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A framework for multi-objective optimization of Arctic offshore support vessels

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ABSTRACT

An Arctic vessel operates in a fragile Arctic environment that requires analyzing an eco-efficiency besides cost-efficiency in the conceptual design – phase that mainly determines a ship's performance. We present a software framework to optimize Arctic offshore support vessels for Cost- and Eco-efficiency using the Artificial Bee Colony algorithm. The framework scans the feasible design space to find a Pareto front, considering essential ship qualities in a specific operational context. The object-oriented structure of the program modules makes them independently reusable for a wide range of applications.

KEY WORDS: Ship design; Offshore; Arctic; Multi-objective optimization; Artificial Bee Colony algorithm.

INTRODUCTION

The modern industry of ship design and shipbuilding is very competitive. A successful player in this market usually specializes in a specific type of vessel and provides integrated solutions for all the production stages, from the initial idea to vessel delivery. A vessel is a complex product of broad cooperation – research institutions, design bureaus, and shipyards aim to provide high-quality results. Any suboptimal solution affects the following stages of ship production, which makes the conceptual ship design a phase with the most impact on ship performance.

Holistic multi-objective optimization of ships is an effective approach to provide competitive design concepts, which considers a ship as a complex system in a specific external operational context (Papanikolaou, 2010) (Priftis, et al., 2018) (Skoupas, et al., 2019) (Bergström, et al., 2016). A complex system consists of many subsystems that interact and compete with each other. Object-oriented programming provides practical tools to model complex systems. The external setting, a ship, and ship subsystems could be modeled as objects with specific methods to simulate their performance and interaction (Miquel, et al., 2020) (Tarovik, et al., 2017).

Arctic offshore support vessel (OSV) is a sophisticated and expensive compromise between a traditional offshore vessel and an icebreaker. An Arctic navigation imposes specific vessel design requirements to operate in ice safely (Kujala, et al., 2019). However, advanced icebreaking capabilities often negatively affect other ship qualities, such as open water seakeeping performance and cost-efficiency. OSVs also must be eco-efficient to minimize ship emissions into the fragile Arctic environment, which motivates the multi-objective optimization.

In contrast to the single-objective optimization that finds only one optimal solution corresponding to a specific input, the multi-objective optimization results in a set of equal-optimal (Pareto optimal) solutions – tradeoffs between the optimization objectives. Any optimization objective of the Pareto optimal solution cannot be improved without making another objective worse. The results of multi-objective optimization are usually presented using a Pareto front graph, where the optimization objectives are plotted on the axes. The graph points corresponding to the Pareto optimal solutions shape the Pareto front, while other suboptimal solutions are shown as a cloud of feasible points. A Pareto front graph is an informative tool for a decision-maker that can represent an entire design space.

In this study, we proposed an object-oriented framework for holistic multi-objective optimization of an OSV that includes: a parametric design model of an OSV, performance assessment models for independently operating and icebreaker-assisted Arctic OSVs, and a novel adaptation of the Artificial Bee Colony (ABC) algorithm (Karaboga & Basturk, 2007) for multi-objective optimization in well-constrained problems. The original ABC algorithm is a single-objective optimization metaheuristic method based on swarm intelligence, specifically the foraging behavior of honeybees. The framework scans the feasible design space to find a Pareto front, representing tradeoffs between cost- and eco-efficiency of an Arctic OSV.

SOFTWARE DESCRIPTION

Table 1 presents a brief description of the essential program units' functionality. Unit 1 includes an adaptation of the original ABC algorithm to solve a multi-objective Mixed-Integer Nonlinear Programming (MINLP) optimization problem in constraints. MINLP means that optimization variables include real and integer numbers and the model of the optimized object includes nonlinear expressions.

Table 1. Description of program units

Unit no.	Description	Constraints
1	The main unit; multi-objective optimization	-
2	Constructor for a class TVessel	+
3	Hull lines creation; freeboard check	+
4	Hydrostatic calculations	-
5	Resistance in open water	-
6	Optimization of propellers; calculation of the required total engine power	+
7	Calculation of cargo capacity (m^3) and cargo deck area (m^2)	+
8	Weight calculations; stability calculations; ballasting and trim control	+
9	Performance models	+
10	Library of engineering methods for Units 2-9	-
11	Reference min and max values for constraints (all units)	-
12	Technical data and ice data for Units 2-10	-

Units 2-8 is a parametric design model of an OSV that calculates all the essential ship design qualities based on the set of parameters (Double and Integer) and records the results to an object of TVessel class (an OSV information model). Unit 9 includes the set of performance assessment models that evaluate cost- and eco-efficiency for independently operating and icebreaker-assisted Arctic OSVs. They use an object of TVessel class as input. Supplementary methods and data are provided in Units 10 – 12.

Figure 1 presents the BPMN (Business Process Model Notation 2.0) diagram of the optimization process. RFR is the break-even rate per one cargo unit (USD/t, a cost-efficiency key performance indicator) (Watson, 1998). EEDI is the amount of CO_2 emissions per one transport work unit (g/t·nautical mile, an eco-efficiency key performance indicator) (IMO, 2018).

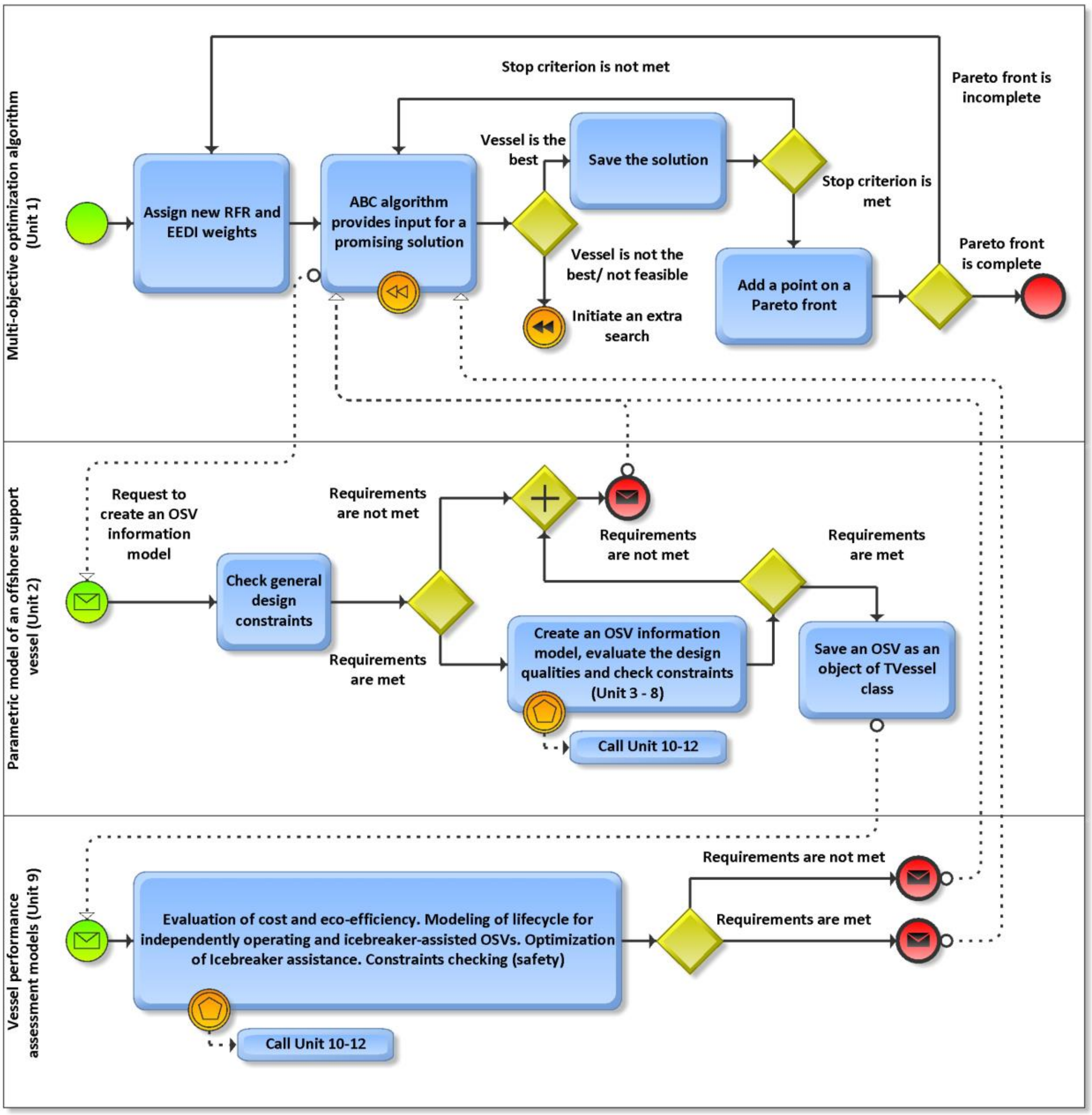

Figure 1. A general BPMN diagram of the optimization process.

We used a scalarized optimization with normalized objective functions to get a Pareto front as per the following equation:

$$\text{Objective function} = \frac{w \cdot RFR}{RFR_{min}} + \frac{(1-w) \cdot EEDI}{EEDI_{min}}$$

where w is a weight factor with a value in a range from 0 to 1.

Scalarized optimization is based on the weighted sum method with step-wise modification of a weight factor w. The normalization of the objective functions using RFR_{min} and $EEDI_{min}$ is necessary to provide a Pareto front homogeneity. The homogenous Pareto front is well informative: it has minor variations in the distances between consecutive points. RFR_{min} and $EEDI_{min}$ are derived from two separate single-objective optimization rounds, using RFR or EEDI as an objective.

Imitating honeybees' foraging behavior in each optimization round, the ABC algorithm processes Units 2-9 as a black box with the constraint checking embedded (see Table 1).

Figure 2 shows an example of optimization results, where black points represent the Pareto front and green points represent other feasible solutions.

The current version of the OSV parametric design model applies to two major types of OSVs – Offshore Supply Vessels and Anchor Handling Tug Supply (AHTS) Vessels –with different icebreaking capabilities: from open water vessels to icebreakers. The performance assessment models are developed for Offshore Supply Vessels only.

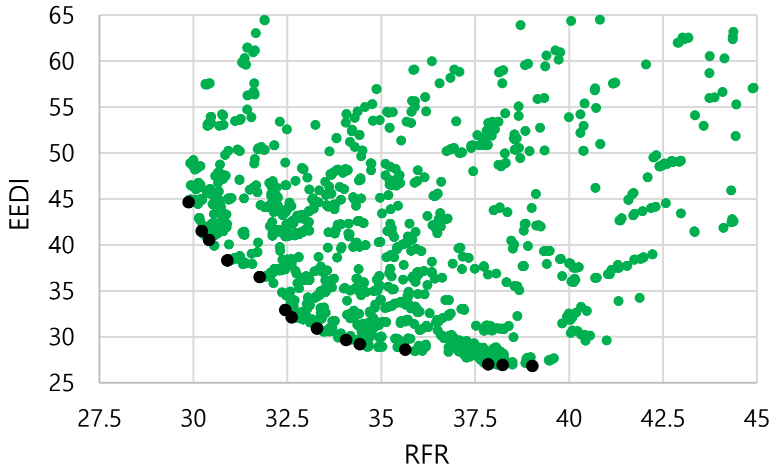

Figure 2. An example of the optimization results. Black points show the Pareto front, and green points show other feasible OSVs.

IMPACT

Existing impact

We used the framework to investigate the impact of Arctic-related factors on offshore support vessels (OSVs) design (Kondratenko & Tarovik, 2020) (Kondratenko & Tarovik, 2018) and to schedule OSVs for the digital twin of the existing support system of an Arctic offshore platform (Tarovik, et al., 2018). The framework is utilized in the ongoing project titled "Goal-based optimization in Arctic offshore support vessels design and fleet composition," with two studies submitted for publication. The first study presents a new risk-based approach to optimize an Arctic offshore drilling support fleet's composition for cost-efficiency. The approach considers all the main duties related to Arctic offshore drillings, including supply, towing, anchor handling, safety standby, oil recovery, fire-fighting, and ice management. The second study presents a new holistic multi-objective design approach to optimize Arctic Offshore Supply Vessels (OSVs) for Cost- and Eco-efficiency and demonstrates all the framework's abilities and advantages.

Potential future impact

The framework can be helpful in the following applications:

- Optimization of open water OSVs (ready to use).
- Modification of the performance models to consider new objectives in optimization (safety, ergonomics, recyclability).
- Optimization of open water and Arctic AHTSs (development of an AHTS performance model is required).
- Adaptation of the framework to optimize open water and Arctic support vessels of different types, for example, wind farm service vessels, offshore construction vessels, diving support vessels.
- The framework's modular structure makes it possible to study a wide range of research questions related to offshore ship and offshore support systems design by minor modifications: every unit or method could be easily replaced without losing the general integrity.
- The multi-objective optimization algorithm is universal and ready to solve the complex Mixed-Integer Nonlinear Programming problems in constraints.

CONCLUSIONS

The provided framework for multi-objective optimization of Arctic offshore support vessels is a decision support system that contributes to the development of competitive solutions in the conceptual ship design. The framework can be useful to plan a new supply fleet and estimate the desired vessel characteristics for an existing vessel’s refurbishment. The system has the following strengths: a) it is efficient, easy to use, fast, and informative; b) it is successfully applied in a series of research studies; c) it has a high potential for future applications.

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