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Abstract:

The increasing awareness about the environmental impact of shipping and the increasingly stricter regulations introduced by the International Maritime Organization are driving the development of solutions to reduce the pollutant emissions from ships. While some previous studies focused on the implementation of a specific technology, others considered a wider perspective and investigated the feasibility of the integration of various technologies on board vessels. Among the screened technologies, organic Rankine cycle (ORC) power systems represent a viable solution to utilize the waste heat contained in the main engine exhaust gases to produce additional power for on board use. The installation of ORC power systems on board ships could result in a reduction of the CO_2 emissions by $5 - 10$ %. Although a number of methods to derive the optimal design of ORC units in marine applications have been proposed, these methods are complex, computationally expensive and require specialist knowledge to be included as part of a general optimization procedure to define the optimal set of technologies to be implemented on board a vessel. This study presents a novel method to predict the performance of ORC units installed on board vessels, based upon the characteristics of the main engine exhaust gases and the ship sailing profile. The method is not computationally intensive, and is therefore suitable to be used in the context of large optimization problems, such as holistic optimization and evaluation of a ship performance given the operational profile, weather and route. The model predicted the annual energy production of two case studies with an accuracy within 4 %.

Keywords:
Organic Rankine cycle power systems, marine, regression model, predictive model

1. Introduction

In the recent years there has been a growing demand for reducing the environmental impact of shipping, as testified by the updated legislation framework introduced by the International Maritime Organization [1,2]. A way to enhance the energy efficiency of vessels consists in utilizing the waste energy released by their main engine(s) for internal purposes. It is a common practice to use this energy for the production of service steam to be used to fulfill the heat demand on board [3]. As shown by Baldi et al. [4-5] the use of the exergy analysis and process integration technique could ensure significant energy savings, when the heating demand on board is large (e.g. for cruise ships). However, in most cases, the excess heat available in the exhaust gases can also be used in waste heat recovery systems (WHR) to generate additional power. In this context, the traditional solution is to use a power turbine and a steam Rankine cycle (SRC) unit. In addition, an increasing number of studies are assessing the potential of implementing organic Rankine cycle (ORC) power systems on board vessels [6]. A previous study from Larsen et al. [7] showed that the ORC technology could lead to higher power productions compared to the SRC technology when considering the implementation on board a vessel powered by a two-stroke engine. Andreasen et al. [8] compared the off-design performance of an ORC and a SCR unit for WHR on board a vessel and concluded that the former leads to higher performance at low engine loads. Previous investigations on the optimal design of ORC units for maritime applications suggested that the ORC unit design process should consider the available heat sources [9], the ship operational profile [10], constraints on the minimum allowed boiler feed temperature, as well as considerations on the maximum allowed additional back pressure on the main engine [11].

The optimal design of ORC units is thus a complex problem, which is generally tackled by developing thermodynamic models for the various components of the system, and by using optimization techniques, such as particle swarm or genetic algorithms. Previous studies attempted to derive simplified methodologies to predict the ORC performance for design-point conditions. Liu et al. [12] investigated the impact of the working fluid evaporation, condensation and critical temperatures, and proposed an equation to estimate the efficiency of an ORC unit. Kuo et al. [13] suggested the use of the Jakob number as an indication of the attainable ORC thermal efficiency. Similarly, Wang et al. [14] proposed the use of the Jakob number in predictive models to estimate the ORC thermal and exergetic efficiencies. Larsen et al. [15] developed multiple regression models to estimate the maximum ORC efficiency, given the boundary conditions of the process. Lecompte et al. [16] derived regression models for the estimation of the maximum attainable second law efficiency for ORC units. These studies aimed at predicting the efficiency of the ORC power system (rather than the net power output), and did not consider the impact of the heat exchanger's pressure drops on the ORC performance. Regarding the ORC part-load performance, Dickes et al. [17] carried out experimental and numerical investigations on a 2 kWe ORC system and proposed a set of equations to characterize the optimal off-design operation of an ORC system. As the equations were derived based on a specific unit, their general applicability is not guaranteed.

The objective of this study is to derive a set models that ensure a rapid and accurate prediction of the annual energy output of an ORC unit optimized for marine applications. The accuracy of the proposed method was validated through two case studies, where the results of the simplified and traditional approaches were compared. The primary novel contributions of this paper are the following: (i) it derives part-load performance curves which are applicable to ORC units of different sizes and operating with different design point conditions; and (ii) it describes a methodology to combine design point and part-load performance curves to identify the ORC design point that maximizes its annual energy production.

The paper is structured as follows: Section 2 explains the applied methods. Section 3 presents and discusses the results. Finally, the conclusions are outlined in Section 4.

2. Methods

2.1. ORC models and optimization procedure

The regression models were built based on data obtained by using thermodynamic models describing the performance of the ORC unit and its components. The ORC model calculations were carried out using the numerical model described in Andreasen et al. [18], which was validated with a maximum relative deviation of 3.3 % in first and second law efficiency, compared to other studies in literature. The model was developed with Matlab, while the thermodynamic properties of the working fluids were retrieved by using Coolprop 4.2.5 [19]. The maximum and minimum ORC allowable pressures were set to 30 bar and 0.045 bar respectively, following the indications by Rayegan et al. [20], Drescher and Brüggeman [21], and MAN Diesel & Turbo [22]. Moreover, the work was limited to subcritical cycle configurations, with a maximum reduced pressure of 0.8, to avoid problems during operation near the critical point. Information on the heat exchanger design and pressure drops were obtained by adopting the models described in Pierobon et al. [23], which were validated with a relative deviation within 4 % both in overall heat transfer coefficient and pressure drop. The following heat exchanger types were selected: once-through for the WHR boiler, and shell and tube for condenser, jacket water preheater and recuperator. In the recuperator, fins were used to enhance the heat transfer coefficient on the shell side. The fluid velocities in the heat exchangers were constrained to be within the ranges suggested by Coulson et al. [24], while special constraints due to the application on board a vessel were applied to the WHR boiler. For the exhaust gases, a minimum velocity of 20 *m/s* and a maximum pressure drop of 1.5 *kPa* were imposed,

according to the recommendations of MAN Diesel & Turbo [11]. These constraints aim at avoiding soot fires in the WHR boiler, and ensuring that the additional back pressure has a negligible impact on the main engine efficiency. Two fuels were considered for the main engine, marine diesel oil (MDO) and liquefied natural gas (LNG). In order to avoid problems related to sulphuric acid corrosion, the boiler feed temperature was constrained to a minimum temperature of 125 °C for the MDO case (sulphur mass content of 0.5 %) [8]. No constraint on the boiler feed temperature was imposed on the LNG-fuelled case, as it was assumed that the impact of the pilot fuel sulphur content is negligible. A simple ORC configuration was considered for LNG-fuelled ships, while a recuperated ORC with jacket water preheater was selected for the MDO case (see Figure 1).
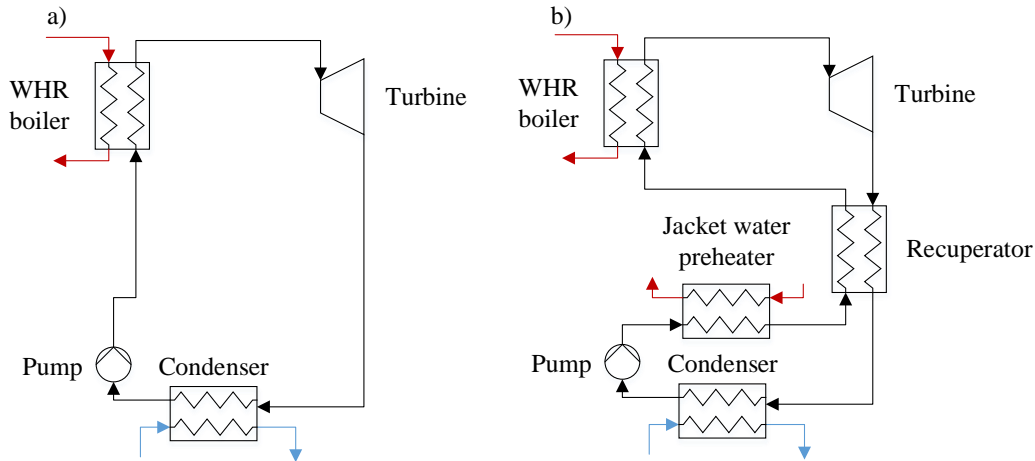

Fig. 1 ORC configurations: a) simple; b) with recuperator and jacket water preheater

All the simulations were carried out using cyclopentane as working fluid due to the good techno-economic performance [8]. Cyclopentane is however a highly flammable fluid and thus special attention should be used when designing and operating the ORC unit (such as using double piping with ventilation and gas leak detection systems [25]). The ORC cycle was optimized so to maximize its net power output, calculated as follows:

$$\dot{W}_{Net} = \dot{W}_t \, \eta_{gear} \, \eta_{gen} - \dot{W}_p - \dot{W}_{p,sw}, \tag{1}$$

Where $\dot{W}_t$, $\dot{W}_p$, $\dot{W}_{p,sw}$ represent the power production of the turbine and the power consumption of the ORC and seawater pumps. η_{gear} and η_{gen} represent the efficiencies of the gearbox and of the electrical generator. The decision variables of the optimization process were the turbine inlet pressure, the superheating degree at the turbine inlet, the working fluid mass flow rate and the condensation temperature. In order to obtain design solutions with low specific costs, the condenser and recuperator minimum pinch point temperatures were set to 8 °C and 10 °C, respectively. The turbine and pump isentropic efficiencies were set to 85 % and 70 %, respectively. Gearbox and electrical generator efficiencies were fixed to 98 %. The optimization procedure was carried out using the particle swarm optimizer available in the Matlab optimization toolbox and by following the steps shown in Figure 2. The off-design performance of the various configurations was estimated with the approach presented by Baldasso et al. [26]. All the configurations were operated with a sliding pressure strategy, while keeping a constant flow of sea water in the condenser. The boiler feed temperature was kept constant in the MDO case, while the fluid superheating at the inlet of the turbine was fixed in the LNG case. The MDO configurations could not be simulated along the whole engine load range, as the constraint of having a constant value for the boiler feed temperature sets a limit on the minimum pressure at which the cycle can be operated [25]. The variation of the turbine efficiency was predicted with the relationship proposed by Schobeiri [27], while the relationship between the mass flow rate and the pressure was assumed to be governed by the Stodola equation [28]. The performance of the electric generator was derived from the

procedure presented by Haglind and Elmegaard [29], while the pump off-design efficiency was obtained from a technical datasheet from Grundfos [30]. The heat exchangers performance was predicted by correcting their *UA* values (the product of the overall heat transfer coefficient, *U*, with heat transfer area, *A*) with a correlation proposed by Incropera [31]. The pressure drops at off-design conditions were assumed to vary according to the square of the fluid mass flow rate [32]. The ORC maximum power output was limited to its design value to avoid issues related to the mechanical and thermal stresses on its components.
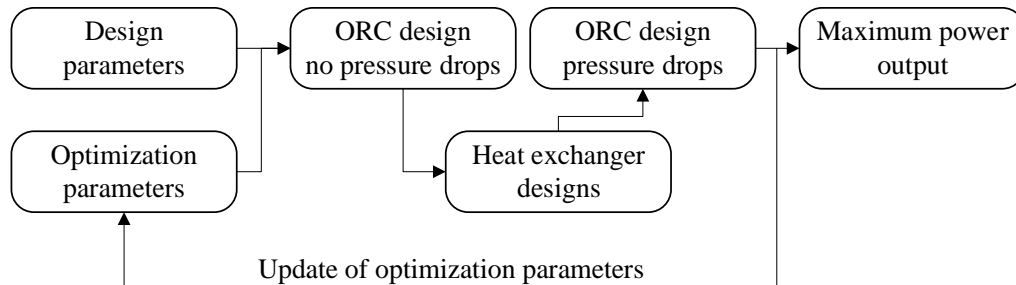

Fig. 2. Flowchart of the optimization procedure for the ORC design

2.2. Regression models and data generation

The design point regression surfaces were obtained by fitting the results of a dataset made of 100 independent optimizations obtained for random values of the main engine exhaust gases mass flow rate and temperature, as well as random values of the sea water temperature. In order to be able to reproduce the behaviour of ORC units tailored for a wide range of engine sizes, the exhaust gas mass flow rates were selected in the range from 5 *kg/s* to 120 *kg/s*, and the exhaust temperatures were considered between 170 °*C* and 320 °*C*. The sea water temperature was assumed to vary in the range from 5 °*C* to 30 °*C*. Data retrieved from the MAN CAES engine calculation tool [33] confirmed that, when considering engines from 5 to 50 *MW* operating with different tuning techniques and sailing both in warm and cold waters, the engine exhaust mass flow rate and temperatures are homogenously distributed within the considered ranges. The samples of the design variables (sea water temperature, exhaust temperature and mass flow rate) were generated with the Sobol method [34] to ensure a good coverage of the search space. Only the samples leading to ORC units with a power ouput in the range 350 *kW* to 3000 *kW* were considered in the regression procedure. The off-design performance of every optimized ORC configuration was evaluated in 20 different and randomly generated off-design conditions. Each half of the randomly generated off-design points were imposed a temperature of the exhaust gases respectively higher and lower than the design point. For all the off-design simulations, the exhaust gas mass flow rate was within 25 to 100 % of the ORC design mass flow rate. The heat source was allowed a deviation of +/- 80 °C compared to the design value. The sea water temperature was kept constant in all the off-design simulations. The procedure for obtaining the data points used to feed the regression surfaces is shown in Figure 3.

The suitability of a proposed regression curve is ensured if the residuals follow a normal distribution and have a constant variance. In addition, the mean of the residuals must be close to zero and there should be no correlation between the residuals themselves and the regression parameters nor the response. The validity of the mentioned aspects for the proposed regression surface models was checked with the scatter plots shown in the following sections.
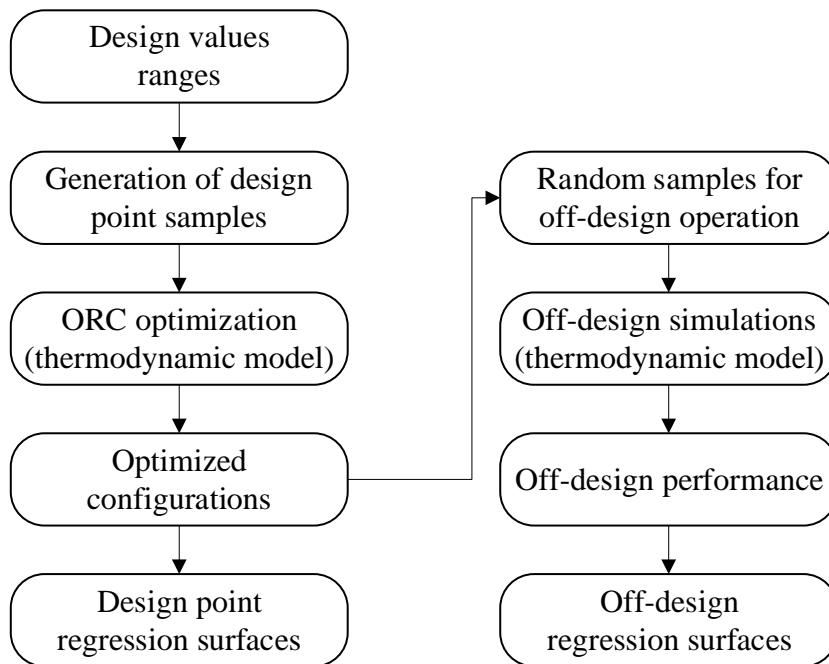
Fig. 3. Procedure used to define the data point to be used to derive the regression surfaces

2.3. Case studies

The suitability of the proposed regression surface models was checked through two test cases. The first case study considered the installation of an ORC unit on board an LNG-fuelled feeder ship powered by a 10.5 MW MAN 7S60E-C10.5-GI engine with low pressure (LP) selective catalytic reduction (SCR) tuning. In the second case study, an ORC unit on board a medium size container vessel powered by a 23 MW MDO-fuelled two-stroke diesel engine with WHR tuning [8] was considered. The two vessels were assumed to operate according to the load profiles shown in Figure 4, respectively for 4380 and 6500 hours annually. These are typical data for the two considered types of vessels. For both case studies, an average sea water temperature of 15 °C was assumed.
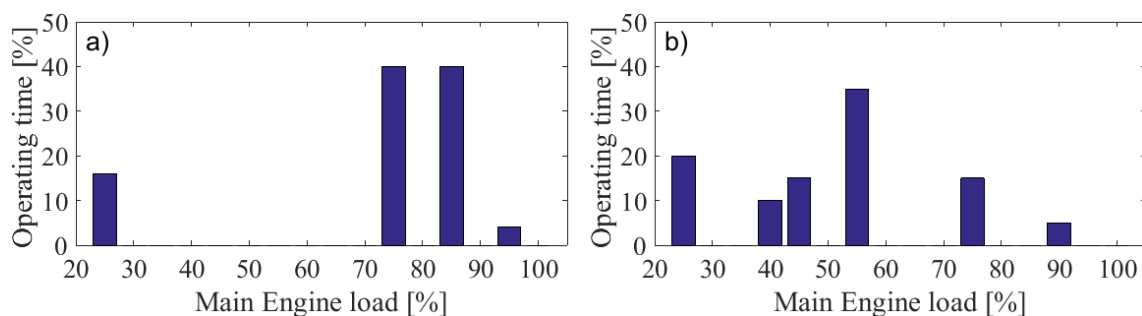

Fig. 4. Annual engine load profile: a) Feeder; b) Container vessel

The maximum annual energy production obtainable by installing an ORC unit on board the two considered vessels was computed both with thermodynamic and regression models. Both the thermodynamic calculations and the estimations using the regression models were carried out following the procedure shown in Figure 5. When using the thermodynamic model, the ORC design parameters and its design point were selected as optimization parameters, while only the latter was optimized when using the regression curves.
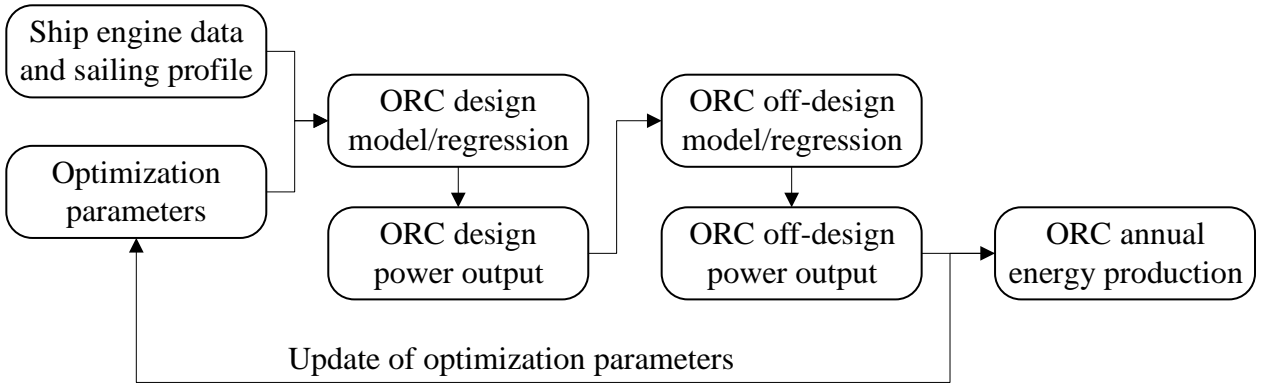
Fig. 5. Procedure to estimate the ORC annual energy production

3. Results and discussion

3.1. Regression models

The fitted regression models for the ORC design power output for the LNG and MDO cases are given in Eq. (2) and Eq. (3), respectively. Equations (4) and (5) were used to fit the ORC off-design performance, respectively for operating points with heat source temperatures higher (Eq. (4)) and lower (Eq. (5)) than the design value.

$$\frac{\dot{W}_{Net}}{\dot{m}_{ex}} = a + b \, \frac{\left(T_{ex,in} - T_{cool,in}\right)^2}{1000}, \tag{2}$$

$$\dot{W}_{Net} = a + b \, \dot{m}_{ex} + c \, T_{cool,in} + d \, \dot{m}_{ex} \cdot T_{hex,in}, \tag{3}$$

$$\dot{W}_{rel} = a + b \, \sqrt{\dot{m}_{ex,rel}} + c \, T_{ex,rel}^2 \, \sqrt{\dot{m}_{ex,rel}} + d \, \Delta T_{ex}, \tag{4}$$

$$\dot{W}_{rel} = a + b \, \sqrt{\dot{m}_{ex,rel}} + c \, T_{ex,rel}^2 \, \sqrt{\dot{m}_{ex,rel}}, \tag{5}$$

Where $\dot{m}_{ex}$ is the mass flow rate of the engine exhaust gases, $T_{ex,in}$ the exhaust gases temperature at the inlet of the boiler, $T_{cool,in}$ the seawater temperature at the inlet of the condenser. The off-design curves were obtained to estimate the relative net power output ($\dot{W}_{rel}$) as a function of the relative values of the exhaust mass flow rate and temperatures, defined as follows:

$$\dot{m}_{ex,rel} = \frac{\dot{m}_{ex,off}}{\dot{m}_{ex,des}}, \tag{6}$$

$$T_{ex,rel} = \frac{T_{ex,in,off}}{T_{ex,in,des}}, \tag{7}$$

$$\Delta T_{ex} = \left\lfloor T_{ex,in,des} - T_{ex,in,off} \right\rfloor, \tag{8}$$

The subscripts *in*, *des* and *off* refer to inlet, design and off-design conditions, respectively. Table 1 shows the regression coefficients and standard errors for the ORC design power, both for the LNG and MDO cases. The regression coefficients and standard errors for the off-design curves are shown in Table 2. The standard errors of each of the coefficients, representing the margins for the model output to remain within a 95 % confidence interval of the observed values, are smaller than the coefficients themselves, suggesting that all the coefficients were identified with a high accuracy.

Table 1. Regression coefficients and standard errors for the ORC design power regression curves

	LNG		MDO	
	Coefficient	Standard error	Coefficient	Standard error
a	-5.384	0.1564	134.2	23.53
b	0.4939	0.002756	-51.46	0.8012
c	-	-	-6.270	0.9441
d	-	-	0.2755	0.003246

Table 2. Regression coefficients and standard errors for the ORC off-design regression curves

	$T_{ex,in,off} > T_{ex,in,des}$		$T_{ex,in,off} < T_{ex,in,des}$	
LNG case				
	Coefficient	Standard error	Coefficient	Standard error
a	-0.3137	0.0096	-0.3906	0.0045
b	-0.8486	0.0391	0.5064	0.0090
c	2.159	0.0320	0.8743	0.0089
d	-0.00859	0.0002	-	-
MDO case				
a	-0.2501	0.0149	-0.3434	0.0113
b	-1.107	0.0627	0.2400	0.0279
c	2.350	0.0500	1.0899	0.0295
d	-0.00888	0.0003	-	-

Table 3 shows the adjusted R^2 value, standard error, F-significance and average relative error in the prediction for the proposed regression curves. For all the cases, the R^2 value approaches unity, while the average relative error is within 4.1 %. According to the F-significances, all models are statistically strong. The P-values (not listed) for each of the coefficients are in the range $1.5 \cdot 10^{-8}$ to $3.8 \cdot 10^{-284}$, confirming that the selected parameters are highly significant for the model results.

Table 3. Statistical parameters for the proposed regression equations

Equation	R^2	Std. error	F-significance	Avg. rel. error (%)
(1) LNG design	0.998	0.465	$1.1 \cdot 10^{-102}$	2.57
(2) MDO design	0.995	51.841	$6.5 \cdot 10^{-63}$	3.50
(3) LNG off-design, $T_{ex,in,off} > T_{ex,in,des}$	0.979	0.035	0	4.10
(4) LNG off-design, $T_{ex,in,off} < T_{ex,in,des}$	0.990	0.019	0	3.65
(5) MDO off-design, $T_{ex,in,off} > T_{ex,in,des}$	0.972	0.037	0	3.88
(6) MDO off-design, $T_{ex,in,off} < T_{ex,in,des}$	0.984	0.021	$6.7 \cdot 10^{-113}$	2.75

For all the six models, the mean of the residuals is below $1 \cdot 10^{-12}$. For the proposed regression equations, the residuals appeared to follow a normal distribution, except for the presence of some tails (see Figure 6). The computed R^2 obtained with a straight trend line were 91.1 % , 98.5 %, 98.5 %, 97.4 %, 93.3 % and 94.2 %, for the six models respectively.
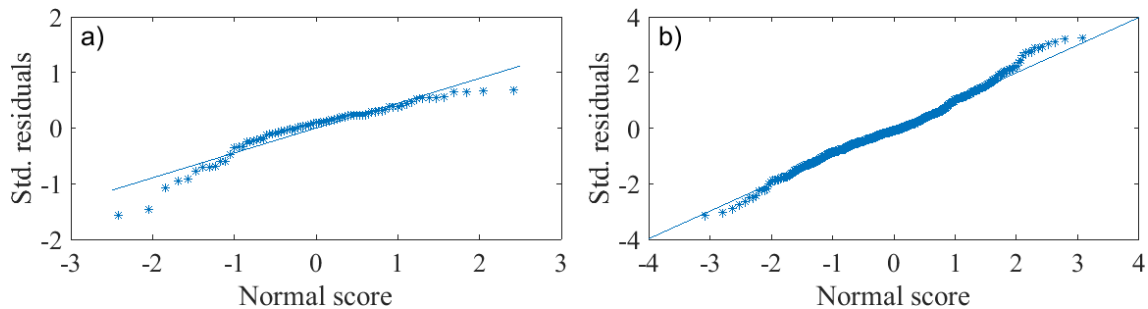

Fig. 6. Normal probability plot: a) Equation (1); b) Equation (3)

Figure 7 shows the scatter plots of the residuals as a function of the predictor variables and of the predicted ORC power output for equation (2). The residuals are scattered around the respective ranges, with minor or negligible patterns. Some pattern in the scatter plots of the residuals appeared in the regression curves for the off-design estimations and they indicate that the selected set of regression parameters does not fully represent the behaviour of the sample data. This highlights the complexity of the ORC behaviour, which is influenced by the design of the heat exchangers, the pressure losses and the main engine load variations, among others.
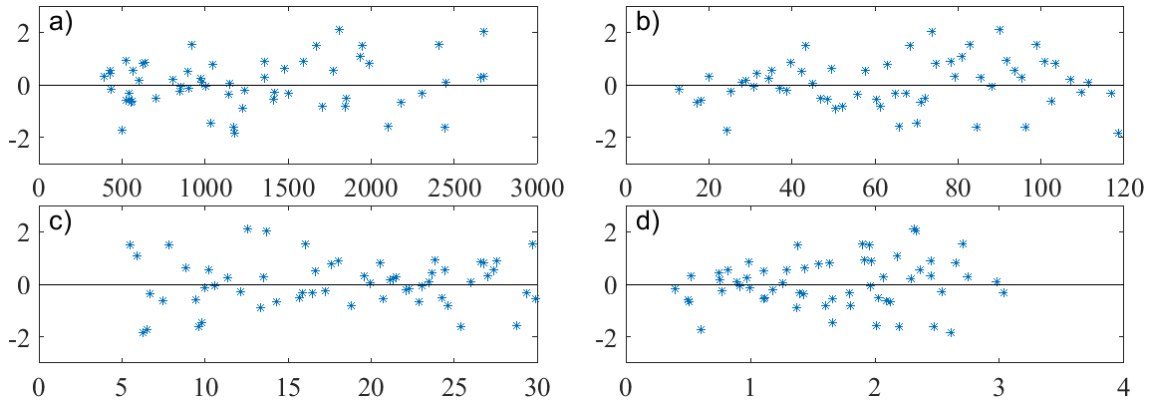

Fig. 7. Standard residuals distribution according to: a) $\dot{W}_{Net}$; b) $\dot{m}_{ex}$; c) $T_{cool,in}$; d) $\frac{\dot{m}_{ex} T_{hex,in}}{10000}$

In the MDO case, the lower operational boundary in terms of power for the ORC output appears highly correlated with the heat source temperature at design point (see Figure 8).
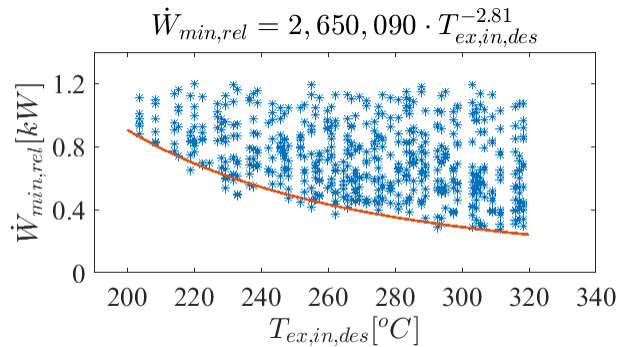
$$\dot{W}_{min,rel} = 2,650,090 \cdot T_{ex,in,des}^{-2.81}$$

Fig. 8. Relationship between heat source design temperature and minimum ORC relative output

Figure 9 shows the predicted values against the regression data for the various regression models and illustrates the fit between data and predictions.
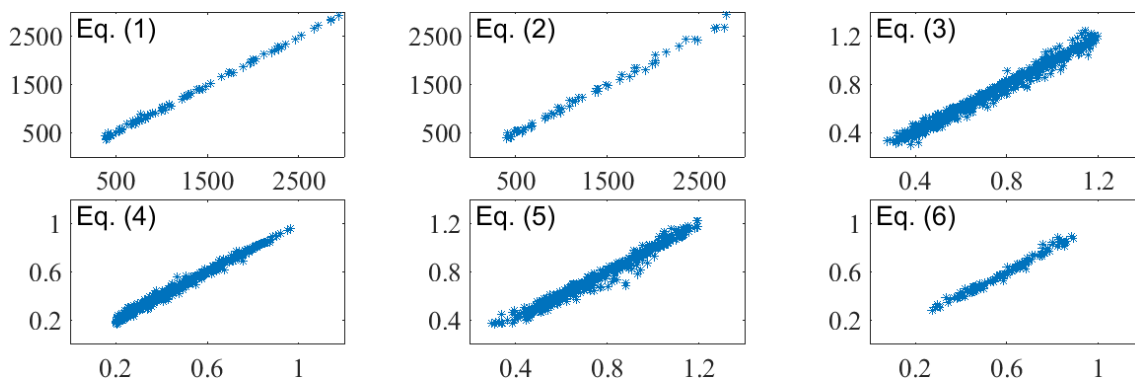

Fig. 9. Predicted values against the regression data for the various equations

3.2. Comparison with thermodynamic models

The results of the overall ORC optimization using both the thermodynamic simulation model and the regression curves are shown in Table 4. Figure 10 shows the computed ORC power production as a function of the main engine load for the two case studies. For the LNG fuelled feeder, the use of the regression equations enabled the identification the optimal load at which the ORC unit should be designed. Both the ORC design power and its annual energy production were predicted with accuracy relative deviation within 4 %. In addition, as shown in Figure 10a, the regression equations were able to properly match the ORC power output profile as a function of the main engine load.

Table 4. Comparison between thermodynamic optimization and regression curves

	Thermodynamic model	Regression curves	Difference (%)
LNG fuelled feeder with LP SCR tuning			
ORC annual production (*MWh*)	1,632	1,698	4.04
ORC design power (*kW*)	469	488	4.05
ORC design load (%)	90.4	90	-0.44
MDO fuelled container vessel with WHR tuning			
ORC annual production (*MWh*)	3,380	3,345	-1.03
ORC design power (*kW*)	1,371	1,227	-10.5
ORC design load (%)	100	89.5	-10.5

More significant differences appeared when analysing the results for the MDO fuelled container vessel. In this case, the annual energy production was predicted with an accuracy of 1 %, but the simplified and thermodynamic approaches identified two different optimal design points for the ORC unit. The simulations carried out with the thermodynamic model suggested that the ORC unit should be designed for an engine load of 100 %, while the regression equations suggested a design engine load of 90 %. Consequently, a difference of around 10 % in the ORC design power output was obtained with the two approaches. As shown in Figure 10b, the estimated ORC power production along the engine loads follows the same trend, except when the engine operates at loads higher than 90 %. However, since the engine is not operated at such high loads (see Figure 4b) this mismatch did not have a strong influence in the estimated annual energy production.
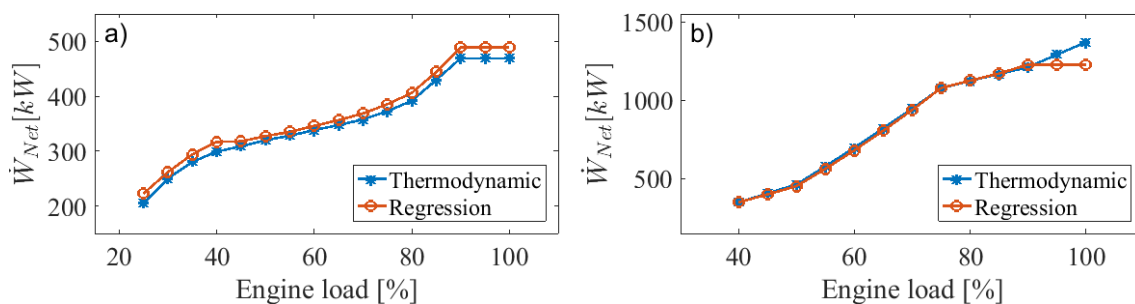

Fig. 10. ORC performance over different engine loads: a) Feeder; b) Container vessel

In order to further verify the robustness of the developed method for the MDO case, two additional analyses were performed. First, the ORC design and its annual energy production were maximized with the thermodynamic model, while constraining the design load to 90 %. Second, the regression equations were used to estimate the annual energy production of an ORC unit designed at 100 % engine load. Figure 11 shows the comparison between the thermodynamic optimizations and the regression estimations for the two design loads. When fixing the ORC design point at 90 % engine load, the two approaches lead to quite similar results. The regression equations predict the ORC design power and its annual energy production with an accuracy of 4.9 % and 1.4 %. When fixing the ORC design point at 100 % engine load, the regression curves overestimate the ORC design

power output by 7.9 %, while under predicting the annual energy production by 6.7 %. This happens because the ORC configuration optimized through the thermodynamic model is able to operate down to an engine load of 40 %, while the regression equations predict that the ORC cannot operate at engine loads below 45 %. This is because the method using the regression equations is based on the assumption that the ORC unit that produces the maximum power output in the design point is also the one resulting in the highest annual energy production. Conversely, the thermodynamic approach is not constrained to this assumption and is able to identify ORC designs that best match the annual operational profile. Baldi et al. [10] previously documented the importance of taking into account of the ORC off-design performance and its impact on the annual ship fuel consumption.
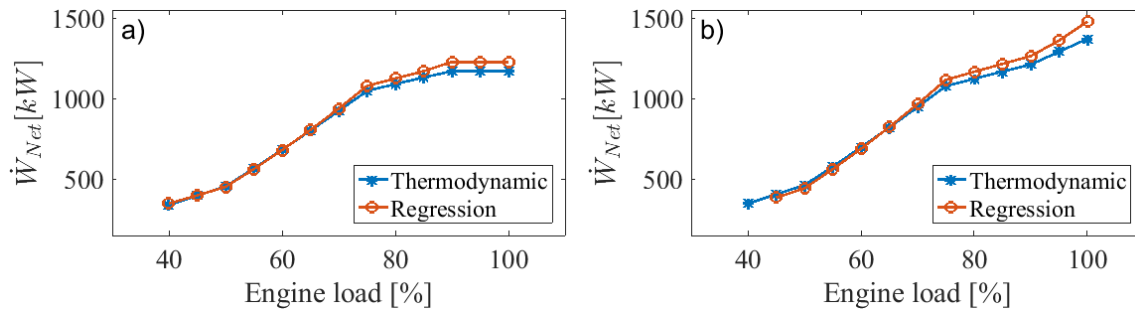

Fig. 11. ORC performance for the container vessel: a) des. load = 90 %; b) des. load = 100 %

4. Conclusions

This work derived a simple approach to estimate the potential of installing ORC power systems for waste heat recovery on board ships. The proposed method is based on the use of regression equations and requires as input parameters the characteristics of the main engine exhaust gases and the vessel sailing profile. The method is not computationally intensive, and therefore suitable to be used in the context of large optimization problems. Both the statistical relevance and the accuracy of the proposed equations were analysed. Compared to the thermodynamic evaluations, a maximum deviation of 6.7 % in the estimated ORC annual energy production was obtained. The regression equations were built upon the assumption that the unit with the maximum power output in design point is also the one leading to the maximum annual energy production. The use of the regression equations in two test cases proved that this assumption did not affect in a significant way the accuracy of the annual estimations.

The simplicity of the proposed method, combined with its accurate estimations, short computational time and few input parameters, makes it a suitable tool to estimate the potential for WHR on board vessels in a wider context. In addition, the method can be used without any prior knowledge in thermodynamics and in the ORC technology.

Acknowledgements

Nomenclature

Abbreviations

Avg	average	*SCR*	selective catalytic reduction

LNG	liquefied natural gas		*Std*	standard
LP	low pressure		*SRC*	steam Rankine cycle
MDO	marine diesel oil		*WHR*	waste heat recovery
ORC	organic Rankine cycle			

Symbols

$\dot{m}$	mass flow rate, kg/s		U	heat transfer coefficient, kW m^2/K
T	Temperature, °C		$\dot{W}$	power, kW

Greek symbols

η	efficiency		Δ	difference

Subscripts

cool	coolant		*min*	minimum
des	design		*off*	off-design
ex	exhaust		*p*	pump
gear	gearbox		*rel*	relative
gen	generator		*sw*	sea water
in	inlet		*t*	turbine

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