Chapter 20
Bilevel Optimization: Theory, Algorithms, Applications and a Bibliography

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Abstract Bilevel optimization problems are hierarchical optimization problems where the feasible region of the so-called upper level problem is restricted by the graph of the solution set mapping of the lower level problem. Aim of this article is to collect a large number of references on this topic, to show the diversity of contributions and to support young colleagues who try to start research in this challenging and interesting field.

Keywords Bilevel optimization · Mathematical programs with complementarity constraints · Optimality conditions · Applications · Necessary optimality conditions · Solution algorithms · Metaheuristics · Optimistic and pessimistic bilevel optimization problems

20.1 Introduction

Bilevel optimization problems are hierarchical optimization problems of two or more players. For defining them consider first a parametric optimization problem

$$\min_y \{f(x, y) : g(x, y) \leq 0,\ \ y \in Y\}, \tag{20.1.1}$$

where $f, g_i : \mathbb{R}^m \times \mathbb{R}^n \to \mathbb{R}$, $i = 1, \dots, p$ and $Y \subseteq \mathbb{R}^n$. Here, equality constraints can be added if the regularity conditions are adapted accordingly. This is the problem of the *lower-level decision maker*, sometimes called the *follower's*

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problem. If problems with more than one decision maker in the lower level are considered, then e.g. a Nash equilibrium is searched for between them. Let

$$\varphi(x) := \min_y \{f(x, y) : g(x, y) \leq 0,\ y \in Y\} \qquad (20.1.2)$$

denote the optimal value function of problem (20.1.1) and

$$\Psi(x) := \{y \in Y : g(x, y) \leq 0,\ f(x, y) \leq \varphi(x)\} \qquad (20.1.3)$$

the solution set mapping of problem (20.1.1). If $\operatorname{gph} \Psi := \{(x, y) : y \in \Psi(x)\}$ is used to abbreviate the graph of the solution set mapping Ψ, the *bilevel optimization problem*

$$\text{'}\min_x\text{'}\{F(x, y) : G(x) \leq 0,\ (x, y) \in \operatorname{gph} \Psi,\ x \in X\} \qquad (20.1.4)$$

can be formulated with $X \subseteq \mathbb{R}^m$, $F : \mathbb{R}^m \times \mathbb{R}^n \to \mathbb{R}$, $G_j : \mathbb{R}^m \to \mathbb{R}$, $j = 1, \ldots, q$. Sometimes, this problem is called the *upper level* optimization problem or the *problem of the leader*. Here we used quotation marks to indicate that this problem is not well-defined in case of multiple lower-level optimal solutions.

For simplicity we assume that $\Psi(x) \neq \emptyset$ for all $x \in X$ with $G(x) \leq 0$. This assumption can be weakened and is only used to guarantee that the optimal value function (20.1.2) and the solution set mapping defined in (20.1.3) are well defined.

20.2 History

Problem (20.1.1), (20.1.4) has been formulated for the first time in an economic context by v. Stackelberg [1245]. Many economic articles investigate related principal-agency problems, see some references below. Hence, it is sometimes called *Stackelberg game* and its solution a Stackelberg equilibrium. About 40 years later, this problem has been introduced into the mathematical community [208, 273, 274, 522, 761, 981]. Since then a large number of articles illustrating different views on the topic, investigating various questions both from theoretical or numerical point-of-view or numerous applications of the problem appeared. It is our aim here to give the reader some insight into the topic and its investigations. Citations in this article refer to items in the bibliography given at the end of this chapter. Without any doubt, this bibliography cannot be complete. Also, due to space limitations, not all items in the large list of references can be mentioned in the text. This, of course, does not mean that the items not used in the text are of less importance.

Bilevel optimization problems are nonconvex and nondifferentiable optimization problems even if all their defining functions are convex and smooth, see [326].

20.3 Overviews and Introductions

Well formulated introductory texts on bilevel optimization can be found in [66, 311, 336, 646, 755, 782, 1311]. Reference [1220] gives an overview over evolutionary methods. In [1084], the authors compare Nash, Cournot, Bertrand and Stackelberg games, describe ideas for solving them as well as some applications, see also [171, 1410]. An overview over the investigations at the Montreal school in the years before 2008 is given in [218]. An overview over solution algorithms for (mixed-integer) linear bilevel optimization problems can be found in [1143], and for general bilevel optimization problems in [1076]. Structural properties of the feasible set of mixed-integer bilevel optimization problems can be found in [138].

Monographs, textbooks and edited volumes on the topic are Bard [131], Dempe [385], Dempe et al. [413], Dempe and Kalashnikov [397], Kalashnikov et al. [710], Migdalas et al. [961], Mesanovic et al. [955], Sakawa [1146], Sakawa and Nishizaki [1151], Shimizu et al. [1200], Stein [1249], Talbi [1270], Xu et al. [1388], Zhang et al. [1458]. Bilevel optimization problems are the topic of a chapter in the monograph [479].

Bilevel optimization problems with many followers and the three-level optimization problem have been investigated in [40, 64, 600–602, 604, 817, 889, 894, 1035]. A comment to [64] can be found in [1227].

We have used constraints in the upper-level problem of the form $G(x) \leq 0$. Sometimes upper-level constraints of the form $G(x, y) \leq 0$, so-called joint constraints, are investigated. These problems are not easy to interpret in a game theoretic context since then, the leader has to select first his / her decision and gives it to the follower. The latter then computes one optimal reply on the leader's choice and gives it back to the leader, who only now is able to check if his / her initial selection was a feasible one. If the follower's selection was not unique, feasibility of the leader's selection also depends on the response of the follower. This was the motivation of the authors in [1192] to suggest to move joint upper-level constraints into the lower level to derive a "correct" definition. This approach is shown to be not correct in [101, 952] since it changes the problem seriously. Joint constraints can make the feasible set of the bilevel optimization problem empty even if $\Psi(x) \neq \emptyset$ for all $x \in X$, or disconnected even if gph Ψ is connected, see [952].

The three-level problem is investigated in [126, 362, 517]. The articles [128, 158, 1131] explain the geometry of bilevel and multilevel optimization problems. A global optimal solution of multilevel optimization problems is approximated in [726]. In [517], three different types of optimistic formulations of three-level optimization problems are suggested and compared. The electrical network defense is formulated as a three-level mixed-integer linear programming model [1411]. Necessary optimality conditions and assumptions guaranteeing the existence of an optimal solution for the three-level optimization problem can be found in [817].

Examples showing nonexistence of optimal solutions can be found in [130].

Survey papers are [148, 335, 384, 387, 435, 707, 713, 884, 934, 935, 960, 1360]. A survey for the pessimistic bilevel optimization problems is [858].

First bibliographies can be found in [386, 1312, 1333].

The formulation of problems with an infinite number of lower-level decision makers as a stochastic bilevel optimization problem is given in [895].

20.4 Theoretical Properties and Relations to Other Optimization Problems

20.4.1 Formulation of the Bilevel Optimization Problem

20.4.1.1 Optimistic vs. Pessimistic Formulation

The formulation of the bilevel optimization problem as given in (20.1.1), (20.1.4) is not clear in case of multiple lower-level optimal solutions for some of the selections of the upper-level decision maker. In that case, the leader may assume that the follower can be motivated to select a best optimal solution in $\Psi(x)$ with respect to the leader's objective function. This is the so-called optimistic or weak formulation of the bilevel optimization problem, investigated in most of the references:

$$\min\{\varphi_o(x) : G(x) \leq 0,\ x \in X\},$$

where

$$\varphi_o(x) = \min_y\{F(x, y) : y \in \Psi(x)\}. \tag{20.4.1}$$

This problem is almost equivalent to

$$\min_{x,y}\{F(x, y) : G(x) \leq 0,\ x \in X,\ (x, y) \in \operatorname{gph} \Psi\}, \tag{20.4.2}$$

see [385]. If the upper-level objective function is of a special type the optimistic bilevel optimization problem can be interpreted as an inverse optimization problem [23, 670, 1470].

Relations to generalized semi-infinite optimization problems can be found in [1250].

If this optimistic assumption is not possible or even not allowed the leader is forced to bound the damage resulting from an unwelcome selection of the follower resulting in the pessimistic or strong formulation of the bilevel optimization problem:

$$\min\{\varphi_p(x) : G(x) \leq 0,\ x \in X\}, \tag{20.4.3}$$

where

$$\varphi_p(x) = \max_y\{F(x, y) : y \in \Psi(x)\}. \tag{20.4.4}$$

The formulation of the pessimistic Stackelberg game is given in [805, 986]. The existence of a pessimistic (strong) or an optimistic (weak) optimal solution is considered in [5, 14, 15, 893], the same based on d.c. optimization is investigated in [8]. For the existence and stability of pessimistic solutions in general spaces, the reader is referred to [833, 834, 836, 840]. Topic of the article [1068] is the existence of solutions in Banach spaces if the solution of the lower-level problem is strongly stable. The possible nonexistence of pessimistic optimal solutions is shown in [893].

In [1370], the pessimistic bilevel optimization problem with an objective function not depending on the lower-level variable is formulated as

$$\min\{F(x) : x \in X,\ G(x, y) \leq 0\ \forall\ y \in \Psi(x)\}. \tag{20.4.5}$$

The relations between this formulation and pessimistic bilevel optimization as given in (20.4.3) are investigated in [1370]. In the same vein, the optimistic bilevel optimization problem reads as

$$\min\{F(x) : x \in X,\ G(x, y) \leq 0\ \exists\ y \in \Psi(x)\}.$$

Using an idea in [787], the pessimistic bilevel optimization is formulated as an optimistic one with a two follower Nash game in the lower level [789]. Since the pessimistic bilevel optimization problem does not have an optimal solution in general, the authors replace the solution set mapping of the lower-level problem with the ε-optimal solutions. They show that the resulting perturbed pessimistic bilevel optimization problem and the optimistic bilevel problem with the two follower Nash game in the lower level are equivalent with respect to global optimal solutions.

20.4.1.2 Optimization over the Efficient Set

The search for a "best" efficient solution of a multicriterial optimization problem can be formulated as a bilevel optimization problem [159, 160, 188, 189, 194, 472, 644, 645, 695, 738, 843, 993, 994, 1241, 1281, 1283, 1296], see also the overview in [1399].

Properties of the problem and the replacement of the upper-level objective function $\langle d, x\rangle$ by a constraint $\langle d, x\rangle \leq t$ for an unknown t in the lower-level problem can be found in [157]. The "best" efficient solution is obtained for the smallest t for which the resulting problem has an optimal solution.

A special model is the simple bilevel optimization problem in [392], where a "best" solution of an optimization problem is searched for. Optimality conditions for that problem can be found in [392], a solution algorithm is given in [1135, 1235, 1236].

Stochastic problems of this type are topic of [193].

20.4.1.3 Semivectorial Bilevel Optimization: Vector-Valued Lower-Level Problems and Problems with Multiobjective Upper-Level Problems

Bilevel optimization problems where the lower-level problem is a multiobjective optimization problem are often called semivectorial bilevel optimization problems [36, 87, 192, 196, 198, 259, 409, 533, 818, 904, 1011, 1105].

Here, the scalarization approach is often used to transform the semivectorial bilevel optimization problem into an optimistic bilevel problem, see e.g. [409]. For that, the scalarization vector appears as new variable in the upper-level problem. In the case that local optimal solutions are computed for the resulting bilevel problem, this is a delicate issue [424].

Using the scalarization approach and indicator functions as terms in the upper-level objective function the semivectorial bilevel optimization problem is transformed into a single-level one for which the nonsmooth Mangasarian-Fromovitz constraint qualification can be satisfied, see [534].

The use of utility functions as well as optimistic and pessimistic approaches to investigate linear bilevel problems with multiobjective functions in both the leader's and the follower's problems can be found in [1015], for the same in the case of stochastic data see [1017].

Multiobjective optimization in the upper level of a linear bilevel optimization problem is the topic of [890, 905], fuzzy optimization approaches are applied in this case in [202]. Problems with multiobjective upper-level problems are investigated in [1418] using a combination of the KKT and the optimal value function approach to transform the bilevel optimization problem into a single-level one.

Optimality conditions for nonlinear bilevel vector optimization problems and a global solver can be found in [551].

20.4.1.4 Fuzzy Bilevel Optimization Problems

The investigation of bilevel optimization problems with fuzzy lower-level problems can be found in [432, 657, 850, 1453, 1457].

The fuzzy linear bilevel optimization problem is transformed into a crisp problem and then solved using a k-th best algorithm in [1100, 1147, 1148, 1454] or using the KKT approach [1449, 1452]. Solving this problem using an interactive approach has been the topic of [1109, 1148, 1152, 1154–1156]. A solution algorithm for fuzzy bilevel optimization problems using α-cuts is given in [225, 542, 544].

For the computation of a satisfactory solution see [786, 1085, 1086, 1127, 1140]. Here, in some sense, an approach is used which is related to multiobjective optimization, see remarks in [388]. The transformation of a bilevel optimization problem using ideas from fuzzy optimization into the problem of maximizing membership functions related to both the objective functions of the leader's and the follower's problem at the same time is not a possible approach for solving the bilevel optimization problem, see [388].

Fuzzy (random) bilevel optimization has been applied

1. in the Shuibuya hydropower project [1385],
2. in logistics planning [702],
3. to model the water exchange in eco-industrial parks [112].

20.4.1.5 Stochastic Problems

The model of stochastic bilevel optimization and solution algorithms can be found in [41, 285, 320, 368, 412, 536, 639, 668, 669, 717, 762, 892, 1052, 1054, 1055, 1078]. Stochastic bilevel multi-leader multi-follower problems are investigated in [367, 1384]. In [367] the authors show uniqueness of the stochastic multi-leader Stackelberg-Nash-Cournot equilibrium and suggest an algorithm for computing it.

The transformation of two-stage stochastic bilevel optimization problems into mixed-discrete optimization problems can be found in [1409].

20.4.1.6 Bilevel Optimization Problems with Fixed-Point Constraints

Existence theorems for bilevel optimization problems with fixed-point constraints are the topic of [847]. Special cases are MPECs and semi-infinite optimization problems.

Robust polynomial bilevel optimization problems are investigated in [322]. Robust Stackelberg problems are the topic of [864].

20.4.1.7 Bilevel Equilibrium Problems

A bilevel equilibrium problem has been formulated in [990] which has been the topic of investigations of many articles since then, see e.g. [888, 1308]. This problem is an hierarchical problem where both the upper and the lower-level problems are formulated as variational inequalities. As in bilevel optimization, the solution of the upper-level problem is a parameter of the lower-level problem and the solution of the lower-level problem is used to formulate the constraint in the upper-level one.

20.4.2 Dependence on Data Perturbations

The dependence of optimal solutions of bilevel optimization problems on data perturbations has been investigated by some authors, see e.g. [13, 1341]. The authors of [12] replace the lower-level problem using ε-optimal solutions and consider convergence of the solutions for $\varepsilon \downarrow 0$. Stability considerations can be found in [399, 511, 681, 833–836, 919], the same using the transformation by an inclusion constraint is given in [448, 449].

A surprising fact is that, global optimal solutions of the bilevel optimization problem need not to remain globally optimal if a constraint is added to the lower-level problem which is inactive at the optimal solution [421, 910].

The structure of the feasible set of bilevel optimization problems has been the topic of [411, 457, 694], see also [1440]. The Mangasarian-Fromovitz constraint qualification is not generically satisfied in the lower-level problem at optimal solutions of (optimistic) bilevel optimization problems. If it is violated for some values of the upper-level variable, the feasible set of the KKT transformation is in general no longer closed. That encouraged the authors of [43] to replace the lower-level problem using the F.-John necessary optimality conditions. Generic properties of an optimal solution of the resulting problem can be found in [43], see [402] with a comment to that approach.

Upper and lower bounds for the optimal objective function value of bilevel problems with interval coefficients are computed in [254]. Bilevel linear programming problems with interval coefficients have also been considered in [1102, 1110, 1162].

An important result related to this is well-posedness of bilevel optimization problems [78].

20.4.3 Possible Transformations

To investigate properties, for the formulation of optimality conditions and solution algorithms, the bilevel optimization problem needs to be transformed into a single-level problem. For this, different approaches are possible. Assume that $Y = \mathbb{R}^n$ in this subsection.

20.4.3.1 Use of the Karush-Kuhn-Tucker Conditions of the Lower-Level Problem

If the functions $y \mapsto f(x, y)$, $y \mapsto g_i(x, y)$, $i = 1, \ldots, p$, are differentiable and a regularity condition is satisfied for the lower-level problem for all $(x, y) \in \operatorname{gph} \Psi$, problem (20.4.2) can be replaced by

$$\begin{aligned} \min_{x,y,u} \{F(x, y) : G(x) \le 0,\ x \in X,& \\ \nabla_y \{f(x, y) + u^\top g(x, y)\} = 0,& \qquad (20.4.6) \\ u \ge 0,\ g(x, y) \le 0,\ u^\top g(x, y) = 0\}.& \end{aligned}$$

It is shown in [967] that this approach is only possible if the lower-level problem is a convex one. Problem (20.4.6) is a so-called mathematical program with equilibrium (or complementarity) constraints (MPEC), see [897]. This problem is a nonconvex optimization problem for which the Mangasarian-Fromovitz constraint qualification is violated at every feasible point [1169]. This transformation is the most often used one, MPECs have intensively been investigated. In [103, 522, 532] the complementarity constraint in the Karush-Kuhn-Tucker (KKT) transformation (20.4.6) is replaced using Boolean variables. Problem (20.4.3) is compared with its transformation using the KKT conditions of the lower-level problem in [110].

Relations between the KKT and the optimal value transformations as well as between the KKT transformation and the original bilevel optimization problem are highlighted in [393]. A similar question is investigated in [1248] for global optimal solutions of the bilevel optimization problem and its KKT transformation formulated as a mixed Boolean optimization problem. The combination of the KKT and the optimal value function approaches for the transformation of bilevel optimization problems (with nonconvex lower-level problems) has been suggested in [1073, 1420]. The MPEC-LICQ is generically satisfied for MPECs [1172]. An example showing that the MPEC-LICQ can be violated for the KKT transformation of a bilevel optimization problem, even if LICQ and a strong sufficient optimality condition of second order are satisfied at the optimal solution of the lower-level problem, can be found in [614] together with a lifting approach to satisfy this regularity condition for the perturbed problems.

20.4.3.2 Use of Necessary Optimality Conditions Without Lagrange Multipliers

Let, for $x \in X$,

$$M(x) := \{y : g(x, y) \leq 0\}$$

denote the feasible set of the lower-level problem, assume that $y \mapsto f(x, y)$ is a convex function and, for arbitrary, fixed $x \in X$, $M(x) \subseteq \mathbb{R}^m$ is a convex set. Then, $y \in \Psi(x)$ if and only if $0 \in \partial_y f(x, y) + N_{M(x)}(y)$, where

$$N_A(z) = \{d : d^\top (w - z) \leq 0 \;\forall\, w \in A\}$$

denotes the normal cone in the sense of convex analysis to a closed set A and it is assumed that $N_A(z) = \emptyset$ if $z \notin A$. Thus, (20.4.2) can be replaced by

$$\min\{F(x, y) : \; G(x) \leq 0, \; x \in X, \; 0 \in \partial_y f(x, y) + N_{M(x)}(y)\}. \tag{20.4.7}$$

Problem (20.4.7) is fully equivalent to (20.4.2). Problem (20.4.7) is also called an optimization problem with a generalized equation or with a variational inequality, it has been studied in [435, 982, 983, 985, 1419].

20.4.3.3 Use of the Optimal Value Function

Problem (20.4.2) can be equivalently replaced by

$$\min\{F(x, y) : G(x) \leq 0,\ x \in X,\ g(x, y) \leq 0,\ f(x, y) \leq \varphi(x)\}. \qquad (20.4.8)$$

This transformation has first been used in [1037, 1038]. Problem (20.4.8) is a nonsmooth optimization problem since the optimal value function $\varphi(x)$ is, even under restrictive assumptions, in general not differentiable. Moreover, the nonsmooth Mangasarian-Fromovitz constraint qualification is violated at every feasible point, see [1072, 1422].

20.4.3.4 Transformation Using a Variational Inequality

If the definition of the normal cone is used, problem (20.4.7) is

$$\begin{aligned}\min\{F(x, y) : G(x) \leq 0,\ x \in X,\ y \in M(x),\\ \langle \nabla_y f(x, y), z - y\rangle \geq 0\ \forall\, z \in M(y)\},\end{aligned} \qquad (20.4.9)$$

where the problem

$$\text{find } y \in M(x) \text{ such that } \langle \nabla_y f(x, y), z - y\rangle \geq 0\ \forall z \in M(x)$$

is often called a generalized variational inequality. Here, f is assumed to be differentiable, see [1424].

The problem of minimizing some objective function subject to the solution of a parametric variational inequality is called a generalized bilevel optimization problem in [835].

Bilevel variational inequalities have been introduced in [714, 1320] and solved e.g. in [164, 832].

The existence of solutions for bilevel variational inequalities, where both the upper- and lower-level problems are formulated using variational inequalities, is topic in [835, 837, 838].

The investigation of bilevel variational inequalities under invexity assumptions can be found in [298].

The application of bilevel optimization to solve fuzzy variational inequalities is suggested in [500].

20.4.3.5 Formulation as a Set-Valued Optimization Problem

Using

$$\mathcal{F}(x) := \bigcup_{y \in \Psi(x)} F(x, y),$$

problem (20.4.2) can be replaced with

$$\text{" min "}\{\mathcal{F}(x) : G(x) \leq 0, \ x \in X\}. \tag{20.4.10}$$

This formulation has been the topic of [428, 1074]. For this approach, the notion of an optimal solution needs to be defined first.

20.4.4 General Properties

Optimal solutions of certain bilevel optimization problems can be found at vertices of the feasible set [128, 177, 241–243, 250, 255, 865, 942, 943].

Since the bilevel optimization problem can be interpreted as a hierarchical game it is interesting to ask if it is beneficial to act as leader, see [53, 701, 704, 1290, 1441].

Optimal solutions of the bilevel optimization problem are in general not Pareto optimal if optimization is done w.r.t. the objective functions of both levels at the same time [388, 1234]. The relationship between the bilevel problem and bicriterial optimization is illustrated in [271, 932, 959, 1359]. The correct formulation of multicriterial optimization problems which are equivalent to the bilevel problem can be found in [516, 531, 667, 1070, 1132]. An application of these results to solve linear bilevel optimization problems is given in [562].

In [1361, 1362, 1366], a possible transformation of an optimal solution of the bilevel optimization problem into a Pareto optimal solution is investigated.

For problems with multiple followers see [692, 1450], problems with multiple leaders have been investigated in [109, 368, 1186]. Nine different kinds of relationships between followers in bilevel optimization problems with multiple followers can be found in [885]. For a variational inequality formulation of problems with multiple leaders we refer to [649]. The existence of optimal solutions for problems with multiple leaders as well as the relation of this problem to its KKT transformation (both with respect to global and local optimal solutions) has been investigated in [109].

Phenomena of inverse Stackelberg problems are described in [1027, 1028].

$\mathcal{NP}$-hardness of bilevel optimization problems has been shown in [130, 185, 439, 676]. Computational complexity of the bilevel knapsack problems is the topic of [278].

Relations to mixed-integer optimization problems are topic of [523]. The investigation of a special problem which is polynomially solvable can be found in [748, 749, 1081].

20.4.5 Problems in Infinite Dimensional Spaces

Bilevel optimization problems in general spaces are considered in [450, 757, 944, 946].

For the investigation of semivectorial bilevel optimization on Riemannian manifolds the reader is referred to [200]. The existence of Stackelberg equilibrium points on strategy sets which are geodesic convex in certain Riemannian manifolds has been shown in [766].

The KKT transformation is applied to the bilevel optimization problem in infinite dimensional spaces in [944]. For the optimal value transformation, regularity conditions and optimality conditions see [1416]

Necessary optimality conditions in form of M-stationarity conditions for problems with second order cone programming problems in the lower-level can be found in [310, 1469]. The robust optimization method for bilevel optimization problems with uncertain data in the lower-level problem can lead to a bilevel programming problem with a second-order cone program in the lower-level [309].

The existence of optimal solutions has been investigated for problems in Banach spaces [837] and for problems in locally convex Hausdorff topological vector spaces [846].

Stackelberg games go back to the original definition by H.v. Stackelberg [1245] and refer to problems where the feasible set of the lower level does not depend on the upper-level variable. Recently investigated related problems are:

1. closed-loop Stackelberg games [734, 976, 1205, 1289],
2. dynamic Stackelberg problems [962, 974, 1012, 1013],
3. reverse Stackelberg problems [578–582]: a special point is the computation of optimal incentive functions resulting in realization of the leader's aim by the follower.
4. Stackelberg differential games [1041]
5. Stackelberg equilibria in an oligopoly [139].

Bilevel optimal control problems are another rather recent area of research. Here, two optimal control problems are combined in a hierarchical sense. Such problems have been considered in [152, 154, 162, 745, 757, 948]. An application of Stackelberg games to optimal control problems can be found in [987]. Pursuit-evasion games are discretized and transformed into a bilevel programming problem in [478].

20.4.6 Discrete Bilevel Optimization Problems

A general introduction into discrete bilevel optimization problems can be found in [1315]. For the special case, when the lower level problem is a parametric knapsack problem see [214, 215, 429, 1089] or a matroid problem [503]. For nonlinear integer bilevel optimization problems see [455, 675].

A transformation of bilevel optimization problems with mixed-integer lower-level problems into a single-level problem using minima of optimal value functions of (partial) lower-level problems is suggested in [813].

Using a special penalization approach, the mixed-discrete bilevel optimization problem can be transformed into a continuous one. Assuming partial calmness, optimality conditions for both the optimistic and the pessimistic problems are derived in [418].

Complexity of a bilevel perfect matching problem is the topic of [549], for the bilevel minimum spanning tree problem see [282, 283].

Optimality conditions for problems with discrete parametric lower-level problems using the radial subdifferential can be found in [501] or, in case of a parametric matroid problem in the lower-level, in [503].

Multi-leader-follower games are investigated in [769, 812, 1048, 1292]. The existence for equilibria in such problems is investigated in [1433]. A Gauss–Seidel method for solving the EPEC transformation of such problems has been developed in [643].

20.5 Optimality Conditions

20.5.1 Strongly Stable Lower-Level Optimal Solution

For necessary optimality conditions and solution algorithms using strongly stationary solutions in the lower-level problem see [370, 371, 373–375, 381, 382, 854, 1038, 1039]. Necessary optimality conditions using the implicit function theorem and variational analysis can be found in [1440]. Here the author verifies that the posed necessary optimality conditions are generically satisfied at local minima of smooth bilevel optimization problems and that partial calmness is often violated. Reference [635] describes an idea to formulate necessary (and sufficient) optimality conditions after deleting some inequality constraints in (20.4.6).

20.5.2 Use of the KKT Transformation

Necessary optimality conditions using the KKT transformation are formulated in [434, 436, 1340] and using a generalized equation in [17, 434].

The transformation using the F.-John conditions applied to the lower-level problem in place of the KKT conditions is investigated in [43], see [402] for an example with a nonconvex lower-level problem where the global optimum cannot be computed with this approach.

Using Boolean variables, the resulting mathematical program with complementarity constraints is transformed into a mixed integer optimization problem in [103], bounds for the sufficiently large constants (big-M) can be found in [445]. Verifying that a given big-M does not cut off any feasible vertex of the linear bilevel optimization problem cannot be done in polynomial time unless $\mathcal{P} = \mathcal{NP}$, see [741].

20.5.3 Transformation Using the Optimal Value Function

The generalized derivative of the optimal value function of the lower-level problem, violation of the MFCQ, and necessary optimality conditions can be found in [302]. Calmness properties of the transformed problem can be found in [633], see also [1037]. Optimality conditions using the optimal value transformation for the optimistic bilevel optimization problem are derived in [394–396, 425, 433, 469, 854, 984, 1422, 1427]. For the case when the lower-level problem is an optimal control problem, see [1413, 1415]. For optimality conditions for infinite and semi-infinite bilevel optimization problems see [452].

Necessary and sufficient optimality conditions based on Fenchel-Lagrange duality are investigated in [6].

Optimality conditions using variational analysis for the pessimistic problem are the topic of [426].

Problems with multiobjective upper-level problems have been investigated in [405, 408, 480]. Convexificators and exhausters can be used to study extremum problems involving functions which are not convex, quasidifferentiable or locally Lipschitz continuous. They are used to derive necessary optimality conditions in [783].

20.5.4 Set-Valued Optimization Approach

Optimality conditions using the formulation of the bilevel optimization problem as a set-valued optimization problem can be found in [428, 1444]. Optimality conditions are derived applying the coderivative of Mordukhovich [982] to the graph of the solution set mapping Ψ, see [1474, 1475].

20.5.5 Transformation into a Semi-infinite Optimization Problem

Optimality conditions using a semi-infinite transformation of the bilevel optimization problem can be found in [127]. A counterexample to this result is given in [323].

20.5.6 Optimality Conditions for Semivectorial Bilevel Problems

Optimality conditions for the pessimistic semivectorial bilevel optimization problem using variational analysis and the transformation using the optimal value function of the lower-level problem can be found in [853]. Application of the scalarization approach to the lower-level problem followed by the KKT or the optimal value transformation of the resulting problem leads to necessary optimality conditions, see [818].

20.5.7 Optimality Conditions for the Simple Bilevel Optimization Problem

The problem of finding a special point in the set of optimal solutions of a convex optimization problem is called a simple bilevel optimization problem. In some sense, this problem parallels the aim to find a "best" (weak) Pareto optimal solution of a multiobjective optimization problem. Optimality conditions for a simple bilevel optimization problem are given in [26, 392].

20.5.8 Optimality Conditions for the Three-Level Optimization Problem

In [832] the lower level is first transformed using the KKT conditions and then, optimality conditions for the resulting problem are formulated using variational analysis.

20.5.9 Other Approaches

The formulation of necessary optimality conditions exploiting convexificators can be found in [115, 404, 1265].

The extremal principle [982] is used for describing necessary optimality conditions in [140, 407]. For problems with set-valued optimization problems in both levels, optimality conditions using the variational principle can be found in [410].

Different optimality conditions and transformations are collected in [415].

Necessary and sufficient optimality conditions using a linearization of the inducible region [296] and by using a description of the tangent cone to the feasible set [1313] have been derived.

Input optimization is used in [1293].

For necessary and sufficient optimality conditions under generalized invexity assumptions see [205].

Necessary conditions for a global optimal solution using a bilevel Farkas lemma can be found in [679].

20.5.10 Second-Order Optimality Conditions

Second order necessary and sufficient optimality conditions for the optimistic bilevel optimization problem are obtained in [406].

20.6 Solution Algorithms

20.6.1 Pessimistic Problem

Properties, existence and stability of the pessimistic bilevel problem are investigated in [423, 770, 873–882].

Using ε-optimal solutions in the lower-level problem, convergence to a pessimistic solution for $\varepsilon \downarrow 0$ is shown in [918].

In [16] the duality gap of the linear lower-level problem is penalized in the upper-level objective function to solve the pessimistic bilevel optimization problem. Some incorrectness in this article is found and corrected in [1483]. The pessimistic linear bilevel optimization problem with multiple followers is solved using a penalization of the duality gap in [1495]. Here, the different followers share some of the resources.

An algorithm for solving the pessimistic bilevel optimization problem using a regularization approach can be found in [170]. For using an entropy approach see [1496].

For use of the k-th best algorithm to solve the pessimistic linear bilevel problem see [1483].

Partial cooperation between the leader and the follower (i.e. weighted sum of the optimistic and the pessimistic approaches) for linear bilevel optimization problems is the topic of [276, 1487].

20.6.2 Optimistic Problem

20.6.2.1 Enumeration

Properties and an algorithm for linear bilevel optimization problems can be found in [1129, 1130].

Enumeration of the basic matrices of the lower-level problem in linear bilevel optimization is suggested in [275, 1000]. Using this idea it is shown in [866] that the algorithm is of polynomial time if the number of variables in the lower-level problem is fixed.

Vertex enumeration plus a descent algorithm is used in [599]. Convergence to a local optimum for linear bilevel optimization problems by investigating adjacent extreme points is shown in [177, 179, 369]. A simplex-type algorithm applied to an exactly penalized problem is suggested in [269]. A descent algorithm computing a local optimal solution for linear-quadratic bilevel optimization problems can be found in [1257, 1260].

The k-th best algorithm has originally been published in [1356], see also [247, 1483]. The same algorithm for bilevel problems with partially shared variables between followers is given in [1193]. For an application of the k-th best algorithm to three-level optimization problems the reader is referred to [600, 1459].

The use of the solution package Pyomo [1087] for solving the optimistic bilevel optimization problem is described in [610].

20.6.2.2 Use of KKT Transformation

Solution algorithms using the Karush-Kuhn-Tucker transformation can be found in [122, 123, 125, 129, 132, 697–699, 886]. Solving the KKT transformation using branch-and-bound is suggested in [133, 522]. Gomory-like cuts in a branch-and-cut algorithm solving the KKT transformation of the bilevel problem are applied in [105].

A penalty function algorithm for problems with quadratic lower-level problems can be found in [916].

Solution algorithm for the problem (20.4.6) after replacing the complementarity constraint using Boolean variables can be found in [104, 608].

Branch-and-bound algorithm is applied in [179, 474, 487, 608], and for problems with multiple followers in [887].

Penalization of the duality gap for bilevel problems with linear lower-level problem is done in [68, 245, 265, 266, 902, 1368, 1397, 1488–1490], for nonlinear lower level problems see [938].

A penalty function approach to the lower-level problem is applied in [24, 25, 1367] to derive an unconstrained optimization problem which can be replaced by its gradient. Similar ideas for problems with connecting upper-level constraints can be found in [659, 950].

Penalization of the complementarity constraint for the linear bilevel optimization problem is done in [1030], the results of this article are corrected in [267], see also [268, 270]. Exact penalization of the complementarity constraint under partial calmness is used in [856].

An approximate global optimal solution is searched for in [1484].

The authors of [634] solve the KKT-transformation by implicit use of the inequality constraints. The complementarity constraints are replaced by concave inequalities in [30].

A successive approximation of the feasible set of the KKT transformation is obtained in [1269].

The use of approximations for both the complementarity constraint and the y-gradient of the Lagrange function of the lower-level problem make the computation of local or global optimal solutions of the bilevel optimization problem possible, see [403] and [953] for an earlier approach. A similar approximation has been used in [1225] in combination with an evolutionary algorithm.

Application of disjunctive cuts to the KKT transformation of the bilevel optimization problem can be found in [102].

Benders decomposition algorithm is realized in [521] for problems with discrete upper and linear lower level problems.

20.6.3 If the Lower-Level Problem Has a Strongly Stationary Solution

Solution algorithms using strong stability of the lower-level optimal solution can be found in [378, 441, 496, 497]. Investigation of large problems is done in [756]. Comparison of different solution algorithms (Hooke-Jeeves algorithm, bilevel descent algorithm, MINOS and others) can be found in [1263].

After inserting the (optimal) solution function of the lower-level problem into the upper-level problem, a nonsmooth optimization problem arises which can be solved using various solution algorithms.

1. An interior point algorithm is applied in [807],
2. a trust region algorithm is the choice in [855],
3. an inexact restoration algorithm where the lower-level problem is solved at each iteration, can be found in [71],
4. a bundle algorithm is suggested in [383, 384, 391]. This approach is generalized to the case of nonunique optimal solutions in the lower-level problem in [430].
5. A feasible direction method is used in [954],
6. a steepest descent algorithm can be found in [1166, 1314],
7. Reference [451] use an extragradient cutting-plane-method,
8. a pattern search method has been described in [456].

20.6.4 Use of the Optimal Value Function of the Lower-Level Problem

Solution algorithms using the optimal value function transformation can be found in [400, 402, 975, 1199].

Smooth upper approximations of the optimal value function of the lower-level problem are used in [100] and in [970, 971] for solving mixed-discrete bilevel problems. If the optimal value function of the lower level problem is convex or concave these properties can be applied for an upper estimation of the feasible set of problem (20.4.8). This has been done for the computation of global and local optimal solutions in [400, 402].

Kriging is used in [1210] for an interpolation of the optimal value function.

The optimal value transformation is used to find relations between Stackelberg and Nash equilibria in [787]. A related algorithm solving bilevel optimization problems where the lower-level problem is fully convex with a parameter independent feasible set is suggested in [788].

A cutting plane approach is applied to a reverse-convex transformation of the problem in [11, 57, 60, 995, 1297–1301].

An algorithm for the computation of an approximate global optimal solution of the optimal value transformation for bilevel optimization problems with nonconvex lower-level problems and a global optimal solution for ones with convex lower-level problems using semidefinite optimization is presented in [322, 678]. A smoothing SQP method for solving these problems is suggested in [1392], a smoothing augmented Lagrangian method in [1390, 1391] and a smoothing projected gradient method in [845].

If all functions describing the bilevel optimization problem are polynomials and the bilevel optimization problem is transformed equivalently into a semi-infinite optimization problem, a combination of the exchange technique with Lasserre-type semidefinite relaxations [1009] can be used to solve the problem. If the constraints in the lower-level problem do not depend on the leader's variables, this algorithm converges to a global optimal solution [1010].

20.6.5 Global Optimization

In [586], focus is on global optimization using the αBB approach.

A branch-and-sandwich algorithm can be found in [742–744, 1057].

Global optimization of the KKT-transformation is done in [1318].

For global optimization using sensitivity analysis in the lower-level problem see [493, 495, 1079].

If the lower-level problem is replaced by a variational inequality, an active set algorithm is suggested in [1342].

An algorithm for the computation of a global optimal solution for bilevel problems with quadratic upper and linear lower-level problems can be found in [1258, 1261, 1262]. Using a transformation with d.c. constraints, the same problems can be solved globally, see [61, 585].

20.6.6 Metaheuristics

Different metaheuristics have been applied to bilevel optimization problems:

1. Different genetic algorithms [67, 256–258, 263, 537, 597, 627, 759, 819, 822, 827, 852, 940, 941, 1016, 1149, 1150, 1153, 1214, 1223, 1346, 1403, 1471].
2. Memetic algorithm [37, 660, 663].
3. Ant colony systems [259].
4. Tabu search algorithm [552].
5. Particle swarm optimization [46, 536, 541, 543, 602, 603, 725, 775, 908, 1324, 1462, 1463, 1477, 1478]. This algorithm is used for solving bilevel linear optimization problems with multiple objective functions in the upper-level problem [48]. In [46] the algorithm is used to approximate the set of Pareto optimal solutions of the multiobjective, nonlinear bilevel optimization problem with linear optimization problems in the lower-level problem which are solved exactly for each particle in the swarm.
6. Evolutionary algorithm [261, 355–357, 820, 914, 1218, 1221, 1347]. Evolutionary algorithm applied to multiobjective bilevel optimization problems using quadratic fibres to approximate the set of Pareto optimal solutions of the lower-level problem [1217].
7. Differential evolution algorithm for problems with multiobjective upper-level problem [826] and for problems with linear equality constraints [784]. The differential evolution algorithm for general bilevel optimization problems is formulated in[74, 75].
8. Simulated annealing [690, 1060, 1144, 1375].
9. Estimation of distribution algorithm [1322].
10. Neural network algorithm [619, 650, 790, 900, 903, 1119, 1195].
11. Fruit fly algorithm [911, 1330].

20.6.7 Special Algorithms

Solution algorithms for special problems can be found in [141, 233, 1135, 1236].

1. Direct search algorithm [953, 1446].
2. Combination of the simplex algorithm with projected gradients [1252].
3. A trust-region algorithm [331, 334, 937].
4. Application of ideas from bicriterial optimization for solving bilevel optimization problems [1304], comment on this algorithm in [271, 1359].
5. Transformation into multicriterial optimization problem using certain membership functions [483]. References [149, 617] show that the algorithms in [125] (Grid search algorithm) and in [180] (parametric complementary pivot algorithm) fail in general.

6. Use of fuzzy optimization to compute a satisfactory solution [95, 654, 969, 1157, 1194, 1485].
7. Use of derivative-free solution algorithms [337].

20.6.8 Integer Bilevel Problems

Solution algorithms for mixed-integer bilevel optimization problems are suggested in [280, 438, 455, 475, 587, 760, 980, 1142, 1363, 1395]. The watermelon algorithm proposed in [1335] is an exact algorithm solving discrete linear bilevel optimization problems using disjunction cuts to remove infeasible solutions for the bilevel problem from the search space. An efficient cutting plane algorithm can be found in [512–514]. A cutting plane algorithm for special discrete bilevel optimization problem is given in [629].

The solution of Boolean bilevel optimization problems using the optimal value reformulation and a cutting plane algorithm has been investigated in [417], see also [883]. An interactive approach to integer bilevel optimization problems can be found in [484]. An extended version of the k-th best algorithm can be found in [1188, 1189]. For a mixture of cutting plane and k-th best algorithm for integer fractional bilevel optimization problems, see [201, 1282].

The exact solution of bilevel assignment problems is topic of [145], special cases of this $\mathcal{NP}$-hard problem can be solved in polynomial time.

For solving integer bilevel optimization problems different solution algorithms have been suggested:

1. Some kind of a k-th best algorithm [1282], see the remarks to that algorithm in [244].
2. A cutting plane approach [380, 587, 1183].
3. A branch and bound algorithm [134].
4. Other approaches can be found in [504].

A polynomial-time algorithm for the bilevel time minimization (or bottleneck) transportation problem can be found in [1182, 1238, 1239, 1380].

20.6.9 Related Problems

Problems where the upper-level constraints and objective function depend on the optimal value function of the lower-level problem can be found in [1199].

20.7 Bilevel Problems with Multiobjective Functions in the Lower or Upper Level, or with Multiple Followers

Problems with vector-valued objective function in the upper-level problem are considered in [252]. For problems with multiple followers the reader is referred to [249, 357]. Semivectorial bilevel optimization problems, i.e. bilevel optimization problems where the lower-level problem has a vector-valued objective function are topic of [192, 196–198, 409, 899, 1486].

In [1491], multiobjective (linear) problems in both levels are considered. The lower-level problem is replaced using Benson's approach. The authors compute a satisfactory solution applying certain *k*-th best approach.

Application of the idea in [531] to problems with multiobjective linear optimization problems in both levels is realized in [1071].

20.8 Applications

Here, we give only topics of diverse applications.

1. Agricultural economics [272, 274], support of biofuel production [135, 136].
2. Agricultural credit distribution to improve rural income [1031].
3. Aid distribution after the occurrence of a disaster [262].
4. Airline revenue management [339].
5. Aircraft structural design [607].
6. Aluminium production [1006–1008].
7. Analysis of the possible mechanisms of optimization of biodiversity [38].
8. Autonomous cars driving [1480].
9. Bioengineering and biotechnology [229, 1067], optimization of bioprocess productivity based on metabolic-genetic network models [671], optimization of low-carbon product family and its manufacturing process [1379].
10. Capacity (expansion) planning [517, 547].
11. Chemical equilibria [324, 1233].
12. Contact shape optimization [634].
13. Control of container cranes in high rack warehouses [745].
14. Credit allocation [1137].
15. Critical infrastructure protection planning [1167].
16. Deception in games [814].
17. Defense applications [59, 209, 808]. Interdiction problems below describe also applications related to defense problems. Electric grid defense planning [40, 1411].
18. Discount decisions for the retailer [729].
19. Dynamic storage pricing strategy in supply hub in industrial park [1088].

20. Ecological problems: Greenhouse gas emissions [618, 637, 803, 891, 1369], water exchange in eco-industrial parks [112, 1273].
21. Electron tomography [1504].
22. Electricity markets and networks [20, 106–108, 120, 172, 184, 498, 546, 615, 616, 636, 639–641, 652, 794, 898, 1256, 1307, 1326, 1354, 1438].

    a. Control of renewable energy generation [1267].
    b. Optimal location and size of storage devices in transmission networks [470].
    c. Bids of wind power producers in the day-ahead market with stochastic market [804]. Real-time pricing schemes in electricity markets [1505]. Optimal strategic bidding of energy producers [632, 765].
    d. Electricity swing option pricing [763].
    e. Local electricity markets under decentralized and centralized designs [799].
    f. Power system vulnerability analysis [96].
    g. Pay-as-clear electricity market with demand elasticity [44].
    h. Transmission-Distribution System Operator Coordination [234].
    i. Three-level model to optimize the operating costs by the system operator [561].

23. Environmental policy [379, 589].
24. Evacuation planning [89, 1114, 1381, 1428, 1481].
25. Facility location and production problem [1, 165, 167–169, 187, 286, 442, 630, 746, 767, 939, 963, 1016, 1080, 1117, 1145, 1264, 1465], facility location and freight transportation problem [350, 596], production planning problem [896]. Best location of stone industrial parks which pollute the environment [536]. Location-allocation problem [917]. Facility location problem with customer's patronization [287]. Competitive facility location problems [758].
26. Fisheries management [1044].
27. Flow shop scheduling problems [2].
28. Gas cash-out problem [414, 716, 720], entry-exit gas market [575].
29. Global investment strategies with financial intermediation [153].
30. Hazardous materials transportation [264, 486].
31. Health insurance problem [1446].
32. Human arm movements [32, 33, 977].
33. Identification of enzymatic capacity constraints [1407].
34. Image segmentation [1096], image reconstruction [446, 1499].
35. Incentive systems [377, 1482], Principal-agent problems [291, 535, 583, 584, 677, 735, 793, 1003, 1097, 1098, 1125, 1128, 1207, 1492].
36. Inferring oncoenzymes [1377].
37. Interdiction problems [29, 40, 116, 119, 219–222, 277, 554, 871, 1004, 1020, 1061, 1118, 1138, 1168, 1232, 1373, 1374, 1378]. Many interdiction problems are formulated as three-level optimization problems, some of the references describe especially tailored solution algorithms. Heuristic algorithms for generalized interdiction problems, where the assumption that the objective function of the leader is opposite to that of the follower is removed, can be found in [515]. In this article the authors report also very extensive computational

results. Optimal resource allocation for the critical infrastructure protection [1019].

38. Inverse optimization [464].
39. Local access networks (LAN) [263].
40. Machine learning problems [156, 306, 307, 773, 1066], statistical learning methods [155], parameter learning in image applications [352, 1023, 1024].
41. Material transportation at the Lancang River Hydropower Base [909].
42. Maximally violated valid inequality generation often has a natural interpretation as a bilevel program [868].
43. Misclassification minimization [924–926, 933].
44. Mechanics [1046].
45. Network problems:

   a. Highway network design [99, 147, 150, 151, 315, 566, 778, 779, 800, 927, 930, 1339, 1342]. Complexity of the highway pricing problem [444, 624]. Network design problem [521, 527–529, 545, 703, 844, 1159, 1266], the same with uncertain travel demand [290, 317]. Sensitivity analysis is used to solve the network design problem in [696]. The algorithm in [800] has been shown not to converge in [929]. Network design problem with congestion effects [928].
   b. The mathematical structure of the strategic pricing problem is investigated in [936].
   c. O-D adjustment problem [303, 328, 458, 519, 1181, 1405], O-D demands estimation [1115], optimal tolls in transportation networks [204, 206, 216, 217, 223, 398, 401, 422, 431, 445, 447, 467, 574, 798, 931]. The same with a real application in Hong Kong [1400].
   d. Solution algorithms for an application in a traffic network [327] with some comments in [329].
   e. Traffic network signal control [605, 724, 1244, 1303, 1406]. Use of traffic flow guidance systems [1202].
   f. Hierarchical transportation network with transshipment facilities [341, 342]. Expansion of a highway network [77].
   g. An overview over pricing problems in transportation and marketing is given in [625]. Multiobjective pricing problems are considered in [1334].
   h. Interaction of public and private sections using the example of Korea [737]. Model for public-private partnerships [795–797].
   i. Review of related problems [958], bilevel traffic management [1053]. Investigation of an approximation algorithm for the toll setting problem [574, 1123]. Different models for traffic assignment problems [870]. A comparison of algorithms for solving a bi-level toll setting problem can be found in [703].
   j. Public Rail Transportation under Incomplete Data [1059].
   k. Computational complexity of the problem is investigated and a cutting plane approach is suggested in [626].
   l. Pricing toll roads under uncertainty [453].

m. In [991] the problem is transformed using the KKT transformation, the complementarity conditions are replaced using the Fischer-Burmeister function and the resulting problems are solved globally.
n. Load balancing in mobile networks [491].
o. Rank pricing problem [240].
p. Transportation of hazardous materials [50, 181, 461, 486, 721, 732].
q. Two-level stochastic optimization problem over transportation network [41].
r. Trajectory planning for a robot [949].
s. Location of hydrogen filling stations to promote the use of electric cars [21, 965].
t. Vehicle routing problem [940].
u. Hub arc location model [1163], the same under competition [343, 344, 912, 1164].
v. Railway transport hub planning [733].
w. School bus routing [1051].

46. Newsboy problem [346, 680, 1500].
47. New product design [1251].
48. Optimal drug combination causing minimal side effects in biomedicine [492].
49. Optimal partial hedging in discrete markets [988].
50. Optimal standardization [567–569].
51. Optimizing bus-size and headway in transit networks [338, 359].
52. Parameter estimation in chemical engineering [191, 973].
53. Physical layer security in cognitive radio networks [499].
54. Pipe network design [1472].
55. Predatory pricing in a multiperiod Stackelberg game [998].
56. Prediction of underground blast-induced ground vibration amplitudes [1047].
57. Price-based market clearing under marginal pricing [506, 507, 509].
58. Price setting problems [780, 781], in part related to toll setting problems in transportation networks. Price setting problems on a network [559] and on an oligopolistic market [1120].
59. Process design problem [324, 325].
60. Product selection with partial exterior financing [750].
61. Profitability of merger in Stackelberg markets [655].
62. Quantitative policy analysis [212].
63. Real-time path planning approach for unmanned aerial vehicles [862].
64. Relations between central economic units and subunits: [4, 121, 124, 128, 289, 740, 806], hazardous waste management [56, 58], applications in economics [211, 227, 228, 251].
65. Resource allocation model [289, 598, 1001, 1002, 1338], special model for HIV control [728] and in wireless networks [233]. Problems with resource allocation constraints lead to minimization problems over the efficient set [1279].
66. Scheduling problems [723].
67. Set invariance characterization of dynamical systems affected by time-delay [792].

68. Stackelberg-Nash-Cournot equilibria [511, 1187, 1287, 1288, 1434]. A stochastic problem of this type is investigated in [354, 1384]. A critical comment to some of the results in [1187] can be found in [477]. Under some conditions, the Stackelberg equilibrium is also a Cournot equilibrium [701]. Stackelberg Equilibria of Linear Strategies in Risk-Seeking Insider Trading [564]. Stackelberg solution in static and dynamic nonzero-sum two-player games (open-loop Stackelberg solution) [576, 1205].
69. Supply chain configuration [256, 774, 1139, 1158, 1403], corporate social responsibility in a supply chain [54, 731], supply chain management [672, 849, 864, 1161, 1336, 1396]. Different metaheuristics are applied to a location-allocation problem related to a supply chain problem. Timberlands supply chain model is investigated in [1425, 1426].
70. Support vector machines are solved as bilevel optimization problem [772].
71. Truss topology optimization [526].
72. Uncapacitated lot-sizing problem [739].
73. Virtual power plants [722, 1448].
74. Water conflict problem between India and Bangladesh [65, 183], water allocation issues [653, 1387, 1389], water distribution system [1231], water rights trading [1349]. Water integration in eco-industrial parks [1095].

20.9 Test Problems

Methods to generate test problems can be found for linear bilevel optimization problems in [989], for more general problems in [236–239, 1034, 1213], see also Chapter 9 of [520]. A bilevel optimization problem library can be found on the internet page *http://coral.ise.lehigh.edu/data-sets/bilevel-instances/*. For another test set see [972]. The seemingly most comprehensive set of test problems can be found in [1497], see also [1498] in this volume.

20.10 Master, PhD and Habilitation Theses

S. Addoune [19], G.B. Allende [42], M. Andersson [69], T. J. Becker[142], O. Ben-Ayed [146], Z. Bi [173], H.C. Bylling [232], W.D. Cai [235], L.M. Case [288], M. Červinka [1309], Y. Chen [299], B. Colson [330, 332], S.M. Dassanayaka [347], S. Dempe [372], S. DeNegre [437], deSilva [440], J. Deuerlein [443], S. Dewez [444], J. Eckardt [471], T. Edmunds [473], A. Ehrenmann [476], D. Fanghänel [502], S. Franke [524], Y. Gao [540], N. Groot [577], F. Harder [609], K. Hatz [613], C. Henkel [631], X. Hu [651], E. Israeli [664], D. Joksimocic [693], F.M. Kue [768], S. Lohse [869], J. Lžičař [907], P. Mehlitz [947], A.G. Mersha [951], G.M. Moore [978], J. Moore [979], S.Nagy, [997], A. Nwosu [1021], W. Oeder [1026], F. Parraga [1050], T. Petersen [1062], A. G. Petoussis [1063], O. Pieume [1069], M. Pilecka

[1072, 1074], P. Pisciella [1077], R. Rog [1124], A. Ruziyeva [1133], R. Saboiev [1136], G. Savard [1165], G. Schenk [1170], H. Schmidt [1171], J. Shaw [1185], S.A Siddiqui [1203], Z.C. Taskin [1276], L. Vicente [1310], S. Vogel [1316], A. Werner [1365], U. Wen [1355], R. Winter [1371], P. Xu [1394], J. Zhang [1466], A.B. Zemkoho [1442, 1443]

Edited volumes are Anandalingam and Friesz [66], Dempe and Kalashnikov [397], Migdalas et al. [961].

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