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BILEVEL OPTIMIZATION: THEORY, ALGORITHMS AND APPLICATIONS

STEPHAN DEMPE

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.

1. Introduction

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

$$\min_y \{f(x,y) : g(x,y) \leq 0,\ y \in Y\}, \tag{1.1}$$

where f, $g_i : \mathbb{R}^m \times \mathbb{R}^n \to \mathbb{R}$, $i = 1, \dots, p$ and $Y \subseteq \mathbb{R}^n$ is a nonempty, closed set. 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 problem. If problems with more than one decision maker in the lower level are considered, e.g. a Nash equilibrium is searched for between them. Let

$$\varphi(x) := \min_y \{f(x,y) : g(x,y) \leq 0,\ y \in Y\} \tag{1.2}$$

denote the optimal value function of problem (1.1) and

$$\Psi(x) := \{y \in Y : g(x,y) \leq 0,\ f(x,y) \leq \varphi(x)\} \tag{1.3}$$

the solution set mapping of problem (1.1). If $\mathbf{gph}\Psi := \{(x,y) : y \in \Psi(y)\}$ is used to abbreviate the graph of the solution set mapping Ψ, the bilevel optimization problem

$$\text{'}\min_x\text{'} \{F(x,y) : G(x) \leq 0,\ (x,y) \in \mathbf{gph}\Psi,\ x \in X\} \tag{1.4}$$

can be formulated with $X \subseteq \mathbb{R}^m,\ F : \mathbb{R}^m \times \mathbb{R}^n \to \mathbb{R},\ G_j : \mathbb{R}^m \to \mathbb{R},\ j = 1, \dots, q.$ 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.

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2. History

Problem (1.1), (1.4) has first be formulated in an economic context by v. Stackelberg [1124]. Many economic articles investigate related principal-agency problems, see some references below. Hence, it is called sometimes Stackelberg game and the solution a Stackelberg equilibrium. About 40 years later, this problem has been introduced into the mathematical community [180, 240, 239, 475, 685, 881]. Since then a large number of articles illustrating different views on the topic, investigating various questions both from theoretical or numerical side or numerous applications of the problem appeared. It is our aim here to give the reader some insight into the topic and its investigations. Without any doubt, this bibliography cannot be complete.

Bilevel optimization problems are nonconvex and nondifferentiable optimization problems, see [290].

3. Overviews and introductions

Well formulated introductory texts on bilevel optimization can be found in [60, 275, 300, 586, 680, 704, 1188]. Sinha et al. [1100] give an overview over evolutionary methods. Pozo et al. [977] compare Nash, Cournot, Bertrand and Stackelberg games, describe ideas for solving them as well as some applications, see also [149, 1278]. An overview over the investigations at the Montreal school in the years before 2008 is given in [190]. An overview over solution algorithms for (mixed-integer) linear bilevel optimization problems can be found in [1026], and for general bilevel optimization problems in [969].

Monographs, textbooks and edited volumes on the topic are Bard [117], Dempe [345], Dempe et al. [373], Kalashnikov et al. [643], Mesanovic et al. [855], Sakawa [1029], Sakawa and Nishizaki [1034], Shimizu et al. [1080], Stein [1128], Talbi [1149], Zhang et al.[1323]. Bilevel optimization problems are the topic of a chapter in the monograph [433].

Bilevel optimization problems with many followers and the three-level optimization problem have been investigated in [57, 37, 548, 549, 550, 552, 796, 791, 931]. A comment to [57] can be found in [1106].

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 [1071] 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 [90, 852] 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 $\mathbf{gph}\Psi$ is connected, see [852].

The three-level problem is investigated in [112, 322, 469]. The articles [114, 139, 1015] explain the geometry of bilevel and multilevel optimization problems. A global optimal solution of multilevel optimization problems is approximated in [659]. In [469], 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 [1279].

Examples showing nonexistence of optimal solutions can be found in [116].

Survey papers are [131, 299, 344, 347, 641, 646, 787, 393, 834, 835, 860, 1233].

First bibliographies can be found in [346, 1189, 1208].

The formulation of problems with an infinite number of lower level decision makers as a stochastic bilevel optimization problem is given in [797].

4. Theoretical properties and relations to other optimization problems

4.1. Formulation of the bilevel optimization problem.

4.1.1. *Optimistic vs. pessimistic formulation.* The formulation of the bilevel optimization problem as given in (1.1), (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

$$\varphi_o(x) = \min_y\{F(x,y) : y \in \Psi(x)\}. \tag{4.1}$$

This problem is almost equivalent to

$$\min_{x,y}\{F(x,y) : G(x) \leq 0,\ x \in X,\ (x,y) \in \mathbf{gph}\Psi\}, \tag{4.2}$$

see [345]. If the upper level objective function is of a special type the optimistic bilevel optimization problem can be interpreted as an inverse optimization problem [22, 607, 1333].

Relations to generalized semi-infinite optimization problems [1130]

If this 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:

$$\min\{\varphi_p(x) : G(x) \leq 0,\ x \in X\}, \tag{4.3}$$

where

$$\varphi_p(x) = \min_y\{F(x,y) : y \in \Psi(x)\}. \tag{4.4}$$

The formulation of the pessimistic Stackelberg game is given in [721, 886]. The existence of a pessimistic (strong) or an optimistic (weak) optimal solution is considered in [4, 13, 14, 795], the same based on d.c. optimization is investigated in [7]. For the existence and stability of pessimistic solutions in general spaces, the reader is referred to [741, 742, 743, 744, 746, 745, 748]. Topic of the article [960] 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 [795].

In [1243], the pessimistic bilevel optimization problem with an objective function not depending on the lower level variable is formulated as

$$\min\{F(x) : x \in X,\ G(x, y) \leq 0\ \forall\ y \in \Psi(x)\}. \tag{4.5}$$

The relations between this formulation and pessimistic bilevel optimization as given in (4.3) are investigated in [1243].

4.1.2. *Optimization over the efficient set.* The search for a "best" efficient solution of a multicriterial optimization problem is formulated as a bilevel optimization problem [141, 168, 426, 584, 585, 629, 892, 893, 1120, 1159, 1161, 1173].

Properties of the problem and replacement of the upper level objective function $\langle d, x\rangle$ by a constraint $\langle d, x\rangle \geq t$ for unknown t in the lower level problem [140].

A special model is the simple bilevel optimization problem in [352], where a "best" solution of an optimization problem is searched for. Optimality conditions for that problem can be found in [352], a solution algorithm is given in [1019, 1114, 1115]. In [667, 750], a "best" solution in the set of Pareto optimal solutions of a multicriterial optimization problem is searched for.

Stochastic problems of this type are topic of [167].

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 [33, 77, 166, 169, 171, 225, 369, 486, 909, 991, 806].

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 [487].

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 [913], the same in case of stochastic data [915]

Multiobjective optimization in the upper level of a linear bilevel optimization problem [807, 792], application of fuzzy optimization in this case [174]. Problems with multiobjective upper level problems are investigated in [1287] using a combination of the KKT and the optimal value approach.

Optimality conditions for nonlinear bilevel vector optimization problems and a global solver can be found in [501]

4.1.4. *Fuzzy bilevel optimization problems.* The investigation of bilevel optimization problems with fuzzy lower level problems can be found in [390, 596, 757, 1322, 1318, 1318].

The fuzzy linear bilevel optimization problem is transformed into a crisp problem and then solved using a k-th best algorithm in [988, 1030, 1031, 1319] or transformed using the KKT approach [1314, 1317]. Solving this problem using an interactive approach has been the topic of [994, 1031]. Solution algorithm for fuzzy bilevel optimization problems using α-cuts is given in [195, 493, 495]. For an interactive solution approach see [1035, 1037, 1039, 1038].

Computation of a satisfactory solution [707, 978, 979, 1011, 1043]. Here, in some sense, an approach is used which is related to multiobjective optimization, see remarks in [348]. 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 [348].

Applications of fuzzy (random) bilevel optimization

(1) in the Shuibuya hydropower project [1257],
(2) in logistics planning [636],
(3) in water exchange in eco-industrial parks [99].

4.1.5. *Stochastic problems.* The model and solution algorithms can be found in [38, 251, 284, 372, 327, 489, 580, 606, 650, 686, 794, 944, 946, 947, 971]. Stochastic bilevel multi-leader multi-follower problems are investigated in [328, 1256]. In [328] the authors show uniqueness of the stochastic multi-leader Stackelberg-Nash-Cournot equilibrium and suggest an algorithm for computing it.

4.1.6. *Bilevel optimization problems with fixed-point constraints.* Existence theorems for bilevel optimization problems with fixed-point constraints are the topic of [754]. Special cases are MPECs and semi-infinite optimization problems.

Robust polynomial bilevel optimization problems are investigated in [286]. Robust Stackelberg problems are the topic of [768].

4.1.7. *Bilevel equilibrium problems.* In 2010 A. Moudafi formulated a bilevel equilibrium problem [889] which has been the topic of investigations of many articles since then, see e.g. [1185]. 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.

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. [12, 1216]. [11] replaces the lower level problem using ε-optimal solutions and considers convergence of the solutions for $\varepsilon \downarrow 0$. Stability considerations can be found in [359, 463, 616, 741, 742, 743, 744, 819], the same using the transformation by an inclusion constraint is given in [406, 407].

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 inactice at the optimal solution [381, 811].

The structure of the feasible set of bilevel optimization problems has been the topic of [628, 371, 414], see also [1305]. Generic properties of an optimal solution of the bilevel problem if the lower level problem is replaced using the F.-John conditions can be found in [40], see [362] with a comment to that approach.

Optimal value range problem for bilevel problems with interval coefficients is investigated in [220]. Bilevel linear programming problem with interval coefficients have also been considered in [990, 995].

An important result related to this is well-posedness of the problems, see [69].

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.

4.3.1. *Use of the Karush-Kuhn-Tucker conditions of the lower level problem.* If the functions $y \mapsto f(x,y),\ y \mapsto g_i(x,y),\ i = 1,\dots,p$, are differentiable and a regularity condition is satisfied for the lower level problem for all $(x,y) \in \mathbf{gph}\Psi$, problem (4.2) can be replaced by

$$\begin{aligned} \min_{x,y,u} \{F(x,y) : \ & G(x) \le 0,\ x \in X, \\ & \nabla_y \{f(x,y) + u^\top g(x,y)\} = 0, \\ & u \ge 0,\ g(x,y) \le 0,\ u^\top g(x,y) = 0\}. \end{aligned} \tag{4.6}$$

It is shown in [867] that this approach is only possible if the lower level problem is a convex one. Problem (4.6) is a so-called mathematical program with equilibrium (or complementarity) constraints (MPEC), see [799]. This problem is a nonconvex optimization problem for which the Mangasarian-Fromovitz constraint qualification is violated at every feasible point [1050]. The relations between problems (4.2) and (4.6) have been investigated in [353]. This transformation is the most often used one, MPECs have been intensively been investigated. In [92, 475, 485] the complementarity constraint in the Karush-Kuhn-Tucker transformation (4.6) are replaced using Boolean variables.

Relations between the KKT and the optimal value transformations as well as between the KKT transformation and the original bilevel optimization problem [353], relations between global optimal solutions of the bilevel optimization problem and its KKT transformation formulated as a mixed Boolean optimization problem [1127]. Combination of the KKT and the optimal value approaches [965, 1289]. The problem (4.6) does not satisfy MPEC-LICQ in general even if the lower level problem satisfies LICQ and the sufficient optimality condition of second order [559].

4.3.2. *Use of necessary optimality conditions without Lagrange multipliers.* Let, for $x \in X$,

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

denote the feaible set of the lower level problem and 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 $0 \in \partial_y f(x,y) + N_{M(x)}(y)$. Thus, (4.2) can be replaced by

$$\min\{F(x,y) :\ G(x) \le 0,\ x \in X,\ 0 \in \partial_y f(x,y) + N_{M(x)}(y)\}, \tag{4.7}$$

where $N_A(z) = \{d : d^\top (w - z) \le 0\}$ 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 $z \notin A$. Problem (4.7) is fully equivalent to (4.2). Problem (4.7) is also called an optimization problem with a generalized equation or with a variational inequality, it has been studied in [393, 882, 883, 885, 1288].

4.3.3. *Use of the optimal value function.* Problem (4.2) can be equivalently replaced by

$$\min\{F(x,y) : G(x) \le 0,\ x \in X,\ g(x,y) \le 0,\ f(x,y) \le \varphi(x)\}. \tag{4.8}$$

This transformation has first been used in [932, 933]. Problem (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 [964, 1291].

4.3.4. *Transformation using a variational inequality.* If the definition of the normal cone is used, problem (4.7) is

$$\min\{F(x,y) : G(x) \le 0,\ x \in X,\ y \in M(x),\ \langle \nabla_y f(x,y), z - y\rangle \ge 0\ \forall\ z \in M(y)\}, \tag{4.9}$$

where the problem

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

is often called a generalized variational inequality. Here, f is assumed to be differentiable, see [1293]

Bilevel variational inequalities have been intoduced in [647, 1197].

The existence of solutions for bilevel variational inequalities is topic in [746].

Investigation of bilevel variational inequalities under invexity assumptions [263]

Application of bilevel optimization to solve fuzzy variational inequalities [453].

Solution algorithm for bilevel VI [145, 730].

4.3.5. *Formulation as a set-valued optimization problem.* Using

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

problem (4.2) can be replaced with

$$\text{"}\min\text{"}\{\mathcal{F}(x) :\ G(x) \le 0,\ x \in X\}. \tag{4.10}$$

This formulation has been the topic of [386, 966]. For this approach, the notion of an optimal solution needs to be defined first.

4.4. **General properties.** Optimal solutions of certain bilevel optimization problems can be found at vertices of the feasible set [114, 155, 207, 208, 221, 209, 216, 769, 844, 843].

Since the bilevel optimization problem can be interpreted as a hierarchical game it interesting to ask if it is beneficial to act as leader? [48, 635, 638, 1167, 1306]

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 [1113, 348]. The relationship between the bilevel problem and bicriterial optimization is illustrated in [237, 832, 859, 1232]. The correct formulation of multicriterial optimization problems which are equivalent to the bilevel problem can be found in [468, 484, 605, 962, 1016]. An application of these results to solve linear bilevel optimization problems is given in [511].

In [1239, 1234, 1235], 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 [626, 1315], problems with multiple leaders have been investigated in [327, 1065]. Nine different kinds of relationships between followers in bilevel optimization problems with multiple followers can be found in [788]. For a variational inequality formulation of problems with multiple leaders we refer to [588].

Phenomena of inverse Stackelberg problems are described in [924, 923].

$\mathcal{NP}$-hardness of bilevel optimization problems has been shown in [116, 163, 397, 611]. Relations to mixed-integer optimization problems are topic of [476]. Investigation of a special problem which is polynomially solvable can be found in [676, 677, 974].

Computational complexity of the bilevel knapsack problems are the tipic of [244].

4.5. **Problems in infinite dimensional spaces.** Bilevel optimization problems in general spaces are considered in [408, 682, 845, 846].

Semivectorial bilevel optimization on Riemannian manifolds [172]. Existence of Stackelberg equilibrium points on strategy sets which are geodesic convex in certain Riemannian manifolds [690].

Use of KKT transformation to the bilevel optimization problem in infinite dimensional spaces [845].

Optimal value transformation, regularity conditions and optimality conditions [1285]

Necessary optimality conditions in form of M stationarity condition for problems with second order cone programming problems in the lower level can be found in [274, 1332].

The existence of solutions has been investigated in [745, 753].

Stackelberg games go back to the original definition by H.v. Stackelberg [1124] and refer to problems where the feasible set of the lower level does not depend on the upper level variable. Recent related problems are

(1) Closed-loop Stackelberg games [664, 876, 1085, 1166],
(2) Dynamic Stackelberg problems [862, 874, 910, 911],
(3) Reverse Stackelberg problems [527, 528, 529, 530, 532, 531]: computation of optimal incentive functions resulting in realization of the leader's aim by the follower,
(4) Stackelberg differential games [935]
(5) Stackelberg equilibria in an oligopoly are considered in [124].

An application of Stackelberg games to optimal control problems can be found in [887].

Bilevel optimal control problems are a new area of research. Here, two optimal control problems are combined in a hierarchical sense. Such problems have been considered in [143, 135, 136, 673, 848].

Two-level hierarchical control systems are considered in [682].

4.6. **Discrete bilevel optimization problems.** General introduction into those problems [1192].

Lower level problem is a parametric knapsack problem [187, 186, 387, 981] or a matroid problem [456].

Solution algorithms for mixed-integer bilevel optimization problems are suggested in [246, 396, 413, 429, 537, 684, 880, 1025, 1236, 1265].

The watermelon algorithm proposed in [1210] is an exact algorithm solving discrete linear bilevel optimization problems using multiway disjunction cuts to remove infeasible solutions for the bilevel problem from the search space.

An efficient cutting plane algorithm can be found in [464, 465, 466].

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 [728].

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 [378].

Solution of Boolean bilevel optimization problems using the optimal value reformulation and a cutting plane algorithm [377], a related article is [786].

Exact solution of bilevel assignment problem [128], special cases of this $\mathcal{NP}$-hard problem can be solved in polynomial time.

Nonlinear integer bilevel optimization problems [413, 610].

Interactive approach to integer bilevel optimization problems [438].

An extended version of the kth best algorithm can be found in [1068, 1067].

Mixture of cutting plane and k-th best algorithm for integer fractional bilevel optimization problems [1160], see also [173]. Cutting plane algorithm for special discrete bilevel optimization problem [571].

Complexity of a bilevel perfect matching problem is the topic of [500], for the bilevel minimum spanning tree problem see [248, 249].

Optimality conditions for problems with discrete parametric lower level problems using the radial subdifferential [454] or in case of a parametric matroid problem in the lower level [456].

5. Optimality conditions

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 [330, 331, 334, 335, 333, 342, 341, 761, 933, 934]. Necessary optimality conditions using implicit function theorem and variational analysis can be found in [1305]. 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. [577] describe an idea to formulate necessary (and sufficient) optimality conditions after deleting some inequality constraints in (4.6).

5.2. **Use of the KKT transformation.** Necessary optimality conditions using the KKT transformation [392, 394, 1215] and using a generalized equation [16, 392].

Transformation using the F.-John conditions applied to the lower level problem in place of the KKT conditions [40], see also [362] for an example with a nonconvex lower level problem where the global optimum cannot be computed with this approach.

An penalty function algorithm for problems with quadratic lower level problems can be found it [816]

Using Boolean variables the resulting mathematical program with complementarity constraints is transformed into a mixed integer optimization problem in [92], bounds for the necessary large constants can be found in [403].

5.3. **Transformation using the optimal value function.** Necessary and sufficient optimality conditions based on Fenchel-Lagrange duality is investigated in [5].

Optimality conditions using variational analysis for the pessimistic problem is investigated in [385].

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 [267].

Optimality conditions using the optimal value transformation for the optimistic bilevel optimizstion problem are derived in [354, 355, 356, 423, 384, 391, 761, 884, 1291, 1294]. In the case when the lower level problem is an optimal control problem: [1281, 1283]. For optimality conditions for infinite and semi-infinite bilevel optimization problems, see [410].

Dempe and Gadhi [365, 368] apply the optimal value transformation to a problem with multiobjective upper level problem to derive necessary optimality conditions, see also [434].

Use of generalized derivatives for point-to-set mappings for deriving necessary optimality conditions [1336, 1337]

Calmness properties of the transformed problem can be found in [575], see also [932].

The optimal value transformation is used to find relations between Stackelberg and Nash equilibria in [708]. A related algorithm solving bilevel optimization problems where the lower level problem is fully convex with a parameter independent feasible set is suggested in [709].

5.4. **Set-valued optimization approach.** Optimality conditions using set-valued optimization [386, 1309].

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 [113]. A counterexample to this result is given in [287].

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 [760].

5.7. **Optimality conditions for the simple bilevel optimization problem.** Optimality conditions for a simple bilevel optimization problem [25, 352].

5.8. **Other approaches.** Convexificators are used in [101, 364, 1145].

The extremal principle is used for describing necessary optimality conditions in [125, 367]. For problems with set-valued optimization problems in both levels, optimality conditions using the variational principle can be found in [370].

Different optimality conditions and transformations [375]

Necessary and sufficient optimality conditions using a linearization of the inducible region [261] and by using a description of the tangent cone to the feasible set [1190].

Input optimization is used in [1169].

Necessary and sufficient optimality conditions under generalized invexity assumptions [177].

5.9. **Second-order optimality conditions.** Second order necessary and sufficient optimality conditions for the optimistic bilevel optimization problem are obtained in [366].

Necessary conditions for a global optimal solution using a bilevel Farkas lemma can be found in [614].

6. Solution algorithms

6.1. **Pessimistic problem.** A. Aboussoror and A. Mansouri [15] penalize the duality gap of the linear lower level problem in the upper level objective function to solve the pessimistic bilevel optimization problem. Some incorrectness in this article is found and corrected in [1342]. Properties, existence and stability of the pessimistic bilevel problem are investigated in [383, 694, 776, 779, 778, 780, 777, 781, 782, 783, 784, 785].

An algorithm for solving the pessimistic bilevel optimization problem using a regularization approach can be found in [148]. For using an entropy approach see [1356].

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 [242, 1347].

Use of ε-optimal solutions in the lower level problem, convergence to a pessimistic solution for $\varepsilon \downarrow 0$ [818].

The pessimistic linear bilevel optimization problem with multiple followers is solved using a penalization of the duality gap in [1355]. Here, the different followers share some of the resources.

For use of k-th best algorithm to solve the pessimistic linear bilevel problem see [1342].

6.2. **Optimistic problem.**

6.2.1. *Enumeration.* Enumeration of the basic matrices of the lower level problem in linear bilevel optimization [241, 898]. Using this idea it is shown in [770] that the algorithm is of polynomial time if the number of variables in the lower level problem is fixed.

Vertex enumeration plus descent algorithm [547]. Convergence to a local optimum for linear bilevel optimization problems by investigating adjacent extreme points [155, 157, 329], using a simplex algorithm applied to an exactly penalized problem [235]. A descent algorithm computing a local optimal solution for linear-quadratic bilevel optimization problems can be found in [1137, 1140].

The k-th best algorithm has originally be published in [1229], see also [213, 1343]. The same algorithm for bilevel problems with partially shared variables between followers is given in [1072]. Application of the kth best algorithm to three-level optimization problems [548, 1324]. Properties and an algorithm for linear bilevel optimization problems [1013, 1014].

Solution package Pyomo for solving the optimistic bilevel optimization problem is described in [558].

6.2.2. *Use of KKT transformation.* Solution algorithms using the Karush-Kuhn-Tucker transformation can be found in [108, 109, 111, 115, 118, 631, 632, 633, 789]. Solving the KKT transformation using branch-and-bound [119, 475]. Application of Gomory-like cuts in a branch-and-cut algorithm solving the KKT transformation of the bilevel problem [94].

Solution algorithm for the problem (4.6) after replacing the complementarity constraint using Boolean variables can be found in [93, 556].

Branch-and-bound algorithm [157, 441, 428, 556], branch-and-bound algorithm for problems with multiple followers [790].

Penalization of the duality gap for bilevel problems with linear lower level problem [62, 211, 231, 232, 804, 1241, 1267, 1350, 1348, 1349], for nonlinear problems see [838].

E. Aiyoshi and K. Shimizu [23, 24, 1240] apply a penalty function to the lower level problem to derive an unconstrained optimization problem which can be replaced by its gradient. Similar ideas for problems with connecting upper level constraints [598, 850].

Penalization of the complementarity constraint for linear bilevel optimization problem [926], correction in [233], see also [234, 236].

Exact penalization of the complementarity constraint under partial calmness [764].

An approximate global optimal solution is searched for in [1344].

Solve the KKT-transformation by implicit use of the inequality constraints [576].

Al-Khayyal et al. [29] use the KKT-transformation of the bilevel problem and replace the complementarity constraints by concave inequalities.

Successive approximation of the feasible set using the KKT transformation [1148].

6.3. **If the lower level problem has a strongly stationary solution.** Investigation of large problems is done in [681].

(1) Interior point algorithm [723],
(2) Trust region algorithm [762],

Comparison of different solution algorithms (Hooke-Jeeves algorithm, bilevel descent algorithm, MINOS and others) can be found in [1143].

An inexact restoration algorithm where the lower level problem is solved at each iteration [64].

Bundle algorithm for problems with strongly stationary lower level solutions [343, 344, 351] and in the case of nonunique lower level problems [388]; feasible direction method under the same assumptions [854], steepest descent algorithm [1047, 1191], use of an extragradient cutting-plane-method [409].

Solution algorithm using strong stability of the lower level optimal solution [338, 399, 449, 450].

6.4. **Use of the optimal value function of the lower level problem.** A cutting plane approach is applied to a reverse-convex transformation of the problem in [10, 52, 55, 894, 1174, 1175, 1176, 1177, 1178].

Solution algorithm using the optimal value function transformation [360, 362, 875, 1079].

Solution algorithm using a smooth upper approximation of the optimal value function of the lower level problem [89].

Upper approximations of the optimal value function of the lower level problem are used for solving mixed-discrete bilevel problems [870, 871].

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 [286, 613]. A smoothing SQP method for solving these problems is suggested in [1263], a smoothing augmented Lagrangian method in [1261, 1262] and a smoothing projected gradient method in [752].

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 [907] 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 optial solution [908].

6.5. **Discrete problems.** Benders decomposition algorithm is realized in [474].

6.6. **Global optimization.** Global optimization using the α **BB** approach [536]

A branch-and-sandwich algorithm used for globally solving the bilevel optimization problem can be found in [670, 671, 672, 949].

Global optimization of the KKT-transformation [1195].

Global optimization using sensitivity analysis in the lower level problem [446, 448, 972]

If the lower level problem is replaced by a variational inequality, an active set algorithm is suggested in [1217].

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 [1138, 1141, 1142]. Using a transformation with d.c. constraints, the same problems can be solved globally, see [535, 581].

6.7. **Metaheuristics.** A genetic algorithm is applied to the certain bilevel optimization problem in [61, 222, 223, 224, 229, 490, 545, 569, 683, 731, 737, 733, 759, 840, 841, 842, 914, 1032, 1033, 1036, 1093, 1103, 1219, 1272, 1334].

A memetic algorithm is applied to solve the bilevel optimization problem in [34, 599, 601].

Ant colony systems algorithm is applied in [225].

Tabu search algorithm [502]

Particle swarm optimization [43, 489, 492, 494, 550, 551, 658, 698, 809, 1201, 1326, 1327, 1338, 1339], this algorithm for solving bilevel linear optimization problems with multiple objective functions in the upper level problem [44]. In [43] 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.

Evolutionary algorithm [227, 315, 316, 317, 732, 814, 1098, 1101, 1220]

Evolutionary algorithm applied to multiobjective bilevel optimization problems using quadratic fibres to approximate the set of Pareto optimal solutions of the lower level problem [1096].

Differential evolution algorithm for problems with multiobjective upper level problem [735] and for problems with linear equality constraints [705]. The differential evolution algorithm for general bilevel optimization problems is formulated in[66, 67].

Simulated annealing [624, 952, 1027, 1247]

Estimation of distribution algorithm [1199]

Neural network algorithm [564, 589, 710, 802, 805, 1003, 1075]

A fruit fly algorithm has been developed in [812, 1205].

6.8. **Special algorithms.** Combination of the simplex algorithm with projected gradients [1132]

Direct search algorithm [853, 1311]

Solution algorithms for special problems can be found in [126, 201, 1019, 1115].

A trust-region algorithm [295, 298, 837]

Application of ideas from bicriterial optimization for solving bilevel optimization problems [1181], comment on this algorithm in [237, 1232].

Transformation into multicriterial optimization problem using certain membership functions [437]. [132, 562] show that the algorithms in [111] (Grid search algorithm) and in [158] (parametric complementary pivot algorithm) fail in general.

Application of disjunctive cuts to the KKT transformation of the bilevel optimization problem [91]

Use of fuzzy optimization to compute a satisfactory solution [84, 593, 869, 1040, 1074, 1345]

Use of derivative-free solution algorithms [301].

6.9. **Integer bilevel problems.** k-th best algorithm [1160], corrected results in [210]

Lower level problem is parametric integer optimization problem [255]

A cutting plane approach [340, 537, 1062], branch and bound [120], using other approaches [457].

6.10. **Related problems.** Here, only some of the algorithms are listed: [65, 75, 76] Interior point algorithms for MPECs: [142]

Problems where the upper level constraints and objective function depend on the optimal value function of the lower level problem [1079].

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 [218].

Problems with multiple followers [215, 317].

Semivectorial bilevel optimization problems, i.e. bilevel optimization problems where the lower level problem has a vector – valued objective function are topic of [369, 801, 1346].

In [1351], 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 Fülöp's idea [484] to problems with multiobjective linear optimization problems in both levels is realized in [963].

8. Applications

(1) Agricultural economics [238, 240], Support of biofuel production [121, 122].
(2) Agricultural credit distribution to improve rural income [927].
(3) Aid distribution after the occurrence of a disaster [228].
(4) Airline revenue management [303].
(5) Aircraft structural design [555].
(6) Aluminium production [904, 905, 906].
(7) Analyzation of the possible mechanisms of optimization of biodiversity [35].

(8) Bioengineering and biotechnology [199, 959], optimization of bioprocess productivity based on metabolic-genetic network models [608], optimization of low-carbon product family and its manufacturing process [1251].
(9) Chemical equilibria [288, 1112].
(10) Optimizing bus-size and headway in transit networks [302, 319].
(11) Capacity (expansion) planning [498, 469].
(12) Contact shape optimization [576].
(13) Control of container cranes in high rack warehouses [673]
(14) Credit allocation [1021].
(15) Critical infrastructure protection planning [1048].
(16) Deception in games [729].
(17) Defense applications [54, 181]. Interdiction problems below describe also applications related to defense problems. Electric grid defense planning [37, 1279].
(18) Discount decisions for the retailer [660].
(19) Dynamic storage pricing strategy in supply hub in industrial park [980].
(20) Ecological problems: Greenhouse gas emissions [563, 579, 719, 793, 1242], water exchange in eco-industrial parks [99, 1151].
(21) Electron tomography [1361].
(22) Environmental policy [339, 538].
(23) Electricity markets and networks [19, 95, 96, 97, 106, 150, 162, 451, 497, 560, 561, 578, 580, 582, 583, 591, 714, 800, 1136, 1184, 1203, 1227, 1304].
    (a) Control of renewable energy generation [1147].
    (b) Optimal location and size of storage devices in transmission networks [424].
    (c) Bids of wind power producers in the day-ahead market with stochastic market clearing are investigated in [720]. Real-time pricing schemes in electricity markets [1362]. The optimal strategic bidding of energy producers is the topic of [574, 689].
    (d) Electricity swing option pricing [687].
    (e) Power system vulnerability analysis is modelled as bilevel optimization problem in [85].
    (f) Pay-as-clear electricity market with demand elasticity [41].
(24) Evacuation planning [79, 998, 1253, 1295, 1253, 1340].
(25) Facility location and production problem [1, 147, 146, 164, 252, 400, 674, 691, 839, 863, 914, 973, 1001, 1028, 1144, 1329], facility location and freight transportation problem [311, 544], production planning problem [798]. Best location of stone industrial parks which pollute the environment [489]. Location - allocation problem [817]. Existence of a Stackelberg equilibrium in a location problem is shown in [572]. Facility location problem with customer's patronization [253].
(26) A polynomial-time algorithm for the bilevel time minimization (or bottleneck) transportation problem can be found in [1061, 1117, 1118, 1252].
(27) Fisheries management [938].
(28) Flow shop scheduling problems [2].
(29) Special game problems [432], multi-leader-follower games [693, 727, 941]. Existence for equilibria in such problems is investigated in [1299].
(30) Gas cash-out problem [374, 649, 653], entry-exit gas market [524].

(31) Hazardous materials transportation [230, 440].
(32) Material transportation at the Lancang River Hydropower Base [810].
(33) Health insurance problem [1311].
(34) Human arm movements [31, 32, 877].
(35) Identification of enzymatic capacity constraints [1276].
(36) Image Segmentation [985], image reconstruction [404, 1357].
(37) Inverse optimization [418].
(38) Local access networks (LAN) [229].
(39) Misclassification minimization [824, 825, 826, 833].
(40) Mechanics [940].
(41) Profitability of merger in Stackelberg markets [594].
(42) Problems over networks
  (a) Highway network design [88, 130, 133, 134, 279, 514, 700, 701, 717, 827, 830, 1214, 1217]. The complexity of the highway pricing problem is the topic of [402, 566]. Network design problem with uncertain travel demand [256, 281]. Sensitivity analysis is used to solve the network design problem in [630]. The algorithm in [717] has been shown not to converge in [829]. The network design problem is also the topic in [496]. The mathematical structure of the strategic pricing problem is investigated in [836].
  (b) O-D adjustment problem [268, 292, 415, 471, 1060, 1274], O-D demands estimation [999], optimal tolls in transportation networks [176, 178, 188, 189, 358, 361, 382, 403, 405, 421, 523, 716, 831, 389]. The same with a real application in Hong Kong [1269]. Network design problem [474, 480, 481, 482, 637, 751, 1042, 1146].
  (c) Solution algorithms for an application in a traffic network [291] with some comments in [293].
  (d) Traffic network signal control [553, 657, 1123, 1180, 1275]. Use of traffic flow guidance systems [1082].
  (e) Hierarchical transportation network with transshipment facilities [306, 305]. Expansion of a highway network [68].
  (f) An overview over pricing problems in transportation and marketing is given in [567]. Multiobjective pricing problems are considered in [1209].
  (g) Interaction of public and private sections using the example of Korea [666]. Model for public-private partnerships [715].
  (h) Review of related problems [858], bilevel traffic management [945]. Investigation of an approximation algorithm for the toll setting problem [523, 1007]. Different models for traffic assignment problems can be found in [774]. A comparison of algorithms for solving a bi-level toll setting problem can be found in [637].
  (i) Public Rail Transportation under Incomplete Data is the topic of [951].
  (j) Computational complexity of the problem is investigated and a cutting plane approach is suggested in [568].
  (k) Pricing toll roads under uncertainty [411].
  (l) In [890] 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.

(m) Load balancing in mobile networks [444].
(n) Transportation of hazardous materials [46, 159, 417, 440, 654, 662].
(o) Two-level stochastic optimization problem over transportation network [38].
(p) Trajectory planning for a robot [849].
(q) Location of hydrogen filling stations to promote the use of electric cars [20, 865].
(r) Vehicle routing problem [840].
(s) An hub arc location model is investigated in [1045].
(t) Railway transport hub planning [663].

(43) Interdiction problems [28, 37, 102, 105, 191, 192, 193, 194, 243, 504, 775, 902, 916, 953, 1002, 1022, 1049, 1111, 1245, 1246, 1249]. 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 leader and the follower objective functions are one the opposite of the other is removed can be found in [467]. In this article the authors report also very extensive computational results.
(44) Uncapacitated lot-sizing problem [668].
(45) Predatory pricing in a multiperiod Stackelberg game [896].
(46) Pipe network design [1335].
(47) Physical layer security in cognitive radio networks [452].
(48) Real-time path planning approach for unmanned aerial vehicles [766].
(49) Set invariance characterization of dynamical systems affected by time-delay [712].
(50) Stackelberg-Nash-Cournot equilibria [463, 1066, 1164, 1165, 1300]. A stochastic problem of this type is investigated in [314, 1256]. A critical comment to some of the results in [1066] can be found in [431]. Under some conditions, the Stackelberg equilibrium is also a Cournot equilibrium [635].
(51) Modeling a subproblem if support vector machines are solved as bilevel optimization problem can be found in [695].
(52) Machine learning problems [138, 271, 272, 696, 958], statistical learning methods [137], parameter learning in image applications [312, 919, 920].
(53) Maximally violated valid inequality generation often has a natural interpretation as a bilevel program [772].
(54) Network design problem with congestion effects [828].
(55) Newsboy problem [309, 615, 1359].
(56) New product design [1131].
(57) Optimal incentive system [337, 1341], Principal-agent problems [257, 488, 533, 534, 612, 665, 713, 901, 986, 987, 1009, 1012, 1087, 1352].
(58) Optimal standardization [515, 518].
(59) Optimal nomenclature of products [516, 517].
(60) Optimal drug combination causing minimal side effects in biomedicine [445].
(61) Parameter estimation in chemical engineering [165, 873].
(62) Product selection with partial exterior financing [678].
(63) Price-based market clearing under marginal pricing [459, 460, 461].

(64) Price setting problems [702, 703], in part related to toll setting problems in transportation networks. Price setting problems on a network [509] and on an oligopolistic market [1004].
(65) Process design problem [288, 289].
(66) Resource allocation problem in wireless networks [201].
(67) Application in quantitative policy analysis: [184].
(68) Scheduling problems [656].
(69) Stackelberg solution in static and dynamic nonzero-sum two-player games (open-loop Stackelberg solution) [525, 1085].
(70) Relations between central economic units and subunits: [3, 107, 110, 114, 255, 669, 722], hazardous waste management [51, 53], applications in economics [183, 197, 198, 217].
(71) Resource allocation [255, 546, 899, 900, 1213]. Problems with resource allocation constraints lead to minimization problems over the efficient set [1157].
(72) Supply chain configuration [222, 697, 1023, 1041, 1272], corporate social responsibility in a supply chain [49, 661], supply chain management [756, 768, 1044, 1211, 1266]. Different metaheuristics are applied to a location-allocation problem related to a supply chain problem.
(73) Truss topology optimization [479].
(74) Virtual power plants [655, 1313].
(75) Water conflict problem between India and Bangladesh [58, 161], water allocation issues [592, 1258, 1260], water distribution system [1110], water rights trading [1222].

9. Test problems

Methods to generate test problems can be found for linear bilevel optimization problems in [888], for more general problems in [203, 204, 205, 206, 930, 1092], see also Chapter 9 of [472]. A bilevel optimization problem library can be found on the internet page. For another test set see [872].

10. Master, PhD and Habilitation thesis

S. Addoune [18], G.B. Allende [39], O. Ben-Ayed [129], Bi [151], W.D. Cai [202], L.M. Case [254], M. Červinka [1186], Y. Chen [264], B. Colson [294, 296], S.M. Dassanayaka [310], S. Dempe [332], S. DeNegre [395], deSilva [398], J. Deuerlein [401], S. Dewez [402], J. Eckardt [425], T. Edmunds [427], A. Ehrenmann [430], D. Fanghänel [455], S. Franke [477], Y. Gao [491], N. Groot [526], F. Harder [557], C. Henkel [573], X. Hu [590], E. Israeli [602], D. Joksimocic [627], F.M. Kue [692], S. Lohse [773], P. Mehlitz [847], A.G. Mersha [851], G.M. Moore [878], J. Moore [879], A. Nwosu [917], W. Oeder [922], F. Parraga [943], T. Petersen [954], A. G. Petoussis [955], O. Pieume [961], M. Pilecka [964, 966], P. Pisciella [970], R. Rog [1008], A. Ruziyeva [1017], R. Saboiev [1020], G. Savard [1046], G. Schenk [1051], H. Schmidt [1052], J. Shaw [1064], S.A Siddiqui [1083], L. Vicente [1187], S. Vogel [1193], A. Werner [1238],U. Wen [1228], R. Winter [1244], P. Xu [1264], J. Zhang [1330], A.B. Zemkoho [1307, 1308]

Edited volumes are Anandalingam and Friesz [59], Dempe and Kalashnikov [357], Migdalas et al. [861]

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