学位論文内容の要旨

学 位 論 文 題 目　Design and Application of Meta-Heuristic Algorithms for Engineering Optimization in Renewable Energy Systems
（再生可能エネルギーシステムにおけるエンジニアリング最適化のためのメタヒューリスティックアルゴリズムの設計と適用）

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Recent shocks such as COVID-19 and the Russia-Ukraine War have shifted the focus of many countries' energy policies to energy security goals. Since the East Asian countries, represented by Japan, are generally well-developed in manufacturing and short on energy, the efficient use of renewable energy has become the focus of research. Take the wind farm layout optimization problem (WFLOP) as an example: to maximize power production for a given wind farm and wind distribution profile, WFLOP seeks to determine the best location for each wind turbine. The turbines in the defined position together form a layout. Fig. 1 shows a top view of the wind farm layout, in which the yellow rhombuses are the wind turbines, the blue trapezoids are the areas affected by the wake, and the orange arrows represent the wind direction. The goal of the optimization is to optimize the wind farm layout from the bad state of Fig.1 (a) to the ideal state of Fig.1 (b).

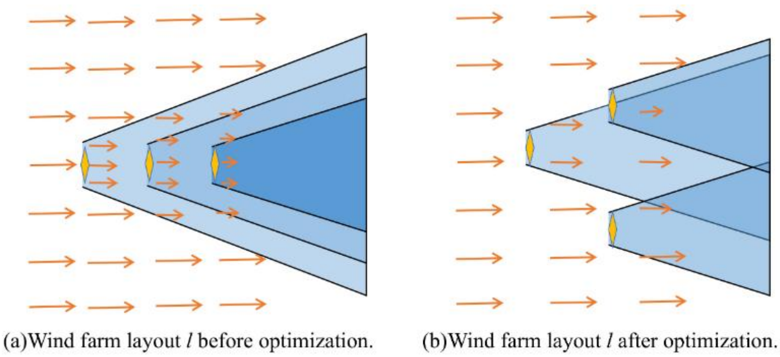

Figure 1: The wake effect behind a wind turbine facing ambient wind speed.

As an important global optimization technique in artificial intelligence, meta-heuristics have proven to be an effective tool for addressing the engineering optimization problems in renewable energy systems, such as the position optimization problem of wave energy converters (WEC) and WFLOP. The Meta-heuristic is one way to quickly arrive at a workable solution when it is challenging or impossible to find the optimal solution to a problem. However, the rift between these engineering optimization problems and meta-heuristics has continued to expand. On the one hand, with the continuous research on meta-heuristics, a large number of new algorithms have emerged. On the other hand, each WEC and WFLOP have different features due to differences in wind/wave speed, type of wind turbines/wave energy converters, wind/wave directions, and regional constraints. According to the "No-Free-Lunch Theorem," it is unrealistic to expect to find the most suitable algorithm for all the WECs and WFLOPs.

The focus of this study is to investigate and design meta-heuristics in more depth so that they can be better used in specific renewable energy optimization problems. The research is divided into two aspects:

Aspects 1: In recent decades, researchers appear to have concluded that maintaining a balance between exploitation and exploration is critical for improving meta-heuristics' performance. This study proposes an intelligent scheme that aims to give the algorithm more decision-making authority to determine when to perform exploration or exploitation. Thus, a spatial information sampling algorithm (SIS) that uses an intelligent scheme is proposed. Experiments at the WEC demonstrated that SIS can effectively improve energy conversion efficiency. However, there are still two drawbacks on the theories of exploitation and exploration. One is that the exploitation and exploration of algorithms are difficult to define, and although there are many algorithms claiming that they achieve a balance between exploitation and exploration, there is rarely mathematical proof. The second is that the so-called exploitation and exploration is a tool to describe the nature of the algorithm itself, which is difficult to combine with the problem being optimized.

Aspects 2: To deal with the above problems, we propose a theory of exploitation and exploration based on population interaction networks (PIN). Meta-heuristic algorithms can be classified into two categories according to PIN: algorithms with Poisson degree distribution and algorithms with power-law degree distribution. Scale-free networks with a power-law distribution increase the likelihood of finding nodes with a lot of links compared to small-world networks with a Poisson distribution. Furthermore, according to our research on exploitation and exploration, " good " individuals with extensive connections are more likely to be involved in exploitation-biased attraction operations. Therefore, algorithms with power-law distributions are more likely to be biased toward exploitation than those with Poisson distributions. The optimization results show that spherical evolution and differential evolution with Poisson distribution outperform two improved versions of differential evolution (CJADE and SCJADE) with power-law distribution on WFLOP. Based on this phenomenon, an improved spherical evolution (ISE) with enhanced exploration capability is proposed.

The results of the study are tested on WEC and WFLOP, respectively. In WEC, the energy conversion efficiency of SIS is improved by 22.46%, 107.53%, 99.82%, and 2.54% relative to the existing method for four wave conditions: Tasmania, Adelaide, Perth, and Sydney. The experimental results on WFLOP show that the average conversion rate of ISE is 93.64%, 89.45%, and 97.22% for the three wind conditions of single wind direction, four wind directions, and six wind directions, respectively. The Wilcoxon signed-rank test, Wilcoxon rank-sum test, and Friedman test results show that SIS and ISE perform significantly better than the other state-of-the-art algorithms in terms of global optimality, avoiding local minima, and solution quality. The main contributions of this study can be summarized as:

1) In this study, we analyze and categorize the properties of some representative meta-heuristics using exploitation and exploration theory and PIN theory. This theory can give more insights into the algorithm design for the WEC and WFLOP, aiming to improve energy conversion efficiency and reduce the time and economic cost of the optimization process.

2) Based on the above theory, we propose SIS to address the WEC problem and ISE to address the WFLOP problem. Experimental results prove that SIS and ISE outperform their competitors by a wide margin.

3) This efficient way of improving the meta-heuristic into a heuristic will bring new inspiration to research in the field of optimization algorithms.

【学位申請審査結果の要旨】（楊　海川）

当博士学位論文審査委員会は，標記の博士学位申請論文を詳細に査読し，投稿された論文の査読プロセスを確認した。本博士論文と従来の論文との類似性指標は 10%であり，剽窃等の問題がないことを確認した。また論文公聴会を令和 5 年 1 月 27 日(金曜日)に公開で開催し，詳細な質疑応答を行って論文の審査を行った。以下に審査結果の要旨を示す。

日本をはじめとする東アジア諸国は、一般に製造業が発達しており、エネルギーが不足しがちであるため、再生可能エネルギーの利用が研究の焦点となっている。人工知能における重要な大域的最適化手法として、メタヒューリスティックは、波力発電装置の位置最適化問題や風力発電所のレイアウト最適化問題など、再生可能エネルギーシステムにおける工学的最適化問題に取り組むための有効なツールであることが証明されている。

本研究の目的は、メタヒューリスティックを深化させ、再生可能エネルギー最適化の分野でより利用しやすく、またエネルギー変換効率を向上させることができるようにすることである。具体的には，先ず新しいメタヒューリスティックを開発し、さらに既存のメタヒューリスティックを最適化される問題の特性に合わせた改良を行った。そのために，空間情報サンプリングアルゴリズムと改良型球面進化アルゴリズムを逐次提案した。波力発電装置の位置最適化問題では、4 つの波浪条件において、空間情報サンプリングアルゴリズムのエネルギー変換効率が既存手法に対して 22.46%、107.53%、99.82%、2.54%向上している。風力発電所のレイアウト最適化問題での実験結果では、改良型球面進化アルゴリズムの平均変換率は、3 つの風況でそれぞれ 93.64%、89.45%、97.2%となった。

本研究の主な貢献は、以下のようにまとめられる：1）本研究では、代表的なメタヒューリスティックについて、開発と探求のバランス理論を用い、その特性を分析・分類した。2）上記の理論に基づき、波力発電装置の位置最適化問題に対応する空間情報サンプリングアルゴリズムと風力発電所のレイアウト最適化問題に対応する改良型球面進化アルゴリズムを提案した。実験の結果、空間情報サンプリングアルゴリズムと改良型球面進化アルゴリズムは競合他社を大きく上回る性能を持つことが証明された。3）このメタヒューリスティックをヒューリスティックに改良する効率的な方法は、最適化アルゴリズムの分野の研究に新たなインスピレーションをもたらすと考えられる。

当博士論文審査委員会は、研究内容及び研究成果を慎重に吟味した結果，本博士学位申請論文が博士の学位を授与することに十分に値するものと認め，合格と判断した。