Classification of Network Optimization Software Packages

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Abstract

Network optimization models and algorithms constitute a core research area of Mathematical Optimization and Computing. We present a wide range of state-of-the-art network optimization software packages and provide up-to-date definitions of the most important issues in algorithm engineering concerning fundamental network optimization problems. Furthermore, we discuss new concepts, trends, and emerging technologies in this research area. Apart from presenting important recent developments in network optimization and their impact on modern organizations and society, the proposed article is a classification of network optimization software packages with a special focus on solvers and benchmark collections. Finally, discussion is made regarding the societal impact and practical managerial significance of network optimization models and software tools.

INTRODUCTION

Combinatorial Optimization is an interdisciplinary branch of Optimization (Migdalas et al., 2013) combining several research fields, e.g., operational research, artificial intelligence, algorithmic theory, and computational complexity theory. The core of combinatorial optimization includes a class of problems that can be modeled using graphs and networks and it is known as Network Optimization (Du & Pardalos, 1993). It is noteworthy that advances in the research area of Network Optimization have a strong impact on supply chain companies (Tseng et al., 2005) and in society in general (Roberts, 1978). Applications of network optimization in supply chain engineering include a large variety not only of classic network location, transportation or routing problems but also combined problems of, e.g., location-routing problems. Also, to mention but a few of the graph theory applications with societal impact, finding an eulerian closed chain meets applications in street-sweeping, RNA chains, etc. Also, applications of graph coloring arise in scheduling committee meetings, planning final examinations schedules in a college, etc.

Nowadays, several network optimization problems such as the classic linear minimum cost network flow problem (Sifaleras, 2013), the transportation problem, or the linear sum assignment problem are easily solvable by polynomial time algorithms. However, a large number of other classic network optimization problems remain intractable (unless P = NP). Problems belonging to this category include the majority of the versions of the well-known Traveling Salesman Problem (TSP), the Vehicle Routing Problem (VRP), several other versions of routing problems, integrated inventory-distribution problems, and network location problems, etc. These problems often require heuristic-based approaches for efficiently solving them in reasonable computational time. For example, a courier service company must reschedule their routes in real time, according to new orders. In such problems, an exact algorithm requiring one hour to compute the optimal solution is usually less useful than an approximation algorithm requiring only a few seconds to find a solution that is 99% sub-optimal.

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BACKGROUND

During the last decades several advances have emerged in the field of network and combinatorial optimization (Cook, 2010). Nowadays, optimization software packages are required for the efficient solution of complex network optimization problems, even of moderate dimensions, due to their computational difficulty. Briefly speaking, an optimization software package is a software package specifically designed to be used for optimization problems. Such network optimization software packages have various differences in their characteristics, technology, and scope (Maros & Khaliq, 2002). The most well-known types of optimization software packages include optimization solvers, problem generators, performance analyzers/profilers, and educational software packages using visualization/animation techniques. An optimization solver is an optimization software package including efficient implementations of optimization algorithms specifically designed for the solution of optimization problems. Furthermore, a network generator is an optimization software package designed for random generating instances of network optimization problems with specific structure and dimension. Moreover, modern performance analyzer/profilers are now available to analyze the efficiency of the source code of an optimization algorithm, identify the bottlenecks in its performance, and suggest ways of computational improvements.

Benchmark collections for mathematical programming problems are also very important for comparing the computational efficiency of network optimization solvers. Roughly speaking, a benchmark collection constitutes a set of computationally difficult problems, either from real-world applications (e.g., real data from railway networks for robust train timetabling problems) or randomly generated. Such sets of benchmark problem instances allow researchers to compare the efficiency of their optimization solvers in common, usually publicly available, problem sets.

Apart from these main types of network optimization software packages, there are also other more general software solutions such as Decision Support Systems (DSS). In this case, network optimization models are usually embedded as components of DSSs, for assisting the decision making process in network-related problems of a business company. Typical examples of this category include DSSs that are used in supply chain design for producing optimal transportation plans that minimize total cost and satisfy service constraints, or optimizing products flow either along transportation lanes, or through distribution centers.

NETWORK OPTIMIZATION SOFTWARE PACKAGES

Problem Generators

Several problem generators and benchmark collections have been proposed in the literature for almost any type of network optimization problem. However, in this section, our main focus is the presentation of publicly available network optimization software packages. A repository of source codes for various problem instance generators is maintained by the Zuse Institute Berlin (ZIB) research institute for applied mathematics and computer science and can be found online at http://www.zib.de/en/services/web-services/mp-testdata/generators.html.

Many random network generators exist for producing instances of the Minimum Cost Network Flow Problem (MCNFP). Such generators provide a large variety of choices regarding, for example, one-way or two-way arcs, the total number of nodes (either sink or source nodes), the total number of arcs, and either lower and/or upper bounds of arc capacities and costs. Klingman et al. (1974) presented the NETGEN generator that provides the user with the ability to produce random MCNFP, transportation, and assignment problem instances. Additionally, Arthur and Frendewey (1994) developed the RAND-NET generator, which produces optimal MCNFP instances with custom dimension and structure.

A number of instance generators for the TSP were proposed for the 8th Implementation Challenge organized by the Center for Discrete Math and Theoretical Computer Science (DIMACS). More details regarding the Challenge (e.g., the testbeds of instances and the methods for evaluating tour quality) are described in Johnson and McGeoch (2002). Instance generation codes and samples of randomly generated instances can be freely downloaded from http://www2.research.att.com/~dsj/chtsp/download.html. Also, Cirasella et al. (2001) developed twelve instance generators for the Asymmetric Traveling Salesmen Problem (ATSP) in C. Their paper analytically describes the results of an experimental comparison of modern heuristics for the ATSP.

Furthermore, Almoustafa, Hanafi, and Mladenović (2013) developed a generator used for producing test instances of the asymmetric distance vehicle routing problem. The complete source code of their generator in C++ is publicly available online at http://www.mi.sanu.ac.rs/~nenad/advrp. Moreover, a new generator of Dynamic VRP (DVRP) instances was developed by Khouadjia M.R. in C++ and is also publicly available at http://paradiseo.gforge.inria.fr/index.php?n=Benchmarks.VRPgenerator. This code provides users with the ability to tune the dynamic problem by changing lengths of routes, changing number of vehicles, and movement of the depot, etc. A paper describing the application of the Variable Neighborhood Search (VNS) metaheuristic framework in DVRP instances was recently published (Sarasola, et al., 2011).

Benchmark Collections

A large number of benchmark collections for various types of network optimization problems are nowadays publicly available. Therefore, several authors are reporting computational results using these benchmark collections in order to compare their algorithm implementations. For example, benchmark problems for a wide range of shortest path problems (e.g., k-shortest paths for either static or dynamic problems) are publicly available after the 9th DIMACS Implementation Challenge on Shortest Paths: http://www.dis.uniroma1.it/challenge9.

Furthermore, TSPLIB is the most well-known library of benchmark problems for the TSP. It contains sample instances for different types of the TSP and related optimization problems and can be found online at http://comopt.ifi.uni-heidelberg.de/software/TSPLIB95. TSPLIB is described in Reinelt (1991) and is not intended to include any further problem instances in the future.

Benchmark collections for challenging DVRP instances (Larsen et al., 2002) are available online by Solomon M. at http://w.cba.neu.edu/~msolomon/problems.htm. Other large-scale, real-world VRP instances provided by Raucq J. can be found at http://www.raucq.be. Another online repository of benchmark problems classified according to the different VRP variants is maintained by the NEO research group in Malaga at http://neo.lcc.uma.es/vrp/vrp-instances.

A benchmark library for network (and discrete) location models (Daskin, 1995), maintained by the Sobolev Institute of Mathematics, can be found online at http://math.nsc.ru/AP/benchmarks/english.html. Moreover, challenging combinations of computationally difficult problems, such as the Location Routing Problem (LRP) that combine the VRP and the Facility Location Problem (FLP), have recently appeared in the literature (Nagy & Salhi, 2007). Problem instances for LRPs are available by Barret S. at http://sweet.ua.pt/sbarreto/_private/SergioBarretoHomePage.htm.

OR-Library was described by Beasley J. E. (1990) and consists of a collection of test data sets for a variety of Operations Research (OR) problems, such as the frequency assignment problem and the minimum labeling spanning tree, etc. OR-Library can be accessed from http://people.brunel.ac.uk/~mastjjb/jeb/info.html. Other types of network optimization benchmark problems include the Survivable Network Design Library (SNDlib) for fixed telecommunication network design proposed in Orlowski et al. (2010) and available at http://sndlib.zib.de. The SteinLib library on

Steiner tree problems in graphs has been presented in Koch et al. (2001) and can be found online at http://steinlib.zib.de. Finally, more recent benchmark instances on the Steiner problem in graphs are described in Rosseti et al. (2004).

Optimization Solvers

Needless to say, a large number of commercial state-of-the-art optimization solvers exist for the solution of various types of network optimization problems. Furthermore, open source optimization solvers attract the interest of many OR researchers and gradually become more efficient.

The Computational Infrastructure for Operations Research (COIN) project (Lougee-Heimer, 2003) provides implementations of several network optimization algorithms. To mention but a few, three well-known projects of COIN, regarding network optimization, are the Coin Graph Classes (Cgc), the Library for Efficient Modeling and Optimization in Networks (LEMON), and VRPH. Cgc is a collection of network representations and algorithms aiming to facilitate the development and implementation of network algorithms and is currently available online from https://projects.coin-or.org/Cgc. LEMON is a C++ template library providing efficient implementations of network optimization algorithms and common graph structures (Dezső et al., 2011) and is available from http://lemon.cs.elte.hu/trac/lemon. VRPH constitutes an open source C++ package for the VRP. VRPH is a software library containing tools to create metaheuristic algorithms for the VRP, and its latest source code can be obtained from http://www.coin-or.org/projects/VRPH.xml. Also, Mascopt is an open source Java-based network optimization library providing tools for solving some network optimization problems (Lalande et al., 2004).

Open VRP is an open-source framework to model and solve a number of variants of the VRP, such as the capacitated VRP (CVRP) and the VRP with Time Windows (VRPTW). Open VRP library is written in Common Lisp and is available online from https://github.com/mck-/Open-VRP. Moreover, the GeoSteiner package (Warme, 2000) solves three versions of the Steiner tree problem (i.e., the Euclidean Steiner tree problem in the plane, the rectilinear Steiner tree problem in the plane, and the minimum spanning tree problem in hypergraphs). Although the code written in ANSI C is freely available online from http://www.diku.dk/hjemmesider/ansatte/martinz/geosteiner, the package also supports the commercial optimization solver CPLEX of IBM.

The Network-Enabled Optimization System (NEOS) server constitutes a free Internet-based service for the solution of optimization problems and provides several interfaces for accessing the available solvers (Ferris et al., 2000). The well-known network optimization solvers MOSEK and RELAX4 are also included for solving linear MCNFPs and other network flow problems. Also, Concorde is an efficient computer code for the Symmetric Traveling Salesman Problem (STSP) and other related network optimization problems. The source code is written in C, and it is freely available for academic research use from http://www.math.uwaterloo.ca/tsp/concorde. Furthermore, the Library of Location Algorithms (LoLA) provides implementations of various algorithmic methods regarding network and graph problems (e.g., median-problems and center-problems) known in location planning. The source codes of the LoLA software library can be downloaded from http://www.mathematik.uni-kl.de/~lola. Finally, other free network optimization solvers for classic network flow problems (e.g, MCNFP, transportation problem, and assignment problem) are reported in Sifaleras (2013).

Performance Analyzers

Performance analyzers in a nutshell allow scientists to diagnose the performance of their optimization solvers. By using such intelligent tools, either the serial or parallel performance of a software package can be greatly improved. Such tools feature advanced options for code analysis and metrics, (e.g., cpu sampling, memory allocation). Among the most well-known profiling tools are the VTune Amplifier XE by Intel, the CodeAnalyst Performance Analyzer by AMD, and the MATLAB Code Profiler by

MathWorks. Although, such profiling tools have more general use (e.g., graphics analysis for game developers), they are very well-suited for large-scale network optimization problems (Dolan & Jorge, 2002).

Web-based Educational Optimization Software Packages

Educational optimization software packages aim to help students to familiarize with optimization algorithms and models rather than to provide efficient solutions of large scale optimization problems. Nowadays, a large number of web-based educational optimization software packages for various network optimization problems such as the TSP, the Steiner tree problem, the MCNFP, and others exist in the literature.

A Java applet by Nestor J. A. that lets the user experiment with different choices of Steiner points for the construction of the (NP-hard) Steiner Rectilinear Tree (SRT) problem can be accessed online at http://workbench.lafayette.edu/~nestorj/cadapplets/STree/SteinerDemo.html. Furthermore, animated examples of heuristic algorithms (e.g., construction and improvement heuristics) for the TSP are available from Mertens S. online at http://www-e.uni-magdeburg.de/mertens/TSP. An animated demonstration of the classic network simplex algorithm for the uncapacitated MCNFP was recently presented in Baloukas et al. (2009) and is available online at http://users.uom.gr/~thanasis/NetworkSimplex.html. Finally, a visualization software package regarding the network primal exterior point Simplex algorithm for the assignment problem was presented in Andreou et al. (2005).

DISCUSSION

Network optimization software packages are of great importance, either from a research or managerial point of view. First, from a research point of view, the large number of network optimization applications and the variety of the domains attracts scientists not only from universities but also from research labs or public bodies to work on the solution of such problems. Researchers are interesting in devising new efficient methods for network optimization problems with high scientific and societal impact (e.g., network flow problems arising from evacuation planning). Due to this reason, a researcher working on a special network optimization problems usually needs to find real-world benchmark data or generate new ones and also to fine tune the implementation of his/her optimization algorithm. Furthermore, a professor teaching a network optimization course usually seeks available educational software packages for his/her class. Other network optimization applications of societal impact include, but are not limited to, multi-agent scheduling in intelligent transport systems, optimal power flow in smart grids, and optimal access point assignment in wireless networks. Also, innovative decision support systems designed for such network optimization problems are nowadays of high commercial value.

From a managerial point of view, companies are equally interested for software solutions involving network models. For example, it is widely accepted that the use of predictive analytic software gives a competitive advantage to companies. Thus, the role of neural network models in business intelligence has been noted by many authors, such as the works by Smith & Gupta (2002) and Zhang (2004). Additionally, due to the explosive growth of digital data (i.e., Big Data), network optimization approaches are also used as analytic tools (i.e., networks analytics) to optimize network investments and maximize the customer experience. For example, a recent report by Wheless & Gandolfo highlights ways of optimizing the commercial value of available and incremental bandwidth and also resource allocation. The report can be accessed online at: http://www.sas.com/partners/directory/accenture/NewGeneration-NetworkAnalytics.pdf. Such network analytic tools can clearly assist communications service providers, to plan their operating and capital expenses.

Furthermore, companies aiming to maximize their business value are interested in computing fast and accurate solutions to various network optimization problems in Logistics, Telecommunications, etc. Therefore, companies in highly competitive areas should find state-of-the-art optimization solvers customized to their needs (e.g., routing). In such cases, and due to high prices of commercial licenses for such products, a company should carefully consult reviews regarding optimization software. The practical managerial significance of identifying the appropriate software tool, tailored in the needs of each company, is crucial for nowadays business. Such regular reviews on optimization software packages for various network optimization problems can be found in the OR/MS Today magazine published by the Institute for Operations Research and the Management Sciences (INFORMS). A recent example is the VRP software survey presented by Partyka & Hall (2014) and can be accessed online at: http://www.orms-today.org/surveys/Vehicle_Routing/vrss.html. This report contains several VRP packages from different vendors, for various supported platforms, and other information (e.g., prices, types of fleets, availability of map street views, and integration with personal navigation devices).

FUTURE RESEARCH DIRECTIONS

A plethora of challenging, intractable versions of network optimization problems exist (e.g., TSP, VRP). Therefore, further research effort is required, using various approaches such as approximation algorithms or metaheuristics (Blum et al., 2011) in order to attack such computationally difficult problems. Another very important research direction is to study the polytope associated to the mathematical formulation of network optimization problems. Such polyhedral studies aim to determine the dimension of the corresponding polytope and identify families of facet-defining cuts. Cornuejols and Harche (1993) presented a polyhedral study of the CVRP. Recently, the polytope associated with a Time Dependent Traveling Salesman Problem (TDTSP) formulation was studied in Abeledo et al. (2013). By using these new cuts, the authors were able to improve the computational performance of a branch-cut-and-price algorithm. The computational value of such research results is very important due to the potential improvement of the efficiency of network optimization solvers.

Additionally, due to the advent of multi-core processors with two or more central processing units (CPUs), as also of multi-core graphics cards with thousands of graphics processing units (GPUs), parallel programming constitutes one of the most promising ways of improving the computational efficiency of optimization solvers (Badr et al., 2006). Such GPU-accelerated computing approaches are now used to produce high performance industry-leading applications. A recent example of a high performance GPU accelerated implementation of 2-opt local search algorithm for the TSP was presented by Rocki & Suda, (2013). Although ,the authors did not implement any sophisticated pruning scheme and/or specialized data structure, they experimentally showed that the optimization algorithm using the GPU local search, tested on AMD and NVIDIA devices, converges from up to 300 times faster compared to the sequential version on average, depending on the problem size.

CONCLUSIONS

Since network optimization makes a very large research area, the suggested list of problem instance generators, benchmark collections, and solvers is, of course, by far not complete. However, we believe that effort made to include relevant literature on classic, well-studied, network optimization problems in this chapter will provide a starting point for studying optimization solvers, finding benchmark collections, and encouraging readers to be interested in these problems. Also, emphasis was given to the practical managerial significance of network optimization methods and software tools. Finally, we hope that the proposed chapter will serve as an excellent reference for students, researchers, and practitioners in information technology.

KEY TERMS AND DEFINITIONS

Benchmark Problems: A data set of computationally difficult problems, either from real-world applications or randomly generated, used by researchers in order to test the efficiency of optimization solvers.

Dynamic Network Optimization Problems: Network optimization problems whose parameters change (e.g., time varying) and are not static.

Integer Optimization: A research sub-area of Optimization, concerning problems whose decision variables take integer values.

Network Generator: An optimization software package designed for random generating instances of network optimization problems with specific structure and dimension.

Network Optimization: A research sub-area of Optimization concerning problems that can be modeled using graphs and networks.

Optimization Software Package: A software package specifically designed to be used for optimization problems.

Optimization Solver: An optimization software package, including efficient implementations of optimization algorithms, specifically designed for the solution of optimization problems.

Performance Analyzer: A software package designed to analyze the efficiency of the source code of an optimization algorithm, identify the bottlenecks in its performance, and suggest ways of computational improvements.

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