by means of OpenStudio and EnergyPlus.

Dynamic simulations are referred to a real trip in the Caribbean Sea and to two different control strategies for optimizing the waste heat recovery available from the ship diesel generators. By shifting from the standard waste heat exploitation scenario to the optimal one a remarkable primary energy saving is obtained (600 MWh/trip, corresponding to 52 t/trip of HFO fuel). Subsequent significant avoided pollutant emissions are also achieved (58 kg/km of $CO_2$, 0.06 kg/km of particulate matter, 4.0 kg/km of NOx, 0.2 kg/km of HC, 2.0 kg/km of SOx). Therefore, on annual basis, about 33 GWh, corresponding to 2.9 kt of fuel, can be saved, resulting in 2.3 M€ per year. By the proposed innovative approach, optimal energy design of ships can be achieved by also comparing different energy saving technologies and equipment sizes. The presented method can be used as a suitable decision-making tool for the base-design of both new and existing ships (to be revamped). Here, novel design criteria can be achieved concerning different ship energy system layouts as well as advanced materials for the energy efficiency of the ship envelope.

Future research efforts will aim at demonstrating that BIM coupled BEM will pave the way to the implementation of ships digital twins and to foster energy design and operating analyses based on modelling and dynamic simulations in the shipping sector.

## CRediT authorship contribution statement

**Annamaria Buonomano:** Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing, Supervision. **Gianluca Del Papa:** Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing. **Giovanni Francesco Giuzio:** Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing. **Robert Maka:** Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing. **Adolfo Palombo:** Conceptualization, Formal analysis, Methodology, Investigation, Data curation, Writing – original draft, Visualization, Writing – review & editing, Supervision.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgement

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