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SteinLib: An Updated Library on Steiner Tree Problems in Graphs

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¹to appear in: *D.-Z. Du and X. Cheng (Eds.), STEINER TREES IN INDUSTRIES*

Abstract

In this paper we present the *SteinLib*, a library of data sets for the Steiner tree problem in graphs. This library extends former libraries on Steiner tree problems by many new interesting and difficult instances, most of them arising from real-world applications. We give a survey on the difficulty of these problem instances by stating references to state-of-the-art software packages that were the first or are currently among the best to solve these instances.

1 Introduction

The availability of computational test sets for combinatorial and integer programming problems is very important for the development and comparison of efficient implementations as well as robust and fast computer codes. For instance, the TSPLIB² [52] has very much influenced the development of very good software for the solution of the traveling salesman problem. The MIPLIB³ [6], which is a library of real-world mixed integer programming problems, is *the* test set for MIP solvers and most comparisons of algorithmic developments in the literature are evaluated on the MIPLIB-instances. Important in this context is also the OR-Library⁴ of Beasley [4], a collection of test data sets for a great variety of Operations Research (OR) problems including the Steiner tree problem in graphs.

In this paper we follow this line and present an updated and revised version of a library for the Steiner tree problem in graphs. Given an undirected graph $G = (V, E)$ and a node set $T \subseteq V$, a *Steiner tree for T in G* is a subset $S \subseteq E$ of the edges such that $(V(S), S)$ contains a path from s to t for all $s, t \in T$, where $V(S)$ denotes the set of nodes incident to an edge in S . In other words, a Steiner tree is an edge set S that spans the set of *terminals* or *basic nodes* T . The *Steiner tree problem in graphs* is to find a minimal Steiner tree with respect to some given edge costs $c_e, e \in E$. For a survey on the Steiner tree problem in graphs see, e.g., [28, 59, 12].

Among others, the mentioned OR-Library of Beasley contains test data for Steiner tree problems. In fact, the OR-Library-Instances B, C, D, and E are *the* source in the Steiner tree community for evaluating and testing new algorithmic developments for the Steiner tree problem, such as heuristics, cutting plane methods, preprocessing techniques and others. In the meantime, however, most of these instances are easy to solve for state-of-the-art software.

In this paper we give a summary of publically available test data for Steiner tree problems. We use or refer to state-of-the-art software packages and show which of these instances are easy to solve and which are still challenging. We will see that the difficulty of a problem instance does not only depend on the size of the problem (i.e., number of nodes, edges and terminals). There are relatively small sized instances that are still hard for current solvers.

²<http://www.iwr.uni-heidelberg.de/iwr/comopt/software/TSPLIB95>

³<http://www.caam.rice.edu/~bixby/miplib/miplib.html>

⁴<http://mscmga.ms.ic.ac.uk/info.html>

All data sets mentioned in the paper are available through the newly updated library on Steiner tree problems *SteinLib*.⁵ We encourage people to add hard problem instances to this library and to contribute in this way to obtain a valuable collection of test data that forms the basis for further improvements in the algorithmic developments for the solution of the Steiner tree problem.

In the following section we give a description of the data format that is used in *SteinLib*. Subsequently, we summarize the currently available problem instances within the Steiner tree library *SteinLib*. We distinguish those problem instances that are provided as graphs and those which have their background as instances for metrical Steiner tree problems but may be represented as graphs according to an appropriate conversion routine.

Besides randomly generated instances, data sets for the Steiner tree problem in graphs arise from various application areas such as biology and phylogeny [21, 48], biochemistry [55], mining [39], forestry [53], the design of sewer networks [65], telecommunication networks [73] or databases [64] as well as VLSI design [40, 38, 35]. Many of the problem instances given in those references describing these applications, however, turn out to be too small to be challenging for current state-of-the-art Steiner tree algorithms. Thus, we mainly restrict ourselves to instances that are still interesting from a computational point of view.

In the literature a great variety of papers provide theoretical results for polynomially solvable special cases of the Steiner tree problem (e.g., for series-parallel or Halin graphs [69]). However, as these instances turn out to be easy no specific data generation routines are provided.

We use the following notation throughout the paper. For a Steiner tree instance with a graph $G = (V, E)$ and a terminal set $T \subseteq V$, we denote by $n = |V|$ the number of nodes, by $m = |E|$ the number of edges, and by $t = |T|$ the number of terminals.

2 Description of the Data Format

In this section we describe the data format that is used in the *SteinLib*. For illustration we use an odd wheel depicted in Figure 1 with terminal nodes 1, 2, 3 and 4. The following lines show this example in the *SteinLib* format.

```
33D32945 STP File, STP Format Version 1.0
```

```
SECTION Comment
```

```
Name "Odd Wheel"
```

```
Creator "T. Koch, A. Martin and S. Voss"
```

```
Remark "Example used to describe the STP data format"
```

```
END
```

```
SECTION Graph
```

```
Nodes 7
```

⁵<http://elib.zib.de/steinlib>

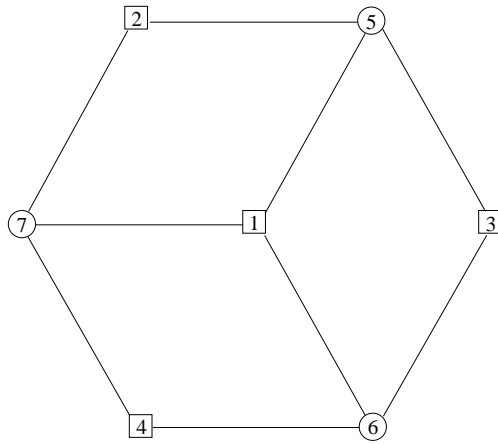


Figure 1: Data format example

```

Edges 9
E 1 5 1
E 1 6 1
E 1 7 1
E 2 5 1
E 2 7 1
E 3 5 1
E 3 6 1
E 4 6 1
E 4 7 1
END

```

```

SECTION Terminals
Terminals 4
T 1
T 2
T 3
T 4
END

```

```

SECTION Coordinates
DD 1 80 50
DD 2 55 5
DD 3 130 50
DD 4 55 95
DD 5 105 5
DD 6 105 95
DD 7 30 50
END

```

Comment	Gives general information about the problem instance, like name and creator.
Graph	Here the graph itself is specified.
Terminals	Lists the terminals for the problem instance.
Coordinates	This is an optional section giving coordinates for the nodes of the graph. This section is only necessary for drawing.
Presolve	This is an optional section stating that this problem is the result of some presolve processing.

Table 1: Section types

The format is line (or row) oriented. Each line is terminated with a line-feed. Everything on a line after (and including) a # is ignored. Blank lines are ignored. The first line of each data file is supposed to be

```
33D32945 STP File, STP Format Version 1.0
```

It contains a so-called magic number as an identification key. It provides an assertion that the data file is indeed a file in the *SteinLib* format.

Then, the file is divided into sections. A section starts with the keyword **SECTION** followed by the name of the section and ends with a line with the keyword **END**. The sections shown in Table 1 are possible and should appear in the given order.

Each line within a section starts with a keyword, indicating the type of the line. Depending on the section different keywords are allowed. Each keyword follows a number of fields in the line. Fields can be either a string, i. e., an arbitrary string enclosed in double quotes, or a number, where integer numbers are allowed only.

The following Figure 2 lists the keywords for each section. The Column *Fields* shows how many strings (S) or numbers (N) are required.

The sections **Graph** and **Terminals** need to be given. Within the section **Graph** we consider either directed or undirected graphs. For directed graphs the keyword **Arcs** must appear and each line of an arc must start with an **A**. In addition, the section **Terminals** must specify a root node. For undirected graphs the keyword **Edges** gives the number of edges and **E** lines in the file. The format does not allow mixed graphs as any undirected edge may easily be represented by two anti-parallel arcs with the same end-nodes.

The sections **Comment**, **Presolve**, and **Coordinates** are optional. If these sections appear to be in the data file, each of their keywords is optional itself. Within the section **Coordinates** all entries must be of the same type. Furthermore, whenever coordinates are given, they must be given for all nodes.

There are further options of the *SteinLib* format like an *include* mechanism for a compact representation of instances that share certain sections. Special keywords for generalized Steiner trees are also available. These options are described in detail on the web-page⁶ of the library.

⁶<http://elib.zib.de/steinlib>

<i>Name</i>	<i>Fields</i>	<i>Description</i>
Section Comment		
Name	1 S	The name of the instance
Date	1 S	The date of the creation of the instance
Creator	1 S	Who did it
Remark	1 S	Some other information
Section Graph		
Nodes	1 N	Number of nodes in the graph
Edges	1 N	Number of edges in the graph
E	3 N	Specification of one edge. The number of E lines must match the number given in the Edges line. The three values are Node1, Node2 and Weight. The nodes are numbered from one to the number given in the Nodes line.
Arcs	1 N	Number of arcs in the graph
A	3 N	Specification of one arc. The number of A lines must match the number given in the Arcs line. The three values are Tail-Node, Head-Node and Weight. The nodes are numbered from one to the number given in the Nodes line.
Section Terminals		
Terminals	1 N	Number of terminals. Must be between one and the number of Nodes given in the Graph section.
Root	1 N	Node number of the Root-Node for directed Steiner tree problems.
T	1 N	Specification of one terminal. The number of T lines must match the number given in the Terminals line. The field specifies the node that is a terminal. The nodes are numbered from one to the number given in the Nodes line.
Section Coordinates		
DD	3 N	2D-Coordinates. The three values are Node-Number, X- and Y-Coordinate.
DDD	4 N	The four values correspond to Node-Number, X-, Y- and Z-Coordinate.
Section Presolve		
Date	1 S	Date of the preprocessing.
Fixed	1 N	The value that must be added to the optimal value of this preprocessed instance to get the optimal value of the original instance.
lower	1 N	A lower bound.
upper	1 N	An upper bound.
time	1 N	Used processing time in seconds.

Figure 2: Description of the keywords

3 The Steiner Tree Problem in Graphs

In this section we summarize existing data sets for the Steiner tree problem in graphs as they have been proposed in the literature. We provide tables where the most important characteristics are given, i.e., the name of the instance, the number of nodes, the number of edges (or arcs) and the number of basic nodes. Column “Opt” shows the objective function value of the best known solution. If this is proven to be optimal, it is written in bold-face.

In Column “D” we provide a *difficulty classification*. In capital letters it is indicated if the instance may be solved to optimality by applying local reduction techniques L. One of the best known mathematical programming formulations for the Steiner tree problem in graphs is a multicommodity flow formulation due to Wong [72]. Theoretically, the linear programming relaxations of this formulation and some other formulations are equivalent [24]. We classify an instance with the letter P when the solution to the linear programming relaxation is non-fractional. All other cases are classified as NP indicating that no polynomial time algorithm is known to date for this instance. Finally, a small s, m, h, d or w indicates that an instance may be solved to optimality within seconds, minutes, hours, days or weeks with state-of-the-art algorithms (based on up-to-date computers). A ? on either of the two values states that the classification is not known. Our difficulty classification relies on numerical experiments we have performed based on [35] and [56] for the Steiner tree problem in graphs. For the metrical Steiner tree problems discussed in Section 4 we additionally refer to [66, 67].

The most influencing data generation scheme in the literature was proposed by Aneja [1] in 1980. Each problem instance corresponds to a randomly generated connected graph with a specified set of n nodes and m edges. To generate instances that guarantee the existence of a feasible solution, connectivity needs to be assured. Therefore, first a random spanning tree of the entire set V of nodes is generated. Additional edges are then added randomly over the graph. Random weights between 1 and 10 are then assigned to all edges. In [1] the number of basic nodes in the set T was chosen to be $\frac{n}{2}$ but may be modified arbitrarily, and problem instances generated along these lines had between 10 and 50 nodes.

This data generation scheme became quite popular in the community and was applied by various authors. Beasley [2] generated a set of 18 instances according to this scheme with 50, 75, and 100 nodes. For each number of nodes the number of basic nodes was chosen to be $\frac{1}{6}n$, $\frac{1}{4}n$, and $\frac{1}{2}n$ and for each graph the number of edges was specified to achieve an average node degree of 2.5 and 4. This set of 18 instances was chosen as a benchmark by several authors later on (e.g., [51, 3]) and became the data set B within the OR-Library [4], see Table 2. Independently, Wong [72] generated similar instances with up to 60 nodes, 120 edges and 30 basic nodes, however, with edge weights being real values from the interval $(0, 1)$. Later on these instances were also used as a benchmark (see, e.g., [3, 10]).

Beasley [3] extended the size of his instances when he generated new data sets (see Tables 3 - 5). As simple reduction techniques were able to solve the

B-data to optimality (see, e.g., [15, 16, 17, 13, 59]) the new problem instances had up to 2500 nodes and 62500 edges.

Another collection of randomly generated examples is described in [10] (see Tables 6 and 7). p401 through p410 are complete graphs with random edge weights from the interval $[1, 1500]$. p455 through p466 are complete graphs with Euclidean weights. For these graphs coordinates between 1 and 900 were assigned to the nodes and edge weights were computed according to Euclidean distances rounded to the nearest integer. Furthermore, instances p601 through p616 are grid graphs with random weights and p619 through p633 with Euclidean weights.

Tables 8 through 11 show the so-called *incidence* instances. These problem instances, described in [13] and [18, 19], are randomly generated and have the following sizes. There are four choices of the node set cardinality $n = 80, 160, 320,$ and 640 , for each of them twenty variants are generated combining four sizes of the terminal set $|T| = \log n, \sqrt{n}, 2\sqrt{n},$ and $\frac{n}{4}$ with five different densities $m = \frac{3n}{2}, n \ln n, \frac{n(n-1)}{2}, 2n,$ and $\frac{n(n-1)}{10}$, all values are rounded down to the next integer. Every variant was drawn five times. The problem names have the pattern $n.t.ei$, where $n = 80, 160, 320,$ and 640 gives the number of nodes of the instance, $t = 0, 1, 2, 3$ indicates which of the four alternatives (in the above sequence) of the sizes for the terminal sets have been chosen, $e = 0, 1, 2, 3, 4$ stands for the five densities, and $i = 1, 2, 3, 4, 5$ distinguishes the five instances drawn for each variant. To give an example, problem 160.411 is the first out of five instances with 160 nodes, $\frac{n(n-1)}{10} = \frac{160 \cdot 159}{10} = 2544$ edges, and $\lfloor \sqrt{n} \rfloor = \lfloor \sqrt{160} \rfloor = 12$ terminals.

In the incidence instances the weight on each edge (i, j) is defined with a sample r from a normal distribution, rounded to the closest integer value with a minimum value of 1 and a maximum value of 500, i.e., $c_{ij} = \min\{500, \max\{1, \text{round}(r)\}\}$. To obtain a graph that is much harder to reduce by preprocessing techniques such as given in [15, 16, 17, 13, 59], three distributions with a different mean value are used. Any edge (i, j) is incident to none, to one or to two basic nodes. The mean of r is 100 for edges (i, j) with $i, j \notin T$ (no incidence with T), 200 on edges (i, j) with one basic node and 300 on edges (i, j) with both end-nodes $i, j \notin T$. The standard deviation for each of the three normal distributions is 5.

One of the challenging problems in the design of electronic circuits is the routing problem which is, roughly speaking, the task to connect terminal sets via wires on a predefined area. Depending on the underlying technology and the design rules subproblems arise that can be formulated as the problem of packing Steiner trees in certain graphs (see [40] for an excellent treatment of this subject). In Tables 12 through 18 we give corresponding real-world VLSI instances. They result from seven different circuits described in [32]. The underlying graphs are grid graphs that contain holes. The holes result from so-called cells that block certain areas of the grid. The sets of terminals are located on the border of these holes. For each of the seven circuits and for each terminal set T_i (where index i runs from 1 to the number of terminal sets of the circuit) we constructed an instance of the Steiner tree problem. For the

Name	$ V $	$ E $	$ T $	D	Opt
b01	50	63	9	Ls	82
b02	50	63	13	Ls	83
b03	50	63	25	Ls	138
b04	50	100	9	Ls	59
b05	50	100	13	Ls	61
b06	50	100	25	Ps	122
b07	75	94	13	Ls	111
b08	75	94	19	Ls	104
b09	75	94	38	Ls	220
b10	75	150	13	Ps	86
b11	75	150	19	Ls	88
b12	75	150	38	Ls	174
b13	100	125	17	Ps	165
b14	100	125	25	Ps	235
b15	100	125	50	Ps	318
b16	100	200	17	Ps	127
b17	100	200	25	Ps	131
b18	100	200	50	Ps	218

Table 2: B-Instances from [2]

Name	$ V $	$ E $	$ T $	D	Opt
c01	500	625	5	Ps	85
c02	500	625	10	Ps	144
c03	500	625	83	Ps	754
c04	500	625	125	Ps	1079
c05	500	625	250	Ls	1579
c06	500	1000	5	Ps	55
c07	500	1000	10	Ps	102
c08	500	1000	83	Ps	509
c09	500	1000	125	Ps	707
c10	500	1000	250	Ps	1093
c11	500	2500	5	Ps	32
c12	500	2500	10	Ps	46
c13	500	2500	83	Ps	258
c14	500	2500	125	Ps	323
c15	500	2500	250	Ls	556
c16	500	12500	5	Ps	11
c17	500	12500	10	Ps	18
c18	500	12500	83	Ps	113
c19	500	12500	125	Ps	146
c20	500	12500	250	Ls	267

Table 3: C-Instances from [3]

Name	$ V $	$ E $	$ T $	D	Opt
d01	1000	1250	5	Ps	106
d02	1000	1250	10	Ps	220
d03	1000	1250	167	Ps	1565
d04	1000	1250	250	Ps	1935
d05	1000	1250	500	Ps	3250
d06	1000	2000	5	Ps	67
d07	1000	2000	10	Ps	103
d08	1000	2000	167	Ps	1072
d09	1000	2000	250	Ps	1448
d10	1000	2000	500	Ps	2110
d11	1000	5000	5	Pm	29
d12	1000	5000	10	Pm	42
d13	1000	5000	167	Ps	500
d14	1000	5000	250	Ps	667
d15	1000	5000	500	Ps	1116
d16	1000	25000	5	Pm	13
d17	1000	25000	10	Pm	23
d18	1000	25000	167	Ps	223
d19	1000	25000	250	Ps	310
d20	1000	25000	500	Ls	537

Table 4: D-Instances from [3]

Name	$ V $	$ E $	$ T $	D	Opt
e01	2500	3125	5	Ps	111
e02	2500	3125	10	Ps	214
e03	2500	3125	417	Ps	4013
e04	2500	3125	625	Ps	5101
e05	2500	3125	1250	Ps	8128
e06	2500	5000	5	Ps	73
e07	2500	5000	10	Pm	145
e08	2500	5000	417	Pm	2640
e09	2500	5000	625	Pm	3604
e10	2500	5000	1250	Pm	5600
e11	2500	12500	5	Pm	34
e12	2500	12500	10	Pm	67
e13	2500	12500	417	Pm	1280
e14	2500	12500	625	Pm	1732
e15	2500	12500	1250	Ps	2784
e16	2500	62500	5	Ph	15
e17	2500	62500	10	Ph	25
e18	2500	62500	417	NPh	564
e19	2500	62500	625	Pm	758
e20	2500	62500	1250	Ls	1342

Table 5: E-Instances from [3]

Name	V	E	T	D	Opt
P4E	100	4950	5	Ps	1138
P4E	100	4950	5	Ps	1228
P4E	100	4950	10	Ps	1609
P4E	100	4950	10	Ps	1868
P4E	100	4950	20	Ps	2345
P4E	100	4950	20	Ps	2959
P4E	100	4950	50	Ps	4474
P4E	200	19900	10	Ps	1510
P4E	200	19900	20	Ps	2545
P4E	200	19900	40	Ps	3853
P4E	200	19900	100	Ps	6234

Name	V	E	T	D	Opt
P4Z	100	4950	5	Ps	155
P4Z	100	4950	5	Ps	116
P4Z	100	4950	5	Ps	179
P4Z	100	4950	10	Ls	270
P4Z	100	4950	10	Ls	270
P4Z	100	4950	10	Ps	290
P4Z	100	4950	20	Ps	590
P4Z	100	4950	20	Ls	542
P4Z	100	4950	50	Ps	963
P4Z	100	4950	50	Ls	1010

Table 6: Instances from [10]

Name	V	E	T	D	Opt
P6E	100	180	5	Ls	7485
P6E	100	180	5	Ps	8746
P6E	100	180	5	Ls	8688
P6E	100	180	10	Ps	15972
P6E	100	180	10	Ps	19496
P6E	100	180	20	Ls	20246
P6E	100	180	20	Ps	23078
P6E	100	180	20	Ls	22346
P6E	100	180	50	Ps	40647
P6E	100	180	50	Ls	40008
P6E	100	180	50	Ls	43287
P6E	200	370	10	Ps	26125
P6E	200	370	20	Ps	39067
P6E	200	370	40	Ps	56217
P6E	200	370	100	Ls	86268

Name	V	E	T	D	Opt
P6Z	100	180	5	Ps	8083
P6Z	100	180	5	Ps	5022
P6Z	100	180	10	Ps	11397
P6Z	100	180	10	Ps	10355
P6Z	100	180	10	Ps	13048
P6Z	100	180	20	Ls	15358
P6Z	100	180	20	Ls	14439
P6Z	100	180	20	Ps	18263
P6Z	100	180	50	Ps	30161
P6Z	100	180	50	Ls	26903
P6Z	100	180	50	Ps	30258
P6Z	200	370	10	Ps	18429
P6Z	200	370	20	Ps	27276
P6Z	200	370	40	Ps	42474
P6Z	200	370	100	Ps	62263

Table 7: Instances from [10]

Name	V	E	T	D	Opt
i080-001	80	120	6	Ps	1787
i080-002	80	120	6	Ps	1607
i080-003	80	120	6	Ps	1713
i080-004	80	120	6	Ps	1866
i080-005	80	120	6	Ps	1790
i080-011	80	350	6	Ps	1479
i080-012	80	350	6	Ps	1484
i080-013	80	350	6	Ps	1381
i080-014	80	350	6	Ps	1397
i080-015	80	350	6	Ps	1495
i080-021	80	3160	6	Ps	1175
i080-022	80	3160	6	Ps	1178
i080-023	80	3160	6	Ps	1174
i080-024	80	3160	6	Ps	1161
i080-025	80	3160	6	Ps	1162
i080-031	80	160	6	Ps	1570
i080-032	80	160	6	Ps	2088
i080-033	80	160	6	Ps	1794
i080-034	80	160	6	Ps	1688
i080-035	80	160	6	Ps	1862
i080-041	80	632	6	Ps	1276
i080-042	80	632	6	Ps	1287
i080-043	80	632	6	Ps	1295
i080-044	80	632	6	NPs	1366
i080-045	80	632	6	Ps	1310
i080-101	80	120	8	Ps	2608
i080-102	80	120	8	Ps	2403
i080-103	80	120	8	Ps	2603
i080-104	80	120	8	Ps	2486
i080-105	80	120	8	Ps	2203
i080-111	80	350	8	NPs	2051
i080-112	80	350	8	Ps	1885
i080-113	80	350	8	Ps	1884
i080-114	80	350	8	Ps	1895
i080-115	80	350	8	Ps	1868
i080-121	80	3160	8	Ps	1561
i080-122	80	3160	8	Ps	1561
i080-123	80	3160	8	Ps	1569
i080-124	80	3160	8	Ls	1555
i080-125	80	3160	8	Ps	1572
i080-131	80	160	8	Ps	2284
i080-132	80	160	8	Ps	2180
i080-133	80	160	8	Ps	2261
i080-134	80	160	8	Ps	2070
i080-135	80	160	8	Ps	2102
i080-141	80	632	8	Ps	1788
i080-142	80	632	8	Ps	1708
i080-143	80	632	8	NPs	1767
i080-144	80	632	8	Ps	1772
i080-145	80	632	8	Ps	1762

Name	V	E	T	D	Opt
i080-201	80	120	16	Ps	4760
i080-202	80	120	16	Ps	4650
i080-203	80	120	16	Ps	4599
i080-204	80	120	16	Ps	4492
i080-205	80	120	16	Ps	4564
i080-211	80	350	16	Ps	3631
i080-212	80	350	16	NPs	3677
i080-213	80	350	16	NPs	3678
i080-214	80	350	16	NPs	3734
i080-215	80	350	16	NPs	3681
i080-221	80	3160	16	Ps	3158
i080-222	80	3160	16	Ps	3141
i080-223	80	3160	16	Ps	3156
i080-224	80	3160	16	Ps	3159
i080-225	80	3160	16	Ps	3150
i080-231	80	160	16	Ps	4354
i080-232	80	160	16	Ps	4199
i080-233	80	160	16	Ps	4118
i080-234	80	160	16	Ps	4274
i080-235	80	160	16	NPs	4487
i080-241	80	632	16	NPm	3538
i080-242	80	632	16	Pm	3458
i080-243	80	632	16	NPm	3474
i080-244	80	632	16	NPs	3466
i080-245	80	632	16	NPs	3467
i080-301	80	120	20	Ps	5519
i080-302	80	120	20	Ps	5944
i080-303	80	120	20	Ps	5777
i080-304	80	120	20	Ps	5586
i080-305	80	120	20	NPs	5932
i080-311	80	350	20	Ps	4554
i080-312	80	350	20	NPs	4534
i080-313	80	350	20	Ps	4509
i080-314	80	350	20	NPs	4515
i080-315	80	350	20	NPs	4459
i080-321	80	3160	20	Ps	3932
i080-322	80	3160	20	Ps	3937
i080-323	80	3160	20	Ps	3946
i080-324	80	3160	20	Ps	3932
i080-325	80	3160	20	Ps	3924
i080-331	80	160	20	NPs	5226
i080-332	80	160	20	NPs	5362
i080-333	80	160	20	Ps	5381
i080-334	80	160	20	Ps	5264
i080-335	80	160	20	Ps	4953
i080-341	80	632	20	Ps	4236
i080-342	80	632	20	NPm	4337
i080-343	80	632	20	NPs	4246
i080-344	80	632	20	NPs	4310
i080-345	80	632	20	NPm	4341

Table 8: Incidence instances from [13, 18]

Name	V	E	T	D	Opt
i160-001	160	240	7	Ps	2490
i160-002	160	240	7	Ps	2158
i160-003	160	240	7	Ps	2297
i160-004	160	240	7	Ps	2370
i160-005	160	240	7	Ps	2495
i160-011	160	812	7	Ps	1677
i160-012	160	812	7	Ps	1750
i160-013	160	812	7	Ps	1661
i160-014	160	812	7	Ps	1778
i160-015	160	812	7	Ps	1768
i160-021	160	12720	7	Ps	1352
i160-022	160	12720	7	Ps	1365
i160-023	160	12720	7	Ps	1351
i160-024	160	12720	7	Ps	1371
i160-025	160	12720	7	Ps	1366
i160-031	160	320	7	Ps	2170
i160-032	160	320	7	Ps	2330
i160-033	160	320	7	NPs	2101
i160-034	160	320	7	Ps	2083
i160-035	160	320	7	Ps	2103
i160-041	160	2544	7	Ps	1494
i160-042	160	2544	7	Ps	1486
i160-043	160	2544	7	NPs	1549
i160-044	160	2544	7	Ps	1478
i160-045	160	2544	7	NPs	1554
i160-101	160	240	12	Ps	3859
i160-102	160	240	12	Ps	3747
i160-103	160	240	12	Ps	3837
i160-104	160	240	12	Ps	4063
i160-105	160	240	12	Ps	3563
i160-111	160	812	12	Ps	2869
i160-112	160	812	12	NPs	2924
i160-113	160	812	12	Ps	2866
i160-114	160	812	12	Ps	2989
i160-115	160	812	12	NPm	2937
i160-121	160	12720	12	Pm	2363
i160-122	160	12720	12	Ps	2348
i160-123	160	12720	12	Ps	2355
i160-124	160	12720	12	Ps	2352
i160-125	160	12720	12	Ps	2351
i160-131	160	320	12	Ps	3356
i160-132	160	320	12	Ps	3450
i160-133	160	320	12	Ps	3585
i160-134	160	320	12	Ps	3470
i160-135	160	320	12	Ps	3716
i160-141	160	2544	12	Ps	2549
i160-142	160	2544	12	NPm	2562
i160-143	160	2544	12	Ps	2557
i160-144	160	2544	12	NPm	2607
i160-145	160	2544	12	Ps	2578

Name	V	E	T	D	Opt
i160-201	160	240	24	NPs	6923
i160-202	160	240	24	Ps	6930
i160-203	160	240	24	Ps	7243
i160-204	160	240	24	Ps	7068
i160-205	160	240	24	Ps	7122
i160-211	160	812	24	NPm	5583
i160-212	160	812	24	NPm	5643
i160-213	160	812	24	NPm	5647
i160-214	160	812	24	NPm	5720
i160-215	160	812	24	NPm	5518
i160-221	160	12720	24	Pm	4729
i160-222	160	12720	24	Pm	4697
i160-223	160	12720	24	Pm	4730
i160-224	160	12720	24	Pm	4721
i160-225	160	12720	24	Pm	4728
i160-231	160	320	24	Ps	6662
i160-232	160	320	24	NPs	6558
i160-233	160	320	24	Ps	6339
i160-234	160	320	24	Ps	6594
i160-235	160	320	24	Ps	6764
i160-241	160	2544	24	NPh	5086
i160-242	160	2544	24	NPh	5106
i160-243	160	2544	24	NPm	5050
i160-244	160	2544	24	NPm	5076
i160-245	160	2544	24	NPm	5084
i160-301	160	240	40	Ps	11816
i160-302	160	240	40	Ps	11497
i160-303	160	240	40	Ps	11445
i160-304	160	240	40	Ps	11448
i160-305	160	240	40	NPs	11423
i160-311	160	812	40	NPm	9135
i160-312	160	812	40	NPm	9052
i160-313	160	812	40	NPh	9159
i160-314	160	812	40	NPm	8941
i160-315	160	812	40	NPm	9086
i160-321	160	12720	40	Pm	7876
i160-322	160	12720	40	NPm	7859
i160-323	160	12720	40	Pm	7876
i160-324	160	12720	40	NPm	7884
i160-325	160	12720	40	NPm	7862
i160-331	160	320	40	Ps	10414
i160-332	160	320	40	NPs	10806
i160-333	160	320	40	Ps	10561
i160-334	160	320	40	Ps	10327
i160-335	160	320	40	Ps	10589
i160-341	160	2544	40	NPh	8331
i160-342	160	2544	40	NPd	8348
i160-343	160	2544	40	NPh	8275
i160-344	160	2544	40	NPh	8307
i160-345	160	2544	40	NPh	8327

Table 9: Incidence instances from [13, 18]

Name	V	E	T	D	Opt
i320-001	320	480	8	Ps	2672
i320-002	320	480	8	Ps	2847
i320-003	320	480	8	Ps	2972
i320-004	320	480	8	Ps	2905
i320-005	320	480	8	Ps	2991
i320-011	320	1845	8	NPs	2053
i320-012	320	1845	8	Ps	1997
i320-013	320	1845	8	Ps	2072
i320-014	320	1845	8	NPs	2061
i320-015	320	1845	8	NPs	2059
i320-021	320	51040	8	Lm	1553
i320-022	320	51040	8	Pm	1565
i320-023	320	51040	8	Pm	1549
i320-024	320	51040	8	Pm	1553
i320-025	320	51040	8	Pm	1550
i320-031	320	640	8	NPs	2673
i320-032	320	640	8	NPs	2770
i320-033	320	640	8	Ps	2769
i320-034	320	640	8	Ps	2521
i320-035	320	640	8	Ps	2385
i320-041	320	10208	8	Ps	1707
i320-042	320	10208	8	Ps	1682
i320-043	320	10208	8	NPm	1723
i320-044	320	10208	8	Ps	1681
i320-045	320	10208	8	Ps	1686
i320-101	320	480	17	Ps	5548
i320-102	320	480	17	Ps	5556
i320-103	320	480	17	Ps	6239
i320-104	320	480	17	Ps	5703
i320-105	320	480	17	Ps	5928
i320-111	320	1845	17	NPm	4273
i320-112	320	1845	17	NPm	4213
i320-113	320	1845	17	NPm	4205
i320-114	320	1845	17	NPm	4104
i320-115	320	1845	17	NPs	4238
i320-121	320	51040	17	Pm	3321
i320-122	320	51040	17	Pm	3314
i320-123	320	51040	17	Pm	3332
i320-124	320	51040	17	Pm	3323
i320-125	320	51040	17	Pm	3340
i320-131	320	640	17	Ps	5255
i320-132	320	640	17	Ps	5052
i320-133	320	640	17	Ps	5125
i320-134	320	640	17	Ps	5272
i320-135	320	640	17	NPs	5342
i320-141	320	10208	17	NPh	3606
i320-142	320	10208	17	Pm	3567
i320-143	320	10208	17	Pm	3561
i320-144	320	10208	17	Ps	3512
i320-145	320	10208	17	NPm	3601

Name	V	E	T	D	Opt
i320-201	320	480	34	Ps	10044
i320-202	320	480	34	Ps	11223
i320-203	320	480	34	Ps	10148
i320-204	320	480	34	Ps	10275
i320-205	320	480	34	NPs	10573
i320-211	320	1845	34	NPm	8039
i320-212	320	1845	34	NPm	8044
i320-213	320	1845	34	NPm	7984
i320-214	320	1845	34	NPm	8046
i320-215	320	1845	34	NPh	8015
i320-221	320	51040	34	NPh	6679
i320-222	320	51040	34	NPh	6686
i320-223	320	51040	34	NPm	6695
i320-224	320	51040	34	NPm	6694
i320-225	320	51040	34	NPm	6691
i320-231	320	640	34	NPs	9862
i320-232	320	640	34	NPs	9933
i320-233	320	640	34	Ps	9787
i320-234	320	640	34	Ps	9517
i320-235	320	640	34	Ps	9945
i320-241	320	10208	34	NPh	7027
i320-242	320	10208	34	NPh	7072
i320-243	320	10208	34	NPh	7044
i320-244	320	10208	34	NPh	7078
i320-245	320	10208	34	NPh	7046
i320-301	320	480	80	Ps	23279
i320-302	320	480	80	Ps	23387
i320-303	320	480	80	Ps	22693
i320-304	320	480	80	Ps	23451
i320-305	320	480	80	NPs	22547
i320-311	320	1845	80	NPd	17945
i320-312	320	1845	80	NPd	18122
i320-313	320	1845	80	NPd	17991
i320-314	320	1845	80	NPd	18088
i320-315	320	1845	80	NPd	17987
i320-321	320	51040	80	NPh	15648
i320-322	320	51040	80	NPh	15646
i320-323	320	51040	80	NPh	15654
i320-324	320	51040	80	NPh	15667
i320-325	320	51040	80	NPh	15649
i320-331	320	640	80	NPs	21517
i320-332	320	640	80	NPs	21674
i320-333	320	640	80	NPs	21339
i320-334	320	640	80	Ps	21415
i320-335	320	640	80	NPs	21378
i320-341	320	10208	80	NPh	16296
i320-342	320	10208	80	NPh	16228
i320-343	320	10208	80	NPh	16281
i320-344	320	10208	80	NPh	16295
i320-345	320	10208	80	NPh	16289

Table 10: Incidence instances from [13, 18]

Name	V	E	T	D	Opt	Name	V	E	T	D	Opt
i640-001	640	960	9	Ps	4033	i640-201	640	960	50	NPs	16079
i640-002	640	960	9	Ps	3588	i640-202	640	960	50	Ps	16324
i640-003	640	960	9	Ps	3438	i640-203	640	960	50	Ps	16124
i640-004	640	960	9	Ps	4000	i640-204	640	960	50	Ps	16239
i640-005	640	960	9	Ps	4006	i640-205	640	960	50	NPs	16616
i640-011	640	4135	9	Ps	2392	i640-211	640	4135	50	NP?	<i>12025</i>
i640-012	640	4135	9	Ps	2465	i640-212	640	4135	50	NP?	<i>11847</i>
i640-013	640	4135	9	Ps	2399	i640-213	640	4135	50	NP?	<i>11910</i>
i640-014	640	4135	9	Ps	2171	i640-214	640	4135	50	NP?	<i>11898</i>
i640-015	640	4135	9	NPs	2347	i640-215	640	4135	50	NP?	<i>12141</i>
i640-021	640	204480	9	Ph	1749	i640-221	640	204480	50	??	<i>9917</i>
i640-022	640	204480	9	??	<i>1671</i>	i640-222	640	204480	50	??	<i>9957</i>
i640-023	640	204480	9	Pm	1754	i640-223	640	204480	50	??	<i>9927</i>
i640-024	640	204480	9	??	<i>1768</i>	i640-224	640	204480	50	??	<i>9938</i>
i640-025	640	204480	9	Pm	1745	i640-225	640	204480	50	??	<i>9933</i>
i640-031	640	1280	9	Ps	3278	i640-231	640	1280	50	NPm	15014
i640-032	640	1280	9	Ps	3187	i640-232	640	1280	50	NPs	14630
i640-033	640	1280	9	Ps	3260	i640-233	640	1280	50	NPm	14797
i640-034	640	1280	9	Ps	2953	i640-234	640	1280	50	Ps	15203
i640-035	640	1280	9	Ps	3292	i640-235	640	1280	50	NPm	14803
i640-041	640	40896	9	Pm	1897	i640-241	640	40896	50	NP?	<i>10230</i>
i640-042	640	40896	9	NPm	1934	i640-242	640	40896	50	NP?	<i>10197</i>
i640-043	640	40896	9	NPm	1931	i640-243	640	40896	50	NP?	<i>10228</i>
i640-044	640	40896	9	NPm	1938	i640-244	640	40896	50	NP?	<i>10263</i>
i640-045	640	40896	9	Pm	1866	i640-245	640	40896	50	NP?	<i>10234</i>
i640-101	640	960	25	Ps	8764	i640-301	640	960	160	Ps	45005
i640-102	640	960	25	Ps	9109	i640-302	640	960	160	Ps	45736
i640-103	640	960	25	Ps	8819	i640-303	640	960	160	Ps	44922
i640-104	640	960	25	Ps	9040	i640-304	640	960	160	Ps	46233
i640-105	640	960	25	NPs	9623	i640-305	640	960	160	Ps	45902
i640-111	640	4135	25	NPm	6167	i640-311	640	4135	160	NP?	<i>35999</i>
i640-112	640	4135	25	NPm	6304	i640-312	640	4135	160	NP?	<i>36057</i>
i640-113	640	4135	25	NP?	<i>6298</i>	i640-313	640	4135	160	NP?	<i>35654</i>
i640-114	640	4135	25	NPm	6308	i640-314	640	4135	160	NP?	<i>35699</i>
i640-115	640	4135	25	NPh	6217	i640-315	640	4135	160	NP?	<i>36003</i>
i640-121	640	204480	25	?m	4906	i640-321	640	204480	160	??	<i>31394</i>
i640-122	640	204480	25	??	<i>4976</i>	i640-322	640	204480	160	??	<i>31353</i>
i640-123	640	204480	25	??	<i>4942</i>	i640-323	640	204480	160	??	<i>31349</i>
i640-124	640	204480	25	??	<i>4955</i>	i640-324	640	204480	160	??	<i>31613</i>
i640-125	640	204480	25	??	<i>4958</i>	i640-325	640	204480	160	??	<i>31380</i>
i640-131	640	1280	25	Ps	8097	i640-331	640	1280	160	NPm	42796
i640-132	640	1280	25	NPs	8154	i640-332	640	1280	160	NPm	42548
i640-133	640	1280	25	Ps	8021	i640-333	640	1280	160	NPm	42345
i640-134	640	1280	25	Ps	7754	i640-334	640	1280	160	NP?	<i>36960</i>
i640-135	640	1280	25	NPs	7696	i640-335	640	1280	160	NPm	43035
i640-141	640	40896	25	NP?	<i>5203</i>	i640-341	640	40896	160	NP?	<i>32128</i>
i640-142	640	40896	25	NP?	<i>5193</i>	i640-342	640	40896	160	NP?	<i>32065</i>
i640-143	640	40896	25	NP?	<i>5194</i>	i640-343	640	40896	160	NP?	<i>32068</i>
i640-144	640	40896	25	NP?	<i>5218</i>	i640-344	640	40896	160	NP?	<i>32097</i>
i640-145	640	40896	25	NP?	<i>5218</i>	i640-345	640	40896	160	NP?	<i>32074</i>

Table 11: Incidence instances from [13, 18]

graph G we have chosen the underlying grid graph restricted to the minimal enclosing rectangle of the terminal set. The distance of two neighbored grid points in horizontal and vertical direction differ for these circuits. This results in different edge costs for horizontal and vertical edges in G .

In the library *SteinLib* we put instances with terminal sets whose cardinality is at least 10. The examples are distinguished by the name of the circuit followed by the index of the terminal set. For example *msm1234* means that the instance is defined by terminal set 1234 of circuit *msm*. As test problem instances we have chosen for each circuit all instances whose two leading non-zeros of the index of the terminal set differ from the two leading non-zeros of all other indices. If there is more than one index with the same two leading non-zeros we have chosen the instance with the smallest index (for instance among examples *msm3727*, *msm3731*, *msm3761*, *msm3786* we have chosen *msm3727*). In addition, we added an instance with the smallest and largest number of terminals for each circuit. Finally, we extended the original test set as introduced in [35] by ten additional instances from the large circuits *alue* and *alut* that contain a large number of terminals. All together we obtain 126 different VLSI test instances.

In Table 19 some instances are shown that we recently obtained from Lin [41]. These instances have their origin in VLSI design and are derived from the placement of rectangular blocks in a 2D plane.

The instances starting with ‘mc’ in Table 20 are generated by Margot [45]. They were randomly generated, either on a grid graph or a complete graph, and were selected as they turned out to be difficult for the branch-and-cut algorithm written by Margot at that time. Table 21 shows some instances on a complete graph with Euclidean weights. Instance *brasil58* was introduced in [22], whereas *berlin52* and *world666* are taken from the TSP library, where some nodes are randomly defined as terminals. Modifying data from the TSP library has been done by Verhoeven [57, 58], too. He uses k -th order Delaunay graphs to derive Steiner tree problem instances from TSP instances. Two data sets are developed called F data (with $n = 783, 1000, m \leq 184597$, and $t = \frac{3n}{20}, \frac{5n}{20}, \frac{7n}{20}$) and G data (with $n \leq 18512, m \leq 325093$, and $t = \frac{3n}{20}, \frac{5n}{20}, \frac{7n}{20}$) with 24 and 18 instances, respectively. More instances from the TSP library appear in Table 27 in connection with metrical Steiner tree problems.

A data generation scheme used quite frequently for producing generalized Steiner problems, see Section 5, goes back to [68]. For the construction of a graph with n nodes he proceeds as follows. The n nodes are randomly distributed over a rectangular grid with integer coordinates (the size of the grid may be specified by the user). Then the distance $d(i, j)$ between any two nodes i and j may be either the Euclidean metric or chosen from the interval $(0, \max L]$ from a uniform random distribution (of course other ideas might be investigated as well) where $\max L \leq \sqrt{2}n$ is the maximum possible Euclidean distance between any two nodes in the grid.

In both models for defining the distance an edge probability

$$P[(i, j)] = \beta \cdot \exp \frac{-d(i, j)}{\max L \cdot \alpha}$$

Name	$ V $	$ E $	$ T $	D	Opt
alue2087	1244	1971	34	Ps	1049
alue2105	1220	1858	34	Ps	1032
alue3146	3626	5869	64	NPs	2240
alue5067	3524	5560	68	Nm	2586
alue5345	5179	8165	68	NPm	3507
alue5623	4472	6938	68	NPm	3413
alue5901	11543	18429	68	Pm	3912
alue6179	3372	5213	67	NPm	2452
alue6457	3932	6137	68	Pm	3057
alue6735	4119	6696	68	Pm	2696
alue6951	2818	4419	67	Pm	2386
alue7065	34046	54841	544	Pd	23881
alue7066	6405	10454	16	Ph	2256
alue7080	34479	55494	2344	NPd	62449
alue7229	940	1474	34	Ps	824

Table 12: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
alut0787	1160	2089	34	Ps	982
alut0805	966	1666	34	Ps	958
alut1181	3041	5693	64	Pm	2353
alut2010	6104	11011	68	Pm	3307
alut2288	9070	16595	68	NPm	3843
alut2566	5021	9055	68	NPm	3073
alut2610	33901	62816	204	Pd	12239
alut2625	36711	68117	879	NPw	35459
alut2764	387	626	34	Ls	640

Table 13: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
diw0234	5349	10086	25	Pm	1996
diw0250	353	608	11	Ls	350
diw0260	539	985	12	Ls	468
diw0313	468	822	14	Ls	397
diw0393	212	381	11	Ls	302
diw0445	1804	3311	33	Ps	1363
diw0459	3636	6789	25	Ls	1362
diw0460	339	579	13	Ls	345
diw0473	2213	4135	25	Ps	1098
diw0487	2414	4386	25	Ps	1424
diw0495	938	1655	10	Ls	616
diw0513	918	1684	10	Ls	604
diw0523	1080	2015	10	Ls	561
diw0540	286	465	10	Ls	374
diw0559	3738	7013	18	Ps	1570
diw0778	7231	13727	24	Ps	2173
diw0779	11821	22516	50	NPh	4440
diw0795	3221	5938	10	Pm	1550
diw0801	3023	5575	10	Pm	1587
diw0819	10553	20066	32	Ph	3399
diw0820	11749	22384	37	Ph	4167

Table 14: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
dmxa0296	233	386	12	Ls	344
dmxa0368	2050	3676	18	Ps	1017
dmxa0454	1848	3286	16	Ls	914
dmxa0628	169	280	10	Ls	275
dmxa0734	663	1154	11	Ls	506
dmxa0848	499	861	16	Ps	594
dmxa0903	632	1087	10	Ps	580
dmxa1010	3983	7108	23	Ls	1488
dmxa1109	343	559	17	Ps	454
dmxa1200	770	1383	21	Ps	750
dmxa1304	298	503	10	Ls	311
dmxa1516	720	1269	11	Ls	508
dmxa1721	1005	1731	18	Ps	780
dmxa1801	2333	4137	17	Pm	1365

Table 15: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
msm0580	338	541	11	Ps	467
msm0654	1290	2270	10	Ls	823
msm0709	1442	2403	16	Ls	884
msm0920	752	1264	26	Ps	806
msm1008	402	695	11	Ps	494
msm1234	933	1632	13	Ps	550
msm1477	1199	2078	31	Ps	1068
msm1707	278	478	11	Ls	564
msm1844	90	135	10	Ps	188
msm1931	875	1522	10	Ps	604
msm2000	898	1562	10	Ls	594
msm2152	2132	3702	37	Ps	1590
msm2326	418	723	14	Ps	399
msm2492	4045	7094	12	Ps	1459
msm2525	3031	5239	12	Ps	1290
msm2601	2961	5100	16	Ps	1440
msm2705	1359	2458	13	Ps	714
msm2802	1709	2963	18	Ps	926
msm2846	3263	5783	89	NPm	3135
msm3277	1704	2991	12	Ls	869
msm3676	957	1554	10	Ls	607
msm3727	4640	8255	21	Ls	1376
msm3829	4221	7255	12	Pm	1571
msm4038	237	390	11	Ls	353
msm4114	402	690	16	Ls	393
msm4190	391	666	16	Ls	381
msm4224	191	302	11	Ls	311
msm4312	5181	8893	10	Pm	2016
msm4414	317	476	11	Ls	408
msm4515	777	1358	13	Ps	630

Table 16: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
gap1307	342	552	17	Ls	549
gap1413	541	906	10	Ls	457
gap1500	220	374	17	Ls	254
gap1810	429	702	17	Ls	482
gap1904	735	1256	21	Ps	763
gap2007	2039	3548	17	NPs	1104
gap2119	1724	2975	29	Ls	1244
gap2740	1196	2084	14	Ps	745
gap2800	386	653	12	Ls	386
gap2975	179	293	10	Ls	245
gap3036	346	583	13	Ps	457
gap3100	921	1558	11	Ps	640
gap3128	10393	18043	104	Pm	4292

Table 17: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
taq0014	6466	11046	128	Ph	5326
taq0023	572	963	11	Ps	621
taq0365	4186	7074	22	Pm	1914
taq0377	6836	11715	136	NPh	6393
taq0431	1128	1905	13	Ps	897
taq0631	609	932	10	Ps	581
taq0739	837	1438	16	NPs	848
taq0741	712	1217	16	Ps	847
taq0751	1051	1791	16	Ps	939
taq0891	331	560	10	Ls	319
taq0903	6163	10490	130	NPh	5099
taq0910	310	514	17	Ls	370
taq0920	122	194	17	Ls	210
taq0978	777	1239	10	Ls	566

Table 18: VLSI instances from [35]

Name	$ V $	$ E $	$ T $	D	Opt
lin01	53	80	4	Ls	503
lin02	55	82	6	Ls	557
lin03	57	84	8	Ls	926
lin04	157	266	6	Ps	1239
lin05	160	269	9	Ls	1703
lin06	165	274	14	Ls	1348
lin07	307	526	6	Ps	1885
lin08	311	530	10	Ps	2248
lin09	313	532	12	Ps	2752
lin10	321	540	20	Ps	4132
lin11	816	1460	10	Ps	4280
lin12	818	1462	12	Ps	5250
lin13	822	1466	16	Ps	4609
lin14	828	1472	22	Ps	5824
lin15	840	1484	34	Ps	7145
lin16	1981	3633	12	Pm	6618
lin17	1989	3641	20	Pm	8405
lin18	1994	3646	25	NPm	9714
lin19	2010	3662	41	Pm	13268
lin20	3675	6709	11	Pm	6673
lin21	3683	6717	20	Pm	9143
lin22	3692	6726	28	Pm	10519
lin23	3716	6750	52	Ph	17560
lin24	7998	14734	16	Pd	15076
lin25	8007	14743	24	Pd	17803
lin26	8013	14749	30	Pm	21757
lin27	8017	14753	36	NPd	20678
lin28	8062	14798	81	Nd	32584
lin29	19083	35636	24	Nd	23765
lin30	19091	35644	31	Ph	27684
lin31	19100	35653	40	??	<i>33435</i>
lin32	19112	35665	53	??	<i>41456</i>
lin33	19177	35730	117	??	<i>58313</i>
lin34	38282	71521	34	??	<i>47234</i>
lin35	38294	71533	45	??	<i>52793</i>
lin36	38307	71546	58	??	<i>58366</i>
lin37	38418	71657	172	??	<i>102874</i>

Table 19: VLSI instances from [41]

Name	$ V $	$ E $	$ T $	D	Opt
mc11	400	760	213	Ps	11689
mc13	150	11175	80	NPm	92
mc2	120	7140	60	NPs	71
mc3	97	4656	45	NPs	47
mc7	400	760	170	Ps	3417
mc8	400	760	188	Ps	1566

Table 20: Instances of F. Margot

Name	$ V $	$ E $	$ T $	D	Opt
berlin52	52	1326	16	Ps	1044
brasil58	58	1653	25	Ps	13655
world666	666	221445	174	Ps	122467

Table 21: Complete Instances

is given indicating the probability that edge (i, j) is included in the graph. The probability uses parameters α and β from $(0, 1]$ to control the density of the graph. That is, β is used for the overall density while α is used to control the proportion of edges with a smaller distance and those with a longer distance. Finally, edge weights for those edges generated are chosen according to one of the above distance models. With this procedure Steiner tree problem instances are generated.

Other sources for Steiner tree problem instances in graphs are, e.g., [11, 46, 51, 60, 71]. These instances are, like the TSP instances of Verhoeven [57, 58], no longer available or are just too simple.

The test data of [11] were randomly generated graphs with 100 nodes, real valued edge weights, a density (i.e., ratio of actual edges to the maximum number of possible edges) of $\frac{1}{2}$, $\frac{3}{4}$, and 1 as well as $t \in \{30, 50, 80\}$. Unfortunately, these instances are no longer available.

The problem instances of [46] were randomly generated with up to 110 nodes. Edges were generated with Euclidean or rectilinear distances so that they fulfill a so-called non-adjacency condition, i.e., no two Steiner nodes are connected with each other.

In [51] random graphs with pre-specified numbers of nodes n have been generated as follows. Two probabilities are fixed, p_e for the probability that an edge exists between any two nodes, and p_t for the probability that a node is specified as a terminal. Under the assumption that only connected graphs will be considered, real edge weights are assigned either uniformly distributed in the range $(0, 1]$ or by a normal distribution with mean 0.5 and standard deviation 0.125. This data generation routine was used and extended by [60, 71]. Furthermore, in both papers randomly generated instances with Euclidean and rectilinear distances were considered.

4 Metrical Steiner Tree Problems Representable in Graphs

Many applications of the Steiner tree problem require the connection of a given set of basic nodes within a metric space. Examples are Euclidean distances, rectilinear distances (building design) or the Hamming metric (phylogeny).

According to Hanan [27] rectilinear Steiner tree problems may be represented as (grid) graphs according to a simple conversion routine. That is, optimal solutions for both ways of representing the data are identical. Based on the x - and y -coordinates of pre-specified or given basic nodes a grid graph

is constructed as follows. The graph is induced by the set of basic nodes by running a vertical line and a horizontal line through each basic node and retaining the finite segments between interconnections of these lines with rectilinear distances as weights.

There is a nice way to represent metrical Steiner tree problems in graphs via the concept of full Steiner trees (or sets). A *full Steiner tree (FST)* for some terminal set T is a Steiner tree for T such that the leaves of the tree are exactly the terminals. One can show that for any Steiner tree instance there is an optimal Steiner tree that can be decomposed into FSTs. Though the computation of all FSTs is difficult in general, it turns out that it often can be done very efficiently for metrical Steiner tree problems. In addition, the number of FSTs is frequently almost linear for many practical instances. Having this set of FSTs at hand we can easily set up a Steiner tree problem in a graph. We introduce nodes for the (original) terminals and for the Steiner nodes appearing in the FSTs, and we introduce edges representing the edges in the FSTs. In fact, the use of FSTs is *the* key to solve large rectilinear and Euclidean Steiner tree problems [66, 67], because in this way the size of the instances can be reduced drastically, see also Tables 23 through 27.

The series of problem instances denoted by R is taken from [54], see Table 22. These are randomly generated instances on grid graphs. Over the years various authors have contributed new best solutions for various of these instances [5, 33, 61]. In the meantime all optimal solutions are known and most instances have to be considered as easy.

5 Generalized Steiner Tree Problems and Modifications

In this section we consider some generalized Steiner tree problems and data generation schemes in that sense that they might lead to interesting instances for the original problem as well. As the number of generalized Steiner tree problems is too large to be considered comprehensively (see, e.g., [28, 59] for some references), we restrict ourselves to only very few in the following subsections.

Modifications of the Steiner tree problem in graphs that are still hard to solve from a theoretical point of view may become easy from an algorithmic point of view. For instance, the cardinality Steiner tree problem arises when all edge weights are equal to 1. We have tested the algorithm of [35] on various problem instances and they always turn out to be easy.

5.1 Directed Steiner Tree Problems

Steiner tree problems may also be considered in directed graphs. We are given a directed graph $D = (V, A)$, a terminal set $T \subseteq V$ with one specific root node $r \in T$ and arc costs $c_a, a \in A$, and we look for an arborescence rooted at r that spans all terminals in T . It is well known that the undirected Steiner tree problem can be modeled as a directed Steiner problem by bidirecting the edges. However, there are directed instances that do not come from undirected graphs.

Name	$ V $	$ E $	$ T $	D	Opt
r01	10	12	5	Ls	187
r02	8	9	6	Ls	164
r03	16	21	7	Ls	236
r04	32	48	8	Ps	254
r05	8	9	6	Ls	226
r06	20	30	12	Ls	242
r07	21	31	12	Ls	248
r08	20	29	12	Ps	236
r09	11	14	7	Ls	164
r10	17	22	6	Ls	177
r11	11	11	6	Ls	144
r12	21	30	9	Ls	180
r13	27	41	9	Ps	150
r14	36	60	12	Ls	260
r15	50	80	14	Ps	148
r16	5	4	3	Ls	160
r17	28	42	10	Ps	200
r18	180	333	62	Ps	404
r19	61	96	14	Ps	188
r20	4	3	3	Ls	112
r21	9	10	5	Ls	192
r22	8	8	4	Ls	63
r23	8	8	4	Ls	65

Name	$ V $	$ E $	$ T $	D	Opt
r24	8	8	4	Ls	30
r25	5	4	3	Ls	23
r26	5	4	3	Ls	15
r27	8	8	4	Ls	133
r28	7	7	4	Ls	24
r29	5	4	3	Ls	200
r30	20	29	12	Ps	110
r31	79	135	14	Ps	259
r32	148	267	19	Ps	313
r33	132	241	18	Ps	268
r34	194	355	19	Ps	241
r35	142	253	18	Ps	151
r36	4	3	4	Ls	90
r37	19	24	8	Ls	90
r38	64	108	14	Ps	166
r39	64	108	14	Ps	166
r40	42	68	10	Ps	155
r41	118	211	20	Ps	224
r42	40	62	15	Ps	153
r43	129	230	16	Ps	255
r44	140	252	17	Ps	252
r45	200	367	19	Ps	220
r46	16	24	16	Ls	150

Table 22: Instances from [54]

Name	V	E	T	D	Opt
es10fst01	18	20	10	?s	22920745
es10fst02	14	13	10	?s	19134104
es10fst03	17	20	10	?s	26003678
es10fst04	18	20	10	?s	20461116
es10fst05	12	11	10	?s	18818916
es10fst06	17	20	10	?s	26540768
es10fst07	14	13	10	?s	26025072
es10fst08	21	28	10	?s	25056214
es10fst09	21	29	10	?s	22062355
es10fst10	18	21	10	?s	23936095
es10fst11	14	13	10	?s	22239535
es10fst12	13	12	10	?s	19626318
es10fst13	18	21	10	?s	19483914
es10fst14	24	32	10	?s	21856128
es10fst15	16	18	10	?s	18641924

Name	V	E	T	D	Opt
es20fst01	29	28	20	?s	33703886
es20fst02	29	28	20	?s	32639486
es20fst03	27	26	20	?s	27847417
es20fst04	57	83	20	?s	27624394
es20fst05	54	77	20	?s	34033163
es20fst06	29	28	20	?s	36014241
es20fst07	45	59	20	?s	34934874
es20fst08	52	74	20	?s	38016346
es20fst09	36	42	20	?s	36739939
es20fst10	49	67	20	?s	34024740
es20fst11	33	36	20	?s	27123908
es20fst12	33	36	20	?s	30451397
es20fst13	35	40	20	?s	34438673
es20fst14	36	44	20	?s	34062374
es20fst15	37	43	20	?s	32303746

Name	V	E	T	D	Opt
es30fst01	79	115	30	?s	40692993
es30fst02	71	97	30	?s	40900061
es30fst03	83	120	30	?s	43120444
es30fst04	80	115	30	?s	42150958
es30fst05	58	71	30	?s	41739748
es30fst06	83	119	30	?s	39955139
es30fst07	53	64	30	?s	43761391
es30fst08	69	93	30	?s	41691217
es30fst09	43	44	30	?s	37133658
es30fst10	48	52	30	?s	42686610
es30fst11	79	112	30	?s	41647993
es30fst12	46	48	30	?s	38416720
es30fst13	65	84	30	?s	37406646
es30fst14	53	58	30	?s	42897025
es30fst15	118	188	30	?s	43035576

Name	V	E	T	D	Opt
es40fst01	93	127	40	?s	44841522
es40fst02	82	105	40	?s	46811310
es40fst03	87	116	40	?s	49974157
es40fst04	55	55	40	?s	45289864
es40fst05	121	180	40	?s	51940413
es40fst06	92	123	40	?s	49753385
es40fst07	77	95	40	?s	45639009
es40fst08	98	137	40	?s	48745996
es40fst09	107	153	40	?s	51761789
es40fst10	107	152	40	?s	57136852
es40fst11	97	135	40	?s	46734214
es40fst12	67	75	40	?s	43843378
es40fst13	78	95	40	?s	51884545
es40fst14	98	134	40	?s	49166952
es40fst15	93	129	40	?s	50828067

Name	V	E	T	D	Opt
es50fst01	118	160	50	?s	54948660
es50fst02	125	177	50	?s	55484245
es50fst03	128	182	50	?s	54691035
es50fst04	106	138	50	?s	51535766
es50fst05	104	135	50	?s	55186015
es50fst06	126	182	50	?s	55804287
es50fst07	143	211	50	?s	49961178
es50fst08	83	96	50	?s	53754708
es50fst09	139	202	50	?s	53456773
es50fst10	139	207	50	?s	54037963
es50fst11	100	131	50	?s	52532923
es50fst12	110	149	50	?s	53409291
es50fst13	92	116	50	?s	53891019
es50fst14	120	167	50	?s	53551419
es50fst15	112	147	50	?s	52180862

Name	V	E	T	D	Opt
es60fst01	123	159	60	?s	53761423
es60fst02	186	280	60	?s	55367804
es60fst03	113	142	60	?s	56566797
es60fst04	162	238	60	?s	55371042
es60fst05	119	148	60	?s	54704991
es60fst06	130	174	60	?s	60421961
es60fst07	188	280	60	?s	58978041
es60fst08	109	133	60	?s	58138178
es60fst09	151	216	60	?s	55877112
es60fst10	133	177	60	?s	57624488
es60fst11	121	154	60	?s	56141666
es60fst12	176	257	60	?s	59791362
es60fst13	157	226	60	?s	61213533
es60fst14	118	149	60	?s	56035528
es60fst15	117	151	60	?s	56622581

Table 23: FST preprocessed instances by [67]

Name	V	E	T	D	Opt
es70fst01	154	209	70	?s	62058863
es70fst02	147	197	70	?s	60928488
es70fst03	181	264	70	?s	61934664
es70fst04	167	231	70	?s	62938583
es70fst05	169	231	70	?s	62256993
es70fst06	187	268	70	?s	62124528
es70fst07	167	230	70	?s	62223666
es70fst08	209	314	70	?s	61872849
es70fst09	161	220	70	?s	62986133
es70fst10	165	225	70	?s	62511830
es70fst11	177	254	70	?s	66455760
es70fst12	142	181	70	?s	63047132
es70fst13	160	219	70	?s	62912258
es70fst14	143	184	70	?s	60411124
es70fst15	178	251	70	?s	62318458

Name	V	E	T	D	Opt
es80fst01	187	255	80	?s	70927442
es80fst02	183	249	80	?s	65273810
es80fst03	189	261	80	?s	65332546
es80fst04	198	280	80	?s	64193446
es80fst05	172	228	80	?s	66350529
es80fst06	172	224	80	?s	71007444
es80fst07	193	271	80	?s	68228475
es80fst08	217	306	80	?s	67452377
es80fst09	236	343	80	?s	69825651
es80fst10	156	197	80	?s	65497988
es80fst11	209	295	80	?s	66283099
es80fst12	147	180	80	?s	65070089
es80fst13	164	211	80	?s	68022647
es80fst14	209	297	80	?s	70077902
es80fst15	197	282	80	?s	69939071

Name	V	E	T	D	Opt
es90fst01	181	231	90	?s	68350357
es90fst02	221	313	90	?s	71294845
es90fst03	284	430	90	?s	74817473
es90fst04	217	299	90	?s	70910063
es90fst05	190	254	90	?s	71831224
es90fst06	215	290	90	?s	68640346
es90fst07	175	221	90	?s	72036885
es90fst08	234	332	90	?s	72341668
es90fst09	234	331	90	?s	67856007
es90fst10	246	356	90	?s	72310409
es90fst11	225	323	90	?s	72310039
es90fst12	207	284	90	?s	69367257
es90fst13	240	349	90	?s	72810663
es90fst14	185	243	90	?s	69188992
es90fst15	207	286	90	?s	71778294

Name	V	E	T	D	Opt
es100fst01	250	354	100	?s	72522165
es100fst02	339	522	100	?s	75176630
es100fst03	189	233	100	?s	72746006
es100fst04	188	235	100	?s	74342392
es100fst05	188	238	100	?s	75670198
es100fst06	301	452	100	?s	74414990
es100fst07	276	401	100	?s	77740576
es100fst08	210	276	100	?s	73033178
es100fst09	248	342	100	?s	77952027
es100fst10	229	312	100	?s	75952202
es100fst11	253	362	100	?s	78674859
es100fst12	266	385	100	?s	76131099
es100fst13	254	361	100	?s	74604990
es100fst14	198	253	100	?s	78632795
es100fst15	231	319	100	?s	70446493

Name	V	E	T	D	Opt
es250fst01	623	876	250	?s	116609813
es250fst02	542	719	250	?s	115150079
es250fst03	543	727	250	?s	114650399
es250fst04	604	842	250	?s	117819530
es250fst05	596	832	250	?s	116927089
es250fst06	596	824	250	?s	116256250
es250fst07	585	799	250	?s	115277351
es250fst08	657	947	250	?s	116833323
es250fst09	570	770	250	?s	116821988
es250fst10	662	951	250	?s	116857628
es250fst11	661	952	250	?s	112889613
es250fst12	619	872	250	?s	119035256
es250fst13	684	993	250	?s	116049496
es250fst14	710	1046	250	?s	116188791
es250fst15	713	1053	250	?s	115558198

Name	V	E	T	D	Opt
es500fst01	1250	1763	500	?s	162978810
es500fst02	1408	2056	500	?s	160756854
es500fst03	1337	1933	500	?s	162664661
es500fst04	1296	1879	500	?s	164110997
es500fst05	1172	1627	500	?s	160586161
es500fst06	1335	1932	500	?s	164685074
es500fst07	1214	1700	500	?s	160124233
es500fst08	1349	1972	500	?s	161248138
es500fst09	1294	1853	500	?s	162100435
es500fst10	1203	1679	500	?s	155581203
es500fst11	1274	1808	500	?s	161674316
es500fst12	1322	1918	500	?s	164009591
es500fst13	1273	1814	500	?s	161324201
es500fst14	1477	2204	500	?s	165984329
es500fst15	1334	1927	500	?s	160758467

Table 24: FST preprocessed instances by [67]

Name	V	E	T	D	Opt
es1000fst01	2865	4267	1000	?m	230535806
es1000fst02	2629	3793	1000	?s	227886471
es1000fst03	2762	4047	1000	?s	227807756
es1000fst04	2778	4083	1000	?s	230200846
es1000fst05	2676	3894	1000	?s	228330602
es1000fst06	2815	4162	1000	?m	231028456
es1000fst07	2604	3756	1000	?s	230945623
es1000fst08	2834	4207	1000	?m	230639115
es1000fst09	2846	4187	1000	?s	227745838
es1000fst10	2546	3620	1000	?s	229267101
es1000fst11	2763	4038	1000	?s	231605619
es1000fst12	2984	4484	1000	?s	230904712
es1000fst13	2532	3615	1000	?s	228031092
es1000fst14	2840	4200	1000	?m	234318491
es1000fst15	2733	3997	1000	?s	229965775

Table 25: FST preprocessed instances by [67]

Name	V	E	T	D	Opt
es10000fst01	27019	39407	10000	NPw	716174280

Table 26: FST preprocessed instances by [67]

Name	V	E	T	D	Opt	Name	V	E	T	D	Opt
a280fst	314	328	280	?s	2502	pla7397fst	8790	9815	7397	?m	22481625
att48fst	139	202	48	?s	30236	pr1002fst	1473	1715	1002	?s	243176
att532fst	1468	2152	532	?m	84009	pr107fst	111	110	107	?s	34850
berlin52fst	89	104	52	?s	6760	pr124fst	154	165	124	?s	52759
bier127fst	258	357	127	?s	104284	pr136fst	196	250	136	?s	86811
d1291fst	1365	1456	1291	?s	481421	pr144fst	221	285	144	?s	52925
d1655fst	1906	2083	1655	?s	584948	pr152fst	308	431	152	?s	64323
d198fst	232	256	198	?s	129175	pr226fst	255	269	226	?s	70700
d2103fst	2206	2272	2103	?s	769797	pr2392fst	3398	3966	2392	?s	358989
d493fst	1055	1473	493	?m	320137	pr264fst	280	287	264	?s	41400
d657fst	1416	1978	657	?m	471589	pr299fst	420	500	299	?s	44671
dsj1000fst	2562	3655	1000	?s	17564659	pr439fst	572	662	439	?s	97400
eil101fst	330	538	101	?s	605	pr76fst	168	247	76	?s	95908
eil51fst	181	289	51	?s	409	rat195fst	560	870	195	?s	2386
eil76fst	237	378	76	?s	513	rat575fst	1986	3176	575	?s	6808
fl1400fst	2694	4546	1400	NP?	<i>18004178</i>	rat783fst	2397	3715	783	?m	8883
fl1577fst	2413	3412	1577	?m	19825626	rat99fst	269	399	99	?s	1225
fl3795fst	4859	6539	3795	NP?	<i>12704393</i>	rd100fst	201	253	100	?s	764269099
fl417fst	732	1084	417	?s	10883190	rd400fst	1001	1419	400	?s	1490972006
fnl4461fst	17127	27352	4461	??	<i>154038</i>	rll1849fst	13963	15315	11849	?h	8779590
gil262fst	537	723	262	?s	2306	rll304fst	1562	1694	1304	?s	236649
kroA100fst	197	250	100	?s	20401	rll323fst	1598	1750	1323	?s	253620
kroA150fst	389	562	150	?s	25700	rll889fst	2382	2674	1889	?s	295208
kroA200fst	500	714	200	?s	28652	rl5915fst	6569	6980	5915	?m	533226
kroB100fst	230	313	100	?s	21211	rl5934fst	6827	7365	5934	?m	529890
kroB150fst	420	619	150	?s	25217	st70fst	133	169	70	?s	626
kroB200fst	480	670	200	?s	28803	ts225fst	225	224	225	?s	1120
kroC100fst	244	337	100	?s	20492	tsp225fst	242	252	225	?s	356850
kroD100fst	216	288	100	?s	20437	u1060fst	1835	2429	1060	?m	21265372
kroE100fst	226	306	100	?s	21245	u1432fst	1432	1431	1432	?s	1465
lin105fst	216	323	105	?s	13429	u159fst	184	186	159	?s	390
lin318fst	678	1030	318	?s	39335	u1817fst	1831	1846	1817	?s	5513053
linhp318fst	678	1030	318	?s	39335	u2152fst	2167	2184	2152	?s	6253305
nrw1379fst	5096	8105	1379	?h	56207	u2319fst	2319	2318	2319	?s	2322
p654fst	777	867	654	?s	314925	u574fst	990	1258	574	?s	3509275
pcb1173fst	1912	2223	1173	?s	53301	u724fst	1180	1537	724	?s	4069628
pcb3038fst	5829	7552	3038	?m	131895	vm1084fst	1679	2058	1084	?s	2248390
pcb442fst	503	531	442	?s	47675	vm1748fst	2856	3641	1748	?s	3194670

Table 27: FST preprocessed TSPLIB instances by [67]

Name	$ V $	$ E $	$ T $	D	Opt
gene181	267	355	25	Ps	88
gene1	267	355	25	Ps	88
gene425	425	554	86	Ps	214
gene42	335	456	43	Ps	126
gene442	442	594	86	Ps	207
gene575	575	824	86	Ps	207
gene602	602	858	86	Ps	209
gene61a	395	512	82	Ps	205
gene61b	570	808	82	Ps	199
gene61c	549	790	82	Ps	196
gene61f	412	552	82	Ps	198

Table 28: Genetic instances from [31]

Table 28 shows such instances arising from problems in genetics [31]. Other examples result from modeling set covering problems as Steiner tree problems.

5.2 Multicast Routing

A great variety of generalizations of the Steiner tree problem may be found in the telecommunications industry such as multicast routing or multi-point problems. For instance, the underlying graph may represent a network for the transport of information between a single source and some destinations such that the (weighted) length of the paths used for this transport is somehow limited (see, e.g., multicast routing or the Steiner tree problem with hop constraints [62, 25]).

Of course additional values need to be defined regarding multicast routing or delay constraints (see, e.g., [68, 9, 23, 42]).

5.3 The Group Steiner Tree Problem

The group Steiner tree problem in graphs is a generalization of the Steiner tree problem where the assumption to connect given fixed basic nodes is relaxed. Instead of basic nodes some regions are considered and the objective is to find a tree of minimum weight connecting at least one point of every region.

Given a connected undirected graph $G = (V, E)$ and g so-called basic sets $T_1, \dots, T_g \subseteq V$, the problem is to find a connected minimum cost subgraph of G such that the node set of this subgraph contains at least one node from each basic set T_i for all $1 \leq i \leq g$. This *group Steiner tree problem* can be found under different names in the literature such as *class Steiner tree problem* or *Steiner problem with basic sets*. It is considered, e.g., in [29, 47].

The data sets considered in [29] are as follows. For a given number of nodes ($n = 10, 50, 250$) a number of groups ($g = 2, \log n, \sqrt{n}, \frac{n}{2}, n$) is specified (for $n = 250$ the authors also use $g = \log^2 n$). The nodes are assigned to groups such that each group has about the same number $\frac{n}{g}$ of nodes. The number of edges is chosen to derive average node degrees of $4, \log n, \sqrt{n}, n - 1$. Starting

Name	V	E	T	D	Opt
wrp3-11	128	227	11	Ps	1100361
wrp3-12	84	149	12	Ps	1200237
wrp3-13	311	613	13	Ps	1300497
wrp3-14	128	247	14	Ps	1400250
wrp3-15	138	257	15	Ps	1500422
wrp3-16	204	374	16	Ps	1600208
wrp3-17	177	354	17	Ps	1700442
wrp3-19	189	353	19	Ps	1900439
wrp3-20	245	454	20	Ps	2000271
wrp3-21	237	444	21	Ps	2100522
wrp3-22	233	431	22	Ps	2200557
wrp3-23	132	230	23	Ps	2300245
wrp3-24	262	487	24	Ps	2400623
wrp3-25	246	468	25	Ps	2500540
wrp3-26	402	780	26	Ps	2600484
wrp3-27	370	721	27	Ps	2700502
wrp3-28	307	559	28	Ps	2800379
wrp3-29	245	436	29	Ps	2900479
wrp3-30	467	896	30	Ps	3000569
wrp3-31	323	592	31	Ps	3100635
wrp3-33	437	838	33	Ps	3300513
wrp3-34	1244	2474	34	Pm	3400646
wrp3-36	435	818	36	Ps	3600610
wrp3-37	1011	2010	37	Pm	3700485
wrp3-38	603	1207	38	Pm	3800656
wrp3-39	703	1616	39	Ph	3900450
wrp3-41	178	307	41	Ps	4100466
wrp3-42	705	1373	42	Pm	4200598
wrp3-43	173	298	43	Ps	4300457
wrp3-45	1414	2813	45	Pm	4500860
wrp3-48	925	1738	48	Pm	4800552
wrp3-49	886	1800	49	Pm	4900882
wrp3-50	1119	2251	50	NPh	5000673
wrp3-52	701	1352	52	NPm	5200825
wrp3-53	775	1471	53	Ps	5300847
wrp3-55	1645	3186	55	NPh	5500888
wrp3-56	853	1590	56	Pm	5600872
wrp3-60	838	1763	60	Ph	6001164
wrp3-62	670	1316	62	Pm	6201016
wrp3-64	1822	3610	64	Ph	6400931
wrp3-66	2521	4858	66	Ph	6600922
wrp3-67	987	1923	67	Pm	6700776
wrp3-69	856	1621	69	Pm	6900841
wrp3-70	1468	2931	70	Pm	7000890
wrp3-71	1221	2414	71	Pm	7101028
wrp3-73	1890	3613	73	Ph	7301207
wrp3-74	1019	1941	74	Pm	7400759
wrp3-75	729	1395	75	Pm	7501020
wrp3-76	1761	3370	76	Ph	7601028
wrp3-78	2346	4656	78	??	<i>7801107</i>
wrp3-79	833	1595	79	Pm	7900444
wrp3-80	1491	2831	80	Pm	8000849
wrp3-83	3168	6220	83	??	<i>8300941</i>
wrp3-84	2356	4547	84	??	<i>8401115</i>
wrp3-85	528	1017	85	NPm	8500739
wrp3-86	1360	2607	86	Pm	86000746
wrp3-88	743	1409	88	NPm	88001175
wrp3-91	1343	2594	91	Ph	91000866
wrp3-92	1765	3613	92	Ph	92000764
wrp3-94	1976	3836	94	NPh	94001181
wrp3-96	2518	4985	96	??	<i>96001202</i>
wrp3-98	2265	4545	98	??	<i>98001294</i>
wrp3-99	2076	4072	99	??	<i>99001131</i>

Name	V	E	T	D	Opt
wrp4-11	123	233	11	Ps	1100179
wrp4-13	110	188	13	Ps	1300798
wrp4-14	145	283	14	Ps	1400290
wrp4-15	193	369	15	Ps	1500405
wrp4-16	311	579	16	Ps	1601190
wrp4-17	223	404	17	Ps	1700525
wrp4-18	211	380	18	Ps	1801464
wrp4-19	119	206	19	Ps	1901446
wrp4-21	529	1032	21	Ps	2103283
wrp4-22	294	568	22	Ps	2200394
wrp4-23	257	515	23	Ps	2300376
wrp4-24	493	963	24	Ps	2403332
wrp4-25	422	808	25	Ps	2500828
wrp4-26	396	781	26	Pm	2600443
wrp4-27	243	497	27	Ps	2700441
wrp4-28	272	545	28	Ps	2800466
wrp4-29	247	505	29	Ps	2900484
wrp4-30	361	724	30	Pm	3000526
wrp4-31	390	786	31	Pm	3100526
wrp4-32	311	632	32	Ps	3200554
wrp4-33	304	571	33	Ps	3300655
wrp4-34	314	650	34	Ps	3400525
wrp4-35	471	954	35	Pm	3500601
wrp4-36	363	750	36	Pm	3600596
wrp4-37	522	1054	37	Pm	3700647
wrp4-38	294	618	38	Ps	3800606
wrp4-39	802	1553	39	Pm	3903734
wrp4-40	538	1088	40	Pm	4000758
wrp4-41	465	955	41	Pm	4100695
wrp4-42	552	1131	42	Pm	4200701
wrp4-43	596	1148	43	Ps	4301508
wrp4-44	398	788	44	NPm	4401504
wrp4-45	388	815	45	Ps	4500728
wrp4-46	632	1287	46	Pm	4600756
wrp4-47	555	1098	47	Ps	4701318
wrp4-48	451	825	48	Ps	4802220
wrp4-49	557	1080	49	Ps	4901968
wrp4-50	564	1112	50	Pm	5001625
wrp4-51	668	1306	51	Pm	5101616
wrp4-52	547	1115	52	Pm	5201081
wrp4-53	615	1232	53	Pm	5301351
wrp4-54	688	1388	54	NPm	5401534
wrp4-55	610	1201	55	Pm	5501952
wrp4-56	839	1617	56	Pm	5602299
wrp4-58	757	1493	58	Pm	5801466
wrp4-59	904	1806	59	NPm	5901592
wrp4-60	693	1370	60	Pm	6001782
wrp4-61	775	1538	61	Ps	6102210
wrp4-62	1283	2493	62	Pm	6202100
wrp4-63	1121	2227	63	Ph	6301479
wrp4-64	632	1281	64	Pm	6401996
wrp4-66	844	1691	66	Pm	6602931
wrp4-67	1518	3060	67	Pm	6702800
wrp4-68	917	1850	68	Pm	6801753
wrp4-69	574	1165	69	Ps	6902328
wrp4-70	637	1269	70	Ps	7003022
wrp4-71	802	1609	71	Pm	7102320
wrp4-72	1151	2274	72	NPm	7202807
wrp4-73	1898	3616	73	Ph	7302643
wrp4-74	802	1620	74	Pm	7402046
wrp4-75	938	1869	75	Pm	7501712
wrp4-76	766	1535	76	Pm	7602040

Table 29: VLSI Wire-Routing instances from industry

from a complete graph, edges are randomly deleted such that the graph remains connected and obtains the desired number of edges. Edge weights are either chosen to be identical or integer values randomly selected from the interval $[1, 100]$.

As the group Steiner problem is motivated by the wire routing phase in physical VLSI design, we add some real-world instances to our library. These are rectilinear instances with 30 to 84 terminal groups (see Table 29). The instances are already converted to a Steiner tree problem in graphs by introducing a pseudo-terminal for each group and connecting the terminals of the group to this pseudo-terminal by an edge with high cost. The original terminals of the group get non-terminals and the pseudo-terminals become the terminals of the Steiner tree instance.

5.4 The Prize Collecting Steiner Problem

The Steiner tree problem in graphs seeks a minimum cost tree connecting a given set of basic nodes or terminals. In various settings, however, even the basic nodes are not known beforehand. The prize-collecting Steiner problem assumes revenues for the inclusion of nodes into a solution. That is, the objective is to maximize the revenues minus the cost of the included edges. This problem has important applications in the telecommunications industry.

Problem instances in the literature are, e.g., modifications from the C and D instances from the OR-Library as well as data representing real-world networks [8, 30].

5.5 The Steiner Tree Packing Problem

As mentioned on page 8 the routing problem in VLSI design can be modeled as the problem of packing Steiner trees in certain graphs. That is we are given a capacitated graph $G = (V, E)$ with edge capacities c_e and edge weights $w_e, e \in E$, and a list of terminal sets $T_1, \dots, T_N \subseteq V$. The task is to find edge sets S_1, \dots, S_N such that each S_i is a Steiner tree for T_i ($i = 1, \dots, N$), the capacity constraints are satisfied, i. e., the number of Steiner trees using edge e is at most c_e , and the total weight of the Steiner trees, i. e., $\sum_{i=1}^N w(S_i)$, is minimized. We have added some small Steiner tree packing problems to the *SteinLib*. These instances are defined on complete rectangular grid graphs, where all terminal sets are located on the outer face. These instances have been used as benchmark test sets in the VLSI literature for the evaluation of heuristics for so-called switchbox routing problems. More information on this subject can be found in [40, 26].

6 Evaluation of the Data Set

In the last decade significant progress has been made regarding the optimal solution of the Steiner tree problem in graphs. Besides heuristics (for surveys see, e.g., [17, 63]) the most important contributions came from clever reduction

techniques (for an update of research see [14]) incorporated into branch-and-bound or branch-and-cut techniques. The currently most successful algorithms have been devised by various authors [10, 13, 35, 43, 44, 50, 56, 70]. With those algorithms most of the data described above may be solved to optimality within computation times deemed practical on up-to-date computers. (See also our difficulty classification given in the above tables.)

A remarkable horse-race happened to be undertaken on one of Beasley’s E-data, i.e., E-18. This instance turned out to be the most prominent one to be “nailed down” throughout the years [35]. Unfortunately, however, this does not allow any deep conclusions regarding the difficulty of various instances. That is, no single formula may be given to indicate whether an instance is difficult and it is not expected to find such a formula.

For metrical Steiner tree problems the key for success is the reduction of the instances by computation of full Steiner trees. Based on these reductions rectilinear instances with thousands of nodes are now tractable [66, 36, 67].

Some obvious observations are as follows. If the number of basic nodes is very small or very large then the Steiner tree problem in graphs becomes somewhat easy as the shortest path problem ($t = 2$) and the minimum spanning tree problem ($t = n$) are polynomially solvable special cases. Furthermore, for t being very small or $t \geq \frac{n}{2}$ some powerful reduction techniques are at hand to solve most of those instances to optimality, cf. [15, 16, 17, 13, 59].

7 Conclusions

In this paper we have described *SteinLib*, a library of problem instances for the Steiner tree problem in graphs. While some instances turned out to be hard for some time most of them have been solved over the years and are no longer challenging for state-of-the-art algorithms and software packages. Therefore, readers are invited to add to the library new instances, especially those that are relevant in practice and turn out to be somewhat hard to solve.

Motivated from different application areas we may obtain difficult instances that may model hard instances from other areas. Examples in this respect are set covering problem instances (see, e.g., [7]), warehouse location problem instances (see, e.g., [37]), or certain lot sizing problems (see, e.g., [20, 62]). In addition it may be of interest to construct instances that turn out to be difficult for current state-of-the-art algorithms. Ideas in this respect may consider to make problem reduction unlikely to work (see, e.g., the incidence instances) and to combine parts of instances that are difficult for one or the other algorithm, such as combining worst case instances for some heuristics (e.g., [49]) with parts that are difficult for primal or dual approaches.

As a possible idea we propose to start, e.g., from simple wheels of some size w as the one given in Figure 1 with size $w = 3$. Now we consider a cycle of size c and replace each node of the cycle by one such wheel. Two neighboring wheels are connected as follows. The non-terminal nodes of one wheel and the terminal nodes of the other build again a wheel replacing the connecting edge of the cycle. To avoid the immediate success of simple reduction techniques all

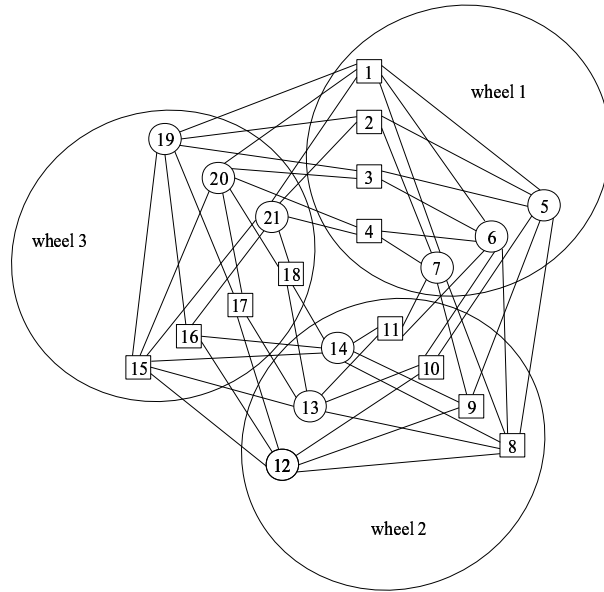


Figure 3: Cycle of wheels with $w = 3$ and $c = 3$

Name	$ V $	$ E $	$ T $	D	Opt
w13c29	783	2262	406	NP?	510
w23c23	1081	3174	552	NP?	694
w3c571	3997	10278	2284	NP?	3050

Table 30: Cycle of wheels instances

edge weights are one. In Figure 3 we provide an example for $w = 3$ and $c = 3$. In Table 30 three instances of moderate size are given as example.

Future research should consider the development of measures and criteria that may be used to determine whether problem instances are hard. Of course those instances (e.g., some of the incidence data) that turned out to be somewhat more difficult to solve should replace the by now well understood B-E data which served as an excellent benchmark for more than a decade.

Another research question refers to the development of problem generators. While different data generation schemes have been described above, optimal solutions to the resulting instances are only known once someone has nailed them down with an appropriate procedure. To avoid these so-called horse-races, it may be of interest to develop data generators that provide instances with known optimal solutions, as these might serve as benchmark instances. The only known generator in this respect [34] provides problem instances based on a mathematical programming formulation of the Steiner tree problem in graphs and the so-called Karush-Kuhn-Tucker optimality conditions. However, this generator provides instances that are easily solvable with currently known state-of-the-art software so that the development of generators providing more versatile instances is still a challenge.

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