Linköping Studies in Science and Technology
Licentiate No. 2012

Contributions to Metaheuristic Algorithms for Real-World Engineering Problems

Abdelazim G. Hussien

LINKÖPING UNIVERSITY

Linköping Studies in Science and Technology
Licentiate Thesis, No. 2012

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Linköping 2025

Typeset using LaTeX

Printed by LiU-Tryck, Linköping 2025

Edition 1:1

ISBN 978–91–8075–991–5 (print)
ISBN 978–91–8075–992–2 (PDF)
https://doi.org/10.3384/9789180759922
ISSN 0280-7971

POPULÄRVETENSKAPLIG SAMMANFATTNING

Licentiatavhandlingen behandlar metaheuristiker vilka är en samling av heuristiker. En heuristik kan sägas vara en tumregel eller en hjälpmetod, som används av algoritmer för att effektivt komma fram till lösningar. Just metaheuristiker är något som används för att vägleda olika optimeringstekniker och som på senare tid har fått stor uppmärksamhet. Anledningen för denna uppmärksamhet är metaheuristikernas förmåga att underlätta lösningar av komplexa och storskaliga problem, speciellt i de fall där klassiska algoritmer, som försöker lösa problemet mer exakt, får svårigheter.

Flera metaheuristiska metoder är baserade på olika processer som förekommer i naturen. Dessa inkluderar olika så kallade evolutionära metoder samt metoder som grundar sig i fysiskt och mänskligt beteende. Dessa har visat sig vara mycket användbara att lösa optimeringsproblem där de finns många bivillkor och där problemen som ska lösas är mycket omfattande och därför beräkningstunga.

I cloud computing (molnberäkningar), genomför vi beräkningar i det så kallade molnet, det vill säga över internet i stället för att utföra dessa beräkningar direkt på våra egna datorer. Vid just molnberäkningar är metaheuristiker användbara. Anledningen till det är att inom både industri och vetenskap har alltmer både beräkningstungt och annat arbete, som tidigare genomförts på persondatorer, flyttats till molnet.

Detta har inneburit att olika operationer som är vanliga för beräkningar i molnet såsom effektiv schedulering av olika beräkningar samt resursfördelning behöver göras mer effektiva för att undvika möjliga prestandaförluster. Dessa observationer utgör motivationen för den forskning som licentiatavhandlingen presenterar. Licentiatavhandlingen undersöker därför olika nya optimeringsmetoder och hur dessa kan bidra till både mer robusta och mer anpassningsbara scheduleringsramverk genom att undersöka dels hur prestandan, dels resurshanteringen kan förbättras men också genom att undersöka hur kostnaden för att utföra beräkningarna kan minimeras.

Licentiatavhandlingen är uppdelad i två delar, där den första delen behandlar den teoretiska bakgrunden där både olika teoretiska optimeringsmetoder och ingenjörsmässiga problem presenteras. I avsnittet presenteras också en diskussion kring aktuella utmaningar som rör schedulering i en molnkontext.

Den andra delen av avhandlingen består av tre publicerade studier som behandlar de praktiska effekterna av olika metoder för att förbättra beräkningsoperationer i molnet. Sammanfattningsvis kan man säga att licentiatavhandlingen behandlar optimeringsdriven schedulering samt hur vi exempelvis genom detta kan utföra beräkningar mer effektivt i molnet.

ABSTRACT

Metaheuristics are powerful optimization techniques that have gained significant attention for their ability to solve complex and large-scale problems where exact algorithms fall short. These methods, including evolutionary algorithms, swarm intelligence, physics-based, and Human-based, are inspired by natural processes and are particularly effective for problems with vast search spaces and multiple constraints. In engineering, metaheuristics are frequently applied to optimize resource allocation, scheduling, and design processes, where traditional methods are computationally intensive or impractical. In cloud computing, task scheduling remains a critical challenge as demand for scalable, high-performance, and cost-effective solutions grows. Metaheuristic optimization offers promising approaches to address the scale, heterogeneity, and dynamic nature of cloud environments.

The increasing reliance on cloud-based systems across industries has amplified the need for efficient task scheduling and resource management solutions. Traditional scheduling approaches often lack the flexibility and adaptability required to handle the dynamic workloads of cloud environments, leading to inefficiencies in resource utilization and task execution time. Motivated by these challenges, this research explores how metaheuristic optimization can enhance cloud task scheduling by improving performance, balancing loads, and minimizing costs. This thesis aims to develop innovative optimization techniques that address these pressing issues, contributing to more robust and adaptive scheduling frameworks for cloud systems.

This thesis is organized into two main parts. The first part provides a theoretical foundation, offering background on optimization methods, an overview of engineering problems, and a discussion of task scheduling challenges in cloud computing. The second part comprises three published studies that illustrate the practical application of the proposed methods. Paper I and II present the Enhanced Evaporation rate Water Cycle Algorithm (EErWCA) and modified Artificial Electric Field Algorithm (mAEFA) techniques for addressing global optimization and engineering problems. Paper III develops hybrid Artificial Gorilla Troops Optimizer with Honey Badger Algorithm (GTOHBA) for optimized cloud task scheduling. Together, these contributions address key research questions, positioning this work within the broader context of optimization-driven scheduling and cloud computing.

Acknowledgments

I would like to extend my deepest appreciation to my advisors, Adrian Pop and Niklas Fors, for their invaluable guidance, patience, and insightful supervision throughout my Ph.D. studies and research. It has been a privilege to collaborate with and learn from them at Linköping University and Lund University. I am especially grateful to Adrian for providing me with the opportunity to undertake this research.

I would also like to express my heartfelt thanks to both the current and former members of PELAB for fostering a supportive and motivating work environment where I have gained so much knowledge. I am deeply grateful to my colleagues and coauthors for their valuable insights and the enriching technical discussions, which have greatly contributed to the articles in this thesis. Their contributions have been essential to the completion of this work.

I would also like to extend my appreciation to everyone who has contributed to the development of the OpenModelica system.

I am deeply grateful to my friends (too many to name, but you know who you are!) for their unwavering support and friendship. To all the Egyptians in Linköping, past and present, I cherish the moments we've shared, facing challenges together and celebrating life's joys. Lastly, I am immensely thankful to my family for their endless love and encouragement. To my late father, who raised me with a love of socializing, and to my mother, for her continued support throughout my life. To my loving wife, Heba, and my two amazing brothers and three wonderful sisters, who have been a constant source of inspiration—thank you.

The work performed in this thesis was funded by ELLIIT - Excellence Center at Linköping-Lund on Information Technology.

Abdelazim G. Hussien
Linköping, Sweden
January 28, 2025

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Part I

Introduction

1 Introduction

The central aim of optimization is to determine the most effective solution from a range of feasible alternatives. It is an essential tool for making decisions and analyzing physical systems. An optimization procedure involves identifying the optimal values for specific system attributes to minimize costs and complete the system design. To achieve this, a problem can be transformed into a mathematical model that includes a fitness function and defines whether the goal is to minimize or maximize, accompanied by a set of constraints. The variables related to the problem are essential for determining the optimal objective among the different available resources. The literature classifies optimization problems in various ways, including constrained versus unconstrained optimization, discrete versus continuous optimization, and single versus multi-objective optimization, as well as deterministic versus stochastic optimization [1]. Unconstrained optimization problems have no restrictions, whereas constrained optimization problems are subject to specific limitations. Continuous optimization problems involve variables that can take on any value, while discrete optimization problems are defined by variables that take on distinct, individual values. Alternatively, optimization problems with a single objective are referred to as single-objective problems, whereas those with multiple objectives are known as many-objective problems. Stochastic optimization involves incorporating randomness either in the objective function or throughout the optimization process [2, 3].

These optimization problems, whether single or many-objective, deterministic or stochastic, have a wide range of applications. For instance, optimization plays a significant role in areas such as economics [4], feature selection [5, 6], pattern recognition [7], Cheminformatics [8], signal processing, deep learning [9], photovoltaic models [10, 11], cloud computing [12], and industrial engineering problems [13, 14].

Generally speaking, optimization techniques are divided into two main categories: exact methods and metaheuristic techniques. The first category includes algorithms like Newton's method and gradient descent, which systematically search the solution space to identify the optimal result. While these methods are straightforward and effective for smaller problems, they become inefficient when applied to complex or high-dimensional problems due to their high computational cost and the fact that they provide only one solution at a time in each iteration [15].

In contrast, metaheuristic algorithms do not guarantee finding the absolute optimal solution but aim to find near-optimal solutions within a reasonable time frame. These methods balance exploration and exploitation of the solution space, making them more suitable for large-scale, real-world applications where exact methods struggle to perform efficiently [16].

One of the most challenging aspects of modern engineering lies in addressing real-world engineering problems, which often involve highly complex designs and require innovative, efficient solutions. These problems are characterized by multiple constraints, non-linear relationships, and large-scale variables, making traditional optimization methods insufficient. To overcome these challenges, researchers have increasingly turned to metaheuristic algorithms. These techniques offer a powerful means of navigating the complex solution spaces of engineering problems, enabling the discovery of near-optimal solutions where conventional approaches struggle [17].

Although metaheuristic techniques are highly effective for solving real-world engineering problems, they are not without challenges. One significant issue is premature convergence, where the algorithm becomes trapped in local optima, limiting its ability to explore the solution space fully. Additionally, some metaheuristics can struggle with search efficiency, leading to incomplete or suboptimal solutions.

The No Free Lunch (NFL) theorem [18] reinforces this limitation by stating that no single algorithm can excel across all problem types. The performance of any algorithm is heavily influenced by the specific characteristics of the problem it is applied to. This insight has driven researchers to develop novel strategies and refine existing algorithms to overcome these limitations, particularly in areas like task scheduling and complex engineering design. Such innovations aim to enhance the adaptability and effectiveness of metaheuristics for diverse real-world applications.

Optimization is the rule of selecting the best design variables to find maximum/minimum values for a specific problem [19, 20]. Optimization approaches examine the search space to find the best optimal/near-optimal results for the given task [21, 22, 23, 24].

Metaheuristic algorithms have gained great attention, and a big interest due to their simplicity and powerfulness in solving optimization tasks, especially complex ones. Metaheuristic algorithms can be divided into two big classes: single-based algorithms and population-based algorithms. The former class contains algorithms like Simulated Annealing (SA) [25], Tabu Search (TS) [26], β-hill Climbing [27] whereas the latter class contains algorithms like Grey Wolf Optimization (GWO) [28], Particle Swarm Optimization (PSO) [29], Salp Swarm Algorithm (SSA) [30, 31], Gravitational Search Algorithm [32], Moth-flame Optimization (MFO) [33], Virus Colony Search (VCS) [34], Crow search algorithm (CSA) [35], Snake Optimizer (SO) [36], Lightning search algorithm (LSA) [37], Ant Lion Optimization (ALO) [38], Harris Hawks Optimization (HHO) [39], and Whale Optimizer Algorithm (WOA) [40, 41].

1.1 Motivation

Real-world engineering problems are becoming more complex and challenging and they require new advanced methods and tools to tackle them.

Modeling, simulation, verification and optimization of Cyber-Physical Systems require both massive and efficient use of computing resources and nowadays the trend is to migrate these tools to cloud-computing.

Cloud computing (CC) is the most recent computing paradigm, offering users seamless, ubiquitous, and cost-effective access to resources for bag-of-tasks (BTA) applications on demand, via the Infrastructure as a Service (IaaS) model [42][43]. Various resources, such as CPU, memory, and storage, can be leased to users, typically in the form of different types of virtual machines. With their powerful computing capabilities, cloud computing infrastructures have been widely utilized to address scheduling problems for bag-of-tasks (BTA) and workflow applications in real-world fields like engineering, chemistry, transportation, physics, astronomy, and biology, among others [44].
Task scheduling (TS), or the assignment problem in cloud computing systems, involves allocating appropriate resources, such as virtual machines (VMs), to competing user applications. The goal is to optimize scheduler performance based on various objectives, including minimizing makespan, improving energy efficiency, reducing execution costs, and maximizing resource utilization [45][46].

Metaheuristic algorithms have been successfully applied to many domains (fields) [47, 48]. Examples of such fields include feature selection [49, 50], cloud computing [51], ransomware detection [52], text mining [53], deep learning [54], signal processing [55], photovoltaic models [11], medical applications [56], and engineering problems [57, 58].

1.2 Problem Formulation

The task scheduling problem (TSP) being an NP-hard problem is one of the core issues that pose a great challenge and motivation to researchers to develop efficient schedulers [59]. Solutions to TSP are categorized into Deterministic algorithms (DA) and Approximation algorithms (AA) [60]. DAs are easily stuck in local optima and are found suitable for only small-scale TSP problems. With the increase in problem size, it becomes infeasible to find DA-based scheduling solutions in a reasonable time. Examples of DAs are mathematical programming, exact solutions, etc. On the contrary, AA methods such as metaheuristic algorithms (MAs) are widely utilized for finding acceptable solutions to complex TSP problems in a reasonable time while optimizing more than one objective at a time. Other reasons for the wide use of AAs are their search efficiency, easy implementation, problem independence, and gradient-free mechanism.

On the other hand, while solving complex engineering problems, metaheuristics (MHs) may have drawbacks such as slow convergence and being trapped in local search domains, resulting in higher computational costs [61]. To address these limitations, researchers have devised hybridized, modified, and enhanced MHs that incorporate more beneficial attributes. A few examples include the hybrid grey wolf and crow search [62], hybrid heat transfer and passing vehicle search [63], hybrid artificial hummingbird-simulated annealing [64], modified symbiotic organisms search [65], modified marine predator algorithm [66], improved ant colony optimization [67] and improved salp swarm algorithm [68]. To create effective MHs, a balance between global diversification and local intensification is crucial. Both exploration and exploitation phases are important in finding superior solutions and achieving results in the least amount of time. Despite numerous hybrid MHs being implemented in engineering design optimization over the last few centuries, the quest for even more potent methods is ongoing. This field continues to evolve and presents new challenges for researchers to address.

1.3 Thesis Outline

Chapter 2 provides foundational insights on optimization classification, engineering problems, and task scheduling problems. Chapter 3 reviews research conducted prior to this thesis, highlighting key questions that guided our work, and a technical overview of the three included publications (Papers I-III).We then conclude the chapter by summarizing our findings in the conclusion section, followed by a discussion of future work directions in the subsequent section. The thesis ends with copies of the three papers detailing our contributions.

2 Background

2.1 Classification of Metaheurstics

Numerous metaheuristic algorithms, each inspired by different sources, have been developed and effectively applied across various fields. These algorithms are generally categorized into four main groups: evolution-inspired methods, physics-inspired methods, swarm-inspired methods, and human-based methods.

- **Evolution-inspired methods** inspired by biological processes, utilize a stochastic, population-based approach. In evolutionary algorithms, an initial random population evolves over generations to generate new solutions through reproduction, mutation, crossover, chemotaxis, and migration, while the least fit solutions are eliminated to improve overall fitness values. Preserving the diversity of the population is essential for the sustainable development of these algorithms.
- **Physics-inspired methods** are inspired by the principles that govern natural phenomena.
- **Swarm-inspired methods** draw inspiration from the behaviors of social insects, school of fish, and herd of animals, representing nature-based algorithms. In swarm intelligence, each individual possesses its own intelligence and behavior; however, their collective integration enhances their ability to tackle complex problems.
- **Human-based methods** are inspired by human beings, with each individual participating in physical activities that impact their performance, alongside non-physical activities such as thinking and behavior that influence their mental processes.

2.2 Some Recent developed algorithms

In this section, we name some of the recent developed algorithms which we have chosen them as a base of our work in this thesis:

- ErWCA [69] is an enhanced version of the Water Cycle Algorithm (WCA) [70] that adds the concept of the evaporation rate of rivers and streams to the original WCA framework.
- The Artificial Electric Field Algorithm (AEFA) is a physics-based algorithm that is a novel introduction by Anita and Yadav [71], inspired by the electrostatic forces outlined by Coulomb's law.
- The Gorilla Troops Optimizer (GTO) [72] is a metaheuristic optimizer inspired by swarm intelligence that emulates the intelligent social behaviors of gorillas in their natural environment.
- HBA is a metaheuristic algorithm introduced by Hashim et al. [23] that belongs to the swarm-inspired category. It mimics the foraging behavior of honey badgers, which use two strategies to locate food: they rely on their sense of smell to find food sources and then dig to catch prey, or they follow honey-guide birds to directly find beehives.

3 Research Overview

This chapter contains the following sub-headings.

3.1 Research Questions

Our main objective is to propose and develop novel approaches and algorithmic variants, applying them to solve a range of NP-hard problems. These advancements aim to enhance the efficiency and accuracy of solving complex optimization challenges, particularly within the realms of engineering and cloud computing. We formulate the following research question:

1. What novel strategies can be developed to mitigate premature convergence in metaheuristic algorithms when applied to complex engineering problems?
2. How can hybrid metaheuristic techniques be designed to balance exploration and exploitation in optimization problems, specifically for task scheduling in cloud computing environments?

3.2 Contributions

The work presented in this thesis is based on the publications listed below.
For each paper, we summarize the contribution of each author and we use the author (I) to refer to the author of this thesis (Abdelazim Hussien)

[73] **Abdelazim G. Hussien**, Fatma A. Hashim, Raneem Qaddoura, Laith Abualigah and Adrian Pop (2022). **An enhanced evaporation rate water-cycle algorithm for global optimization**. Processes, 10(11), 2254.

- The paper was planned to be submitted to Conference but we miss the deadline. So we extend it to a journal paper. The author carried out the implementation, testing, development, and validation of the developed approach. Fatma A. Hashim suggested the optimizer. Raneem Qaddoura and Laith Abualigah help in writing. Adrian Pop help in Conceptualization, visualization, investigation, validation. He also supervise the work and revise the paper

[74] **Abdelazim G Hussien**, Adrian Pop, Sumit Kumar, Fatma A Hashim, and Gang Hu. **A Novel Artificial Electric Field Algorithm for Solving Global Optimization and Real-World Engineering Problems.** In: Biomimetics 9.3 (2024), p. 186.

- The author together with Sumit Kumar tried to work in the Artificial Electric Field Algorithm to develop an enhanced version of it. Fatma A. Hashim helped to make the algorithm better. After that the author test the algorithm using CEC and real-world industrial problems. Adrian help in conceptualization, investigation, writing, and addressing the reviewers comments besides supervision and validation

[75] **Abdelazim G Hussien**, Amit Chhabra, Fatma A Hashim, and Adrian Pop. **A novel hybrid Artificial Gorilla Troops Optimizer with Honey Badger Algorithm for solving cloud scheduling problem**. In: Cluster Computing (2024), pp. 1–36.

- The author tried to hybridized Artificial Gorilla Troops Optimizer (GTO) with Honey Badger Algorithm (HBA). Fatma A. Hashim helped to make the algorithm better. Amit helped me doing the experiments results and formulating the problem in cloud concept. Adrian help in guiding me, supervising, writing the original draft and replying to reviewers.

3.3 Conclusions

The developed algorithm EErWCA which replace the original exploitation phase in ErWCA with slime mould algorithm (SMA) and embedded local escape operator escaping from local optima that has been tested using 29 functions from the CEC 2017 and 3 enginnering problem. The statistical analysis and experimental results prove the superiority of the EErWCA algorithm. The mAEFA approach is created by integrating the original AEFA algorithm with Lévy flights, simulated annealing, and mechanisms such as Adaptive s-best Mutation and the Natural Survivor Method (NSM). The statistical analysis and experimental results prove the superiority of the mAEFA algorithm.
The GTOHBA approach effectively addresses the cloud task scheduling problem by minimizing makespan and energy consumption through the hybridization of GTO and HBA algorithms. Experimental results demonstrated that GTOHBA outperformed classical metaheuristics and achieved superior performance in simulations using CloudSim. However, its limitations, as indicated by the No Free Lunch theory, highlight the need for further testing across diverse problem domains. Future research will focus on expanding the approach to include additional objectives and exploring hybridizations with other swarm intelligence algorithms.

3.4 Future Work

In the future, we intend to evaluate our proposed approach by integrating additional objectives into the cloud task scheduling model, utilizing workflow workloads alongside Bag-of-Tasks applications. Additionally, we aim to develop more hybrid metaheuristics by combining GTO with other swarm intelligence algorithms to address both the cloud scheduling problem and other NP-Hard challenges.

Also, in the future, we plan to enhance the ParModAuto automatic parallelization library by incorporating metaheuristic optimizations, specifically focusing on swarm intelligence and biologically inspired techniques, to further improve simulation execution speed. Additionally, we will evaluate the impact of matching and tearing choices on the parallelization opportunities within the resulting task graph.

Additionally, we intend to integrate all these metaheuristic algorithms and benchmark functions (CEC'05, CEC'14, CEC'17, CEC'20, CEC'22) into a comprehensive open-source package developed in Julia, a recent high-performance programming language. This package will be designed to be seamlessly used for optimization from Modelica compilers or any other tools, enhancing usability and performance.

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