

Robust Sensitivity Analysis of the Optimal Value of Linear Programming

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Abstract

We propose a framework for sensitivity analysis of linear programs (LPs) in minimization form, allowing for simultaneous perturbations in the objective coefficients and right-hand sides, where the perturbations are modeled in a compact, convex uncertainty set. This framework unifies and extends multiple approaches for LP sensitivity analysis in the literature and has close ties to worst-case linear optimization and two-stage adaptive optimization. We define the minimum (best-case) and maximum (worst-case) LP optimal values, p^- and p^+ , over the uncertainty set, and we discuss issues of finiteness, attainability, and computational complexity. While p^- and p^+ are difficult to compute in general, we prove that they equal the optimal values of two separate, but related, copositive programs. We then develop tight, tractable conic relaxations to provide lower and upper bounds on p^- and p^+ , respectively. We also develop techniques to assess the quality of the bounds, and we validate our approach computationally on several examples from—and inspired by—the literature. We find that the bounds on p^- and p^+ are very strong in practice and, in particular, are at least as strong as known results for specific cases from the literature.

Keywords: Sensitivity analysis, minimax problem, nonconvex quadratic programming, semidefinite programming, copositive programming, uncertainty set.

1 Introduction

The standard-form linear program (LP) is

$$\begin{aligned} \min \quad & \hat{c}^T x \\ \text{s. t.} \quad & \hat{A}x = \hat{b} \\ & x \geq 0 \end{aligned} \tag{1}$$

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where $x \in \mathbb{R}^n$ is the variable and $(\hat{A}, \hat{b}, \hat{c}) \in \mathbb{R}^{m \times n} \times \mathbb{R}^m \times \mathbb{R}^n$ are the problem parameters. In practice, $(\hat{A}, \hat{b}, \hat{c})$ may not be known exactly or may be predicted to change within a certain region. In such cases, *sensitivity analysis* (SA) examines how perturbations in the parameters affect the optimal value and solution of (1). Ordinary SA considers the change of a single element in $(\hat{A}, \hat{b}, \hat{c})$ and examines the corresponding effects on the optimal basis and tableau; see [8]. SA also extends to the addition of a new variable or constraint, although we do not consider such changes in this paper.

Beyond ordinary SA, more sophisticated approaches that allow simultaneous changes in the coefficients \hat{c} or right-hand sides \hat{b} have been proposed by numerous researchers. Bradley et al. [4] discuss the *100-percent rule* that requires specification of directions of increase or decrease from each \hat{c}_j and then guarantees that the same basis remains optimal as long as the sum of fractions, corresponding to the percent of maximum change in each direction derived from ordinary SA, is less than or equal to 1. Wendell [36, 37, 38] develops the *tolerance approach* to find the so-called *maximum tolerance percentage* by which the objective coefficients can be simultaneously and independently perturbed within *a priori* bounds. The tolerance approach also handles perturbations in one row or column of the matrix coefficients [31] or even more general perturbations in all elements of the matrix coefficients under certain assumptions [30]. Freund [15] investigates the sensitivity of an LP to simultaneous changes in matrix coefficients. In particular, he considers a linear program whose coefficient matrix depends linearly on a scalar parameter θ and studies the effect of small perturbations on the the optimal objective value and solution; see also [21, 22, 28]. Readers are referred to [35] for a survey of approaches for SA of problem (1).

An area closely related to SA is *interval linear programming* (ILP), which can be viewed as *multi-parametric linear programming* with independent interval domains for the parameters [17, 18, 26]. Steuer [33] presents three algorithms for solving LPs in which the objective coefficients are specified by intervals, and Gabrel et al. [16] study LPs in which the right-hand sides vary within intervals and discuss the maximum and minimum optimal values. Mraz [27] considers a general situation in which the matrix coefficients and right-hand sides change within intervals and calculates upper and lower bounds for the associated optimal values. A comprehensive survey of ILP has been given by Hladik [20].

To the best of our knowledge, in the context of LP, no authors have considered simultaneous LP parameter changes in a general way, i.e., perturbations in the objective coefficients \hat{c} , right-hand sides \hat{b} , and constraint coefficients \hat{A} within a general region (not just intervals). The obstacle for doing so is clear: general perturbations lead to nonconvex quadratic programs (QPs), which are NP-hard to solve (as discussed below).

In this paper, we extend—and in many cases unify—the SA literature by employing

modern tools for nonconvex QPs. Specifically, we investigate SA for LPs in which (\hat{b}, \hat{c}) may change within a general compact, convex set \mathcal{U} , called the *uncertainty set*. Our goal is to calculate—or bound—the corresponding minimum (best-case) and maximum (worst-case) optimal values. Since these values involve the solution of nonconvex QPs, we use standard techniques from *copositive optimization* to reformulate these problems into convex *copositive programs* (COPs), which provide a theoretical grounding upon which to develop tight, tractable convex relaxations. We suggest the use of *semidefinite programming* (SDP) relaxations, which also incorporate valid conic inequalities that exploit the structure of the uncertainty set. We refer the reader to [10] for a survey on copositive optimization and its connections to semidefinite programming. Relevant definitions and concepts will also be given in this paper; see Section 1.1.

Our approach is related to the recent work on *worst-case linear optimization* introduced by Peng and Zhu [29] in which: (i) only \hat{b} is allowed to change within an ellipsoidal region; and (ii) only the worst-case LP value is considered. (In fact, one can see easily that, in the setup of [29] based on (i), the best-case LP value can be computed in polynomial time via second-order-cone programming, making it less interesting to study in their setup.) The authors argue that the worst-case value is NP-hard to compute and use a specialized nonlinear semidefinite program (SDP) to bound it from above. They also develop feasible solutions to bound the worst-case value from below and show through a series of empirical examples that the resulting gaps are usually quite small. Furthermore, they also demonstrate that their SDP-based relaxation is better than the so-called *affine-rule approximation* (see [2]) and the Lasserre *linear matrix inequality* relaxation (see [24, 19]).

Our approach is more general than [29] because we allow both \hat{b} and \hat{c} to change, we consider more general uncertainty sets, and we study both the worst- and best-case values. In addition, instead of developing a specialized SDP approach, we make use of the machinery of copositive programming, which provides a theoretical grounding for the construction of tight, tractable conic relaxations using existing techniques. Nevertheless, we have been inspired by their approach in several ways. For example, their proof of NP-hardness also shows that our problem is NP-hard; we will borrow their idea of using primal solutions to estimate the quality of the relaxation bounds; and we test some of the same examples.

We mention two additional connections of our approach with the literature. In [3], Bertsimas and Goyal consider a two-stage adaptive linear optimization problem under right-hand side uncertainty with a min-max objective. A simplified version of this problem, in which the first-stage variables are non-existent, reduces to worst-case linear optimization; see the introduction of [3]. In fact, Bertsimas and Goyal use this fact to prove that their problem is NP-hard via the so-called max-min fractional set cover problem, which is a specific

worst-case linear optimization problem studied by Feige et al. [14]. Our work is also related to the study of *adjustable robust optimization* [2, 34], which allows for two sets of decisions—one that must be made before the uncertain data is realized, and one after. In fact, our problem can be viewed as a simplified case of adjustable robust optimization having no first-stage decisions. On the other hand, our paper is distinguished by its application to sensitivity analysis and its use of copositive and semidefinite optimization.

We organize the paper as follows. In Section 2, we extend many of the existing approaches for SA by considering simultaneous, general changes in (\hat{b}, \hat{c}) and the corresponding effect on the LP optimal value. Precisely, we model general perturbations of (\hat{b}, \hat{c}) within a compact, convex set \mathcal{U} —the uncertainty set, borrowing terminology from the robust-optimization literature—and define the corresponding minimum and maximum optimal values p^- and p^+ , respectively. We call our approach *robust sensitivity analysis*, or *RSA*. Then, continuing in Section 2, we formulate the calculation of p^- and p^+ as nonconvex bilinear QPs (or BQPs) and briefly discuss attainability and complexity issues. We also discuss how p^- and p^+ may be infinite and suggest alternative bounded variants, q^- and q^+ , which have the property that, if p^- is already finite, then $q^- = p^-$ and similarly for q^+ and p^+ . Compared to related approaches in the literature, our discussion of finiteness is unique. We then discuss the addition of redundant constraints to the formulations of q^- and q^+ , which will strengthen later relaxations. Section 3 then establishes COP reformulations of the nonconvex BQPs by directly applying existing reformulation techniques. Then, based on the COPs, we develop tractable SDP-based relaxations that incorporate the structure of the uncertainty set \mathcal{U} , and we also discuss procedures for generating feasible solutions of the BQPs, which can also be used to verify the quality of the relaxation bounds. In Section 4, we validate our approach on several examples, which demonstrate that the relaxations provide effective approximations of q^+ and q^- . In fact, we find that the relaxations admit no gap with q^+ and q^- for all tested examples.

We mention some caveats about the paper. First, we focus only on how the optimal value is affected by uncertainty, not the optimal solution. We do so because we believe this will be a more feasible first endeavor; determining how general perturbations affect the optimal solution can certainly be a task for future research. Second, as mentioned above, we believe we are the first to consider these types of general perturbations, and thus the literature with which to compare is somewhat limited. However, we connect with the literature whenever possible, e.g., in special cases such as interval perturbations and worst-case linear optimization. Third, since we do not make any distributional assumptions about the uncertainty of the parameters, nor about their independence or dependence, we believe our approach aligns well with the general spirit of *robust optimization*. It is important to

note, however, that our interest is *not* robust optimization and is *not* directly comparable to robust optimization. For example, while in robust optimization one wishes to find a single optimal solution that works well for all realizations of the uncertain parameters, here we are only concerned with how the optimal value changes as the parameters change. Finally, we note the existence of other relaxations for nonconvex QPs including LP relaxations (see [32]) and Lasserre-type SDP relaxations. Generally speaking, LP-based relaxations are relatively weak (see [1]); we do not consider them in this paper. In addition, SDP approaches can often be tailored to outperform the more general Lasserre approach as has been demonstrated in [29]. Our copositive- and SDP-based approach is similar; see for example the valid inequalities discussed in Section 3.2.

1.1 Notation, terminology, and copositive optimization

Let \mathbb{R}^n denote n -dimensional Euclidean space represented as column vectors, and let \mathbb{R}_+^n denote the nonnegative orthant in \mathbb{R}^n . For a scalar $p \geq 1$, the p -norm of $v \in \mathbb{R}^n$ is defined $\|v\|_p := (\sum_{i=1}^n |v_i|^p)^{1/p}$, e.g., $\|v\|_1 = \sum_{i=1}^n |v_i|$. We will drop the subscript for the 2-norm, e.g., $\|v\| := \|v\|_2$. For $v, w \in \mathbb{R}^n$, the inner product of v and w is defined as $v^T w = \sum_{i=1}^n v_i w_i$ and the Hadamard product of v and w is defined by $v \circ w := (v_1 w_1, \dots, v_n w_n)^T \in \mathbb{R}^n$. $\mathbb{R}^{m \times n}$ denotes the set of real $m \times n$ matrices, and the trace inner product of two matrices $A, B \in \mathbb{R}^{m \times n}$ is defined $A \bullet B := \text{trace}(A^T B)$. \mathcal{S}^n denotes the space of $n \times n$ symmetric matrices, and for $X \in \mathcal{S}^n$, $X \succeq 0$ denotes that X is positive semidefinite. In addition, $\text{diag}(X)$ denotes the vector containing the diagonal entries of X .

We also make several definitions related to *copositive programming*. The $n \times n$ *copositive cone* is defined as

$$\mathcal{COP}(\mathbb{R}_+^n) := \{M \in \mathcal{S}^n : x^T M x \geq 0 \forall x \in \mathbb{R}_+^n\},$$

and its dual cone, the *completely positive cone*, is

$$\mathcal{CP}(\mathbb{R}_+^n) := \{X \in \mathcal{S}^n : X = \sum_k x^k (x^k)^T, x^k \in \mathbb{R}_+^n\},$$

where the summation over k is finite but its cardinality is unspecified. The term *copositive programming* refers to linear optimization over $\mathcal{COP}(\mathbb{R}_+^n)$ or, via duality, linear optimization over $\mathcal{CP}(\mathbb{R}_+^n)$. A more general notion of copositive programming is based on the following

ideas. Let $\mathcal{K} \subseteq \mathbb{R}^n$ be a closed, convex cone, and define

$$\begin{aligned}\mathcal{COP}(\mathcal{K}) &:= \{M \in \mathcal{S}^n : x^T M x \geq 0 \ \forall x \in \mathcal{K}\}, \\ \mathcal{CP}(\mathcal{K}) &:= \{X \in \mathcal{S}^n : X = \sum_k x^k (x^k)^T, \ x^k \in \mathcal{K}\}.\end{aligned}$$

Then *generalized copositive programming* is linear optimization over $\mathcal{COP}(\mathcal{K})$ and $\mathcal{CP}(\mathcal{K})$ and is also sometimes called *set-semidefinite optimization* [11]. In this paper, we work with generalized copositive programming, although we will use the shorter phrase *copositive programming* for convenience.

2 Robust Sensitivity Analysis

In this section, we introduce the concept of robust sensitivity analysis of the optimal value of the linear program (1). In particular, we define the best-case optimal value p^- and the worst-case optimal value p^+ over the uncertainty set \mathcal{U} , which contains general perturbations in the objective coefficients \hat{c} and the right-hand sides \hat{b} . We then propose nonconvex bilinear QPs (BQPs) to compute p^- and p^+ . Next, we clarify when p^- and p^+ could be infinite and propose finite, closely related alternatives q^+ and q^- , which can also be formulated as nonconvex BQPs. Importantly, we prove that q^- equals p^- whenever p^- is finite; the analogous relationship is also proved for q^+ and p^+ .

2.1 The best- and worst-case optimal values

In the Introduction, we have described \hat{b} and \hat{c} as parameters that could vary, a concept that we now formalize. Hereafter, (\hat{b}, \hat{c}) denotes the *nominal*, “best guess” parameter values, and we let (b, c) denote perturbations with respect to (\hat{b}, \hat{c}) . In other words, the true data could be $(\hat{b} + b, \hat{c} + c)$, and we think of b and c as varying. We also denote the *uncertainty set* containing all possible perturbations (b, c) as $\mathcal{U} \subseteq \mathbb{R}^m \times \mathbb{R}^n$. Throughout this paper, we assume the following:

Assumption 1. \mathcal{U} is compact and convex, and \mathcal{U} contains $(0, 0)$.

Given $(b, c) \in \mathcal{U}$, we define the perturbed optimal value function at (b, c) as

$$p(b, c) := \min\{(\hat{c} + c)^T x : \hat{A}x = \hat{b} + b, \ x \geq 0\}. \quad (2)$$

For example, $p(0, 0)$ is the *nominal optimal value* of the *nominal problem* based on the nominal parameters. The main idea of robust sensitivity analysis is then to compute the infimum

(best-case) and supremum (worst-case) of all optimal values $p(b, c)$ over the uncertainty set \mathcal{U} , i.e., to calculate

$$p^- := \inf\{p(b, c) : (b, c) \in \mathcal{U}\}, \quad (3)$$

$$p^+ := \sup\{p(b, c) : (b, c) \in \mathcal{U}\}. \quad (4)$$

We illustrate p^- and p^+ with a small example.

Example 1. Consider the nominal LP

$$\begin{aligned} \min \quad & x_1 + x_2 \\ \text{s. t.} \quad & x_1 + x_2 = 2 \\ & x_1, x_2 \geq 0 \end{aligned} \quad (5)$$

and the uncertainty set

$$\mathcal{U} := \left\{ (b, c) : \begin{array}{l} b_1 \in [-1, 1] \\ c_1 \in [-0.5, 0.5], c_2 = 0 \end{array} \right\}.$$

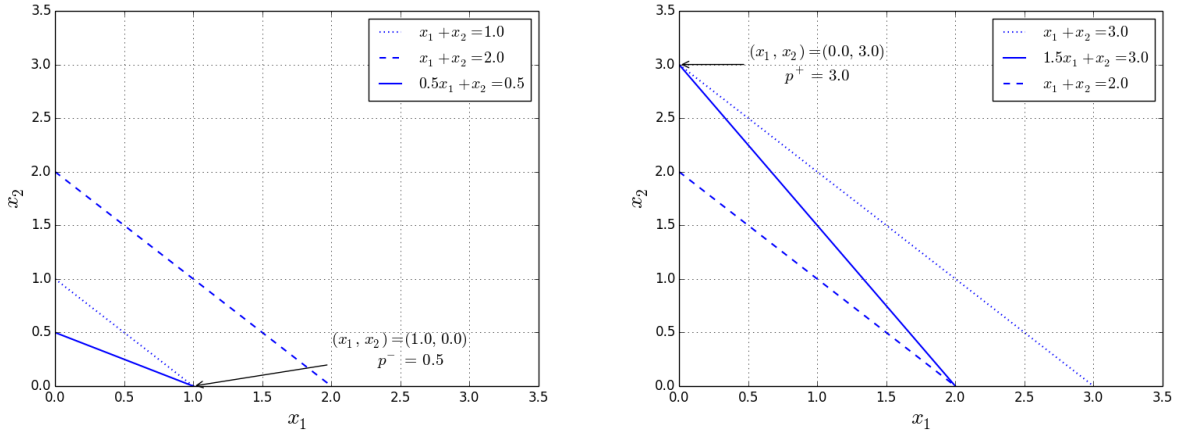
Note that the perturbed data $\hat{b}_1 + b_1$ and $\hat{c}_1 + c_1$ remain positive, while $\hat{c}_2 + c_2$ is constant. Thus, the minimum optimal value p^- occurs when b_1 and c_1 are minimal, i.e., when $b_1 = -1$ and $c_1 = -0.5$. In this case, $p^- = 0.5$ at the solution $(x_1, x_2) = (1, 0)$. In a related manner, $p^+ = 3$ when $b_1 = 1$ and $c_1 = 0.5$ at the point $(x_1, x_2) = (0, 3)$. Actually, any perturbation with $c_1 \in [0, 0.5]$ and $b_1 = 1$ realizes the worst-case value $p^+ = 3$. Figure 1 illustrates this example.

We can obtain a direct formulation of p^- by simply collapsing the inner and outer minimizations of (3) into a single nonconvex BQP:

$$\begin{aligned} \inf_{b, c, x} \quad & (\hat{c} + c)^T x \\ \text{s. t.} \quad & \hat{A}x = \hat{b} + b, x \geq 0 \\ & (b, c) \in \mathcal{U}. \end{aligned} \quad (6)$$

The nonconvexity comes from the bilinear term $c^T x$ in the objective function. In the special case that $(b, c) \in \mathcal{U}$ implies $c = 0$, i.e., when there is no perturbation in the objective coefficients, we have the following:

Remark 1. If \mathcal{U} is tractable and $c = 0$ for all $(b, c) \in \mathcal{U}$, then p^- can be computed in polynomial time as the optimal value of (6) with $c = 0$, which is a convex program.



(a) Illustration of the best-case optimal value (b) Illustration of the worst-case optimal value

Figure 1: Illustration of Example 1. Note that the dashed line in both (1a) and (1b) corresponds to the feasible region of the nominal problem.

A direct formulation for p^+ can, under a fairly weak assumption, be gotten via duality. Define the perturbed primal and dual feasible sets for any $(b, c) \in \mathcal{U}$:

$$P(b) := \{x : \hat{A}x = \hat{b} + b, x \geq 0\},$$

$$D(c) := \{(y, s) \geq 0 : \hat{A}^T y + s = \hat{c} + c, s \geq 0\}.$$

For instance, $P(0)$ and $D(0)$ are the primal-dual feasible sets of the nominal problem. Next define the dual LP for (2) as

$$d(b, c) := \max\{(\hat{b} + b)^T y : (y, s) \in D(c)\}.$$

Considering the extended notion of strong duality, which handles the cases of infinite values, we have that $d(b, c) = p(b, c)$ when at least one of $P(b)$ and $D(c)$ is nonempty. Hence, under the assumption that every $(b, c) \in \mathcal{U}$ yields $P(b) \neq \emptyset$ or $D(c) \neq \emptyset$, a direct formulation for p^+ can be constructed by replacing $p(b, c)$ in (3) with $d(b, c)$ and then collapsing the subsequent inner and outer maximizations into the single nonconvex BQP

$$\begin{aligned} & \sup_{b,c,y,s} && (\hat{b} + b)^T y \\ & \text{s. t.} && \hat{A}^T y + s = \hat{c} + c, \quad s \geq 0 \\ & && (b, c) \in \mathcal{U}. \end{aligned} \tag{7}$$

Here again, the nonconvexities arise due to the bilinear term $b^T y$ in the objective. If $(b, c) \in \mathcal{U}$ implies $b = 0$, then p^+ can be calculated in polynomial time:

Remark 2. If \mathcal{U} is tractable and $b = 0$ for all $(b, c) \in \mathcal{U}$, then p^+ can be computed in polynomial time as the optimal value of (7) with $b = 0$, which is a convex program.

We summarize the above discussion in the following proposition:

Proposition 1. *The best-case value p^- equals the optimal value of (6). Moreover, if $P(b) \neq \emptyset$ or $D(c) \neq \emptyset$ for all $(b, c) \in \mathcal{U}$, then the worst-case value p^+ equals the optimal value of (7).*

We view the condition in Proposition 1—that at least one of $P(b)$ and $D(c)$ is nonempty for each $(b, c) \in \mathcal{U}$ —to be rather mild. Said differently, the case that $P(b) = D(c) = \emptyset$ for some $(b, c) \in \mathcal{U}$ appears somewhat pathological. For practical purposes, we hence consider (7) to be a valid formulation of p^+ . Actually, in the next subsection, we will further restrict our attention to those $(b, c) \in \mathcal{U}$ for which both $P(b)$ and $P(c)$ are nonempty. In such cases, each $p(b, c)$ is guaranteed to be finite, which—as we will show—carefully handles the cases when p^+ and p^- are infinite.

Indeed, the worst-case value p^+ could equal $+\infty$ due to some perturbed $P(b)$ being empty as shown in the following example:

Example 2. *In Example 1, change the uncertainty set to*

$$\mathcal{U} := \left\{ (b, c) : \begin{array}{l} b_1 \in [-3, 1] \\ c_1 \in [-0.5, 0.5], c_2 = 0 \end{array} \right\}.$$

Then $p(b, c) = +\infty$ whenever $b_1 \in [-3, -2)$ since then the primal feasible set $P(b)$ is empty. Then $p^+ = +\infty$ overall. However, limiting b_1 to $[-2, 1]$ yields a worst-case value of 3 as discussed in Example 1.

Similarly, p^- might equal $-\infty$ due to some perturbed LP having unbounded objective value, implying infeasibility of the corresponding dual feasible set $D(c)$.

2.2 Attainability and complexity

In this brief subsection, we mention results pertaining to the attainability of p^- and p^+ and the computational complexity of computing them.

By an existing result concerning the attainability of the optimal value of nonconvex BQPs, we have that p^- and p^+ are attainable when \mathcal{U} has a relatively simple structure:

Proposition 2 (theorem 2 of [25]). *Suppose \mathcal{U} is representable by a finite number of linear constraints and at most one convex quadratic constraint. Then, if the optimal value of (6) is finite, it is attained. A similar statement holds for (7).*

In particular, attainability holds when \mathcal{U} is polyhedral or second-order-cone representable with at most one second-order cone. Moreover, the bilinear nature of (6) implies that, if the optimal value is attained, then there exists an optimal solution (x^*, b^*, c^*) with (b^*, c^*) an extreme point of \mathcal{U} . The same holds for (7) if its optimal value is attained.

As discussed in the Introduction, the worst-case value p^+ has been studied by Peng and Zhu [29] for the special case when $c = 0$ and b is contained in an ellipsoid. The authors demonstrate (see their proposition 1.1) that calculating p^+ in this case is NP-hard. By the symmetry of duality, it thus also holds that p^- is NP-hard to compute in general.

2.3 Finite variants of p^- and p^+

We now discuss closely related variants of p^+ and p^- that are guaranteed to be finite and to equal p^+ and p^- , respectively, when those values are themselves finite. We require the following feasibility and boundedness assumption:

Assumption 2. *Both feasible sets $P(0)$ and $D(0)$ are nonempty, and one is bounded.*

By standard theory, $P(0)$ and $D(0)$ cannot both be nonempty and bounded. Also define

$$\bar{\mathcal{U}} := \{(b, c) \in \mathcal{U} : P(b) \neq \emptyset, D(c) \neq \emptyset\}.$$

Note that $(0, 0) \in \bar{\mathcal{U}}$ due to Assumption 2. In fact, $\bar{\mathcal{U}}$ can be captured with linear constraints that enforce primal-dual feasibility and hence is a compact, convex subset of \mathcal{U} :

$$\bar{\mathcal{U}} = \left\{ (b, c) \in \mathcal{U} : \begin{array}{l} \hat{A}x = \hat{b} + b, x \geq 0 \\ \hat{A}^T y + s = \hat{c} + c, s \geq 0 \end{array} \right\}.$$

Analogous to p^+ and p^- , define

$$q^+ := \sup\{p(b, c) : (b, c) \in \bar{\mathcal{U}}\} \tag{8}$$

$$q^- := \inf\{p(b, c) : (b, c) \in \bar{\mathcal{U}}\}. \tag{9}$$

The following proposition establishes the finiteness of q^+ and q^- :

Proposition 3. *Under Assumptions 1 and 2, both q^+ and q^- are finite.*

Proof. We prove the contrapositive for q^- . (The argument for q^+ is similar.) Suppose $q^- = -\infty$. Then there exists a sequence $\{(b^k, c^k)\} \subseteq \bar{\mathcal{U}}$ with finite optimal values $p(b^k, c^k) \rightarrow -\infty$. By strong duality, there exists a primal-dual solution sequence $\{(x^k, y^k, s^k)\}$ with

$(\hat{c} + c)^T x^k = (\hat{b} + b)^T y^k \rightarrow -\infty$. Since $\bar{\mathcal{U}}$ is bounded, it follows that $\|x^k\| \rightarrow \infty$ and $\|y^k\| \rightarrow \infty$.

Consider the sequence $\{(z^k, d^k)\}$ with $(z^k, d^k) := (x^k, b^k)/\|x^k\|$. We have $\hat{A}z^k = \hat{b}/\|x^k\| + d^k$, $z^k \geq 0$, and $\|z^k\| = 1$ for all k . Moreover, $\hat{b}/\|x^k\| + d^k \rightarrow 0$. Hence, there exists a subsequence converging to $(\bar{z}, 0)$ such that $\hat{A}\bar{z} = 0$, $\bar{z} \geq 0$, and $\|\bar{z}\| = 1$. This proves that the recession cone of $P(0)$ is nontrivial, and hence $P(0)$ is unbounded. In a similar manner, $D(0)$ is unbounded, which means Assumption 2 does not hold. \square

Note that the proof of Proposition 3 only assumes that \mathcal{U} , and hence $\bar{\mathcal{U}}$, is bounded, which does not use the full power of Assumption 1.

Similar to p^- , a direct formulation of q^- can be constructed by employing the primal-dual formulation of $\bar{\mathcal{U}}$ and by collapsing the inner and outer minimizations of (9) into a single nonconvex BQP:

$$\begin{aligned} q^- &= \inf_{b,c,x,y,s} (\hat{c} + c)^T x \\ &\text{s. t.} \quad \hat{A}x = \hat{b} + b, \quad x \geq 0 \\ &\quad \hat{A}^T y + s = \hat{c} + c, \quad s \geq 0 \\ &\quad (b, c) \in \mathcal{U}. \end{aligned} \tag{10}$$

Likewise for p^+ , after replacing $p(b, c)$ in (8) by $d(b, c)$, we can collapse the inner and outer maximizations into a single nonconvex BQP:

$$\begin{aligned} q^+ &= \sup_{b,c,x,y,s} (\hat{b} + b)^T y \\ &\text{s. t.} \quad \hat{A}x = \hat{b} + b, \quad x \geq 0 \\ &\quad \hat{A}^T y + s = \hat{c} + c, \quad s \geq 0 \\ &\quad (b, c) \in \mathcal{U}. \end{aligned} \tag{11}$$

The following proposition establishes $q^+ = p^+$ when p^+ is finite and, similarly, $q^- = p^-$ when p^- is finite.

Proposition 4. *If p^+ is finite, then $q^+ = p^+$, and if p^- is finite, then $q^- = p^-$.*

Proof. We prove the second statement only since the first is similar. Comparing the formulation (6) for p^- and the formulation (10) for q^- , it is clear that $p^- \leq q^-$. In addition, let (b, c, x) be any feasible solution of (6). Because p^- is finite, $p(b, c)$ is finite. Then the corresponding dual problem is feasible, which implies that we can extend (b, c, x) to a solution (b, c, x, y, s) of (10) with the same objective value. Hence, $p^- \geq q^-$. \square

In the remaining sections of the paper, we will focus on the finite variants q^- and q^+ given by the nonconvex QPs (10) and (11), which optimize the optimal value function $p(b, c) =$

$d(b, c)$ based on enforcing primal-dual feasibility. It is clear that we may also enforce the complementary slackness condition $x \circ s = 0$ without changing these problems. Although it might seem counterintuitive to add the redundant, nonconvex constraint $x \circ s = 0$ to an already difficult problem, in Section 3, we will propose convex relaxations to approximate q^- and q^+ , in which case—as we will demonstrate—the relaxed versions of the redundant constraint can strengthen the relaxations.

3 Copositive Formulations and Relaxations

In this section, we use copositive optimization techniques to reformulate the RSA problems (10) and (11) into convex programs. We further relax the copositive programs into conic, SDP-based problems, which are computationally tractable.

3.1 Copositive formulations

In order to formulate (10) and (11) as COPs, we apply a result of [6]; see also [5, 9, 12]. Consider the general nonconvex QP

$$\begin{aligned} \inf \quad & z^T W z + 2 w^T z \\ \text{s. t.} \quad & E z = f, \quad z \in \mathcal{K} \end{aligned} \tag{12}$$

where \mathcal{K} is a closed, convex cone. Its copositive reformulation is

$$\begin{aligned} \inf \quad & W \bullet Z + 2 w^T z \\ \text{s. t.} \quad & E z = f, \quad \text{diag}(E Z E^T) = f \circ f \\ & \begin{pmatrix} 1 & z^T \\ z & Z \end{pmatrix} \in \mathcal{CP}(\mathbb{R}_+ \times \mathcal{K}), \end{aligned} \tag{13}$$

as established by the following lemma:

Lemma 1 (corollary 8.3 in [6]). *Problem (12) is equivalent to (13), i.e.: (i) both share the same optimal value; (ii) if (z^*, Z^*) is optimal for (13), then z^* is in the convex hull of optimal solutions for (12).*

The following theorem establishes that problems (10) and (11) can be reformulated as copositive programs according to Lemma 1. The proof is based on describing how the two problems fit the form (12).

Theorem 1. *Problems (10) and (11) to compute q^- and q^+ are solvable as copositive programs of the form (13), where*

$$\mathcal{K} := \text{hom}(\mathcal{U}) \times \mathbb{R}_+^n \times \mathbb{R}^m \times \mathbb{R}_+^n$$

and

$$\text{hom}(\mathcal{U}) := \{(t, b, c) \in \mathbb{R}_+ \times \mathbb{R}^m \times \mathbb{R}^n : t > 0, (b, c)/t \in \mathcal{U}\} \cup \{(0, 0, 0)\}$$

is the homogenization of \mathcal{U} .

Proof. We prove the result for just problem (10) since the argument for problem (11) is similar. First, we identify $z \in \mathcal{K}$ in (12) with $(t, b, c, x, y, s) \in \text{hom}(\mathcal{U}) \times \mathbb{R}_+^n \times \mathbb{R}^m \times \mathbb{R}_+^n$ in (10). In addition, in the constraints, we identify $Ez = f$ with the equations $\hat{A}x = t\hat{b} + b$, $\hat{A}^T y + s = t\hat{c} + c$, and $t = 1$. Note that the right-hand-side vector f is all zeros except for a single entry corresponding to the constraint $t = 1$. Moreover, in the objective, $z^T W z$ is identified with the bilinear term $c^T x$, and $2w^T z$ is identified with the linear term $\hat{c}^T x$. With this setup, it is clear that (10) is an instance of (12) and hence Lemma 1 applies to complete the proof. \square

3.2 SDP-based conic relaxations

As discussed above, the copositive formulations of (10) and (11) as represented by (13) are convex yet generally intractable. Thus, we propose SDP-based conic relaxations that are polynomial-time solvable and hopefully quite tight in practice. In Section 4 below, we will investigate their tightness computationally.

We propose relaxations that are formed from (13) by relaxing the cone constraint

$$M := \begin{pmatrix} 1 & z^T \\ z & Z \end{pmatrix} \in \mathcal{CP}(\mathbb{R}_+ \times \mathcal{K}).$$

As is well known—and direct from the definitions—cones of the form $\mathcal{CP}(\cdot)$ are contained in the positive semidefinite cone. Hence, we will enforce $M \succeq 0$. It is also true that $M \in \mathcal{CP}(\mathbb{R}_+ \times \mathcal{K})$ implies $z \in \mathcal{K}$, although $M \succeq 0$ does not necessarily imply this. So, in our relaxations, we will also enforce $z \in \mathcal{K}$. Including $z \in \mathcal{K}$ improves the relaxation and also helps in the calculation of bounds in Section 3.3

Next, suppose that the description of $\mathbb{R}_+ \times \mathcal{K}$ contains at least two linear constraints, $a_1^T z \leq b_1$ and $a_2^T z \leq b_2$. By multiplying $b_1 - a_1^T z$ and $b_2 - a_2^T z$, we obtain a valid, yet redundant, quadratic constraint $b_1 b_2 - b_1 a_2^T z - b_2 a_1^T z + a_1^T z z^T a_2 \geq 0$ for $\mathcal{CP}(\mathbb{R}_+ \times \mathcal{K})$. This quadratic inequality can in turn be linearized in terms of M as $b_1 b_2 - b_1 a_2^T z - b_2 a_1^T z + a_1^T Z a_2 \geq$

0, which is valid for $\mathcal{CP}(\mathbb{R}_+ \times \mathcal{K})$. We add this linear inequality to our relaxation; it is called an *RLT constraint* [32]. In fact, we add all such RLT constraints arising from all pairs of linear constraints present in the description of $\mathbb{R}_+ \times \mathcal{K}$.

When the description of $\mathbb{R}_+ \times \mathcal{K}$ contains at least one linear constraint $a_1^T z \leq b_1$ and one second-order-cone constraint $\|d_2 - C_2^T z\| \leq b_2 - a_2^T z$, where d_2 is a vector and C_2 is a matrix, we will add a so-called *SOC-RLT constraint* to our relaxation [7]. The constraint is derived by multiplying the two constraints to obtain the valid quadratic second-order-cone constraint

$$\|(b_1 - a_1^T z)(d_2 - C_2^T z)\| \leq (b_1 - a_1^T z)(b_2 - a_2^T z).$$

After linearization by M , we have the second-order-cone constraint

$$\|b_1 d_2 - d_2 a_1^T z - b_1 C_2^T z + C_2^T Z a_1\| \leq b_1 b_2 - b_1 a_2^T z - b_2 a_1^T z + a_1^T Z a_2.$$

Finally, recall the redundant complementarity constraint $x \circ s = 0$ described at the end of Section 2.3, which is valid for both (10) and (11). Decomposing it as $x_i s_i = 0$ for $i = 1, \dots, n$, we may translate these n constraints to (13) as $z^T H_i z = 0$ for appropriately defined matrices H_i . Then they may be linearized and added to our relaxation as $H_i \bullet Z = 0$.

To summarize, let RLT denote the set of (z, Z) satisfying all the derived RLT constraints, and similarly, define SOCRLT as the set of (z, Z) satisfying all the derived SOC-RLT constraints. Then the SDP-based conic relaxation for (13) that we propose to solve is

$$\begin{aligned} \inf \quad & W \bullet Z + 2 w^T z \\ \text{s. t.} \quad & Ez = f, \text{diag}(EZE^T) = f \circ f \\ & H_i \bullet Z = 0 \quad \forall i = 1, \dots, n \\ & (z, Z) \in \text{RLT} \cap \text{SOCRLT} \\ & \begin{pmatrix} 1 & z^T \\ z & Z \end{pmatrix} \succeq 0, \quad z \in \mathcal{K}. \end{aligned} \tag{14}$$

It is worth mentioning that, in many cases, the RLT and SOC-RLT constraints will already imply $z \in \mathcal{K}$, but in such cases, we nevertheless write the constraint in (14) for emphasis; see also Section 3.3 below.

When translated to the problem (10) for calculating q^- , the relaxation (14) gives rise to a lower bound $q_{\text{sdp}}^- \leq q^-$. Similarly, when applied to (11), we get an upper bound $q_{\text{sdp}}^+ \geq q^+$.

3.3 Bounds from feasible solutions

In this section, we discuss two methods to approximate q^- from above and q^+ from below, i.e., to bound q^- and q^+ using feasible solutions of (10) and (11), respectively.

The first method, which has been inspired by [29], utilizes the optimal solution of the SDP relaxation (14). Let us discuss how to obtain such a bound for (10), as the discussion for (11) is similar. We first observe that any feasible solution (z, Z) of (14) satisfies $Ez = f$ and $z \in \mathcal{K}$, i.e., z satisfies all of the constraints of (12). Since (12) is equivalent to (10) under the translation discussed in the proof of Theorem 1, z gives rise to a feasible solution (x, y, s, b, c) of (10). From this feasible solution, we can calculate $(\hat{c} + c)^T x \geq q^-$. In practice, we will start from the optimal solution (z^-, Z^-) of (14). We summarize this approach in the following remark.

Remark 3. *Suppose that (z^-, Z^-) is an optimal solution of the relaxation (14) corresponding to (10), and let $(x^-, y^-, s^-, b^-, c^-)$ be the translation of z^- to a feasible point of (10). Then, $r^- := (\hat{c} + c^-)^T x^- \geq q^-$. Similarly, we define $r^+ := (\hat{b} + b^+)^T y^+ \leq q^+$ based on an optimal solution (z^+, Z^+) of (14) corresponding to (11).*

Our second method for bounding q^- and q^+ using feasible solutions is a sampling procedure detailed in Algorithm 1. The main idea is to generate randomly a point $(b, c) \in \bar{\mathcal{U}}$ and then to calculate $p(b, c)$, which serves as an upper bound of p^- and a lower bound of p^+ , i.e., $p^- \leq p(b, c) \leq p^+$. Multiple points (b^k, c^k) and values $p^k := p(b^k, c^k)$ are generated and the best bounds $p^- \leq v^- := \min_k \{p^k\}$ and $\max_k \{p^k\} =: v^+ \leq p^+$ are saved. In fact, by the bilinearity of (10) and (11), we may restrict attention to the extreme points (b, c) of $\bar{\mathcal{U}}$ without reducing the quality of the resultant bounds; see also the discussion in Section 2.2. Hence, Algorithm 1 generates—with high probability—a random extreme point of $\bar{\mathcal{U}}$ by optimizing a random linear objective over $\bar{\mathcal{U}}$, and we generate the random linear objective as a vector uniform on the sphere, which is implemented by a well-known, quick procedure. Note that, even though the random objective is generated according to a specific distribution, we cannot predict the resulting distribution over the extreme points of $\bar{\mathcal{U}}$.

As all four of the bounds $r^-, r^+, v^-,$ and v^+ are constructed from feasible solutions, we can further improve them heuristically by exploiting the bilinear objective functions in (10) and (11). In particular, we employ the standard local improvement heuristic for programs with a bilinear objective and convex constraints (e.g., see [23]). Suppose, for example, that we have a feasible point $(x^-, y^-, s^-, b^-, c^-)$ for problem (10) as discussed in Remark 3. To attempt to improve the solution, we fix the variable c in (10) at the value c^- , and we solve the resulting convex problem for a new, hopefully better point $(x^1, y^1, s^1, b^1, c^1)$, where $c^1 = c^-$. Then, we fix x to x^1 , resolve, and get a new point $(x^2, y^2, s^2, b^2, c^2)$, where $x^2 = x^1$. This

Algorithm 1 Sampling procedure to bound q^- from above and q^+ from below

Inputs: Instance with uncertainty set \mathcal{U} and restricted uncertainty set $\bar{\mathcal{U}}$. Number of random trials T .

Outputs: Bounds $v^- := \min_k \{p^k\} \geq p^-$ and $v^+ := \max_k \{p^k\} \leq p^+$.

for $k = 1, \dots, T$ **do**

Generate $(f, g) \in \mathbb{R}^m \times \mathbb{R}^n$ uniformly on the unit sphere.

Calculate $(b^k, c^k) \in \text{Arg min}\{f^T b + g^T c : (b, c) \in \bar{\mathcal{U}}\}$.

Set $p^k := p(b^k, c^k)$.

end for

alternating process is repeated until there is no further improvement in the objective of (10), and the final objective is our bound r^- .

In Section 4 below, we use the bounds r^- , r^+ , v^- , and v^+ to verify the quality of our bounds q_{sdp}^- and q_{sdp}^+ . Our tests indicate that neither bound, r^- nor v^- , dominates the other—and similarly for the bounds r^+ and v^+ . Hence, we will actually report the better of each pair: $\min\{r^-, v^-\}$ and $\max\{r^+, v^+\}$. Also, for the calculations of v^- and v^+ , we always take $T = 10,000$ in Algorithm 1.

4 Computational Experiments

In this section, we validate our approach by testing it on six examples from the literature as well as an example of our own making. The first three examples in Section 4.1 correspond to classical sensitivity analysis approaches for LP; the fourth example in Section 4.2 corresponds to an interval LP in inventory management; the fifth example in Section 4.3 corresponds to a systemic-risk calculation in financial systems; and the last example in Section 4.4 is a transportation network flow problem. We implement our tests in Python (version 2.7.6) with Mosek (version 7.1.0.33) as our convex-optimization solver. All of Mosek’s settings are set at their defaults, and computations are conducted on a Macintosh OS X Yosemite system with a quad-core 3.20GHz Intel Core i5 CPU and 8 GB RAM.

4.1 Examples from classical sensitivity analysis

Consider the following nominal problem from [35]:

$$\begin{aligned}
 \min \quad & -12x_1 - 18x_2 - 18x_3 - 40x_4 \\
 \text{s. t.} \quad & 4x_1 + 9x_2 + 7x_3 + 10x_4 + x_5 = 6000 \\
 & x_1 + x_2 + 3x_3 + 40x_4 + x_6 = 4000 \\
 & x_1, \dots, x_6 \geq 0.
 \end{aligned}$$

The optimal basis is $B = \{1, 4\}$ with optimal solution $\frac{1}{3}(4000, 0, 0, 200, 0, 0)$ and optimal value $p(0, 0) = -18667$. According to standard, “textbook” sensitivity analysis, the optimal basis persists when the coefficient of x_1 lies in the interval $[-16, -10]$ and other parameters remain the same. Along this interval, one can easily compute the best-case value -24000 and worst-case value -16000 , and we attempt to reproduce this analysis with our approach. So let us choose the uncertainty set

$$\mathcal{U} = \left\{ (b, c) \in \mathbb{R}^2 \times \mathbb{R}^6 : \begin{array}{l} b_1 = b_2 = 0 \\ c_1 \in [-4, 2] \\ c_2 = \dots = c_6 = 0 \end{array} \right\},$$

which corresponds precisely to the above allowable decrease and increase on the coefficient of x_1 . Note that Assumptions 1 and 2 are satisfied. We thus know from above that $q^- = -24000$ and $q^+ = -16000$. Since $b = 0$ in \mathcal{U} , Remark 2 implies that q^+ is easy to calculate. So we apply our approach, i.e., solving the SDP-based relaxation, to approximate q^- . The relaxation value is $q_{\text{sdp}}^- = -24000$, which recovers q^- exactly. The CPU time for computing q_{sdp}^- is 0.10 seconds.

Our second example is also based on the same nominal problem from [35], but we consider the 100%-rule. Again, we know that the optimal basis $B = \{1, 4\}$ persists when the coefficient of x_1 lies in the interval $[-16, -10]$ (and all other parameters remain the same) or separately when the coefficient of x_2 lies in the interval $[-134/3, +\infty]$ (and all other parameters remain the same). In accordance with the 100%-rule, we choose to decrease the coefficient of x_1 , and thus its allowed interval is $[-16, -12]$ of width 4. We also choose to decrease the coefficient of x_2 , and thus its allowed interval is $[-134/3, -18]$ of width $80/3$. The 100%-rule ensures that the optimal basis persists as long as the sum of fractions, corresponding to the percent of maximum changes in the coefficients of x_1 and x_2 , is less than or equal to 1. In other words, suppose that \tilde{c}_1 and \tilde{c}_2 are the perturbed values of the coefficients of x_1 and x_2 , respectively, and that all other coefficients stay the same. Then the nominal optimal basis persists for $(\tilde{c}_1, \tilde{c}_2)$ in the following simplex:

$$\left\{ (\tilde{c}_1, \tilde{c}_2) : \begin{array}{l} \tilde{c}_1 \in [-16, -12] \\ \tilde{c}_2 \in [-134/3, -18] \\ \frac{-12-\tilde{c}_1}{4} + \frac{-18-\tilde{c}_2}{80/3} \leq 1 \end{array} \right\}.$$

By evaluating the three extreme points $(-12, -18)$, $(-16, -18)$ and $(-12, -134/3)$ of this set with respect to the nominal optimal solution, one can calculate the best-case optimal value as $q^- = -24000$ and the worst-case optimal value as $q^+ = -18667$. We again apply

our approach in an attempt to recover empirically the 100%-rule. Specifically, let

$$\mathcal{U} = \left\{ (b, c) : \begin{array}{l} b_1 = b_2 = 0 \\ c_1 \in [-4, 0], c_2 \in [-\frac{80}{3}, 0] \\ -\frac{c_1}{4} - \frac{c_2}{80/3} \leq 1 \\ c_3 = \dots = c_6 = 0 \end{array} \right\}.$$

Note that Assumptions 1 and 2 are satisfied. Due to $b = 0$ and Remark 2, we focus our attention on q^- . Calculating the SDP-based relaxation value, we see that $q_{\text{sdp}}^- = -24000$, which recovers q^- precisely. The CPU time is 0.15 seconds

Our third example illustrates the tolerance approach, and we continue to use the same nominal problem from [35]. As mentioned in the Introduction, the tolerance approach considers simultaneous and independent perturbations in the objective coefficients by calculating a maximum tolerance percentage such that, as long as selected coefficients are accurate to within that percentage of their nominal values, the nominal optimal basis persists; see [38]. Let us consider perturbations in the coefficients of x_1 and x_2 with respect to the nominal problem. Applying the tolerance approach of [38], the maximum tolerance percentage is 1/6 in this case. That is, as long as the two coefficient values vary within $-12 \pm 12/6 = [-14, -10]$ and $-18 \pm 18/6 = [-21, -15]$, respectively, then the nominal optimal basis $B = \{1, 4\}$ persists. By testing the four extreme points of the box of changes $[-14, -10] \times [-21, -15]$ with respect to the optimal nominal solution, one can calculate the best-case optimal value as $q^- = -21333$ and the worst-case optimal value as $q^+ = -16000$. To test our approach in this setting, we set

$$\mathcal{U} := \left\{ (b, c) : \begin{array}{l} b_1 = b_2 = 0, c_3 = \dots = c_6 = 0 \\ c_1 \in [-2, 2], c_2 \in [-3, 3] \end{array} \right\}$$

and, as in the previous two examples, we focus on q^- . Assumptions 1 and 2 are again satisfied, and we calculate the lower bound $q_{\text{sdp}}^- = -21333$, which recovers q^- precisely. The CPU time for computing q_{sdp}^- is 0.13 seconds.

4.2 An example from interval linear programming

We consider an optimization problem that is typical in inventory management, and this particular example originates from [16]. Suppose one must decide the quantity to be ordered during each period of a finite, discrete horizon consisting of T periods. The goal is to satisfy exogenous demands d_k for each period k , while simultaneously minimizing the total of purchasing, holding, and shortage costs. Introduce the following variables for each period

k :

s_k = stock available at the end of period k ;

x_k = quantity ordered at the beginning of period k .

Items ordered at the beginning of period k are delivered in time to satisfy demand during the same period. Any excess demand is backlogged. Hence, each x_k is nonnegative, each s_k is free, and

$$s_{k-1} + x_k - s_k = d_k.$$

The order quantities x_k are further subject to uniform upper and lower bounds, u and l , and every stock level s_k is bounded above by U . At time k , the purchase cost is denoted as c_k , the holding cost is denoted as h_k , and the shortage cost is denoted g_k . Then, the problem can be formulated as the following linear programming problem (assuming that the initial inventory is 0):

$$\begin{aligned}
\min \quad & \sum_{k=1}^T (c_k x_k + y_k) \\
\text{s. t.} \quad & s_0 = 0 \\
& s_{k-1} + x_k - s_k = d_k \quad k = 1, \dots, T \\
& y_k \geq h_k s_k \quad k = 1, \dots, T \\
& y_k \geq -g_k s_k \quad k = 1, \dots, T \\
& l \leq x_k \leq u \quad k = 1, \dots, T \\
& s_k \leq U \quad k = 1, \dots, T \\
& x_k, y_k \geq 0 \quad k = 1, \dots, T.
\end{aligned} \tag{15}$$

As in [16], consider an instance of (15) in which $T = 4$, $u = 1500$, $l = 1000$, $U = 600$, and all costs are as in Table 1. Moreover, suppose the demands d_k are each uncertain and may be estimated by the intervals $d_1 \in [700, 900]$, $d_2 \in [1300, 1600]$, $d_3 \in [900, 1100]$, and $d_4 \in [500, 700]$. From [16], the worst-case optimal value over this uncertainty set is $q^+ = 25600$. For our approach, it is easy to verify that Assumptions 1 and 2 are satisfied, and solving our SDP-based conic relaxation with an uncertainty set corresponding to the intervals on d_k , we recover q^+ exactly, i.e., we have $q_{\text{sdp}}^+ = 25600$. The CPU time for computing our SDP optimal value is 1,542 seconds.

Since the uncertainties only involve the right-hand sides, Remark 1 implies that the best-case value q^- can be calculated in polynomial-time by solving an LP that directly incorporates the uncertainty.

Period (k)	Purchasing cost (c_k)	Holding cost (h_k)	Shortage cost (g_k)
1	7	2	3
2	1	1	4
3	10	1	3
4	6	1	3

Table 1: Costs for each period of an instance of the inventory management problem

4.3 Worst-case linear optimization

We next consider an example for calculating systemic risk in financial systems, which is an application of worst-case linear optimization (WCLO) presented in [29].

For an interbank market, systemic risk is used to evaluate the potential loss of the whole market as a response to the decisions made by the individual banks [13, 29]. Specifically, let us consider a market consisting of n banks. We use an $n \times n$ matrix \hat{L} to denote the liability relationship between any two banks in the market. For instance, the element \hat{L}_{ij} represents the liability of bank i to bank j . In the market, banks can also receive exogenous operating cash flows to compensate their potential shortfalls on incoming cash flows. We use \hat{b}_i to denote the exogenous operating cash flow received by bank i . Given the vector \hat{b} , we calculate the systemic loss $l(\hat{b})$ of the market, which measures the amount of overall failed liabilities [29]:

$$\begin{aligned}
l(\hat{b}) = \min_x \quad & \sum_{i=1}^n (1 - x_i) \\
\text{s. t.} \quad & (\sum_{j=1}^n \hat{L}_{ij})x_i - \sum_{j=1}^n \hat{L}_{ji}x_j \leq \hat{b}_i \quad \forall i = 1, \dots, n \\
& x_i \leq 1 \quad \forall i = 1, \dots, n.
\end{aligned}$$

Here the decision variables x_i represent the ratio of the total dollar payment by bank i to the total obligation of bank i . These ratios are naturally less than or equal to 1 ($x_i \leq 1$) as the banks do not pay more than their obligations. In contrast, $1 - x_i$ denotes the ratio of bank i failing to fulfill its obligations. Furthermore, we have a less-than-or-equal-to sign in the first constraint as the system allows *limited liability* (see [13]). Finally, the objective is to minimize the total failure ratio of the system.

In practice, however, there exist uncertainties in the exogenous operating cash flows. Allowing for uncertainties, the worst-case systemic risk problem [29] is given as

$$\begin{aligned}
\max_{b \in \mathcal{V}} \quad & \min_x \sum_{i=1}^n (1 - x_i) \\
\text{s. t.} \quad & (\sum_{j=1}^n \hat{L}_{ij})x_i - \sum_{j=1}^n \hat{L}_{ji}x_j \leq \hat{b}_i + Q_i b \quad \forall i = 1, \dots, n \\
& x_i \leq 1 \quad \forall i = 1, \dots, n.
\end{aligned}$$

Instance	$\max\{r^+, v^+\}$	gap ⁺	q_{sdp}^+	$t_{\text{sdp}}^+(s)$
1	0.521	0.0%	0.521	0.66
2	1.429	0.0%	1.429	0.82
3	1.577	0.0%	1.577	0.83
4	0.344	0.0%	0.344	0.68
5	0.724	0.0%	0.724	0.73
6	0.690	0.0%	0.690	0.80
7	1.100	0.0%	1.100	0.73
8	0.458	0.0%	0.458	0.78
9	0.427	0.0%	0.427	0.74
10	0.300	0.0%	0.300	0.78

Table 2: Results for the systemic-risk example

where $\mathcal{V} := \{b \in \mathbb{R}^m : \|b\| \leq 1\}$ denotes the uncertainty set, $Q \in \mathbb{R}^{n \times m}$ for some $m \leq n$ corresponds to an affine scaling of \mathcal{V} , and Q_i denotes the i -th row of Q . After converting the nominal LP to our standard form, we can easily put the systemic risk problem into our framework by defining $\mathcal{U} := \{(b, c) : b \in \mathcal{V}, c = 0\}$ and slightly changing our \bar{U} to reflect the dependence on the affine transformation as represented by the matrix Q .

Similar to table 4 in [29], we randomly generate 10 instances of size $m \times n = 3 \times 5$. In accordance with Remark 1, which states that q^- is easy to calculate in this case, we focus our attention on the worst-case value q^+ . It is straightforward to verify Assumptions 1 and 2. In Table 2, we list our 10 upper bounds¹ (one for each of the 10 instances) in the column titled q_{sdp}^+ , and we report the computation time (in seconds) for all 10 instances under the column marked t_{sdp}^+ . To evaluate the quality of q_{sdp}^+ , we also calculate $\max\{r^+, v^+\}$ for each instance and the associated relative gap:

$$\text{gap}^+ = \frac{q_{\text{sdp}}^+ - \max\{r^+, v^+\}}{\max\{|\max\{r^+, v^+\}|, 1\}} \times 100\%.$$

The computation times for computing r^- and r^+ are trivial, while the average computation time for computing v^- and v^+ is about 77 seconds.

From the results in Table 2, we see clearly that our approach recovers q^+ for all 10 instances, which also matches the quality of results from [29].

¹Mosek encountered numerical problems on some—but not all—of the generated system-risk instances. In Table 2, we show 10 instances on which Mosek had no numerical issues. From private communication with the Mosek developers, it appears that the upcoming version of Mosek (version 8) will have fewer numerical issues on these instances.

Supplier	Customer									
	1	2	3	4	5	6	7	8	9	10
1					2		3		2	
2	3	3	4					1	4	
3			4	5	3					
4	1	2		1	3	1			8	2
5	4			3			2	1	2	1

Table 3: The unit transportation costs associated with the arcs of the network.

4.4 A network flow problem

Next we consider a transportation network flow problem from [39], which has $m_1 = 5$ suppliers/origins and $m_2 = 10$ customers/destinations for a total of $m = 15$ facilities. The network is bipartite and consists of $n = 24$ arcs connecting suppliers and customers; see Figure 2. Also shown in Figure 2 are the (estimated) supply and demand numbers (\hat{b}) for each supplier and customer. In addition, the (estimated) unit transportation costs (\hat{c}) associated with the arcs of the network are given in Table 3. Suppose at the early stages of planning, the supply and demand units and the unit transportation costs are uncertain. Thus, the manager would like to quantify the resulting uncertainty in the optimal transportation cost.

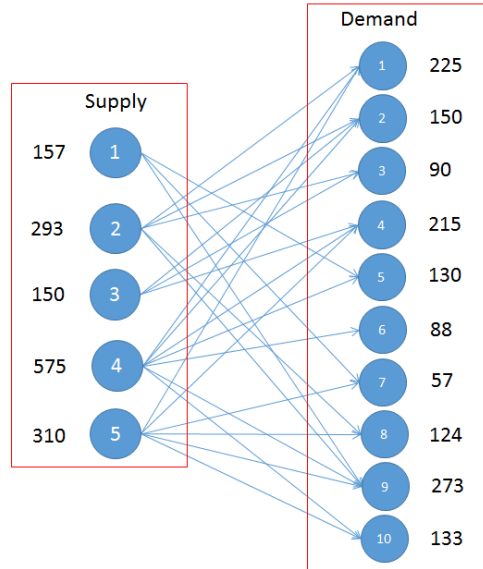


Figure 2: The transportation network of the 5 suppliers and 10 customers.

We consider three cases for the uncertainty set, each of which is also parameterized by a scalar $\gamma \in (0, 1)$. In the first case (“POLY”), we consider the polyhedral uncertainty set

$$\mathcal{U}_1(\gamma) = \{(b, c) : \|b\|_1 \leq \gamma \|\hat{b}\|_1, \|c\|_1 \leq \gamma \|\hat{c}\|_1 \};$$

in the second case (“SOC”), we consider the second-order-cone uncertainty set

$$\mathcal{U}_2(\gamma) := \{(b, c) : \|b\| \leq \gamma \|\hat{b}\|, \|c\| \leq \gamma \|\hat{c}\| \};$$

and in the third case (“MIX”), we consider a mixture of the first two cases:

$$\mathcal{U}_3(\gamma) := \{(b, c) : \|b\|_1 \leq \gamma \|\hat{b}\|_1, \|c\| \leq \gamma \|\hat{c}\| \}.$$

For each, γ controls the perturbation magnitude in b and c relative to \hat{b} and \hat{c} , respectively. In particular, we will consider three choices of γ : 0.01, 0.03, and 0.05. For example, $\gamma = 0.03$ roughly means that b can vary up to 3% of the magnitude of \hat{b} . In total, we have three cases with three choices for γ resulting in nine overall experiments.

Assumptions 1 and 2 are satisfied in this example, and so we apply our approach to bound q^- and q^+ ; see Table 4. Our 18 bounds (lower and upper bounds for each of the nine experiments) are listed in the two columns titled q_{sdp}^- and q_{sdp}^+ , respectively. We also report the computation times (in seconds) for all 18 instances under the two columns marked t_{sdp}^- and t_{sdp}^+ . We also compute $r^-, v^-, r^+,$ and v^+ and define the relative gaps

$$\begin{aligned} \text{gap}^- &= \frac{\min\{r^-, v^-\} - q_{\text{sdp}}^-}{\max\{|\min\{r^-, v^-\}|, 1\}} \times 100\%, \\ \text{gap}^+ &= \frac{q_{\text{sdp}}^+ - \max\{r^+, v^+\}}{\max\{|\max\{r^+, v^+\}|, 1\}} \times 100\%. \end{aligned}$$

Again, the computation times for r^- and r^+ are trivial. The average computation time for computing v^- and v^+ is about 216 seconds.

Table 4 shows that our relaxations capture q^- and q^+ in all cases. As ours is the first approach to study general perturbations in the literature, we are aware of no existing methods for this problem with which to compare our results.

4.5 The effectiveness of the redundant constraint $x \circ s = 0$

Finally, we investigate the effectiveness of the redundant complementarity constraint in (10) and (11) by also solving relaxations without the the linearized version of the constraint. As it turns out, in all calculations of q_{sdp}^- , dropping the linearized complementarity constraint does not change the relaxation value. However, in all calculations of q_{sdp}^+ , dropping it has a

Case	γ	q_{sdp}^-	gap ⁻	$\min\{r^-, v^-\}$	$\max\{r^+, v^+\}$	gap ⁺	q_{sdp}^+	$t_{\text{sdp}}^-(s)$	$t_{\text{sdp}}^+(s)$
POLY	0.01	2638.4	0.0%	2638.4	3088.8	0.0%	3088.8	3551	4259
	0.03	2139.6	0.0%	2139.6	3437.4	0.0%	3437.4	5106	4433
	0.05	1640.9	0.0%	1640.9	3769.8	0.0%	3769.8	5330	4244
SOC	0.01	2745.6	0.0%	2745.6	2981.6	0.0%	2981.6	190	122
	0.03	2498.9	0.2%	2504.3	3212.1	0.0%	3212.1	174	112
	0.05	2257.6	0.2%	2263.0	3442.7	0.0%	3442.7	150	124
MIX	0.01	2724.1	0.0%	2724.1	3008.4	0.0%	3008.4	997	838
	0.03	2429.2	0.0%	2429.2	3281.9	0.0%	3281.9	908	731
	0.05	2134.3	0.0%	2134.3	3560.7	0.0%	3560.7	1001	851

Table 4: Results for the transportation network problem

Example	q_{sdp}^+	gap	value without constraint
Sec. 4.1 (#1)	-16000	100%	0
Sec. 4.1 (#2)	-18667	100%	0
Sec. 4.1 (#3)	-16000	100%	0
Sec. 4.2	25600	1671%	453298
Sec. 4.4 (POLY 0.01)	3088.8	5.7%	3265.8
Sec. 4.4 (POLY 0.03)	3437.4	2.7%	3528.5
Sec. 4.4 (POLY 0.05)	3769.8	2.3%	3855.6
Sec. 4.4 (SOC 0.01)	2981.6	87.6%	5593.1
Sec. 4.4 (SOC 0.03)	3212.1	84.3%	5920.2
Sec. 4.4 (SOC 0.05)	3442.7	81.6%	6252.7
Sec. 4.4 (MIX 0.01)	3008.4	10.3%	3319.4
Sec. 4.4 (MIX 0.03)	3281.9	5.2%	3453.5
Sec. 4.4 (MIX 0.05)	3560.7	3.6%	3689.4

Table 5: Effectiveness of the linearized complementarity constraint

significant effect as shown in Table 5. In the table, the gap is defined as

$$\text{gap} = \frac{(\text{value without constraint}) - q_{\text{sdp}}^+}{\max\{|q_{\text{sdp}}^+|, 1\}} \times 100\%.$$

5 Conclusion

In this paper, we have introduced the idea of robust sensitivity analysis for the optimal value of LP. In particular, we have discussed the best- and worst-case optimal values under general perturbations in the objective coefficients and right-hand sides. We have also presented finite variants that avoid cases of infeasibility and unboundedness. As the involved problems are nonconvex and very difficult to solve in general, we have proposed copositive reformu-

lations, which provide a theoretical basis for constructing tractable SDP-based relaxations that take into account the nature of the uncertainty set, e.g., through RLT and SOC-RLT constraints. Numerical experiments have indicated that our approach works very well on examples from, and inspired by, the literature. In future research, it would be interesting to improve the solution speed of the largest relaxations and to explore the possibility of also handling perturbations in the constraint matrix.

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