



Designing an energy efficient deckhouse for icebreakers using dynamic simulation and multi-objective optimization

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ABSTRACT

In this study, the most cost effective solutions for insulation thickness, types of windows, wall panels and the ventilation heat recovery are found using a dynamic IDA-ICE-simulation program and a genetic algorithm, with the aim at maximizing the thermal comfort in deckhouse of an icebreaker. The final result is a design concept that provides recommendations and guidelines for energy effective superstructure in cold circumstances. The results suggest that 38 % energy saving potential (101kWh/m²) in overall thermal consumption, 39 % emission reduction and 26% decrease in predicted percentage dissatisfied (PPD) can be obtained in deckhouse areas.

INTRODUCTION

The increase in the oil price, the forecasts of the climate change and the stricter emission standards for vessels have made the shipping companies pay more attention to the energy consumption of vessels. Traditionally, the energy consumption has been tried to be reduced by decreasing the ship resistance and improving the efficiency of engines. The energy consumption of the vessels' internal systems has not received so much attention. The HVAC systems and structural solutions of the vessel can be used for finding new opportunities for decreasing the total energy consumption of the vessel.

Though the above areas have been well covered in scientific research and literature, issues such as the energy-efficiency of deckhouses and processes onboard have not been paid attention to as much. The significance of thermal energy consumption has been acknowledged (Schneekluth and Bertram, 1998), however, and shipping companies have become willing to improve overall energy-efficiency with the expectation of reduced fuel costs and better customer image (Mäki-Jouppila, 2012). The rise in energy prices and the current emphasis on environmentally-friendly technology also promote this development, encouraging companies to find out new energy saving measures.

The energy saving potential related to the deckhouses of ships operating on the arctic areas has not been examined so far, but Häkkinen (1993) points out that heating the residential premises take 18 % of the total thermal energy demand and 1.4 % of the total energy input (fuel energy) of an ice-breaker. Indoor conditions and thermal comfort play a major role, because of the long periods of time the crew members spend onboard. The sealed and air-tight structures, in turn, represent a challenge to the control of air quality and thermal conditions (Kim and Lee, 2010).

Structures and building services onboard are basically designed following the traditional practices and experiences. The standard ISO 7547 presents regulatory guidelines for the design of heating, ventilation and air-conditioning systems, but they are established for tropical conditions and thus may result in incorrect solutions when applied to ships operating on the arctic areas. On the other hand, purely following the regulations determining the given level of energy-efficiency and thermal comfort does not guarantee the most cost-effective design practice (Hamdy et al., 2011).

For the above reasons, a multi-objective optimization routine is useful, because the best indoor environment and the most cost-effective solutions can be found simultaneously. This type of approach has been recently reported in terms of buildings by several researchers, such as Hasan et al. (2008) and Hamdy et al. (2011). In buildings, significant energy savings have been obtained through improved design practices. Gustavsson & Joelsson (2010), for example, state that the transition from conventional to low-energy solutions might reduce the primary energy demand of an ordinary residential building by 40-60 %.

The present study implements a genetic algorithm-based optimization (GenOpt) in terms of the whole-building simulation tool IDA-ICE to minimize the difference life-cycle costs and predicted percentage of dissatisfied in comparison with the reference design. Alternative designs are provided to the deckhouse envelope structure, heat distribution, and heat recovery system. The results can be generalized to similar vessels operating in similar conditions, whereas the approach is useful for all the ship types in all climates.

METHODS

The present study is a simulation-based optimization, entailing three objective functions, namely: i) the predicted percentage of dissatisfied (PPD), ii) annual energy consumption (E) and iii) difference life-cycle costs (dLCC). The optimized design scheme is a vector of binary decision variables x , the value representing option of insulation, window type, wall panel, type of heat recovery, and type of auxiliary heater. For each design, there is one value of each objective function. The optimization problem is of the form

$$\min f_1(\bar{x}) = \min PPD \quad (1)$$

$$\min f_2(\bar{x}) = \min E$$

$$\min f_3(\bar{x}) = \min dLCC$$

The optimization problem is subjected to the following constraints.

Only one type of design option i can be selected in a design scheme from each portfolio of options. Therefore

$$x_i = \begin{cases} 1, & \text{if option } i \text{ is selected} \\ 0, & \text{else} \end{cases}$$

and

$$\sum_i x_i = 1$$

The thermal comfort index (PPD) [10] is calculated from

$$PPD = 100 - 95e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (2)$$

where PMV is the predicted mean vote, i.e. the mean response of a large group of people according to the ASHRAE thermal sensation scale -3 (cold)...+3 (hot). The PMV is calculated from

$$PMV = (0.303e^{-0.036M} + 0.028)L \quad (3)$$

where M is metabolic rate and L is thermal load defined as the difference between the internal heat production and the heat loss to the actual environment for a person hypothetically kept at comfort values of skin temperature and evaporative heat loss by sweating at the actual activity level.

The life-cycle costs of a ship incorporate a plethora of cost elements, including construction and operational costs, such as crew costs, maintenance, insurances, administrative costs, harbour charges, tugging, emission charges and fuel costs (Watson, 2002). There is no justification to deal with all these cost elements in the cost optimization, but it is more reasonable to only calculate the difference costs between the reference design portfolio (conventional design) and any other design. According to Hasan et al. (2008), the difference life cycle cost is defined as:

$$dLCC = LCC - LCC_r = dIC + dOC + dMC + dRC \quad (4)$$

where LCC is the discounted life-cycle cost of the target design and LCC_r is that of a pre-selected reference design. Consequently, the reference is represented by dLCC_r = 0. The difference costs for investment, operation, maintenance and replacement are dIC, dOC, dMC and dRC, respectively. Assuming we have 1...j...n options to be selected in the whole design, the difference cost of investment is

$$dIC = \sum_{j=1}^n dIC_j \quad (5)$$

Correspondingly, dOC can be calculated from

$$dOC = ae_p dE \quad (6)$$

where a is the discount factor, e_p is the price of energy and dE is the difference between the annual energy consumption of the target and the reference designs. The difference costs of maintenance and replacement are included in operational costs (dOC), but they are neglected in the present study, because of lack of appropriate information for the cost allocation. The discount rate is real interest rate, where inflation and the escalation of energy price are subtracted (Hasan et al., 2008).

The study utilizes the whole-building simulation tool IDA-ICE, an advanced tool for the dynamic simulation of heat transfer and airflows in buildings, allowing the modelling of multi-zone buildings, internal and solar gains and outdoor climate. The software is widely used in Scandinavia both in commercial and research use. It has been developed by the Royal Institute of Technology and the Swedish Institute of Applied Mathematics, reported in detail by Björnell et al. (1999) and Shalin (1996) and well tested in several studies, e.g. Achermann and Zweifel (2003) and Traversi et al. (2001). The optimization algorithm (GenOpt) is a

genetic algorithm, which starts the search randomly within the given range of solutions of the objective function, directing the process towards the optimal solution using stochastic operators (Hamdy et al., 2011). GenOpt also controls the iterative simulation-based optimization process, calling the simulation program for each round, and retrieving and logging the input and output data (Wetter, 2001). The interaction between IDA-ICE and GenOptis illustrated in Figure 1.

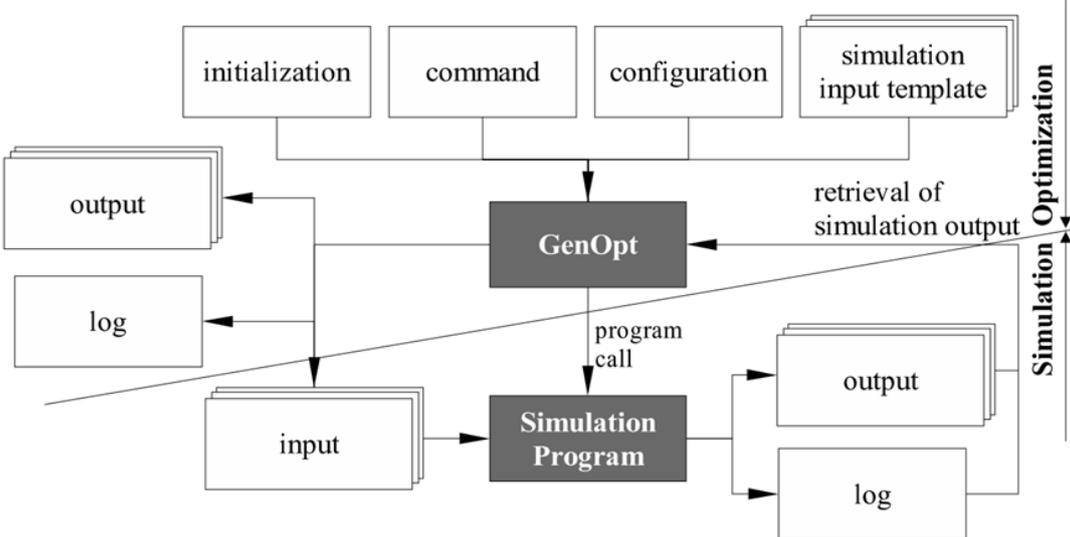


Figure 1 The interaction between IDA-ICE and GenOpt

The target building is the deckhouse of an icebreaker to be built at the Arctech Helsinki Shipyard. The icebreaker is at a conceptual design phase. For the IDA-ICE simulation, the deckhouse is divided into six separate zones: 1) cabins, 2) hospital, 3) administrative rooms (the bridge deck, offices, meeting rooms etc.), 4) other public rooms (gym, restaurant etc.), 5) gaps, and 6) non-heated spaces. A blueprint is shown in Figure 2. The 3D model of the simulated deckhouse is in Figure 3.



Figure 2 A blueprint of the simulated zones



Figure 3 A 3D model of the deckhouse

The ASHRAE climatic data of the Yakutsk area (close to Sahalin Island) is employed (ASHRAE, 2001). The requirements for the indoor comfort, based on the ship classification rules (DNV, 2011) are used as a constraint. The energy analysis deals with the part of the deckhouse upwards from the main deck. The simulation does not account for the ship movement, but the vessel is assumed to be immobile in its average operational position.

The reference (conventional) design entails centralized supply air heating and mechanical ventilation without heat recovery. The heat originates from steam generated in an oil-fuelled boiler and distributed through a water-glycol circulation. Moreover, there are individually controlled electrical heaters in each room. The steel structures are not modified in the optimization, because due to strength issues the changes would impact the design of the entire vessel and thus make the approach more complicated. For similar reasons, the type and the sizing of the primary thermal energy source is not concerned. All the structures are modeled and archived in the IDA-ICE structure library. The design options and their characteristics are summarized in Tables 1-5.

Table 1. Design options.

Component	variation	Wall area/ number of items	Number of variation
Insulation1, wall type 1	60/70/80mm S60	716.4 m ²	3
Insulation2, wall type 1	60/70/80mm W80	716.4 m ²	3
Insulation, wall type2	140/160/180mm F100	50 m ²	3
Insulation, wall type3	100/120/140mm W100	191 m ²	3
Insulation1, wall type4	60/70/80mm S60	30 m ²	3
Insulation2, wall type4	60/70/80mm F100	30 m ²	3
Windows	1/2/3/4 (see table 3)	30 pcs	4
Wall panels	1/2/3/4 (see table 4)	987.5 m ²	4
Heat recovery	Off/on	1 pcs	2
Number of versions			23328

Table 2. Insulations.

Code	Insulationtype	Density [kg/m ³]	Heatconductivity[W/mK]
F100 =	fireslab 100	100	0,033
W100 =	wiredmat 100	100	0,034
W80 =	wiredmat 80	80	0,035
S60 =	slab 60	60	0,033

Table 3. Windows.

Windows	Thickness [mm]	U-value [W/m ² *K]	Visibletransmittance	Solartrans.	Solarheatgain-coefficient
19mm - 8mm Air - 6mm	33	3,098	0,815	0,692	0,764
15mm - 16mm Argon - 6mm	37	2,712	0,815	0,692	0,765
15mm - 16mm Argon - 4mm Pilkington S1N	35	1,183	0,784	0,486	0,624
15mm - 16mm Argon - 4mm Pilkington S1N - 16mm Argon - 4mm	55	0,938	0,713	0,41	0,551

Table 4. Wall panels.

Panels	Specificheat [kJ/kgK]	Heatconductivity[W/mK]	Density [kg/m ³]	Thickness [mm]
1	1,4	0,036	160	25
2	0,8	0,034	160	25
3	0,8	0,035	220	50
4	0,8	0,034	160	50

Table 5. Heat recovery.

Heat recovery	Efectiveness
off	0
on	0,5

RESULTS

Table 6 summarizes the reference design and the six (6) most preferred design concepts achieved through optimization. The corresponding energy consumptions, difference costs, PPD and emissions are presented in Table 7.

Table 6. Summary of the reference design and optimized design concepts.

	Unit	Concept						
		reference	1	2	3	4	5	6
Insulations								
S60 (a0)	Thikcnss [mm]	60	80	70	80	60	70	70
W80 (a1)	[mm]	60	80	60	80	60	70	70
F100 (a2)	[mm]	140	180	140	160	140	140	160
W100 (a3)	[mm]	100	140	100	140	100	120	120
S60 (a4)	[mm]	60	80	60	70	60	70	70
F100 (a5)	[mm]	60	70	60	80	70	70	70
Windows	U-value [W/m ² K]	3,098	0,938	2,712	0,938	2,712	2,712	1,183
Wall panels	Heat conductivity [W/mK]	0,036	0,034	0,036	0,036	0,036	0,036	0,034
	Thikcnss [mm]	25	50	25	25	25	25	25
Heat recovery	Efectiveness	0	0	0	0	0,5	0,5	0,5

Table 7. Energy use, difference costs, PPD and emissions of the reference design and optimized design concepts.

Concept	e/m ² [kWh]	dOC/m ² [€]	dIC/m ² [€]	dLCC/m ² [€]	Ppd
Reference	266,2	0,0	0,0	0,0	24,6
1	259,0	-12,1	23,3	11,2	18,3
2	265,2	-1,8	-0,3	-2,2	23,2
3	261,0	-8,8	3,1	-5,6	19,0
4	173,3	-189,2	0,9	-188,2	23,6
5	168,9	-196,8	3,1	-193,6	22,0
6	165,2	-203,2	27,2	-176,1	18,3

The results suggest that the total energy consumption can be decreased 38 % at maximum. This is mainly due to heat recovery added in the ventilation system. The lowest PPD is obtained with the design concepts 1 and 6. The result correlates, expectedly, with window and the envelope. The lowest life-cycle costs are achieved with the design scheme 5. The discount rates affect significantly the life-cycle costs, but do not significantly change the preference related to optimized design concepts. By increasing the escalation of energy price to 5 %, however, the difference life-cycle costs of the cheapest design concept (5) would increase from 193.6 to 466.3 3 €/m². The duration of average cabin temperatures with selected three design concepts is presented in Fig. 5.

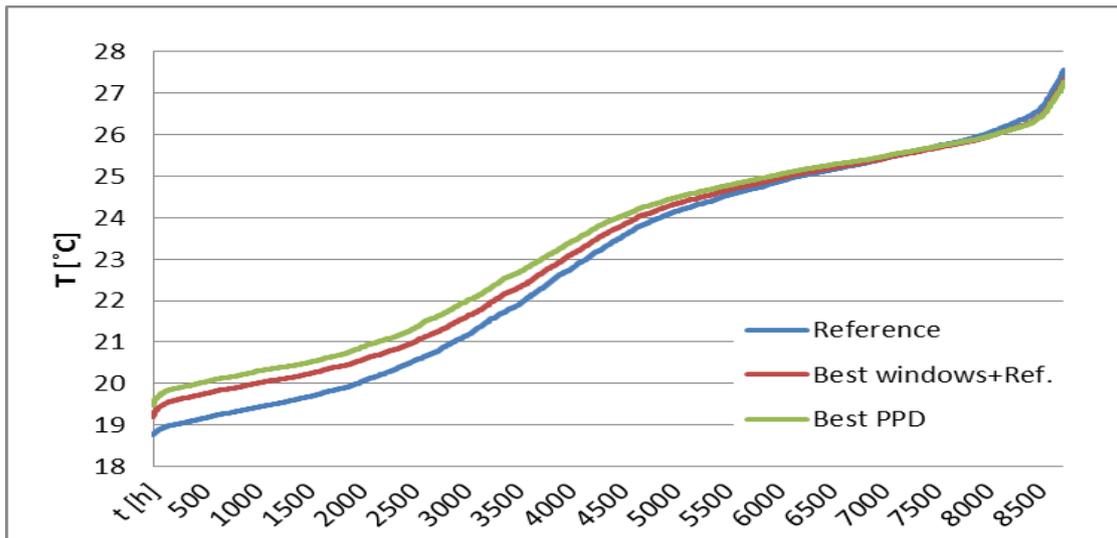


Figure 4 Duration of cabin temperatures

As seen in Fig. 4, the reference design results in the cabin temperature below 20 °C circa 2000 hours during the year. With the best windows, the number of hours is reduced to 1000 h, and with the optimal design to less than 400 hours. Optimized envelope also restrains temperature fluctuations and maintains higher cabin temperatures during winter. By contrast, the design options investigated in the present study do not significantly affect the summer temperatures. Figure 5 is a sample print of the values of the objective function “PPD” for the reference design and for alternative designs. It indicates the achievable decrease of PPD-value, and the corresponding additional capital costs to be paid. The data also reveals the position of the reference design with respect to optimized designs, and a comparison between solutions obtained by the GenOpt algorithm versus “brute-force” method that was applied to verify the optimized solutions representing the global minimum and maximum values of the objective functions.

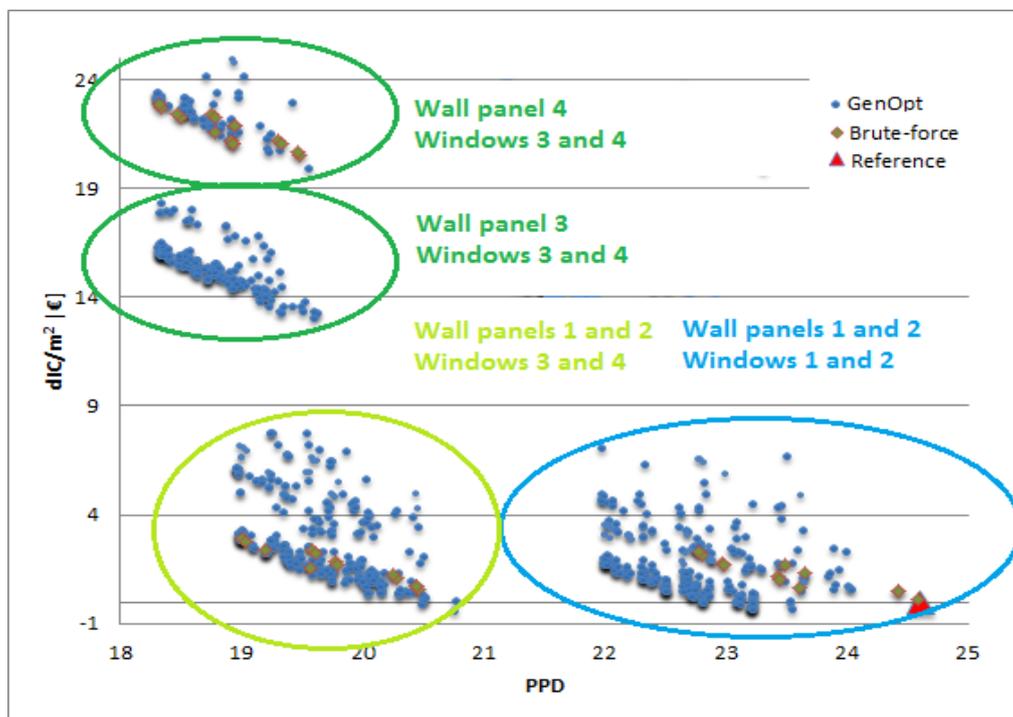


Figure 5 Optimization results - objective function PPD vs. difference capital costs

The result indicates that the most cost-effective solution to improve the indoor thermal comfort is obtained using wall panels 1 and 2 and windows 3 and 4.

DISCUSSION

Using the whole-building performance simulation tool IDA-ICE and a genetic algorithm-based optimization (GenOpt), we found out the most preferred deckhouse envelope structure, heat distribution and heat recovery system for an icebreaker. The optimal design entails a combination of design options that minimizes the difference life-cycle costs and predicted percentage of dissatisfied in comparison with the conventional design practice.

Our results suggest that only adding the ventilation heat recovery, the thermal energy consumption of the deckhouse can be reduced approximately by 90 kWh/m². Moreover, the optimized design concept entails improved insulation and windows. Wall panels do not significantly affect the thermal energy consumption. The optimized design reduces the thermal energy consumption by 38 % and the PPD by 26 % (when compared to the reference design). The result is comparable with the findings of Gustavsson & Joelsson (2008), who obtained 40-60 % savings in primary energy consumption of a single-family house. The lowest-cost design concept entails thinner insulation in the floor and less energy-efficient windows, which results in the PPD of nearly the same level as with the reference design. The energy saving potential of 37 % is still achieved, which reduces the life-cycle costs. Although our results clearly indicate the benefit of heat recovery, its use in extremely cold conditions is challenging due to icing. Clear benefit of heat recovery has not been showed through experiences, either. In these conditions, design schemes with improved windows and insulation should be preferred to maintain the best possible thermal comfort.

Whole-building simulation and optimization was proven to be a proper tool to evaluate the energy and indoor comfort issues in the marine environment. The model of the deckhouse was a quite complicated multi-zone model, one simulation taking approximately 35 minutes. In the present study, the total number of alternative designs was 23328, which would have signified the accumulated simulation time of 567 days with the brute-force method. The optimization algorithm reduced the number of evaluated designs to 1000, and therefore the simulation time to twelve days.

The key uncertainties of the present study are associated with modeling, assumptions and difficulties to predict the position of the ship exactly. The human behavior is practically impossible to predict accurately (Ryan and Sanquist, 2012). The IDA-ICE simulation tool employs the traditional thermal comfort models, the use of which in terms of marine environment are criticized e.g. by Jang et al. (2007) and Hongmin et al. (2011).

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