An Extension of the Lin-Kernighan-Helsgaun TSP Solver for Constrained Traveling Salesman and Vehicle Routing Problems

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Abstract

This report describes the implementation of an extension of the Lin-Kernighan-Helsgaun TSP solver for solving constrained traveling salesman and vehicle routing problems. The extension, which is called LKH-3, is able to solve a variety of well-known problems, including the sequential ordering problem (SOP), the traveling repairman problem (TRP), variants of the multiple traveling salesman problem (mTSP), as well as vehicle routing problems (VRPs) with capacity, time windows, pickup-and-delivery and distance constraints. The implementation of LKH-3 builds on the idea of transforming the problems into standard symmetric traveling salesman problems and handling constraints by means of penalty functions. Extensive testing on benchmark instances from the literature has shown that LKH-3 is effective. Best known solutions are often obtained, and in some cases, new best solutions are found. The program is free of charge for academic and non-commercial use and can be downloaded in source code. A comprehensive library of benchmark instances and the best obtained results for these instances can also be downloaded.

1. Introduction

The Lin-Kernighan-Helsgaun TSP solver, LKH [1, 2], is a state-of-the-art heuristic solver for the traveling salesman problem. LKH implements a powerful local search heuristic for the TSP based on the variable depth local search of Lin and Kernighan [3]. LKH has produced optimal solutions for all solved problems we have been able to obtain; including an 85,900-city instance (at the time of writing, the largest nontrivial instance solved to optimality). Furthermore, the algorithm has improved the best known solutions for a series of large-scale instances with unknown optima, among these a 1,904,711-city instance (World TSP).

However, in many practical situations, the TSP has additional constraints such as limited resources, time windows and precedence constraints. Since the current version of LKH, LKH-2, is highly customized for the standard TSP and cannot accommodate constraints, its usage is extremely limited in these situations. Furthermore, solving problems that involve multiple traveling salesmen is not straightforward.

This is the motivation for extending LKH-2 with facilities handling constraints and multiple traveling salesmen. The extension, named LKH-3, is currently able to solve the following problem types:

ACVRP: Asymmetric capacitated vehicle routing problem
BWTSP: Black and white traveling salesman problem
CCVRP: Cumulative capacitated vehicle routing problem
CVRP: Capacitated vehicle routing problem
CVRPTW: Capacitated vehicle routing problem with time windows
DCVRP: Distance constrained capacitated vehicle routing problem
1-PDTSP: One-commodity pickup-and-delivery traveling salesman problem
m-**PDTSP**: Multi-commodity pickup-and-delivery traveling salesman problem
*m*1-**PDTSP**: Multi-commodity one-to-one pickup-and-delivery traveling salesman problem
MTRP: Multiple traveling repairman problem
MTRPD: Multiple traveling repairman problem with distance constraints
*m***TSP**: Multiple traveling salesmen problem
OVRP: Open vehicle routing problem
PDPTW: Pickup-and-delivery problem with time windows
PDTSP: Pickup-and-delivery traveling salesman problem
PDTSPF: Pickup-and-delivery traveling salesman problem with FIFO loading
PDTSPL: Pickup-and-delivery traveling salesman problem with LIFO loading
RCTVRP: Risk-constrained cash-in-transit vehicle routing problem
RCTVRPTW: Risk-constrained cash-in-transit vehicle routing with time windows
SOP: Sequential ordering problem
TRP: Traveling repairman problem
TSPPD: Traveling salesman problem with pickups and deliveries
TSPTW: Traveling salesman problem with time windows
VRPB: Vehicle routing problem with backhauls
VRPBTW: Vehicle routing problem with backhauls and time windows
VRPMPD: Vehicle routing problem with mixed pickup and delivery
VRPMPDTW: Vehicle routing problem with mixed pickup and delivery and time windows
VRPSPD: Vehicle routing problem with simultaneous pickup and delivery
VRPSPDTW: Vehicle routing problem with simultaneous pickup-delivery and time windows

Extensive testing on benchmark instances from the literature has shown that LKH-3 is effective. Best known solutions are often obtained, and in some cases, new best solutions are found.

The next sections describe the implementation of LKH-3.

2. Basic ideas

2.1 Transformations

An asymmetric problem with *n* cities is transformed into a symmetric problem with 2*n* cities using the transformation method of Jonker and Volgenant [4]. This transformation method is already implemented in LKH-2 and has been very successful for solving ATSP [5]. Note in this connection that some of the problems to be solved by LKH-3 are best conceived as asymmetric problems, even if the costs are symmetric. This is for example the case for problems with time windows. These problems are first transformed by LKH-3 to asymmetric problems before they are transformed to symmetric problems. A positive side effect of this approach is that LKH-3 is able to solve asymmetric versions of these problem types.

A vehicle routing problem usually involves more than one vehicle and may therefore be conceived as a multiple traveling salesman problem. Fortunately, a multiple traveling salesman problem with a single home city (depot) can easily be transformed to a standard traveling salesman problem [6]. A symmetric TSP with *m* salesmen can be solved using a symmetric TSP augmented with *m* - 1 copies of the home city, where infinite costs are assigned between home cities [7]. For those symmetric problems that are not transformed to asymmetric problems, LKH-3 uses the improved transformation by Jonker and Volgenant [8].

2.2 Penalty functions

LKH-3 uses penalty functions for handling constraints. A penalty function returns a value that depends on how much the given constraints are violated. In contrast to the traditional usage of penalty functions, where a penalty value is added to (or multiplied with) the objective value, these two values are kept separate by LKH-3. Associated with each tour is a pair (P, C), where P is the penalty of the tour, and C is its cost. Let T_1 and T_2 be two tours with associated pairs (P_1, C_1) and (P_2, C_2). Then T_1 is *better* than T_2 if $(P_1 < P_2) \vee (P_1 = P_2 \wedge C_1 < C_2)$. In other words: minimizing penalty is the primary objective, whereas minimizing cost is the secondary. A penalty function has been implemented for each problem type.

When a move on a given tour produces a better, the move is said to be *improving*. To check that a move is improving, the move is made, and the penalty and cost for the resulting tour are computed and compared with the penalty and cost of the original tour. If no improvement is found, the move is retracted.

2.3 Special moves

The data structure used in LKH for tour representation, a two-level tree [9], gives an average time complexity of $O(\sqrt{N})$ for making a move, where N is the number of cities. The average time complexity for move retraction is the same since this is performed by an inverted move.

The most time-consuming part of the move checking procedure is the penalty computation. Its worst-case time complexity is $O(N)$. Speedup may often be achieved by using the fact that the computation may be terminated as soon as the value becomes greater than the value for the current best tour. Some speedup might also be achieved by starting the computation in the route that most recently caused the computation to terminate However, worst-case time complexity is still $O(N)$.

The time complexity of the penalty computation necessitates that the number of moves to be checked should be small. The advanced high-order move types available in LKH can be used, but they will often be too time consuming. Therefore, a new specially designed 5-opt move generator is provided. Compared with the 5-opt move generator in LKH-2, the new generator mainly considers moves that do not reverse a segment on the tour. Furthermore, it adds a restricted exploration of sequential 4- and 5-opt moves as well as non-sequential 4- and 6-opt moves. In this way, the number of moves to consider is reduced considerably. Note that restricting the move search in this way has no consequence for asymmetric problem instances since moves that reverse a segment are forbidden anyway.

3. Input

LKH-3 includes code for reading problem instances and for printing solutions. Input is given in two separate files:

> (1) a *problem file* and
> (2) a *parameter file*

3.1 The problem file

The problem file contains a specification of the problem instance to be solved. The file format is an extension of the TSPLIB format [10]. A problem file consists of a *specification part* and of a *data part*. The specification part contains information on the file format and on its contents. The data part contains explicit data.

3.1.1 The specification part

All entries in this section are of the form <keyword> : <value>, where <keyword> denotes an alphanumerical keyword and <value> denotes alphanumerical or numerical data. Below is given a list of the new keywords in LKH-3:

> SALESMEN : *<integer>*
> Specifies the number of salesmen (= vehicles).
>
> VEHICLES : *<integer>*
> Specifies the number of vehicles (= salesmen).
>
> DISTANCE : *<real>*
> The maximum length allowed for each route in a vehicle route problem.
>
> RISK_THRESHOLD : *<integer>*
> The maximum risk allowed for each route in a risk constrained problem.
>
> SCALE : *<integer>*
> A scale factor for Euclidean instances. Distances are multiplied by this factor.

Note that the keyword CAPACITY, which is used for specifying the vehicle capacity, belongs to the original version of the TSPLIB format.

New distance functions have also been added:

EXACT_2D, EXACT_3D:
Euclidean distance multiplied by 1000 and rounded to nearest integer.

FLOOR_2D, FLOOR_3D:
Euclidean distance rounded down to the last integer.

TOR_2D, TOR_3D:
Toroidal distance.

3.1.2 The data part

Depending on the choice of specifications, some additional data may be required. These data are given in corresponding data sections following the specification part. Each data section begins with the corresponding keyword. The length of the section is either implicitly known from the format specification, or the section is terminated by an appropriate endof-section identifier.

LKH-3 extends the TSPLIB format with the following data sections:

BACKHAUL_SECTION :
This section is used for specifying VRPB instances. It contains a list of backhaul nodes. This section is terminated by a -1.

PICKUP_AND_DELIVERY_SECTION :
This section is used for specifying pickup-and-delivery instances. Each line is of the form

<integer> <integer> <real> <integer> <integer>

The first integer gives the number of the node.
The second integer gives its demand (ignored for PDTSPF, PDTSPL, VRPMPD and VRPSPD instances).
The third and fourth number give the earliest and latest time for the node.
The fifth number specifies the service time for the node.
The last two integers are used to specify pickup and delivery. For a PDPTW, PDTSP, PDTSPF and PDTSPL instance, the first of these integers gives the index of the pickup sibling, and the second integer gives the index of the delivery sibling. For a VRPMPD and VRPSPD instance, the two integers simply give the size of the pickup and delivery for the node.

SERVICE_TIME_SECTION :
The service times of all nodes of a CVRP are given in the form (per line)

<integer> <real>

The integer specifies a node number, the real its service time. The depot node must also occur in this section. Its service time is 0.

TIME_WINDOW_SECTION :
Time windows are given in this section. Each line is of the form

<integer> <real>

The first integer specifies a node number. The two reals specify earliest and latest arrival time for the node, respectively.

The keyword DEPOT_SECTION, which is used for specifying depots, belongs to the original version of the TSPLIB format. The section is terminated by a -1. Note, however, that LKH-3 at present only allows one depot.

3.2 The parameter file

The parameter file contains control parameters for the solution process. The solution process is typically carried out using default values for the parameters. The default values have proven to be adequate in many applications. However, for applications with penalty functions, better performance is achieved by choosing other values. For such applications, experiments have shown that the following setting works well:

MOVE_TYPE = 5 SPECIAL
GAIN23 = NO
KICKS = 1
KICKTYPE = 4
MAX_SWAPS = 0
POPULATION_SIZE = 10

The specially designed 5-opt move procedure is chosen by setting MOVE_TYPE to 5 SPECIAL.

By setting GAIN23 to NO, the exploration of non-sequential moves at the end of each trial is turned off. Notice, however, that some non-sequential moves after all are explored by the chosen move procedure.

The default perturbation method in LKH is a random walk on the candidate graph. But this method destroys the tour a lot. Instead, by setting KICKS to 1 and KICK_TYPE to 4, a random double-bridge-kick move is chosen. This move is a non-sequential 4-opt move that replaces only 4 edges on the tour by 4 non-tour edges.

By setting MAX_SWAPS to 0, no attempts are made to find improving moves of a higher order than specified by the basic move type (5 SPECIAL).

The genetic algorithm of LKH with a population size of 10 is used.

The parameter settings above may be chosen by just writing

SPECIAL

in the beginning of the parameter file.

LKH-3 adds the following new or extended parameter settings:

BWTSP = *<integer> <integer>* [*<integer>*]
Specifies the three parameters (B, Q, L) to a BWTSP instance.
    B: Number of black nodes.
    Q: Maximum number of white nodes on "black-to-black" paths.
    L: Maximum length of any "black-to-black" path.
Default: 0 0.

DEPOT = *<integer>*
Specifies the depot node.
Default: 1.

INITIAL_TOUR_ALGORITHM = { … | CVRP | MTSP | SOP }
Specifies the algorithm for obtaining an initial tour.
Default: WALK.

MAKESPAN = { YES | NO }
Specifies if makespan optimization is to be used for a TSPTW instance.
Default: NO.

MOVE_TYPE = *<integer>* [SPECIAL]
Specifies the move type to be used in local search. An integer value $k >= 2$ signifies that a sequential k-opt move is to be used. The specifier SPECIAL can be given in order to use specially designed moves. For this type of moves, k must be 3 or 5.
Default: 5.

MTSP_MIN_SIZE = *<integer>*
Specifies the minimum number of cities each salesman must visit in an *m*TSP or CVRP instance. If negative, its value is set to
    DIMENSION / (ceil(1.0 * DIMENSION / MTSP_MAX_SIZE) + 1)
Default: 1.

MTSP_MAX_SIZE = *<integer>*
Specifies the maximum number of cities each salesman may visit in an *m*TSP or CVRP instance.
Default: value of DIMENSION - 1.

MTSP_OBJECTIVE = [MINMAX | MINMAX_SIZE | MINSUM]
Specifies the objective function type for a multiple traveling salesman problem.
    MINMAX   - Minimize the length of the longest route.
    MINMAX_SIZE - Minimize the size of the largest route.
    MINSUM   - Minimize the length of the overall tour.
All routes must satisfy the MTSP_MIN_SIZE and MTSP_MAX_SIZE constraints.

MTSP_SOLUTION_FILE = *<string>*
Specifies the name of a file where the solution of an *m*TSP (or VRP) instance is to be written.

SALESMEN = *<integer>*
Specifies the number of salesmen/vehicles.
Default: 1.

SCALE = *<integer>*
Scale factor for Euclidean instances.
Default: 1.

SINTEF_SOLUTION_FILE = *<string>*
Specifies the name of a file where the solution of an *m*TSP or VRP instance is to be written.
The solution is written in SINTEF format.

VEHICLES = *<integer>*
Specifies the number of vehicles/salesmen.
Default: 1.

4. Summary of benchmark tests

LKH-3 has been tested extensively on benchmark instances from the literature. The table below summarizes the results. The first two columns give the problem type and number of test instances for this type. The three last columns give the number of times the solution found by LKH-3 was better than, equal to, or worse than the best known solution (BKS).

Problem type	Instances	< BKS	= BKS	> BKS
ACVRP	32	0	32	0
BWTSP	38	0	38	0
CCVRP	164	**53**	74	37
CVRP	509	**44**	327	138
CVRPTW	405	**2**	302	101
DCVRP	22	**1**	17	4
1-PDTSP	2036	**380**	1528	78
m-PDTSP	892	**118**	724	50
*m*1-PDTSP	1178	**21**	1157	0
*m*TSP	127	**51**	72	4
MTRP	1040	**7**	1033	0
MTRPD	180	0	180	0
OVRP	111	**4**	101	6
PDPTW	222	**3**	180	139
PDTSP	163	**5**	156	2
PDTSPF	77	**2**	47	28
PDTSPL	126	**15**	97	14
RCTVRP	378	**79**	283	16
RCTVRPTW	24	0	24	0
SOP	163	**9**	150	4
TRP	130	**21**	109	0
TSPPD	600	0	600	0
TSPTW	900	**47**	853	0
VRPB	149	**4**	141	4
VRPBTW	15	**3**	12	0
VRPMPD	70	**9**	55	6
VRPMPDTW	70	**9**	53	8
VRPSPD	266	**20**	148	98
VRPSPDTW	68	**46**	20	2

5. Conclusions

LKH-3 is based on the simple idea of transforming the problems to standard traveling salesman problems and handling the involved constraints by means of penalty functions. Despite its simplicity, extensive testing on benchmark instances from the literature has shown that LKH-3 is effective for solving a variety of problem types. Best known solutions are often obtained, and in some cases, new best solutions are found.

The program is free of charge for academic and non-commercial use and can be downloaded in source code via http://webhotel4.ruc.dk/~keld/research/LKH-3. A comprehensive library of test instances (about 10,000) and the best solutions obtained by LKH-3 for these instances can also be downloaded. A comparison with the best known solutions are given in tables.

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RCTVRP: Risk-constrained cash-in-transit vehicle routing problem

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VRPB: Vehicle routing problem with backhauls

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