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Efficient constraint multi-objective optimization with applications in ship design

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Chapter 1

Introduction

Multi-objective optimization involves the concurrent optimization of conflicting objectives, aiming to identify a group of solutions that reveal a trade-off among optimal solutions instead of a single optimal solution. Finding these trade-offs is particularly challenging when the evaluation methods of the solutions are computationally expensive. The complexity further increases when constraints are present in the optimization problem. Examples of such constraint multi-objective problems can be found in various engineering design problem domains, including aerospace [33, 34], automotive [116, 157], civil [1, 42], marine [115, 149], and others.

This work shows how feasible optimal solutions in the constraint multi-objective optimization problem domains can be found with optimization algorithms. The primary focus of this work is the development of constraint multi-objective optimization algorithms, with a secondary objective to apply the newly developed algorithms to ship design optimization problems. Before multi-objective algorithms were used, the classical way to optimize multi-objective problems in the maritime industry was to optimize one objective at a time or use traditional mathematical optimization techniques such as the weighted sum method. The pragmatic weighted sum approach combines objectives by multiplying them with predefined weights into one objective. The weighted sum of the objectives is then optimized until an optimal feasible solution is found. However, the weighted sum method has some disadvantages, since a priori weight selection can be difficult, the outcome is sensitive to the weight selection, and if only one weight combination is selected only one solution will be discovered instead of the entire Pareto frontier [99]. Advantages in multi-objective evolutionary algorithms have made multi-objective optimization more common and accessible in the past 30 years [10] and thereby also more usable for the maritime industry.

In ship design, multi-objective optimization can be applied in different design phases. Ship design typically consists of three phases, the preliminary design stage, the contract design stage, and the detailed design stage. According to Taggart [139], early design stages occupy the smallest amount of time. In the first design phases, the operational requirements are translated into phyisical and technical characteristics [89]. This is done by finding the balance between the need of the customer and the available budget, resulting in one or more possible design solutions [54]. Despite the limited amount of time spent in the early design stages, it is estimated that 60 to 80 percent of the total life cycle cost is already locked in after the preliminary design stage [127]. Depending on the experience of the involved Naval Architects, this can be quite risky. The design decisions are typically hard to reverse and are also often made with limited design problem knowledge. It is because of the large room for improvement and the relatively large decision freedom in the early design stage that this work focuses on applying multi-objective algorithms in the preliminary design stage. This is done by investigating what optimization algorithms are needed when using two different design methods:

1. In the empirical design method the main dimensions and ship characteristics are determined by investigating and learning from similar-built vessels.
2. The simulated design method uses 3-D models connected to simulation software that evaluate the ship designs created by naval architects.

The constraint multi-objective problems arising from these two design methodologies exhibit significant differences, particularly when accounting for the required computational effort. Where the empirical design method is computationally inexpensive and relatively simplistic, the simulated design method is computationally more demanding and can lead to really challenging conditions for identifying promising feasible Pareto efficient solutions. More details about the design methodologies are described in Chapter 3.

The availability of design data and more exact and computationally demanding simulation software has led to the need for more advanced optimization algorithms and techniques. The constraint multi-objective optimization algorithms developed in this doctoral dissertation aim to fill this gap. The main scientific contribution therefore is also the newly developed algorithms and methodologies for constraint multi-objective optimization. The proposed methodologies are thoroughly described, tested, and compared to state-of-the-art constraint multi-objective optimization algorithms. The new algorithms have extended the horizons of knowledge in the field of multi-objective optimization and now give engineers from different domains the tools needed to more efficiently deal with computationally demanding constraint multi-objective optimization problems.

1.1 Research Questions

Finding feasible Pareto efficient solutions for computationally demanding optimization problems is not a straightforward task. The primary research question is therefore as follows:

How to identify the Pareto frontier of constraint multi-objective optimization problems with only a few function evaluations?

The secondary objective is to apply the new algorithms to ship design optimization problems. The research question is therefore separated into the following sub-research questions:

RQ1: What are typical ship design optimization problem characteristics?

RQ2: How can data be used to find feasible Pareto efficient ship design solutions?

RQ3: How to find the Pareto frontier of computationally expensive problems?

RQ3.1: How to deal with expensive multi-objective problems?

RQ3.2: How to efficiently satisfy constraints in multi-objective optimization?

RQ3.3: How to propose multiple solutions for evaluation in parallel?

RQ3.4: How to deal with a mix of expensive and inexpensive functions?

RQ3.5: How do the proposed algorithms compare to state-of-the-art algorithms?

RQ4: What is the performance of the proposed algorithms in real-world scenarios?

1.2 Outline

The research questions are answered in different chapters of this dissertation. The remainder of this thesis is organized as follows: In Chapter 2 the problem notations and relevant preliminaries are given for efficient constraint multi-objective optimization.

Chapter 3 describes ship design optimization problem characteristics and answers research question 1. In Chapter 4 research question 2 is answered and it is shown how multi-objective optimization algorithms are used in combination with machine learning in an empirical ship design method. The largest scientific contribution of this research is described in Chapter 5. In this chapter, the main research question is answered, and multi-objective optimization algorithm configurations are proposed for solving parallel simulation-based optimization problems with mixed expensive constraints and objectives. In Chapter 6 research question 4 is answered and the algorithms from the previous chapter are used to optimize real-world ship design optimization problems. Finally, conclusions are drawn in Chapter 7.

1.3 Publications of this thesis

The majority of the work in this thesis has been published before in academic journals and conference proceedings. The contents of this thesis consist of the following papers.

[146] **Roy de Winter**. Parallel constrained multi-objective optimization for ship design damage stability problem with (in)expensive function evaluations. In *Marine 2023*, page 1. Marine 2023, Scipedia, 2023.

[147] **Roy de Winter**, Thomas Bäck, and Niki van Stein. Modular optimization framework for mixed expensive and inexpensive real-world problems. In *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO)*, 2024.

[148] **Roy de Winter**, Philip Bronkhorst, Bas van Stein, and Thomas Bäck. Constrained multi-objective optimization with a limited budget of function evaluations. *Memetic Computing*, 14:151–164, 2022.

[149] **Roy de Winter**, Jan Furustam, Thomas Bäck, and Thijs Muller. Optimizing ships using the holistic accelerated concept design methodology. In Tetsuo Okada, Katsuyuki Suzuki, and Yasumi Kawamura, editors, *Practical Design of Ships and Other Floating Structures (PRADS)*, pages 38–50, Singapore, 2021. Springer.

[152] **Roy de Winter**, Bas Milatz, Julian Blank, Niki van Stein, Thomas Bäck, and Kalyanmoy Deb. Parallel multi-objective optimization for expensive and inexpensive objectives and constraints. *Swarm and Evolutionary Computation*, 86:101508, 2024.

[153] **Roy de Winter**, Bas van Stein, and Thomas Bäck. SAMO-COBRA: A fast surrogate assisted constrained multi-objective optimization algorithm. In Hisao

Ishibuchi, Qingfu Zhang, Ran Cheng, Ke Li, Hui Li, Handing Wang, and Aimin Zhou, editors, *International Conference on Evolutionary Multi-Criterion Optimization (EMO)*, pages 270–282. Springer, 2021.

[154] **Roy de Winter**, Bas van Stein, Matthys Dijkman, and Thomas Bäck. Designing ships using constrained multi-objective efficient global optimization. In Giuseppe Nicosia, Panos Pardalos, Giovanni Giuffrida, Renato Umeton, and Vincenzo Sciacca, editors, *International Conference on Machine Learning, Optimization, and Data Science*, pages 191–203. Springer, 2018.

[156] **Roy de Winter**, Bas van Stein, and Thomas Bäck. Multi-point acquisition function for constraint parallel efficient multi-objective optimization. In *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO)*, pages 511–519, 2022.

[155] **Roy de Winter**, Bas van Stein, and Thomas Bäck. Ship design performance and cost optimization with machine learning. In *20st Conference on Computer and IT Applications in the Maritime Industries (COMPIT)*, pages 185–196. Hamburg University of Technology, 2020.

1.4 Other Work by the Author

Besides the papers that form the content of this thesis, the author has also been involved in the conceptualization, writing, and review process of the following papers:

[10] Thomas Bäck, Anna V Kononova, Bas van Stein, Hao Wang, Kirill Antonov, Roman Kalkreuth, Jacob de Nobel, Diederick Vermetten, **Roy de Winter**, and Furong Ye. Evolutionary algorithms for parameter optimization—thirty years later. *Evolutionary Computation*, 31(2):81–122, 2023.

[27] Philip Bronkhorst, **Roy de Winter**, Thijs Velner, and Austin A Kana. Enhancing offshore service vessel concept design by involving seakeeping-developing a framework to efficiently design high-performance offshore service vessel concepts. In Volker Bertram, editor, *22nd Conference on Computer and IT Applications in the Maritime Industries (COMPIT)*, pages 273–287. Hamburg University of Technology, Schriftenreihe Schiffbau, 2022.

[75] Gideon Hanse, **Roy de Winter**, Bas van Stein, and Thomas Bäck. Optimally weighted ensembles for efficient multi-objective optimization. In *International Conference on Machine Learning, Optimization, and Data Science*, pages 144–156. Springer, 2021.

[80] Qi Huang, **Roy de Winter**, Bas van Stein, Thomas Bäck, and Anna V Kononova. Multi-surrogate assisted efficient global optimization for discrete problems. In *2022 IEEE Symposium Series on Computational Intelligence (SSCI)*, pages 1650–1658. IEEE, 2022.

[103] Bas Milatz, **Roy de Winter**, Jelle DJ van de Ridder, Martijn van Engeland, Francesco Mauro, and Austin A Kana. Parameter space exploration for the probabilistic damage stability method for dry cargo ships. *International Journal of Naval Architecture and Ocean Engineering*, page 100549, 2023.

[150] **Roy de Winter**, Fu Xing Long, Andre Thomaser, Niki van Stein, de, Thomas Bäck, and Anna V Kononova. Landscape analysis based vs. domain-specific optimization algorithm selection for engineering design applications: A clear case. In *2024 IEEE Conference on Artificial Intelligence (CAI)*. IEEE, 2023.

[151] **Roy de Winter**, Bas Milatz, Julian Blank, Niki van Stein, Thomas Bäck, and Kalyanmoy Deb. Hot off the press: Parallel multi-objective optimization for expensive and inexpensive objectives and constraints. In *Proceedings of the Genetic and Evolutionary Computation Conference (GECCO)*, 2024.

[162] Lucas Van Rooij, **Roy de Winter**, Anna V Kononova, and Bas van Stein. Explainable AI for ship design analysis with AIS and static ship data. In *15th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS)*, pages 1521–1535, 2022.

[163] Niki van Stein, de **Roy de Winter**, Thomas Bäck, and Anna V Kononova. AI for Expensive Optimization Problems in Industry. In *2023 IEEE Conference on Artificial Intelligence (CAI)*, pages 251–254. IEEE, 2023.