

A. Kaveh

Advances in Metaheuristic Algorithms for Optimal Design of Structures



Springer

A. Kaveh

Advances in Metaheuristic Algorithms for Optimal Design of Structures



Springer

A. Kaveh
School of Civil Engineering, Centre of Excellence
for Fundamental Studies in Structural Engineering
Iran University of Science and Technology
Tehran, Iran

ISBN 978-3-319-05548-0 ISBN 978-3-319-05549-7 (eBook)
DOI 10.1007/978-3-319-05549-7
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2014937527

© Springer International Publishing Switzerland 2014

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed. Exempted from this legal reservation are brief excerpts in connection with reviews or scholarly analysis or material supplied specifically for the purpose of being entered and executed on a computer system, for exclusive use by the purchaser of the work. Duplication of this publication or parts thereof is permitted only under the provisions of the Copyright Law of the Publisher's location, in its current version, and permission for use must always be obtained from Springer. Permissions for use may be obtained through RightsLink at the Copyright Clearance Center. Violations are liable to prosecution under the respective Copyright Law.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

While the advice and information in this book are believed to be true and accurate at the date of publication, neither the authors nor the editors nor the publisher can accept any legal responsibility for any errors or omissions that may be made. The publisher makes no warranty, express or implied, with respect to the material contained herein.

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

Recent advances in structural technology require greater accuracy, efficiency, and speed in design of structural systems. It is therefore not surprising that new methods have been developed for optimal design of real-life structures and models with complex configurations and a large number of elements.

This book can be considered as an application of metaheuristic algorithms to optimal design of skeletal structures. The present book is addressed to those scientists and engineers, and their students, who wish to explore the potential of newly developed metaheuristics. The concepts presented in this book are not only applicable to skeletal structures and finite element models but can equally be used for design of other systems such as hydraulic and electrical networks.

The author and his graduate students have been involved in various developments and applications of different metaheuristic algorithms to structural optimization in the last two decades. This book contains part of this research suitable for various aspects of optimization for skeletal structures.

This book is likely to be of interest to civil, mechanical, and electrical engineers who use optimization methods for design, as well as to those students and researchers in structural optimization who will find it to be necessary professional reading.

In Chap. 1, a short introduction is provided for the development of optimization and different metaheuristic algorithms. Chapter 2 contains one of the most popular metaheuristic known as the Particle Swarm Optimization (PSO). Chapter 3 provides an efficient metaheuristic algorithm known as Charged System Search (CSS). This algorithm has found many applications in different fields of civil engineering. In Chap. 4, Magnetic Charged System Search (MCSS) is presented. This algorithm can be considered as an improvement to CSS, where the physical scenario of electrical and magnetic forces is completed. Chapter 5 contains a generalized metaheuristic so-called Field of Forces Optimization (FFO) approach and its applications. Chapter 6 presents the recently developed algorithm known as Dolphin Echolocation Optimization (DEO) mimicking the behavior of dolphins. Chapter 7 contains a powerful parameter independent algorithm, called Colliding Bodies Optimization (CBO). This algorithm is based on one-dimensional collisions

between bodies, with each agent solution being considered as the massed object or body. After a collision of two moving bodies having specified masses and velocities, these bodies are separated with new velocities. This collision causes the agents to move toward better positions in the search space. In Chap. 8, Ray Optimization Algorithm (ROA) is presented in which agents of the optimization are considered as rays of light. Based on the Snell's light refraction law when light travels from a lighter medium to a darker medium, it refracts and its direction changes. This behavior helps the agents to explore the search space in early stages of the optimization process and to make them converge in the final stages. In Chap. 9, the well-known Big Bang-Big Crunch (BB-BC) algorithm is improved (MBB-BC) and applied to structural optimization. Chapter 10 contains application of Cuckoo Search Optimization (CSO) in optimal design of skeletal structures. In Chap. 11, Imperialist Competitive Algorithm (ICA) and its application are discussed. Chaos theory has found many applications in engineering and optimal design. Chapter 12 presents Chaos Embedded Metaheuristic (CEM) Algorithms. Finally, Chap. 13 can be considered as a brief introduction to multi-objective optimization. In this chapter a multi-objective optimization algorithm is presented and applied to optimal design of large-scale skeletal structures.

I would like to take this opportunity to acknowledge a deep sense of gratitude to a number of colleagues and friends who in different ways have helped in the preparation of this book. Professor F. Ziegler encouraged and supported me to write this book. My special thanks are due to Mrs. Silvia Schilgerius, the senior editor of the Applied Sciences of Springer, for her constructive comments, editing, and unfailing kindness in the course of the preparation of this book. My sincere appreciation is extended to our Springer colleagues Ms. Beate Siek and Ms. Sashivadhana Shivakumar.

I would like to thank my former and present Ph.D. and M.Sc. students, Dr. S. Talatahari, Dr. K. Laknejadi, Mr. V.R. Mahdavi, Mr. A. Zolghadr, Mrs. N. Farhoudi, Mr. S. Massoudi, Mr. M. Khayatazad, Mr. M. Ilchi, Mr. R. Sheikholeslami, Mr. T. Bakhshpour, and Mr. M. Kalate Ahani, for using our joint papers and for their help in various stages of writing this book. I would like to thank the publishers who permitted some of our papers to be utilized in the preparation of this book, consisting of Springer Verlag, Elsevier and Wiley.

My warmest gratitude is due to my family and in particular my wife, Mrs. L. Kaveh, for her continued support in the course of preparing this book.

Every effort has been made to render the book error free. However, the author would appreciate any remaining errors being brought to his attention through his email address: alikhavah@iust.ac.ir.

Tehran, Iran
February 2014

A. Kaveh

Contents

1	Introduction	1
1.1	Metaheuristic Algorithms for Optimization	1
1.2	Optimal Design of Structures and Goals of the Present Book	2
1.3	Organization of the Present Book	3
	References	8
2	Particle Swarm Optimization	9
2.1	Introduction	9
2.2	PSO Algorithm	10
2.2.1	Development	10
2.2.2	PSO Algorithm	12
2.2.3	Parameters	13
2.2.4	Premature Convergence	16
2.2.5	Topology	17
2.2.6	Biases	18
2.3	Hybrid Algorithms	19
2.4	Discrete PSO	21
2.5	Democratic PSO for Structural Optimization	21
2.5.1	Description of the Democratic PSO	21
2.5.2	Truss Layout and Size Optimization with Frequency Constraints	23
2.5.3	Numerical Examples	25
	References	37
3	Charged System Search Algorithm	41
3.1	Introduction	41
3.2	Charged System Search	41
3.2.1	Background	41
3.2.2	Presentation of Charged Search System	45
3.3	Validation of CSS	52
3.3.1	Description of the Examples	52
3.3.2	Results	53

3.4	Charged System Search for Structural Optimization	60
3.4.1	Statement of the Optimization Design Problem	60
3.4.2	CSS Algorithm-Based Structural Optimization Procedure	66
3.5	Numerical Examples	68
3.5.1	A Benchmark Truss	68
3.5.2	A 120-Bar Dome Truss	72
3.5.3	A 26-Story Tower Space Truss	73
3.5.4	An Unbraced Space Frame	77
3.5.5	A Braced Space Frame	81
3.6	Discussion	82
3.6.1	Efficiency of the CSS Rules	82
3.6.2	Comparison of the PSO and CSS	84
3.6.3	Efficiency of the CSS	85
	References	85
4	Magnetic Charged System Search	87
4.1	Introduction	87
4.2	Magnetic Charged System Search Method	87
4.2.1	Magnetic Laws	88
4.2.2	A Brief Introduction to Charged System Search Algorithm	90
4.2.3	Magnetic Charged System Search Algorithm	92
4.2.4	Numerical Examples	98
4.2.5	Engineering Examples	109
4.3	Improved Magnetic Charged System Search	116
4.3.1	A Discrete IMCSS	117
4.3.2	An Improved Magnetic Charged System Search for Optimization of Truss Structures with Continuous and Discrete Variables	117
	References	132
5	Field of Forces Optimization	135
5.1	Introduction	135
5.2	Formulation of the Configuration Optimization Problems	136
5.3	Fundamental Concepts of the Fields of Forces	136
5.4	Necessary Definitions for a FOF-Based Model	138
5.5	A FOF-Based General Method	139
5.6	An Enhanced Charged System Search Algorithm for Configuration Optimization	140
5.6.1	Review of the Charged System Search Algorithm	140
5.6.2	An Enhanced Charged System Search Algorithm	142
5.7	Design Examples	143
5.7.1	An 18-Bar Planar Truss	143
5.8	Discussion	153
	References	154

6	Dolphin Echolocation Optimization	157
6.1	Introduction	157
6.2	Dolphin Echolocation in Nature	157
6.3	Dolphin Echolocation Optimization	158
6.3.1	Introduction to Dolphin Echolocation	158
6.3.2	Dolphin Echolocation Algorithm	159
6.4	Structural Optimization	169
6.5	Numerical Examples	170
6.5.1	Truss Structures	170
6.5.2	Frame Structures	180
	References	192
7	Colliding Bodies Optimization	195
7.1	Introduction	195
7.2	Colliding Bodies Optimization	195
7.2.1	The Collision Between Two Bodies	196
7.2.2	The CBO Algorithm	197
7.2.3	Test Problems and Optimization Results	202
7.3	CBO for Optimum Design of Truss Structures with Continuous Variables	214
7.3.1	Flowchart and CBO Algorithm	214
7.3.2	Numerical Examples	217
7.3.3	Discussion	225
	References	230
8	Ray Optimization Algorithm	233
8.1	Introduction	233
8.2	Ray Optimization for Continuous Variables	234
8.2.1	Definitions and Concepts from Ray Theory	234
8.2.2	Ray Optimization Method	238
8.2.3	Validation of the Ray Optimization	243
8.3	Ray Optimization for Size and Shape Optimization of Truss Structures	251
8.3.1	Formulation	251
8.3.2	Design Examples	253
8.4	An Improved Ray Optimization Algorithm for Design of Truss Structures	262
8.4.1	Introduction	262
8.4.2	Improved Ray Optimization Algorithm	263
8.4.3	Mathematical and Structural Design Examples	266
	References	275
9	Modified Big Bang–Big Crunch Algorithm	277
9.1	Introduction	277
9.2	Modified BB-BC Method	277
9.2.1	Introduction to BB-BC Method	277
9.2.2	A Modified BB-BC Algorithm	280

9.3	Size Optimization of Space Trusses Using a MBB–BC Algorithm	283
9.3.1	Formulation	283
9.3.2	Design Examples	284
9.4	Optimal Design of Schwedler and Ribbed Domes Using MBB–BC Algorithm	297
9.4.1	Introduction	297
9.4.2	Dome Structure Optimization Problems	299
9.4.3	Pseudo-Code of the Modified Big Bang–Big Crunch Algorithm	302
9.4.4	Elastic Critical Load Analysis of Spatial Structures	304
9.4.5	Configuration of Schwedler and Ribbed Domes	304
9.4.6	Results and Discussion	308
9.4.7	Discussion	312
	References	314
10	Cuckoo Search Optimization	317
10.1	Introduction	317
10.2	Optimum Design of Truss Structures Using Cuckoo Search Algorithm with Lévy Flights	318
10.2.1	Formulation	318
10.2.2	Lévy Flights as Random Walks	319
10.2.3	Cuckoo Search Algorithm	320
10.2.4	Optimum Design of Truss Structures Using Cuckoo Search Algorithm	322
10.2.5	Design Examples	324
10.2.6	Discussions	332
10.3	Optimum Design of Steel Frames	334
10.3.1	Optimum Design of Planar Frames	335
10.3.2	Optimum Design of Steel Frames Using Cuckoo Search Algorithm	337
10.3.3	Design Examples	337
10.3.4	Discussions	343
	References	346
11	Imperialist Competitive Algorithm	349
11.1	Introduction	349
11.2	Optimum Design of Skeletal Structures	350
11.2.1	Constraint Conditions for Truss Structures	351
11.2.2	Constraint Conditions for Steel Frames	351
11.3	Imperialist Competitive Algorithm	353
11.4	Design Examples	357
11.4.1	Design of a 120-Bar Dome Shaped Truss	357
11.4.2	Design of a 72-Bar Spatial Truss	359

11.4.3	Design of a 3-Bay, 15-Story Frame	360
11.4.4	Design of a 3-Bay 24-Story Frame	362
11.5	Discussions	366
	References	368
12	Chaos Embedded Metaheuristic Algorithms	369
12.1	Introduction	369
12.2	An Overview of Chaotic Systems	370
12.2.1	Logistic Map	373
12.2.2	Tent Map	373
12.2.3	Sinusoidal Map	373
12.2.4	Gauss Map	373
12.2.5	Circle Map	374
12.2.6	Sinus Map	374
12.2.7	Henon Map	374
12.2.8	Ikeda Map	374
12.2.9	Zaslavskii Map	375
12.3	Use of Chaotic Systems in Metaheuristics	375
12.4	Chaotic Update of Internal Parameters for Metaheuristics	376
12.5	Chaotic Search Strategy in Metaheuristics	379
12.6	A New Combination of Metaheuristics and Chaos Theory	381
12.6.1	The Standard PSO	381
12.6.2	The CPVPSO Phase	383
12.6.3	The CLSPSO Phase	383
12.6.4	Design Examples	384
12.7	Discussion	388
	References	390
13	A Multi-swarm Multi-objective Optimization Method for Structural Design	393
13.1	Introduction	393
13.2	Preliminaries	395
13.3	Background	396
13.3.1	Charged System Search	397
13.3.2	Clustering	398
13.4	MO-MSCSS	399
13.4.1	Algorithm Overview	400
13.4.2	Search Process by CSS Algorithm	401
13.4.3	Charge Magnitude of Particles	403
13.4.4	Population Regeneration	404
13.4.5	Mutation Operator	405
13.4.6	Global Archive Updating Process	406
13.4.7	Constraint Handling	407
13.5	Structural Optimization	407
13.5.1	Statement of the Considered Optimization Design Problem	407

13.6	Numerical Examples	409
13.6.1	Unconstrained Multi-objective Problems	409
13.6.2	Constrained Multi-objective Problems	416
13.7	Discussions	423
	References	425

Chapter 1

Introduction

1.1 Metaheuristic Algorithms for Optimization

In today's extremely competitive world, human beings attempt to exploit the maximum output or profit from a limited amount of available resources. In engineering design, for example, choosing design variables that fulfill all design requirements and have the lowest possible cost is concerned, i.e. the main objective is to comply with basic standards but also to achieve good economic results. Optimization offers a technique for solving this type of problems.

The term "optimization" refers to the study of problems in which one seeks to minimize or maximize a function by systematically choosing the values of variables from/within a permissible set. In one hand, a vast amount of research has been conducted in this area of knowledge, hoping to develop effective and efficient optimization algorithms. On the other hand, the application of the existing algorithms to real projects has been the focus of many studies.

In the past, the most commonly used optimization techniques were gradient-based algorithms which utilized gradient information to search the solution space near an initial starting point [1, 2]. In general, gradient-based methods converge faster and can obtain solutions with higher accuracy compared to stochastic approaches. However, the acquisition of gradient information can be either costly or even impossible to obtain the minima. Moreover, this kind of algorithms is only guaranteed to converge to local optima. Furthermore, a good starting point is quite vital for a successful execution of these methods. In many optimization problems, prohibited zones, side limits and non-smooth or non-convex functions should be taken into consideration. As a result, these non-convex optimization problems cannot easily be solved by these methods.

On the other hand other types of optimization methods, known as metaheuristic algorithms, are not restricted in the aforementioned manner. These methods are suitable for global search due to their capability of exploring and finding promising regions in the search space at an affordable computational time. Metaheuristic algorithms tend to perform well for most of the optimization problems [3, 4].

This is because these methods refrain from simplifying or making assumptions about the original problem. Evidence of this is their successful applications to a vast variety of fields, such as engineering, physics, chemistry, art, economics, marketing, genetics, operations research, robotics, social sciences, and politics.

The word *heuristic* has its origin in the old Greek work *heuriskein*, which means the art of discovering new strategies (rules) to solve problems. The suffix *meta*, also is a Greek word, means “upper level methodology”. The term *metaheuristic* was introduced by F. Glover in the paper [5].

A heuristic method can be considered as a procedure that is likely to discover a very good feasible solution, but not necessarily an optimal solution, for a considered specific problem. No guarantee can be provided about the quality of the solution obtained, but a well-designed heuristic method usually can provide a solution that is at least nearly optimal. The procedure also should be sufficiently efficient to deal with very large problems. The heuristic methods are often considered as *iterative algorithm*, where each iteration involves conducting a search for a new solution that might be better than the best solution found previously. After a reasonable time when the algorithm is terminated, the solution it provides is the best one that was found during any iteration. A metaheuristic is formally defined as an iterative generation process which guides a subordinate heuristic by combining intelligently different concepts for exploring (global search) and exploiting (local search) the search space, learning strategies are used to structure information in order to find efficiently near-optimal solutions [5–7].

Metaheuristic algorithm has found many applications in different areas of applied mathematics, engineering, medicine, economics and other sciences. These methods are extensively utilized in the design of different systems in civil, mechanical, electrical, and industrial engineering. At the same time, one of the most important trends in optimization is the constantly increasing emphasis on the interdisciplinary nature of the field.

1.2 Optimal Design of Structures and Goals of the Present Book

In the area of structural engineering that is the main concern of this book, one tries to achieve certain objectives in order to optimize weight, construction cost, geometry, layout, topology and time satisfying certain constraints. Since resources, fund and time are always limited, one has to find solutions to optimal usage of these resources.

The main goal of this book is to introduce some well established and the most recently developed metaheuristics for optimal design of structures. Schematic of the chapters of the present book in one glance is shown in Fig. 1.1.

Most of these methods are either nature-based or physics-based algorithms, Fig. 1.2. Though many design examples are included, however, the results may

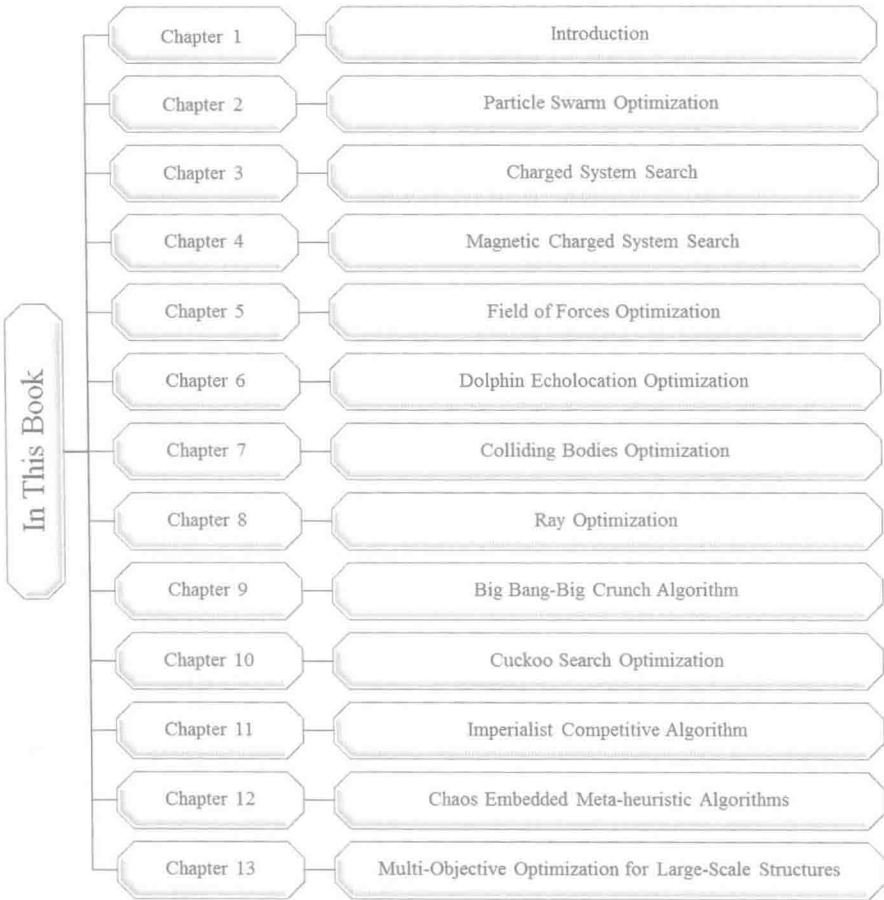


Fig. 1.1 Schematic of the chapters of the present book in one glance

or may not have small constraint violations, and do not constitute the main objective of the book.

1.3 Organization of the Present Book

After this introductory chapter, the remaining chapters of this book are organized in the following manner:

Chapter 2 introduces the well-known Particle Swarm Optimization (PSO) algorithms. These algorithms are nature-inspired population-based metaheuristic algorithms originally accredited to Eberhart, Kennedy and She. The algorithms mimic the social behavior of birds flocking and fishes schooling. Starting with a

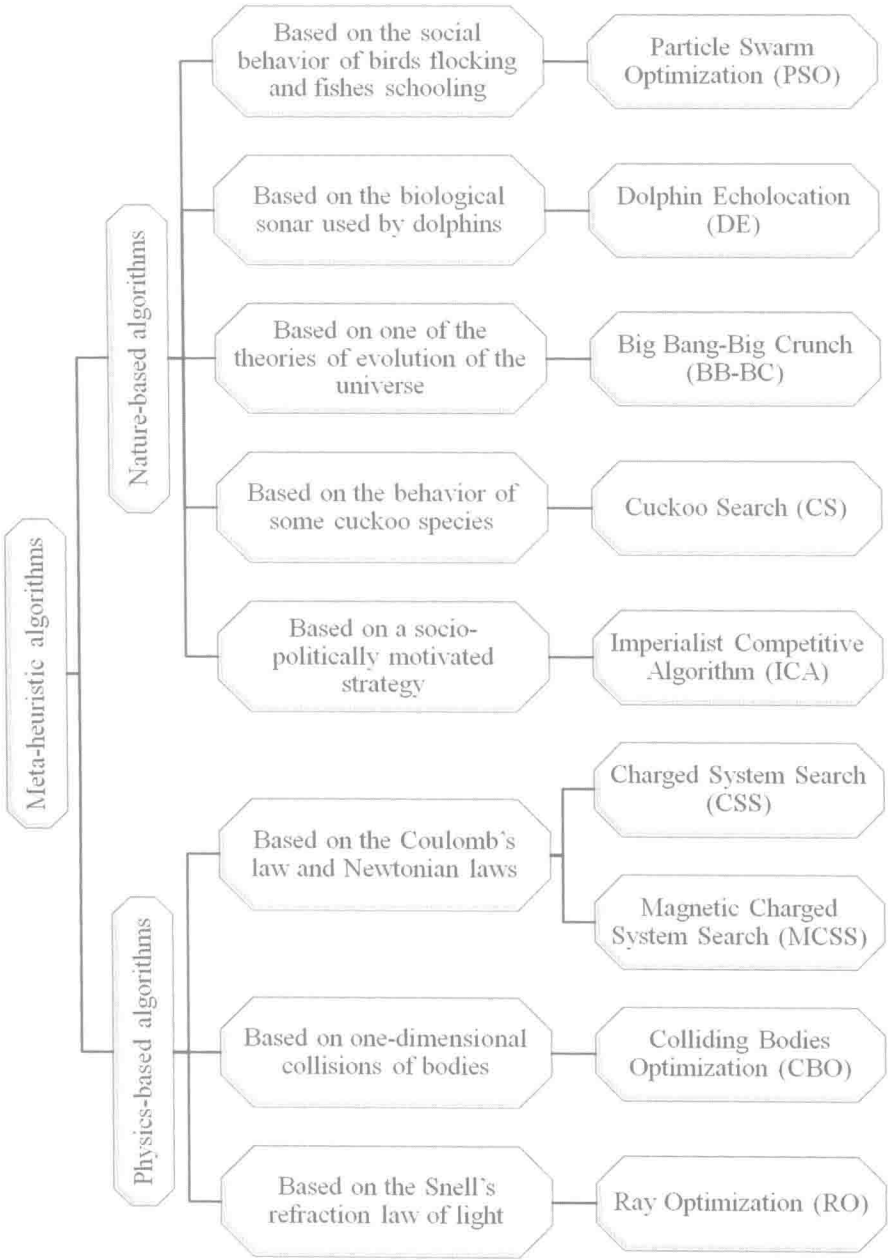


Fig. 1.2 Classification of the metaheuristics presented in this book

randomly distributed set of particles (potential solutions), the algorithms try to improve the solutions according to a quality measure (fitness function). The improvisation is preformed through moving the particles around the search space by means of a set of simple mathematical expressions which model some inter-particle communications. These mathematical expressions, in their simplest and most basic form, suggest the movement of each particle towards its own best experienced position and the swarm's best position so far, along with some random perturbations.

Chapter 3 presents the well established Charged System Search Algorithm (CSS), developed by Kaveh and Talatahari. This chapter consists of two parts. In the first part an optimization algorithm based on some principles from physics and mechanics is introduced. In this algorithm the governing Coulomb law from electrostatics and the Newtonian laws of mechanics are utilized. CSS is a multi-agent approach in which each agent is a Charged Particle (CP). CPs can affect each other based on their fitness values and their separation distances. The quantity of the resultant force is determined by using the electrostatics laws and the quality of the movement is determined using Newtonian mechanics laws. CSS can be utilized in all optimization fields; especially it is suitable for non-smooth or non-convex domains. CSS needs neither the gradient information nor the continuity of the search space. In the second part, CSS is applied to optimal design of skeletal structures and high performance of CSS is illustrated.

Chapter 4 extends the algorithm of the previous chapter and presents the Magnetic Charged System Search, developed by Kaveh, Motie Share and Moslehi. This chapter consists of two parts. In first part, the standard Magnetic Charged System Search (MCSS) is presented and applied to different numerical examples to examine the efficiency of this algorithm. The results are compared to those of the original charged system search method. In the second part, an improved form of the MCSS algorithm, denoted by IMCSS, is presented and also its discrete version is described. The IMCSS algorithm is applied to optimization of truss structures with continuous and discrete variables to demonstrate the performance of this algorithm in the field of structural optimization.

Chapter 5 presents a generalized CSS algorithm known as the Field of Forces Optimization. Although different metaheuristic algorithms have some differences in approaches to determine the optimum solution, however their general performance is approximately the same. They start the optimization with random solutions; and the subsequent solutions are based on randomization and some other rules. With the progress of the optimization process, the power of rules increases, and the power of randomization decreases. It seems that these rules can be modelled by a familiar concept of physics known as the *fields of forces* (FOF). FOF is a concept which is utilized in physics to explain the reason of the operation of the universe. The virtual FOF model is approximately simulated by using the concepts of real world fields such as gravitational, magnetic or electric fields.

Chapter 6 presents the recently developed algorithm known as Dolphin Echolocation Optimization, proposed by Kaveh and Farhodi. Nature has provided inspiration for most of the man-made technologies. Scientists believe that dolphins are the second to human beings in smartness and intelligence. Echolocation is the

biological sonar used by dolphins and several kinds of other animals for navigation and hunting in various environments. This ability of dolphins is mimicked in this chapter to develop a new optimization method. There are different metaheuristic optimization methods, but in most of these algorithms parameter tuning takes a considerable time of the user, persuading the scientists to develop ideas to improve these methods. Studies have shown that metaheuristic algorithms have certain governing rules and knowing these rules helps to get better results. Dolphin Echolocation takes advantages of these rules and outperforms some of the existing optimization methods, while it has few parameters to be set. The new approach leads to excellent results with low computational efforts.

Chapter 7 contains the most recently developed algorithm so-called Colliding Bodies Optimization proposed by Kaveh and Mahdavi. This chapter presents a novel efficient metaheuristic optimization algorithm called Colliding Bodies Optimization (CBO), for optimization. This algorithm is based on one-dimensional collisions between bodies, with each agent solution being considered as the massed object or body. After a collision of two moving bodies having specified masses and velocities, these bodies are separated with new velocities. This collision causes the agents to move toward better positions in the search space. CBO utilizes simple formulation to find minimum or maximum of functions; also it is internally parameter independent.

Chapter 8 presents the Ray Optimization (RO) Algorithm originally developed by Kaveh and Khayat Azad. Similar to other multi-agent methods, Ray Optimization has a number of particles consisting of the variables of the problem. These agents are considered as rays of light. Based on the Snell's light refraction law when light travels from a lighter medium to a darker medium, it refracts and its direction changes. This behaviour helps the agents to explore the search space in early stages of the optimization process and to make them converge in the final stages. This law is the main tool of the Ray Optimization algorithm. This chapter consists of three parts. In first part, the standard Ray optimization is presented and applied to different mathematical functions and engineering problems. In the second part, RO is employed for size and shape optimization of truss structures. Finally in the third part, an improved ray optimization (IRO) algorithm is introduced and applied to some benchmark mathematical optimization problems and truss structure examples.

Chapter 9 presents a modified Big Bang-Big Crunch (BB-BC) Algorithm. The standard BB-BC method is developed by Erol and Eksin, and consists of two phases: a Big Bang phase, and a Big Crunch phase. In the Big Bang phase, candidate solutions are randomly distributed over the search space. Similar to other evolutionary algorithms, initial solutions are spread all over the search space in a uniform manner in the first Big Bang. Erol and Eksin associated the random nature of the Big Bang to energy dissipation or the transformation from an ordered state (a convergent solution) to a disorder or chaos state (new set of solution candidates).

Chapter 10 presents the Cuckoo Search (CS) Optimization developed by Yang and colleagues. In this chapter CS is utilized to determine optimum design of