Tractable approximation of hard uncertain optimization problems

Ernst Roos, Dick den Hertog

Department of Econometrics and Operations Research, Tilburg University

Aharon Ben-Tal

Faculty of Industrial Engineering and Management, Technion - Israel Institute of Technology

Frans J.C.T. de Ruiter

CQM, Eindhoven, The Netherlands

Jianzhe Zhen

Risk Analytics and Optimization Chair, École Polytechnique Fédérale de Lausanne, Switzerland

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Abstract

Robust Optimization is a widespread approach to treat uncertainty in optimization problems. Finding a computationally tractable formulation of the robust counterpart of an uncertain optimization problem is a key step in applying this approach. Techniques for finding a computationally tractable robust counterpart are available for constraints concave in the uncertain parameters. In many problems, however, the uncertain parameters appear in a convex way, which is problematic as no general techniques exist for such problems. In this paper, we provide a systematic way to construct conservative approximations to such problems. Specifically, we reformulate the original problem as an adjustable robust optimization problem in which the nonlinearity of the original problem is captured by the new uncertainty set. This adjustable robust optimization problem is linear whenever the original uncertainty set is polyhedral, which allows for the application of a multitude of techniques from adjustable robust optimization. Additionally, we prove that preprocessing a constraint with a concave transformation that preserves its convexity can tighten the conservative approximation obtained. We subsequently apply our theory to quadratic constraints, constraints that are the sum of maxima and the sum of maxima squared, as well as constraints from geometric programming. We demonstrate the quality of the approximations with a study of geometric programming problems and numerical examples from radiotherapy optimization, which contain a constraint of the sum of maxima squared type.

Keywords: robust optimizatoin, nonlinear inequality, convex analysis

1 Introduction

In practice, optimization problems frequently contain some form of uncertainty. This uncertainty arises as a result of prediction, estimation or implementation errors, for example. Robust Optimization (RO) is one of the main approaches to address such uncertainty and was initiated by Ben-Tal and Nemirovski (1998) and El Ghaoui and Lebret (1997).

Whereas other approaches, such as Stochastic Programming (Shapiro et al., 2014) or Distributionally Robust Optimization (see e.g. Wiesemann et al. (2014)), assume that the uncertain parameters are random variables with fully or partially known distribution functions, RO models uncertainty by means of an uncertainty set. This set contains all possible scenarios for the uncertain parameters one wants to safeguard against.

One of the main advantages of robust optimization is the computational tractability of the resulting optimization problems. Indeed, it has been shown that the robust counterparts of many types of problems are tractable. Ben-Tal et al. (2009) give a comprehensive account of robust optimization techniques to obtain such tractable formulations. A general approach to finding computationally tractable reformulations is presented in Ben-Tal et al. (2015), where a technique is presented that is applicable to any constraint that is convex in the optimization variables and concave in the uncertain parameters. This technique does not necessarily lead to a closed-form robust counterpart for any convex uncertainty set, but does present solutions for the commonly considered uncertainty sets like polyhedral and ellipsoidal uncertainty.

In contrast, obtaining a tractable robust counterpart for constraints that are *convex* in the uncertain parameters is, in general, hard (Chassein and Goerigk, 2019). Such constraints are, however, common; they appear, for example, in inventory management problems, geometric programming and conic optimization. In this paper, we consider general constraints that are convex in both the optimization variables and the uncertain parameters. More specifically, we convert the robust counterpart to an equivalent adjustable robust optimization problem. This enables us to treat the converted problem with existing techniques for Adjustable Robust Optimization (ARO), such as (non)linear decision rules and Fourier-Motzkin elimination. When the original uncertainty set is polyhedral, the resulting ARO problem is linear, and hence these techniques yield readily solvable conservative approximations to the true robust counterpart. In particular, aside from a conservative approximation resulting from linear decision rules, we consider a particular lifting that can greatly increase the quality of the resulting approximation.

For specific types of constraints such as second-order cone (SOC) and semidefinite programming (SDP) constraints combined with specific uncertainty sets, e.g., norm-bounded or polyhedral uncertainty sets, computationally tractable approximations exist in the literature. Our approach yields the same approximations as some of them, is tighter than some of them, and most importantly it yields approximations for a wide class of problems for which there is no approximation available in the literature. We first discuss the differences of our approach with other approaches in the literature in more detail.

Our approach is a generalization of the approach in Zhen et al. (2017). For polyhedral uncertainty sets, they use a similar idea of reformulation to an adjustable robust optimization problem such that conservative approximations can be constructed based on existing ARO techniques. The approach they describe, however, is only applicable to second-order cone and semidefinite programming constraints, while the approach we propose is much more general, as it can be applied to a broad class of constraints that are convex in both the uncertain parameters and the decision variables. Moreover, their approach is restricted to polyhedral uncertainty sets, contrary to our approach. Also note that our proposed method may avoid an extra level of approximation that is needed in Zhen et al. (2017) due to the introduction of additional adjustable variables in that paper; see Examples 3-5 of that paper. For these cases, the conservative approximation from our method is at least as tight as the ones from Zhen et al. (2017), while our reformulation contains less optimization variables.

The work by De Ruiter et al. (2018) seemingly treats a wider class of problems: *adaptive* robust optimization problems. They use a different approach, sequential dualization, to treat these problems, which requires the strong relatively complete recourse assumption. This assumption implies that each here-and-now decision is strictly feasible. Therefore, for the non-adaptive problems we consider, the method of De Ruiter et al. (2018) is not applicable.

In Bertsimas and Sim (2006), a method for norm-based uncertainty sets and homogeneous constraint functions is proposed. We prove that for those norm-based uncertainty sets that are also polyhedral (e.g., box, ℓ_1, budget uncertainty set) our approach yields tighter approximations. For general uncertainty sets defined by nonlinear convex functions, our approximation is equal to the approximation of Bertsimas and Sim (2006). Our approach extends this method, since it can handle all linear and convex uncertainty sets, and all (i.e., also nonhomogeneous) convex constraint functions.

Several papers (El Ghaoui and Lebret (1997); El Ghaoui et al. (1998); Ben-Tal et al. (2002)) consider the special combination of (conic) quadratic constraint functions and ellipsoidal types of uncertainty sets. For this specific case, their result is exact. The final problem they have to solve is an SDP problem. For this specific case our approach obtains an approximation, but our final problem is a computationally less demanding conic quadratic optimization problem.

For the sum-of-max-of-linear-functions, Ben-Tal et al. (2005) and Gorissen and Den Hertog (2013) propose to use Linear Decision Rules (LDRs) for the analysis variables that are needed to linearize the "max" terms. We prove that our LDR approximation is the same as their approximation. However, our approach extends their approach, since for the reformulated problem, which is an adjustable robust linear optimization problem, we can also use more advanced decision rules or other approaches.

Additionally, we treat possible alternative formulations to the original problem and discuss the potential differences in the conservative approximation our approach yields for said formulations. We show that applying a concave transformation that preserves the convexity of the original constraint yields an approximation that is at least as tight as applying our approach to the original constraint.

We discuss the application of our approach to four important classes of constraints for which no computationally tractable exact reformulation of the robust counterpart is known: quadratic, sum-of-max, sum-of-max squared and log-sum-exp constraints. In particular, we discuss how our approach and the one proposed by Zhen et al. (2017) compare for quadratic constraints, which can be equivalently stated as second-order cone constraints. We also provide numerical results for radiotherapy optimization problems containing a sum-of-max squared constraint and geometric programming problems that contain log-sum-exp constraints. These numerical experiments illustrate the quality of the conservative approximation provided in this paper and additionally show that this approximation is highly tractable.

The paper is organized as follows. Section 2 treats the general reformulation we propose for polyhedral uncertainty sets, as well as possible alternative formulations and methods to solve said reformulation. Section 3 treats optimization problems with four classes of constraints: quadratic constraints, sum-of-max constraints, sum-of-max squared constraints and log-sum-exp constraints. Section 4 extends the results from Section 2 to general convex uncertainty sets and provides additional theory that compares our approach with the existing literature. Section 5 contains numerical results for geometric programming and radiotherapy optimization.

Notation. Throughout this paper we use the following notation.

Let $f : \mathbb{R}^n \to \mathbb{R}$ be a closed convex function with domain $\mathrm{dom}(f) = \{x \mid f(x) < \infty\}$. The *convex conjugate*, which we refer to as conjugate, of f is defined as

$$f^*(y) = \sup_{x \in \mathrm{dom}(f)} \left\{ y^\top x - f(x) \right\}.$$

The *perspective function* of f is defined by

$$(f\lambda)(x) = \begin{cases} \lambda f\left(\frac{x}{\lambda}\right) & \lambda > 0 \\ f_\infty(x) & \lambda = 0, \end{cases}$$

which implies $(f\lambda)$ is a closed convex function, and where f_∞ is the *recession function* of f, defined by (Rockafellar, 1970, Corollary 8.5.2):

$$f_\infty(y) = \lim_{\lambda \downarrow 0} \lambda f\left(\frac{y}{\lambda}\right). \tag{1}$$

We write $\lambda f\left(\frac{x}{\lambda}\right)$ for the perspective function throughout the rest of the paper, implicitly assuming that for $\lambda = 0$, we use $f_\infty(x)$.

The *support function* of a set U is the conjugate of that set's *indicator function.* This indicator function is defined as:

$$\delta(x \mid U) = \begin{cases} 0 & \text{if } x \in U \\ \infty & \text{otherwise,} \end{cases}$$

and thus the support function is given by

$$\delta^*(y \mid U) = \sup_{x \in U} y^\top x.$$

This support function paves the way for an alternative definition of the recession function of f, which we also use (Rockafellar, 1970, Theorem 13.3):

$$f_\infty(y) = \delta^*(y \mid \mathrm{dom}(f^*)). \tag{2}$$

For $f(x) = \sum_{i=1}^n \sqrt{1 + x_i^2}$, for example, the recession function is equal to $f_\infty(y) = \|y\|_2$. An in-depth analysis of the recession function, including a table of recession functions of some well-known functions, can be found in Appendix A.

2 The Robust Counterpart

2.1 Reformulation to ARO

In this paper, we consider a general convex constraint given by

$$f\left(A(x)\zeta + b(x)\right) \leq 0 \qquad \forall \zeta \in U, \tag{P}$$

where $f : \mathbb{R}^p \to \mathbb{R}$ is convex and closed, $A : \mathbb{R}^n \to \mathbb{R}^{p\times L}$ and $b : \mathbb{R}^n \to \mathbb{R}^p$ are affine. For ease of exposure, we assume that U is a nonempty polyhedron given by

$$U = \left\{\zeta \in \mathbb{R}^L_+ \;\middle|\; D\zeta = d\right\}, \tag{3}$$

for some $D \in \mathbb{R}^{q\times L}$ and $d \in \mathbb{R}^q$ for now. We extend our results to general convex uncertainty sets in Section 4.

This formulation allows for many important classes of constraints, such as quadratic, sum-of-max (with and without square) and log-sum-exp functions, which we discuss in Section 3. Other examples are (sums of) norms and negative entropy. Furthermore, all functions $g(x, \zeta)$ that are jointly convex in x and ζ can be written as $f\left(A(x)\zeta + b(x)\right)$, by choosing

$$A(x) = \begin{bmatrix} I \\ O \end{bmatrix}, \qquad b(x) = \begin{bmatrix} 0 \\ x \end{bmatrix}.$$

A direct implication of this remark is that we can also find conservative approximations for constraints

$$g\left(x, y(\zeta)\right) \leq 0 \qquad \forall \zeta \in U, \tag{4}$$

where g is jointly convex in x and y for adjustable variables y, that is, jointly convex constraints in adjustable robust optimization problems. Specifically, such constraints can be treated by substituting a linear decision rule $y = s + S\zeta$, such that $g\left(x, s + S\zeta\right)$ can be written as $f\left(A(s, S, x)\zeta + b(s, S, x)\right)$. We do remark that substituting a linear decision rule for y yields a conservative approximation to (4), and thus our approach yields a conservative approximation to this conservative approximation of (4).

We also note that by choosing to consider the function $f(A(x)\zeta + b(x))$ we cannot handle all constraints convex in both x and ζ. Functions of the form $b(x)^\top g(\zeta)$, for an affine function b and convex function g, cannot, for example, be formulated as $f(A(x)\zeta + b(x))$. An example of such functions occurs in brachytherapy optimization (Gorissen et al., 2013). Other examples include, but are not limited to capital budgeting problems and multinomial logit models (Alfandari and García, 2018).

It is also important to discuss the added value of our approach for a more general convex function over the previously developed approaches for second-order cone programming (SOCP) and semidefinite programming (SDP) constraints by Zhen et al. (2017). Although many (nominal) problems can be reformulated as an SOCP, the robust counterparts of these equivalent problems are not necessarily the same. As an example, we consider a constraint on the sum of maxima squared:

$$\sum_{i=1}^{p} \max\left\{A_i(x)\zeta + b_i(x),\ 0\right\}^2 \le \gamma \qquad \forall \zeta \in U, \tag{5}$$

and its SOCP reformulation

$$\forall \zeta \in U : \begin{cases} \|y(\zeta)\|_2 \le \gamma & (6a) \\ A_i(x)\zeta + b_i(x) \le y_i(\zeta) \qquad i = 1, \ldots, p & (6b) \\ 0 \le y_i(\zeta) \qquad i = 1, \ldots, p. & (6c) \end{cases}$$

While the non-robust versions of (5) and (6) are clearly equivalent, (5) and (6) are in fact only equivalent if the newly introduced variables y_i are considered to be adjustable (Gorissen et al., 2015). As existing techniques for SOCP problems with uncertainty do not allow for adjustable variables, some form of (linear) decision rule should be substituted for $y_i(\zeta)$ in order to apply them. Such an approach would thus lead to constructing a conservative approximation of the conservative approximation of (6) obtained by substituting the decision rules. Our approach, on the other hand, can be applied to (5) directly, eliminating one of these layers of approximation.

In order to find a conservative approximation to (P), we first transform the problem into an equivalent linear adjustable robust optimization problem.

Theorem 1. *Let $f : \mathbb{R}^p \to \mathbb{R}$ be a closed convex function and let $A : \mathbb{R}^n \to \mathbb{R}^{p\times L}$ and $b : \mathbb{R}^n \to \mathbb{R}^p$ be affine functions. Let $U \subseteq \mathbb{R}^L$ be a polyhedron as defined in* (3)*. Then, $x \in \mathbb{R}^n$ satisfies*

$$f\left(A(x)\zeta + b(x)\right) \le 0 \qquad \forall \zeta \in U,$$

if and only if it satisfies the following set of adjustable robust optimization constraints:

$$\forall w \in \operatorname{dom}(f^*),\ \exists \lambda \in \mathbb{R}^q : \begin{cases} d^\top \lambda + w^\top b(x) - f^*(w) \le 0 & (7a) \\ D^\top \lambda \ge A(x)^\top w. & (7b) \end{cases}$$

Proof. Because f is a closed convex function we have that

$$f(z) = f^{**}(z) = \sup_{w \in \operatorname{dom} f^*} \left\{z^\top w - f^*(w)\right\}.$$

Substituting this into (P) yields

$$
\begin{aligned}
& & \forall \zeta \in U \;:\; f\left(A(x)\zeta + b(x)\right) \leq 0 \\
\iff & & \forall \zeta \in U \;:\; \sup_{w \in \operatorname{dom} f^*} \left\{ \left(A(x)\zeta + b(x)\right)^\top w - f^*(w) \right\} \leq 0 \\
\iff & & \sup_{\zeta \in U} \left\{ \sup_{w \in \operatorname{dom} f^*} \left\{ \left(A(x)^\top w\right)^\top \zeta + b(x)^\top w - f^*(w) \right\} \right\} \leq 0 \\
\iff & & \sup_{w \in \operatorname{dom} f^*} \left\{ \sup_{\zeta \in U} \left\{ \left(A(x)^\top w\right)^\top \zeta \right\} + b(x)^\top w - f^*(w) \right\} \leq 0 \qquad (8) \\
\iff & & \sup_{w \in \operatorname{dom} f^*} \left\{ \inf_{\lambda \in \mathbb{R}^q} \left\{ d^\top \lambda \mid D^\top \lambda \geq A(x)^\top w \right\} + b(x)^\top w - f^*(w) \right\} \leq 0 \qquad (9) \\
\iff & & \forall w \in \operatorname{dom} f^*,\; \exists \lambda \in \mathbb{R}^q \;:\; \begin{cases} d^\top \lambda + b(x)^\top w - f^*(w) \leq 0 \\ D^\top \lambda \geq A(x)^\top w \end{cases}
\end{aligned}
$$

where (8) and (9) are equivalent because of strong LP duality. □

The equivalent formulation given in (7) can be interpreted as a set of linear adjustable robust optimization constraints, because it states that for each value of w there must exist a value λ that satisfies the constraints, that is, the value of λ can depend on w. In the field of Robust Optimization such a variable λ is referred to as an adjustable variable, as its value can be adjusted after the value of the uncertain parameter w is revealed.

We note that a similar result holds if the nonnegativity constraint in U is omitted. Then the inequality in (7b) becomes an equality constraint, which can be used to eliminate some adjustable variables λ. Eliminating variables in this way is equivalent to imposing linear decision rules for those variables (Zhen and Den Hertog, 2017, Lemma 2). Moreover, we remark that Theorem 1 does not rely on A and b being affine in x. For more general functions, however, the resulting problem (7) is not linear, and thus much harder to solve.

In the subsequent section, we will discuss two approximations to (P) that are both the result of using a linear decision rule for the adjustable variable λ. There are some results in the literature that discuss the optimality and approximation guarantees of such linear decision rules (see, e.g., Bertsimas et al. (2010), Bertsimas and Goyal (2012), Iancu et al. (2013) and Simchi-Levi et al. (2019)). Unfortunately, all these results discuss problems that have right-hand side uncertainty, that is, linear adjustable robust optimization problems in which the coefficients of both the static and adjustable variables are not subject to uncertainty. For the adjustable problem (7) we consider, this means that both $A(x)$ and $b(x)$ should not depend on x. In the context of the original constraint (P), this implies there is no decision variable x. Hence, these results do not apply to any particular example of the problem we consider.

The one result we know of that is applicable to our problem setting is the optimality of linear decision rules for a simplex uncertainty set (Zhen et al., 2018). In our setting, specifically, that means our approximation is tight whenever the domain of f^* is a simplex, i.e., when f is the maximum of its arguments.

2.2 Conservative Approximation

Since the equivalent formulation derived in Theorem 1 is a set of adjustable robust linear constraints, conventional techniques for such problems can be applied. A common technique to obtain a computationally tractable conservative approximation to adjustable robust constraints is limiting the adjustable variables to be linear decision rules in the uncertain parameters (Ben-Tal et al., 2004). This results in the following conservative approximation. The proof of Theorem 2 can be found in Appendix B.

Theorem 2. *If there exist $u \in \mathbb{R}^q$ and $V \in \mathbb{R}^{q\times p}$ for a given $x \in \mathbb{R}^n$ such that*

$$\begin{cases} d^\top u + f\left(b(x) + V^\top d\right) \leq 0 & (10a) \\ f_\infty\left(A_i(x) - V^\top D_i\right) \leq D_i^\top u \qquad i = 1,\dots,L, & (10b) \end{cases}$$

holds, then x also satisfies (P)*.*

In general, the tractability of the resulting problem (10) is dependent on the original function f and f_∞, where it is important to remark that f_∞ is conically representable by definition. Furthermore, we know for any f that is positively homogeneous, it holds that $f_\infty = f$ and thus (10) can be solved efficiently if and only if the original nominal problem can be. For more information on positively homogeneous functions and this identity, we refer to the discussion in Appendix A. Sections 3.1 and 3.3 describe examples for which problem (10) can be solved about as efficiently as the original nominal problem and f is not positively homogeneous.

Possible other techniques that can be used to solve or approximate the adjustable robust linear formulation given in Theorem 1 include, but are not limited to, finite adaptability, see e.g. (Bertsimas and Caramanis, 2007; Postek and Den Hertog, 2016), Fourier-Motzkin elimination (Zhen et al., 2018) and nonlinear decision rules, done by (Ben-Tal et al., 2009; Bertsimas et al., 2011). Finite adaptability approaches are mostly used to solve adjustable robust linear problems with mixed-integer recourse decisions, while for problems with continuous recourse decisions, the approaches quickly become large optimization problems before any effective partitions are found. Fourier-Motzkin elimination is a complementary method that is often used to improve the solutions from existing methods, and the method can be effective if the redundant constraints from each elimination can be detected efficiently, e.g., when the uncertainty only appears on the right-hand side. Unfortunately, this is not the case for the adjustable problem we consider. Nonlinear decision rules are discussed and numerically tested in Zhen et al. (2017) for a special case of (P), where $f(\cdot)$ is SOC or SDP representable. The tractability of the conservative approximations depends on the structure of the decision rules and $\mathrm{dom}(f^*)$. For instance, if $\mathrm{dom}(f^*)$ is a unit ball, (partial) quadratic decision rules can be used, which produces tighter conservative approximations than the ones from linear decision rules; see Zhen et al. (2017).

Alternatively, a tighter conservative approximation than the one described in Theorem 2 can be found by lifting the nonlinearity of $f^*(w)$ to the uncertainty set and using a slightly more involved decision rule. Similar ideas for lifting a set have been applied in an adaptive *distributionally* robust setting by Bertsimas et al. (2019). The resulting system of inequalities (11) is convex and includes $2q + qp + n$ variables compared to the original n in (P). The proof of Theorem 3 can be found in Appendix B.

Theorem 3. *If there exist $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q\times p}$ and $r \in \mathbb{R}^q$ for a given $x \in \mathbb{R}^n$ such that*

$$\begin{cases} d^\top u + \left(1 + d^\top r\right) f\left(\frac{V^\top d + b(x)}{1+d^\top r}\right) \leq 0 \\ 1 + d^\top r \geq 0 \end{cases} \tag{11a}$$

$$\begin{cases} -D_i^\top u + \left(-D_i^\top r\right) f\left(\frac{A_i(x) - V^\top D_i}{-D_i^\top r}\right) \leq 0 \\ -D_i^\top r \geq 0 \end{cases} \qquad i = 1, \dots, L, \tag{11b}$$

holds, then x also satisfies (P). *Here, D_i and $A_i(x)$ denote the i-th column of D and $A(x)$, respectively. Moreover,* (11) *is a tighter conservative approximation than* (10)*.*

The tighter conservative approximation derived in Theorem 3 includes the perspective of the original constraint function f and its tractability is thus highly reliant on the tractability of this perspective. A disadvantage of perspective functions is that they can lead to numerical issues in practice (Jung et al., 2013). For conically representable f, however, we know that the perspective is conically representable as well, and hence these numerical issues can be circumvented by using this conic reformulation. We refer to Appendix C for the mathematical proof of this statement.

It is important to note that there is no simple relation between the quality of the two derived approximations. In fact, our two numerical experiments illustrate two different extremes. In the first experiment we observe that the approximation in Theorem 3 is close to perfect, while the approximation in Theorem 2 deteriorates quickly as the number of uncertain parameters increases. In the other experiment, however, the two approximations coincide.

2.3 Alternative Formulations

In Robust Optimization, robust counterparts of equivalent deterministic formulations are not necessarily equivalent (Gorissen et al., 2015). In the same spirit, conservative approximations obtained by our approach from equivalent uncertain formulations are not necessarily equivalent. In this section, we explore alternative formulations to the initial formulation of the problem and comment on the effects of using these formulations on the quality of the obtained conservative approximation.

Our first observation is that making the constraint 'more linear', that is, transforming it with a strictly increasing, concave function, can potentially result in a tighter conservative approximation. The following theorem formalizes this idea.

Theorem 4. *Let X denote the range of f and let $g : X \to \mathbb{R}$ be concave, strictly increasing and differentiable and such that $g \circ f$ is convex. Moreover, let g be such that $g'(0) = 1$. Then applying Theorem 3 to*

$$g\left(f\left(A(x)\zeta + b(x)\right)\right) \leq g(0) \qquad \forall \zeta \in U, \tag{12}$$

yields a conservative approximation that is at least as tight as the approximation obtained by applying Theorem 3 to (P)*.*

Proof. Applying Theorem 3 to (P) yields

$$
\begin{cases}
d^\top u + \left(1 + d^\top r\right) \cdot f\left(\dfrac{V^\top d + b(x)}{1 + d^\top r}\right) \leq 0 & & \text{(13a)} \\
1 + d^\top r \geq 0 & & \text{(13b)} \\
-D_i^\top u + \left(-D_i^\top r\right) \cdot f\left(\dfrac{A_i(x) - V^\top D_i}{-D_i^\top r}\right) \leq 0 & i = 1, \ldots, L & \text{(13c)} \\
-D_i^\top r \geq 0 & i = 1, \ldots, L, & \text{(13d)}
\end{cases}
$$

as a conservative approximation. If, on the other hand, we apply Theorem 3 to (12) we obtain the following conservative approximation:

$$
\begin{cases}
d^\top u + \left(1 + d^\top r\right) \left[g\left(f\left(\dfrac{V^\top d + b(x)}{1 + d^\top r}\right)\right) - g(0)\right] \leq 0 & & \text{(14a)} \\
1 + d^\top r \geq 0 & & \text{(14b)} \\
-D_i^\top u + \left(-D_i^\top r\right) \left[g\left(f\left(\dfrac{A_i(x) - V^\top D_i}{-D_i^\top r}\right)\right) - g(0)\right] \leq 0 & i = 1, \ldots, L & \text{(14c)} \\
-D_i^\top r \geq 0 & i = 1, \ldots, L, & \text{(14d)}
\end{cases}
$$

Observe that (13a) is equivalent to

$$
f\left(\frac{V^\top d + b(x)}{1 + d^\top r}\right) \leq -\frac{d^\top u}{1 + d^\top r}, \tag{15}
$$

and (14a) is equivalent to

$$
f\left(\frac{V^\top d + b(x)}{1 + d^\top r}\right) \leq g^{-1}\left(g(0) - \frac{d^\top u}{1 + d^\top r}\right). \tag{16}
$$

Therefore, (14a) leads to a tighter conservative approximation than (13a) if (15) implies (16), that is, if

$$
-\frac{d^\top u}{1 + d^\top r} \leq g^{-1}\left(g(0) - \frac{d^\top u}{1 + d^\top r}\right) \iff g\left(-\frac{d^\top u}{1 + d^\top r}\right) \leq g(0) - \frac{d^\top u}{1 + d^\top r}.
$$

From Taylor's theorem and the fact that g is concave, we know that

$$
g\left(-\frac{d^\top u}{1 + d^\top r}\right) \leq g(0) + \frac{-d^\top u}{1 + d^\top r} g'(0) = g(0) + \frac{-d^\top u}{1 + d^\top r},
$$

where we use that $g'(0) = 1$ in the last inequality. Similarly, we can prove that (13c) implies (14c) and thus (14) is a tighter conservative approximation than (13). □

It is important to note that any concave, strictly increasing function g can be scaled such that $g'(0) = 1$, without affecting the feasible region for x in (12). In particular, this means that applying the natural logarithm or the square root to a constraint yields an approximation that is at least as tight, given that the resulting constraint is still convex. An example of this can be found in geometric programming which can be convexly represented as an exponential sum or as the natural logarithm of said sum. While the latter has become the more prevalent formulation recently, this theorem shows that it is the reformulation to look at in a robust optimization setting. This theorem thus shows that the latter formulation yields the tighter approximation. More information on geometric programming can be found in Section 3.4.

Another example is found in comparing two versions of a norm-bounded constraint:

$$\|\cdot\|_p \leq \rho \qquad \text{versus} \qquad \|\cdot\|_p^p \leq \rho^p,$$

for some $p \in [1, +\infty)$. The former constraint is the more prevalent one, and is fortunately also the one that yields the tighter conservative approximation. The theorem thus confirms the use of common formulations over other possible equivalent formulations.

A last example is found in sum-of-max squared constraints, where taking the square root does not destroy convexity. Specifically, if f is given by

$$f(v) = \sum_{j=1}^{p} \max\{v_j, 0\}^2,$$

and $g(x) = 2\sqrt{x+1}$, Theorem 4 states that applying our approximations to $g \circ f$ might yield tighter approximations.

Our next observation regards the treatment of constants in the constraint. More specifically, we note that including a constant in the function definition leads to the exact same conservative approximation as leaving it on the right-hand side does. In other words, it can be shown that for any $c \in \mathbb{R}$, applying Theorem 3 to

$$f\left(A(x)\zeta + b(x)\right) \leq c \qquad \forall \zeta \in U,$$

leads to an equivalent conservative approximation as applying Theorem 3 to

$$\tilde{f}\left(A(x)\zeta + b(x)\right) \leq 0 \qquad \forall \zeta \in U,$$

where $\tilde{f} = f - c$.

3 Theoretical Applications

3.1 Quadratic Programming

In this section, we consider the general uncertain quadratic constraint given by

$$\zeta^\top H(x)^\top H(x)\zeta + h(x)^\top \zeta \leq g(x) \qquad \forall \zeta \in U, \tag{17}$$

where $H : \mathbb{R}^n \to \mathbb{R}^{p\times L}$, $h : \mathbb{R}^n \to \mathbb{R}^L$ and $g : \mathbb{R}^n \to \mathbb{R}$ are affine functions and U is a polyhedron as defined in (3). Because such a quadratic constraint can also be represented as a conic quadratic constraint, our approach can potentially yield two different conservative approximations. The first approximation is found by defining $f : \mathbb{R}^{p+1} \to \mathbb{R}$, $A : \mathbb{R}^n \to \mathbb{R}^{(p+1)\times L}$ and $b : \mathbb{R}^n \to \mathbb{R}^{p+1}$ by:

$$f\begin{pmatrix} z \\ z_0 \end{pmatrix} = z^\top z + z_0, \qquad A(x) = \begin{bmatrix} H(x) \\ h(x)^\top \end{bmatrix}, \qquad b(x) = \begin{bmatrix} \mathbf{0} \\ -g(x) \end{bmatrix},$$

such that (17) is equivalent to

$$f\left(A(x)\zeta + b(x)\right) \le 0 \qquad \forall \zeta \in U.$$

Theorem 3 then gives the following conservative approximation for (17):

$$\begin{cases} d^\top u + \left(1 + d^\top r\right) f\begin{pmatrix} \frac{V^\top d}{1+d^\top r} \\ \frac{V_0^\top d}{1+d^\top r} \end{pmatrix} \le g(x) & \\ \qquad\qquad\qquad 1 + d^\top r \ge 0 & \qquad\qquad (18a) \\ \left(-D_i^\top r\right) f\begin{pmatrix} \frac{H_i(x) - V^\top D_i}{-D_i^\top r} \\ \frac{h_i(x) - V_0^\top D_i}{-D_i^\top r} \end{pmatrix} \le D_i^\top u & i = 1, \dots, L, \qquad (18b) \\ \qquad\qquad\qquad -D_i^\top r \ge 0 & \end{cases}$$

where $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q\times p}$, $V_0 \in \mathbb{R}^q$ and $r \in \mathbb{R}^q$.

Alternatively, one can show that (17) is equivalent to:

$$\left\| \begin{matrix} \left(1 + h(x)^\top \zeta - g(x)\right)/2 \\ H(x)\zeta \end{matrix} \right\|_2 \le \left(1 - h(x)^\top \zeta + g(x)\right)/2 \qquad \forall \zeta \in U.$$

Defining $\tilde{f} : \mathbb{R}^{p+2} \to \mathbb{R}$, $\tilde{A} : \mathbb{R}^n \to \mathbb{R}^{(p+2)\times L}$ and $\tilde{b} : \mathbb{R}^n \to \mathbb{R}^{p+2}$ by

$$\tilde{f}\begin{pmatrix} z \\ \hat{z} \\ z_0 \end{pmatrix} = \left\| \begin{matrix} z \\ \hat{z} \\ z_0 \end{matrix} \right\|_2 + z_0, \qquad \tilde{A}(x) = \begin{bmatrix} \frac{1}{2}h(x)^\top \\ \frac{1}{2}h(x)^\top \\ H(x) \end{bmatrix}, \qquad \tilde{b}(x) = \begin{bmatrix} -\frac{1+g(x)}{2} \\ \frac{1-g(x)}{2} \\ 0 \end{bmatrix},$$

we can write this equivalently as

$$\tilde{f}\left(\tilde{A}(x)\zeta + \tilde{b}(x)\right) \le 0 \qquad \forall \zeta \in U.$$

We note that $\tilde{f}$ is positively homogeneous and thus Theorem 2 and 3 yield the same conservative approximation:

$$\begin{cases} d^\top u + d^\top V_0 + \left\| \begin{matrix} V^\top d \\ d^\top r + (1 - g(x))/2 \end{matrix} \right\|_2 \le \frac{1 + g(x)}{2} & \qquad (19a) \\ \frac{h_i(x)}{2} + \left\| \begin{matrix} H_i(x) - V^\top D_i \\ \frac{h_i(x)}{2} - D_i^\top r \end{matrix} \right\|_2 \le D_i^\top u + D_i^\top V_0 & i = 1, \dots, L, \qquad (19b) \end{cases}$$

where $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q\times p}$, $V_0 \in \mathbb{R}^q$ and $r \in \mathbb{R}^q$.

The following result states that the two approximations above are equivalent, that is, the original form of the constraint is irrelevant here, as the resulting approximation from our approach has the exact same feasible region. We remark that this result extends to constraints where $H(x)$, $h(x)$ and $g(x)$ are not affine functions. The approximation to such constraints is generally computationally intractable, however. The proof of the following theorem can be found in E.

Theorem 5. *The conservative approximations* (18) *and* (19) *are equivalent, that is, for any* $x \in \mathbb{R}^n$ *for which there exist* $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q\times p}$, $V_0 \in \mathbb{R}^q$ *and* $r \in \mathbb{R}^q$ *that satisfy* (18), *there exist* $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q\times p}$, $V_0 \in \mathbb{R}^q$ *and* $r \in \mathbb{R}^q$ *that satisfy* (19) *and vice versa.*

3.2 Sum-of-Max Constraints

In this section, we consider constraints that are the sum of maxima of multiple arguments. Constraints of this form are often used to penalize undesirable characteristics of a solution. An example of this can be found in radiotherapy optimization, where failing to deliver the prescribed dose of radiation to the target should be penalized while exceeding the prescribed dose should not be (Shepard et al., 1999; De Boeck et al., 2014). Mathematically this can be achieved by penalizing the maximum of the difference between the prescribed dose and actual dose and zero.

We consider $f : \mathbb{R}^p \to \mathbb{R}$ to be given by

$$f(v) = \sum_{j=1}^{m} \max_{k \in K_j} \{v_k\}, \tag{20}$$

such that (P) is given by

$$\sum_{j=1}^{m} \max_{k \in K_j} \{A_k(x)\zeta + b_k(x)\} \leq 0 \qquad \forall \zeta \in U, \tag{21}$$

where $K_j \subseteq \{1, \dots, p\}$, for $j = 1, \dots, m$ and $A_k(x)$ is the k-th row of $A(x)$. Because f is positively homogeneous, we know from Lemma 2 in Appendix A that $f_\infty = f$, and a conservative approximation for (21) is thus given by

$$\begin{cases} d^\top u + f\left(b(x) + V^\top d\right) \leq 0 & (22a) \\ f\left(A_i(x) - V^\top D_i\right) \leq D_i^\top u \qquad i = 1, \dots, L. & (22b) \end{cases}$$

Traditionally, the robust counterpart of a sum-of-max constraint is reformulated by introducing auxiliary adjustable variables y_j to reformulate (21) (Ben-Tal et al., 2005; Gorissen and Den Hertog, 2013):

$$\forall \zeta \in U, \ \exists y \in \mathbb{R}^m : \begin{cases} \displaystyle\sum_{j=1}^{m} y_j \leq 0 & (23a) \\ A_k(x)\zeta + b_k(x) \leq y_j \qquad \forall k \in K_j, \ \ j = 1, \dots, m. & (23b) \end{cases}$$

If linear decision rules are used to solve (23), the resulting approximation coincides with (22). For the proof of this statement we refer to Appendix F. Ardestani-Jaafari and Delage (2016) show that for box and budget uncertainty sets, linear decision rules are optimal in solving (23) under some additional assumptions regarding the structure of $A(x)$. By the equivalence to our approach for linear decision rules, this means that linear decision rules in our approach are also optimal for box and budget uncertainty sets under these additional assumptions.

For polyhedral uncertainty sets that are not a box or a budget uncertainty set or for which the additional assumptions made by Ardestani-Jaafari and Delage (2016) are not satisfied, linear decision rules are not necessarily optimal. In this case, using the approach we suggest can be beneficial as it allows for other techniques from adjustable robust optimization to be used, such as nonlinear decision rules or Fourier-Motzkin elimination.

When considering sum-of-max constraints, we can in fact also apply our approach for ellipsoidal uncertainty, without approximating the ellipsoidal uncertainty set by a polyhedron. To accomplish this, we use the fact that $f^*(w) = 0$ on its domain and that this domain is a simplex, and thus a polyhedron. This means we can apply Theorem 1 twice to find an equivalent linear ARO problem. It turns out that, in fact, this linear ARO problem is exactly (23) with the original ellipsoidal uncertainty set.

The results in this section suggest that the techniques we propose to tackle hard uncertain convex inequalities can coincide or generalize existing linearization techniques involving adjustable variables. In particular, we find that for sum-of-max constraints we obtain a reformulation that allows for more advanced adjustable robust optimization techniques to be used than just a simple linear decision rule. While applying more advanced decision rules in (23) can be cumbersome due to U being a general polyhedron, it is much easier in the adjustable formulation we obtain, as there the uncertainty set is a cartesian product of simplices. Moreover, eliminating an adjustable variable y_j with Fourier-Motzkin elimination in (23) simply results in enumerating all possible options with regard to the j-th maximum.

3.3 Sum-of-Max Squared

A more intricate version of a sum-of-max constraint is obtained by squaring the maxima before summing them. This type of constraint or penalty function is particularly interesting for problems where heavily violating a single requirement is (much) more problematic than moderately violating a number of requirements. An example of such a problem is a cancer treatment planning problem, where the homogeneity of the dose administered to the target volume is an important consideration. For ease of exposition, we focus on functions $f : \mathbb{R}^p \to \mathbb{R}$ of the form

$$f(v) = \sum_{j=1}^{p} \max\{v_j, 0\}^2,$$

and note that we consider a non-zero right-hand side, γ, for this constraint, as $f(v) \geq 0$ for all v. To apply our approximation method, we note that

$$f_\infty(v) = \begin{cases} 0 & \text{if } v \leq 0 \\ +\infty & \text{otherwise,} \end{cases}$$

and

$$\lambda f\left(\frac{v}{\lambda}\right) = \frac{1}{\lambda} f(v),$$

that is, f is positively homogeneous of order 2. A conservative approximation of the constraint is thus given by applying Theorem 2:

$$\begin{cases} d^\top u + \sum_{j=1}^{p} \max\left\{b_j(x) + V_j^\top d, 0\right\}^2 \leq \gamma & \\ \qquad\qquad\qquad\qquad D_i^\top u \geq 0 & i = 1, \dots, L \\ \qquad\qquad\qquad A_i(x) - V^\top D_i \leq 0 & i = 1, \dots, L. \end{cases}$$

A tighter conservative approximation can be found by applying Theorem 3. For this particular choice of f, (11) can be reformulated to:

$$\begin{cases} d^\top u + \sum_{j=1}^{p} y_j^0 \leq \gamma & \\ \left\| \begin{matrix} z_j^0 \\ \frac{1}{2}\left(1 + d^\top r - y_j^0\right) \end{matrix} \right\|_2 \leq \frac{1}{2}\left(1 + d^\top r + y_j^0\right) & j = 1, \ldots, p \\ z^0 \geq 0 & \\ z^0 \geq b(x) + V^\top d & \\ 1 + d^\top r \geq 0 & \\ \sum_{j=1}^{p} y_j^i \leq D_i^\top u & i = 1, \ldots, L \\ \left\| \begin{matrix} z_j^i \\ \frac{1}{2}\left(-D_i^\top r - y_j^i\right) \end{matrix} \right\|_2 \leq \frac{1}{2}\left(-D_i^\top r + y_j^i\right) & j = 1, \ldots, p, \;\; i = 1, \ldots, L \\ z^i \geq 0 & i = 1, \ldots, L \\ z^i \geq A_i(x) - V^\top D_i & i = 1, \ldots, L \\ -D_i^\top r \geq 0 & i = 1, \ldots, L, \end{cases}$$

where the auxiliary variables $z^0, z^i \in \mathbb{R}^p$ model the maximum of $V^\top d + b(x)$ and 0 and $A_i(x) - V^\top D_i$ and 0, for $i = 1, \ldots, L$, respectively. Furthermore, the auxiliary variables $y^0, y^i \in \mathbb{R}^p$ model $\frac{(z_j^0)^2}{1+d^\top r}$ and $\frac{(z_j^i)^2}{-D_i^\top r}$, respectively. We demonstrate the use of the above conservative approximations with a numerical example in Section 5.2.

3.4 Geometric Programming

In general, a geometric programming constraint is given by (Boyd et al., 2007):

$$f(Cx + c) \leq 0, \tag{26}$$

for some $C \in \mathbb{R}^{p \times n}$, $c \in \mathbb{R}^p$, where f is the log-sum-exp function given by

$$f(z) = \log\left(e^{z_1} + \cdots + e^{z_p}\right).$$

Note that we choose this particular formulation of a geometric programming constraint as Theorem 4 shows that this results in a potentially tighter conservative approximation than using simply the sum of exponential terms. In this paper, we focus on uncertainty in C. We note that h is a convex function in both the uncertain parameters C and the decision variables x. As the argument in (26) is affine in both C and x we note that there exist affine mappings $A : \mathbb{R}^n \to \mathbb{R}^{p \times L}$ and $b : \mathbb{R}^n \to \mathbb{R}^p$ such that the robust counterpart of (26) is given by

$$f(A(x)\zeta + b(x)) \leq 0 \qquad \forall \zeta \in U, \tag{27}$$

where ζ contains all elements of C and thus $L = p \cdot n$ and U is the polyhedron defined in (3).

Recall that the conservative approximation resulting from Theorem 3 involves the perspective of the log-sum-exp function. We know that a constraint modeled by f can be represented as an exponential cone (Serrano, 2015), and problems including such constraints can thus be solved efficiently. Recall that we show that any perspective of a conically representable function is conically representable with the same cone in Appendix C, and thus (11) can be solved efficiently.

Alternatively, we can use the conservative approximation as formulated in Theorem 2. To this end we note that the recession function of f is given by:

$$f_\infty(y) = \max\left\{y_i \mid i = 1, \ldots, n\right\},$$

and thus we find that

$$\begin{cases} d^\top u + f\left(V^\top d + b(x)\right) \leq 0 & \quad (28a) \\ \max\limits_{k}\left\{A_{ki}(x) - V_k^\top D_i\right\} \leq D_i^\top u \qquad i = 1, \ldots, L, & \quad (28b) \end{cases}$$

is a conservative approximation of (27), where $A_{ki}(x)$ is the element on the k-th row and i-th column of $A(x)$ and V_k is the k-th column of V. We note that (28b) can easily be reformulated as linear constraints.

4 Extension to general convex uncertainty sets

In this section, we consider (P) with a general convex uncertainty set that is given by

$$U = \left\{\zeta \in \mathbb{R}^L_+ \mid h_\ell(\zeta) \leq 0 \quad \ell = 1, ..., q\right\}, \tag{29}$$

where $h_\ell : \mathbb{R}^p \to \mathbb{R}$ is convex and closed. The assumption that $U \subseteq \mathbb{R}^L_+$ is without loss of generality because one can always lift the set U into $\mathbb{R}^L_+$ by setting $\zeta = \zeta^+ - \zeta^-$ in (P), where $\zeta^+, \zeta^- \in \mathbb{R}^L_+$, and incorporate the non-convex projection of Bertsimas and Sim (2006) if U is norm-based.

In case the set U is conic quadratic representable, we can approximate the set U by a polyhedron using the work by Ben-Tal and Nemirovski (2001). After having the polyhedral description, all techniques from the previous section can be applied. We note that the polyhedral approximation is polynomial in the dimension of the conic quadratic representation of the set, as well as $\frac{1}{\epsilon}$, where ϵ is the accuracy of approximation. Furthermore, a large value of ϵ, and therefore a crude approximation of the uncertainty set, is often acceptable as the uncertainty set is a modelers' choice and not a hard constraint. There is another option, which can also be applied for sets that are not conic quadratic representable, and is outlined in the theorem below. The proof of Theorem 6 can be found in Appendix B.

Theorem 6. *Let $f : \mathbb{R}^p \to \mathbb{R}$ be a closed convex function and let $A : \mathbb{R}^n \to \mathbb{R}^{p\times L}$ and $b : \mathbb{R}^n \to \mathbb{R}^p$ be affine functions. Let $U \subseteq \mathbb{R}^L$ be a convex set as defined in* (29) *and* $\mathrm{ri}(U) \neq \emptyset$. *Then, $x \in \mathbb{R}^n$ satisfies*

$$f\left(A(x)\zeta + b(x)\right) \leq 0 \qquad \forall \zeta \in U,$$

if and only if it satisfies the following set of adjustable robust optimization constraints:

$$\forall (w_0, w) \in W,\ \exists \lambda \in \mathbb{R}^q_+, \{u_\ell\}_\ell \subset \mathbb{R}^p : \begin{cases} \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + b(x)^\top w + w_0 \leq 0 & \text{(30a)} \\ A(x)^\top w \leq \sum_{\ell=1}^q u_\ell. & \text{(30b)} \end{cases}$$

where the uncertainty set W is defined by

$$W = \left\{ (w_0, w) \in \mathbb{R}^{p+1} \mid w_0 + f^*(w) \leq 0 \right\}.$$

The adjustable variables $(\lambda, \{u_\ell\}_\ell)$ in (30) may appear in a nonlinear way, and imposing linear decision rules would again lead to robust constraints with convex uncertainties. In order to obtain the tractable conservative approximation of (30) in Theorem 7, we treat the adjustable variables $(\lambda, \{u_\ell\}_\ell)$ in (30) as static. The proof of Theorem 7 can be found in Appendix B.

Theorem 7. *If there exist $\lambda \in \mathbb{R}^q_+$ and $u_\ell \in \mathbb{R}^p$, $\ell = 1, ..., q$, for a given $x \in \mathbb{R}^n$ such that*

$$\begin{cases} \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + f(b(x)) \leq 0 & \text{(31a)} \\ f_\infty(A_i(x)) \leq \sum_{\ell=1}^q u_{i\ell} \qquad i = 1, \dots, L, & \text{(31b)} \end{cases}$$

holds, then x also satisfies (P) *with $U \subseteq \mathbb{R}^L$ as defined in* (29)*.*

Here, we restrict the adjustable variable $(\lambda, \{u_\ell\}_\ell)$ to be linear decision rule of w_0 without static component, which yields

$$\begin{aligned} & \sum_{\ell=1}^q w_0 \lambda_\ell h_\ell^*(w_0 u_\ell / w_0 \lambda_\ell) + b(x)^\top w + w_0 \leq 0 \qquad \forall (w_0, w) \in W \\ \Longrightarrow\quad & \sup_{(w_0,w)\in W} \left\{ w_0 \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + b(x)^\top w + w_0 \right\} \leq 0 \\ \Longleftrightarrow\quad & \sup_{(w_0,w)\in W} \left\{ b(x)^\top w + \left(1 + \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell)\right) w_0 \right\} \leq 0 \\ \Longleftrightarrow\quad & \left(1 + \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell)\right) f\left(\frac{b(x)}{1 + \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell)}\right) \leq 0, \\ \Longleftrightarrow\quad & \begin{cases} z f\left(\frac{b(x)}{z}\right) \leq 0 \\ 1 + \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) \leq z \end{cases} \end{aligned}$$

where the last equivalence follows from the definition of the conjugate.

For a special case when $f(\cdot)$ is positively homogeneous, the set of constraints in (31) is equivalent to

$$\begin{cases} \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + f(b(x)) \leq 0 \\ f(A_i(x)) \leq \sum_{\ell=1}^q u_{i\ell} \qquad i = 1, ..., L. \end{cases} \tag{32}$$

The obtained set of finite convex constraints (32) is in fact the tractable reformulation of the following robust convex constraint

$$\sum_{i=1}^{L} \zeta_i f\left(A(x)_i\right) + f\left(b(x)\right) \leq 0 \qquad\qquad \forall \zeta \in U,$$

which coincides with the conservative approximation of Bertsimas and Sim (2006) for a robust convex constraint (P) where $f(\cdot)$ is positively homogeneous.

In summary, if the robust convex constraint (P) has non-polyhedral convex uncertainty, we propose to impose static decision rules to adjustable variables in the adjustable robust *nonlinear* reformulation (30), and the obtained approximation (32) coincides with that of Bertsimas and Sim (2006) if homogeneous $f(\cdot)$ is considered. Since our approach does not require $f(\cdot)$ to be homogeneous in (P), our approach generalizes the approach of Bertsimas and Sim (2006) to non-homogeneous functions. For (P) with a polyhedral uncertainty set, we propose to impose linear decision rules to adjustable variables in the adjustable robust *linear* reformulation (7), and the obtained approximations (10) and (11) are tighter than the one from (31) using static decision rules. In this case, our approximations via linear decision rules are tighter than the ones from Bertsimas and Sim (2006). Additionally, our approach allows for progressive approximation while their method does not. Note that this progressive approximation as described in Appendix D works similarly for a general convex uncertainty set. We also remark that in the case where the uncertainty set consists of both linear and nonlinear constraints, the approaches can be combined, that is, linear decision rules can be used for the adjustable variables corresponding to the linear constraints while static rules are used for the other adjustable variables.

5 Numerical Results

5.1 Geometric Programming

For our first numerical experiment we test our approach on several randomly generated geometric programming instances, identically structured to the instances used by Hsiung et al. (2008). In particular, this means we treat geometric programming problems with a linear objective, and a number of two-term log-sum-exp inequality constraints with uncertainty:

$$\begin{aligned} \min_{x} \quad & c^\top x \\ \text{s.t.} \quad & \log\left(e^{\left(-\mathbf{1}+B_i^{(1)}\zeta\right)^\top x} + e^{\left(-\mathbf{1}+B_i^{(2)}\zeta\right)^\top x}\right) \leq 0 \qquad \forall \zeta \in U,\ i = 1,\dots,m, \end{aligned} \tag{33}$$

where $c = \mathbf{1} \in \mathbb{R}^n$ is the all ones vector, and $B_i^{(1)}$, $B_i^{(2)} \in \mathbb{R}^{n\times L}$ are randomly generated sparse matrices with sparsity density 0.1 whose nonzero elements are uniformly distributed on the interval $[0, 1]$. The uncertainty set U is assumed to be a box, that is,

$$U = \left\{\zeta \in \mathbb{R}^L \;\middle|\; \|\zeta\|_\infty \leq 1\right\}. \tag{34}$$

Note that since U is symmetric around 0, we can restrict $B_i^{(1)}$, $B_i^{(2)}$ to be nonnegative.

	Approximation Error	Computation Time (s)
Lower bound	-0.00%	3.3
Theorem 3	0.02%	1.3
Theorem 2	1.44%	1.1

Table 1: Approximation error with respect to the exact solution and computation time for 20 randomly generated instances of type (33) with $n = m = 100$ and $L = 5$.

We first consider a set of 20 small examples with $n = m = 100$ and $L = 5$. Since L, the number of uncertain parameters, is small, (33) can be solved exactly by enumerating the 2^L vertices of U. For larger L, however, we need to resort to comparing our solutions' objective value to a lower bound. To this end, we use a lower bound based on the work of Hadjiyiannis et al. (2011) and Zhen et al. (2017) that uses the optimal solution to a conservative approximation to find potentially critical scenarios in the uncertainty set. The lower bound is then constructed by solving a model that only safeguards for this finite set of critical scenarios. For more details we refer the reader to Appendix D.

Table 1 lists the approximation error with respect to the exact solution and computation time of the solutions to the conservative approximations resulting from Theorem 2 and 3. Moreover, to evaluate the quality of the obtained lower bound, we have included the approximation error with respect to the exact solution and computation time of the proposed lower bound as well. We define the approximation error (in percentage) with respect to a solution x^* equally to (Hsiung et al., 2008):

$$100 \left(\frac{e^{c^\top \hat{x}}}{e^{c^\top x^*}} - 1 \right),$$

where $\hat{x}$ is the solution to our approximation. In other words, we compare the objective value of different solutions to the robust geometric programming problem in posynomial form. We note that the -0.00 we report for the lower bound means we are unable to differentiate the objective value from the optimal objective value within a reasonable numerical precision. We remark that the lower bound does not necessarily yield a feasible solution to the original problem, but it serves us well in evaluating the approximations in higher dimensions, where we are unable to obtain the exact objective value.

Clearly, for instances of this size the lower bound is particularly good. Moreover, it is an order of magnitude closer to the exact robust objective value compared to the solutions we find using our conservative approximation. Therefore, we expect that using the lower bound instead of the exact robust solution for larger instances has hardly any effect on the approximation error we report.

To analyze how our approach scales with more uncertain parameters, Figure 1 shows the average approximation error with respect to the lower bound and computation time of both approximations for several values of L over 20 random instances. There is a clear difference between the two decision rules in approximation quality and computation time. The more involved decision rule used in Theorem 3 performs very well, having an approximation error below 0.5% for all sizes except $L = 18$. The simple decision rule used in Theorem 2 performs quite a bit worse with an approximation error between 1% and 5% at first, and quickly increases for larger values of L. Both approximations are highly tractable, and their computation time increases linearly with respect to the number of uncertain parameters L. We remark that no results for $L = 19$ or $L = 20$ are included, as a large proportion of the randomly generated instances of this size were infeasible. Note that not only the approximations we propose are infeasible, but the robust instances itself are as well. This can be verified through noting that the optimization problem used to obtain the lower bound is infeasible when enough scenarios are included. We note that Hsiung et al. (2008) report approximation errors between 30% and 0.1% dependent on the quality of approximation used, for $L = 5$ and $n = m = 500$.

Besides box uncertainty, we also consider a budget uncertainty set given by

$$U = \left\{ \zeta \in \mathbb{R}^L \mid \|\zeta\|_\infty \leq 1, \ \ \|\zeta\|_1 \leq \Gamma \cdot L \right\}. \tag{35}$$

In this uncertainty set, the parameter $\Gamma \in [0, 1]$ controls the level of uncertainty. It can be interpreted as the maximum fraction of uncertain parameters that is allowed to deviate maximally at the same time. Figure 2 depicts the numerical results for a budget uncertainty set with $\Gamma = \frac{1}{2}$. We first note that for this budget uncertainty set, all instances with $L = 19$ and $L = 20$ are feasible. The approximation error follows a very similar trend to the one observed for box uncertainty in Figure 1 for smaller L, but there is a clear difference for larger L, where the approximation error for the budget uncertainty set is smaller. This causes us to suspect that the (extreme) increase in approximation error that was observed for the box uncertainty is

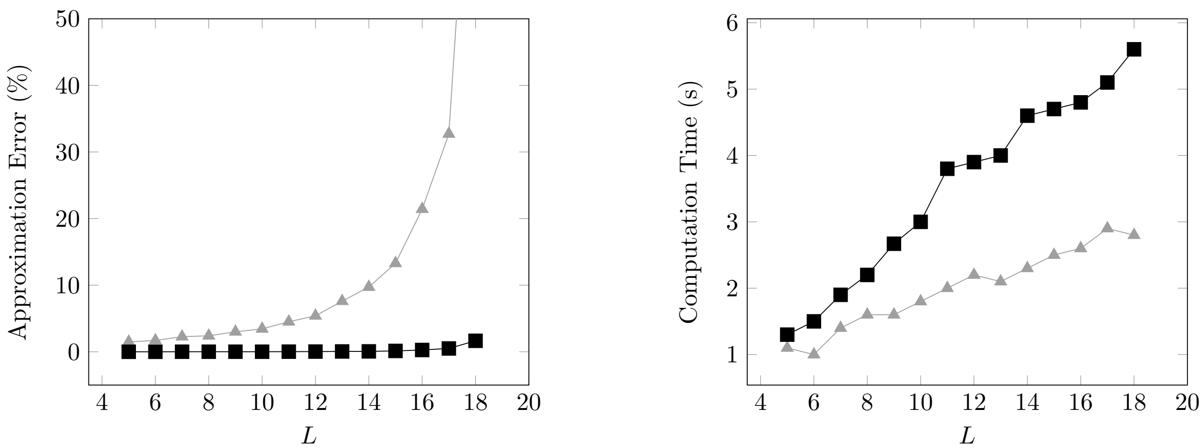

Figure 1: Average results of solving approximations to (33) over twenty randomly generated instances for a box uncertainty set (34). Results corresponding to Theorem 2 are depicted by triangles and results corresponding to Theorem 3 are shown as squares. The approximation error is reported with respect to the lower bound obtained from the approach proposed by Hadjiyiannis et al. (2011).

related to the problems getting close to infeasibility for $L \geq 17$. The computation time follows a slightly more erratic pattern for the budget uncertainty set, and is slightly higher than for the box uncertainty set, but is largely comparable in magnitude.

This example clearly illustrates that using the more involved approximation that results from using a lifted decision rule in Theorem 3 can be very beneficial. For all these uncertain geometric programming problems we find a solution very close to the optimal solution using this approximation. Moreover, the required computation time is very reasonable and not much higher than for the approximation from Theorem 2 that struggles to find high quality solutions in this experiment.

The solutions to the geometric programming problems have been obtained using Julia with the JuMP interface (Dunning et al., 2017) and the Mosek solver for exponential cones (MOSEK ApS, 2019). The experiments were conducted on a desktop with 8 GB RAM and a 3.4 GHz Intel Core i7 processor.

5.2 Radiotherapy Optimization

Our second numerical experiment concerns a specific problem from radiotherapy optimization: inverse treatment planning of beam-on times for 3D small animal radiotherapy (Balvert et al., 2015). The core problem in treatment planning is ensuring a sufficient dose γ of radiation to the planning target volume (PTV) while minimizing the dose to the tissue around that target volume, also known as the organs at risk ($\mathcal{OAR}$). To this end, we are interested in minimizing a weighted combination of the dose 'shortage' in the PTV and the dose delivered to the $\mathcal{OAR}$. The decision variables in this problem are the locations and beam-on times for all beams used. In this specific application, we assume the beam locations are given and we attempt to find

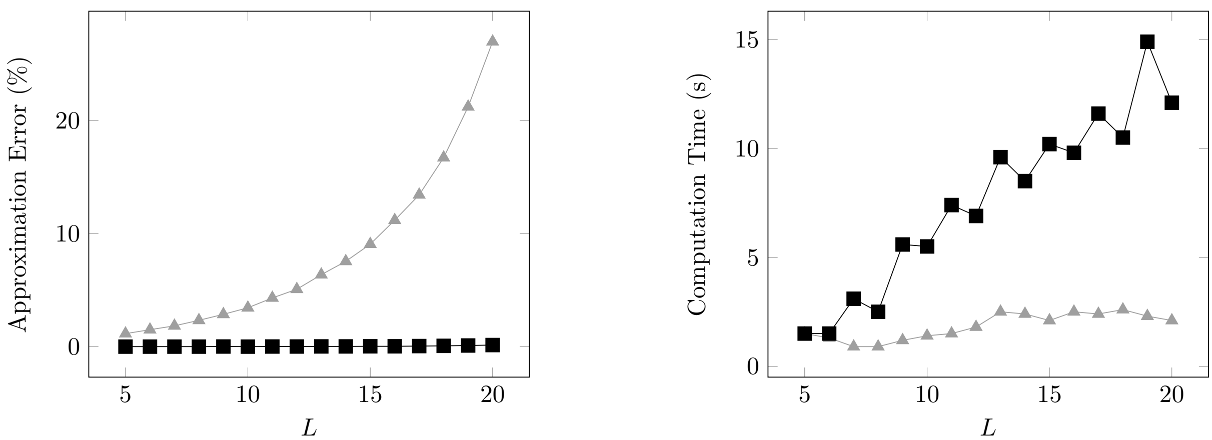

Figure 2: Average results of solving approximations to (33) over twenty randomly generated instances for a budget uncertainty set (35) with $\Gamma = \frac{1}{2}$. Results corresponding to Theorem 2 are depicted by triangles and results corresponding to Theorem 3 are shown as squares. The approximation error is reported with respect to the lower bound obtained from the approach proposed by Hadjiyiannis et al. (2011).

optimal beam-on times t.

It is customary in radiotherapy optimization to discretize each tissue structure into voxels. Sets of these voxels are denoted by $\mathcal{I}_{PTV}$ and $\mathcal{I}_s$ for all $s \in \mathcal{OAR}$, respectively. The dose delivered to a tissue structure is then computed as the average dose delivered to its voxels. Given these voxels, one can compute the dose rates from all beams to all voxels, referred to as the matrix Γ. The i-th row of this matrix, Γ_i, then corresponds to the dose rate of all beams to voxel i. We specifically consider the following mathematical optimization problem:

$$\min_{t,\tau} \ \tau \tag{36a}$$

$$\begin{aligned} \text{s.t.} \ & w_{PTV} \frac{1}{|\mathcal{I}_{PTV}|} \sum_{i \in \mathcal{I}_{PTV}} \max\left\{\gamma - \Gamma_i^\top t, 0\right\}^2 \\ & \qquad + (1 - w_{PTV}) \sum_{s \in \mathcal{OAR}} w_s \frac{1}{|\mathcal{I}_s|} \sum_{i \in \mathcal{I}_s} \Gamma_i^\top t \le \tau \end{aligned} \tag{36b}$$

$$t \geq 0, \tag{36c}$$

which is a slight adaptation of the problem described by Balvert et al. (2015). Here, w_{PTV} and w_s for all $s \in \mathcal{OAR}$ represent predefined weights. In particular, we choose to use a squared penalty function for undelivered dose to the PTV, similar to Fredriksson (2013, Eq. 1). Irregardless of whether the regular or squared penalty function is used, little research has been done on robust or uncertain versions of (36). An important reason for this is the general convex nature of constraint (36b), along with the fact that a natural type of uncertainty in this problem is implementation error (Van Dye et al., 2013; Van der Merwe et al., 2017), which always leads to constraints that are convex in the uncertain parameters.

In this numerical example, we therefore focus on implementation error. In particular, we consider multiplicative implementation error, that is, we replace t by $t \circ (\mathbf{1} + \epsilon)$, where $\circ$ denotes the element-wise multiplication of two vectors, and ϵ is the uncertain vector that models the implementation error. We note that, at least in this context, additive implementation error of the form $t + \Delta t$ would make little sense, as this would presume that there would also potentially be some implementation error if one chooses not to use a certain beam ($t_b = 0$).

We solve both approximations we derive in this work for Case 3 discussed by Balvert et al. (2015). In this case, there are 6 different beam angles, that is, $t \in \mathbb{R}^6$, and the PTV consists of 112,738 voxels, while the four organs at risk consist of 207,974, 2,261,739, 177,165 and 212,864 voxels. We consider box uncertainty for ϵ, with three different maximum values: 0.01, 0.05 and 0.1. For all three, the solutions to the two approximations coincide. Unfortunately, due to the size of the problem, we cannot obtain the exact robust solution. We are, however, able to obtain lower bounds using the technique described in Appendix D and report the approximation error with respect to that lower bound in Table 2. Furthermore, we find that the nominal solution performs 4.4% worse in the worst-case than the robust solution we find, which in turn performs 4.9% worse than the nominal solution when no uncertainty is present. It should be noted that the approximation resulting from Theorem 2 can be solved in a matter of seconds, much like the model without uncertainty.

Maximum Implementation Error	1.00%	5.00%	10.00%
Approximation Error	1.13%	5.57%	10.91%

Table 2: Approximation error of both approximation methods with respect to the lower bound for Case 3 discussed by Balvert et al. (2015) for different sizes of the uncertainty set.

We note that although we treat a constraint with sum-of-max squared terms in this numerical experiment, we unfortunately cannot use the results from Theorem 4 here to obtain a potentially tighter approximation. The cause of this are the linear terms in the constraint, which lead to a non-convex constraint if we apply the square root.

All results in this section have been obtained using Julia with the JuMP interface (Dunning et al., 2017) and the Gurobi solver. The experiments were conducted on a desktop with 8 GB RAM and a 3.4 GHz Intel Core i7 processor.

6 Conclusions

In Robust Optimization, finding a tractable reformulation of the robust counterpart of the uncertain inequalities of interest is essential. While a systematic approach to find such tractable reformulations already exists when the inequalities of interest are concave in the uncertain parameters, no general results are available when they are convex. This paper fills that gap for by providing a reformulation of such problems to adjustable robust optimization problems.

These adjustable robust optimization problems can be approximated using static decision rules for any convex uncertainty set. When the original uncertainty set is polyhedral, we use linear decision rules to obtain an improved approximation. We show these approximations extend various techniques from the literature. Moreover, we introduce a lifting that has great potential to improve the resulting approximation, as illustrated in numerical experiments for uncertain geometric programming.

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A Recession Functions

As discussed earlier, the recession function can be defined in multiple ways. In this paper, we mainly use it to concisely denote the support function of the domain of a function's conjugate. An advantage of the recession function besides concise notation is the relative ease of computing a recession function. Let $f^1, \ldots, f^m$ be convex, proper and lower semicontinuous functions. Then, the following composition rules for recession functions are valid (Auslender and Teboulle, 2006, Proposition 2.6.1, 2.6.2):

1. Let f be defined by $f(x) = \sum_{i=1}^m f^i(x)$. Then $f_\infty(y) = \sum_{i=1}^m f^i_\infty(y)$;
2. Let f be defined by $f(x) = \sup_{i\in\{1,\ldots,m\}} f^i$. Then $f_\infty(y) = \sup_{i\in\{1,\ldots,m\}} f^i_\infty(y)$.

Moreover, if $g : \mathbb{R}^m \to \mathbb{R} \cup \{+\infty\}$ is a proper convex function, A is a linear map from $\mathbb{R}^n$ to $\mathbb{R}^m$ and $\psi : (-\infty, b) \to \mathbb{R})$ for $0 \le b \le +\infty$ is convex and nondecreasing with $\psi_\infty(1) > 0$ it holds that (Auslender and Teboulle, 2006, Proposition 2.6.3, 2.6.4):

3. Let f be defined by $f(x) = g(Ax)$. Then $f_\infty(y) = g_\infty(Ay)$;
4. Let f be defined by
$$f(x) = \begin{cases} \psi(g(x)) & \text{if } x \in \mathrm{dom}\,(g) \\ +\infty & \text{otherwise.} \end{cases}$$
Then
$$f_\infty(y) = \begin{cases} \psi_\infty(f_\infty(y)) & \text{if } y \in \mathrm{dom}\,(f_\infty) \\ +\infty & \text{otherwise.} \end{cases}$$

Using the above composition rules as well as the recession functions of some often encountered basic functions f, one can directly find the recession function of the function of interest. An overview of some common recession functions is given in Table 3. It should be noted that the recession function is always conically representable, as its epigraph is the recession cone of the epigraph of f and thus is a cone by definition (Rockafellar, 1970, p. 66). We additionally remark that for all positively homogeneous functions of order one, or equivalently all functions such that $f^*(y) = 0$ on its domain, it holds that $f_\infty(x) = f(x)$.

Lemma 1. *Let $f : \mathbb{R}^n \to \mathbb{R}$ be a closed, convex function. It then holds that f is positively homogeneous if and only if $f^*(y) = 0$ for all $y \in \operatorname{dom}(f^*)$.*

Proof. '$\Longrightarrow$': Assume f is positively homogeneous. Suppose $\exists x^* \in \operatorname{dom}(f^*)$ such that $f^*(x^*) = \alpha \neq 0$. We first consider the case where $\alpha > 0$. We know

$$\alpha = \sup_{y \in \mathbb{R}^n} \left\{ y^\top x - f(y) \right\},$$

that is, there exists a sequence $(y_k)_{k=0}^\infty$ with $y_k \in \mathbb{R}^n \quad \forall k$ such that

$$\lim_{k \to \infty} \left\{ y_k^\top x - f(y_k) \right\} = \alpha.$$

Now let $\lambda > 0$ and define the sequence $(z_k)_{k=0}^\infty$ by $z_k = \lambda y_k$. Then

$$\begin{aligned} \lim_{k \to \infty} \left\{ z_k^\top x - f(z_k) \right\} &= \lim_{k \to \infty} \left\{ \lambda y_k^\top x - f(\lambda y_k) \right\} \\ &= \lambda \lim_{k \to \infty} \left\{ y_k^\top x - f(y_k) \right\} \\ &= \lambda \alpha > \alpha, \end{aligned}$$

which is a contradiction with α being the supremum as defined by (A).

Now consider the case where $\alpha < 0$. We know for sure that

$$\alpha \geq 0^\top x - f(0) = -f(0).$$

Let $\lambda > 0$. Then, because f is positively homogeneous, we know that

$$f(0) = f(\lambda \cdot 0) = \lambda f(0),$$

and thus $f(0) = 0$. This implies $\alpha \geq 0$, which is a contradiction.

$f(x)$	$f_\infty(y)$
$\sqrt{1 + x^\top Q x}$ $(Q \succeq 0)$	$\sqrt{y^\top Q y}$
$x^\top Q x + q^\top x + c$ $(Q \succeq 0)$	$\begin{cases} q^\top y & \text{if } Qy = 0 \\ +\infty & \text{if } Qy \neq 0 \end{cases}$
$\log \sum_{i=1}^n e^{x_i}$ $(n > 1)$	$\max \{ y_i \mid i = 1, \ldots, n \}$
$\sum_{i=1}^n \sqrt{1 + x_i^2}$	$\lVert y \rVert_2$
$\sum_{i=1}^m \max_{k \in K_i} \{x_k\}$	$\sum_{i=1}^m \max_{k \in K_i} \{y_k\}$
$\lVert x \rVert_2$	$\lVert y \rVert_2$

Table 3: Some examples of functions f with recession functions f_∞.

'$\Longleftarrow$': Assume $f^*(y) = 0$ for all $y \in \operatorname{dom}(f^*)$. Because f is closed and convex we know

$$f(x) = f^{**}(x) = \sup_{y \in \operatorname{dom}(f^*)} \left\{ y^\top x - f^*(x) \right\} = \sup_{y \in \operatorname{dom}(f^*)} \left\{ y^\top x \right\}.$$

Let $\lambda > 0$. We find

$$\begin{aligned} f(\lambda x) &= f^{**}(\lambda x) \\ &= \sup_{y \in \operatorname{dom}(f^*)} \left\{ y^\top (\lambda x) \right\} \\ &= \lambda \sup_{y \in \operatorname{dom}(f^*)} \left\{ y^\top x \right\} \\ &= \lambda f^{**}(x) = f(x), \end{aligned}$$

and thus we find that f is positively homogeneous. $\square$

Lemma 2. *Let $f : \mathbb{R}^n \to \mathbb{R}$ be a closed, convex and positively homogeneous function. It then holds that $f_\infty = f$.*

Proof. We use definition (1) for the recession function to find:

$$\begin{aligned} f_\infty(x) &= \lim_{\lambda \downarrow 0} \lambda f\left(\frac{x}{\lambda}\right) \\ &= \lim_{\lambda \downarrow 0} f(x) \\ &= f(x), \end{aligned}$$

because f is positively homogeneous. $\square$

B Proofs for Conservative Approximations

Proof of Theorem 2. We know from Theorem 1 that (P) is equivalent to (7). Here, we restrict the adjustable variable λ to be a linear decision rule, that is,

$$\lambda = u + Vw.$$

Substituting this decision rule in the first constraint yields

$$\begin{aligned} & & d^\top \lambda + b(x)^\top w - f^*(w) \leq 0 & \qquad \forall w \in \operatorname{dom} f^* \\ \Longrightarrow & & d^\top u + \sup_{w \in \operatorname{dom} f^*} \left\{ \left(b(x) + V^\top d\right)^\top w - f^*(w) \right\} \leq 0 & \\ \Longleftrightarrow & & d^\top u + f\left(b(x) + V^\top d\right) \leq 0, & \end{aligned}$$

where the last equivalence follows from the definition of the conjugate. For the second constraint we find

$$\begin{aligned} & & D_i^\top \lambda \geq A_i(x)^\top w & \qquad \forall w \in \operatorname{dom} f^*,\ i = 1, \dots, L \\ \Longrightarrow & & \delta^*\left(A_i(x) - V^\top D_i \,\middle|\, \operatorname{dom} f^*\right) \leq D_i^\top u & \qquad i = 1, \dots, L \\ \Longleftrightarrow & & f_\infty\left(A_i(x) - V^\top D_i\right) \leq D_i^\top u & \qquad i = 1, \dots, L, \end{aligned}$$

where the last equivalence follows from (2). $\square$

Proof of Theorem 3. From Theorem 1 we know (P) is equivalent to (7). We lift the nonlinear term $f^*(w)$ to the uncertainty set, that is, we introduce an auxiliary uncertain parameter w_0 such that we find that (7) is equivalent to

$$\forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W,\ \exists \lambda \in \mathbb{R}^q : \begin{cases} d^\top \lambda + w^\top b(x) + w_0 \leq 0 & (37a) \\ D^\top \lambda \geq A(x)^\top w, & (37b) \end{cases}$$

where the new uncertainty set W is defined by

$$W = \left\{ \begin{pmatrix} w_0 \\ w \end{pmatrix} \in \mathbb{R}^{p+1} \;\middle|\; w_0 + f^*(w) \leq 0 \right\}.$$

The support function of this new uncertainty set is essential for deriving a tractable robust counterpart and is equal to:

$$\begin{aligned} \delta^*\left(\begin{pmatrix} z_0 \\ z \end{pmatrix} \middle| W \right) &= \sup_{(w_0 \;\; w)^\top \in W} \left\{ z_0 w_0 + z^\top w \right\} \\ &= \begin{cases} \sup_{w \in \mathbb{R}^p} \left\{ z^\top w - z_0 f^*(w) \right\} & \text{if } z_0 > 0 \\ \sup_{w \in \operatorname{dom} f^*} \left\{ z^\top w \right\} & \text{if } z_0 = 0 \\ +\infty & \text{otherwise} \end{cases} \\ &= \begin{cases} z_0 \sup_{w \in \mathbb{R}^p} \left\{ w^\top \frac{z}{z_0} - f^*(w) \right\} & \text{if } z_0 > 0 \\ f_\infty(z) & \text{if } z_0 = 0 \\ +\infty & \text{otherwise} \end{cases} \\ &= \begin{cases} z_0 f\left(\frac{z}{z_0}\right) & \text{if } z_0 \geq 0 \\ +\infty & \text{otherwise.} \end{cases} \end{aligned} \tag{38}$$

Now, we once again use a linear decision rule for λ of the form

$$\lambda = u + Vw + rw_0, \tag{39}$$

where $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q \times p}$ and $r \in \mathbb{R}^q$, and thus we obtain a conservative approximation for (P). Substituting this decision rule in (37a) yields

$$\begin{aligned} & d^\top \lambda + b(x)^\top w + w_0 \leq 0 && \forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W \\ \Longrightarrow\quad & d^\top (u + Vw + rw_0) + b(x)^\top w + w_0 \leq 0 && \forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W \\ \Longleftrightarrow\quad & d^\top u + \begin{pmatrix} w_0 \\ w \end{pmatrix}^\top \begin{pmatrix} 1 + d^\top r \\ V^\top d + b(x) \end{pmatrix} \leq 0 && \forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W \\ \Longleftrightarrow\quad & d^\top u + \delta^*\left(\begin{pmatrix} 1 + d^\top r \\ V^\top d + b(x) \end{pmatrix} \middle| W \right) \leq 0 \\ \Longleftrightarrow\quad & \begin{cases} d^\top u + \left(1 + d^\top r\right)^\top f\left(\frac{V^\top d + b(x)}{1 + d^\top r}\right) \leq 0 \\ \qquad\qquad\qquad\qquad 1 + d^\top r \geq 0 \end{cases}, \end{aligned} \tag{40}$$

where the last equivalence holds because of the definition of the support of W in (38). Note that (40) is exactly (11a). Similarly, substituting the linear decision rule for λ in (37b) we find

$$\begin{aligned}
& & D_i^\top \lambda \geq A_i(x)^\top w & \qquad \forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W,\ i = 1,\dots,L \\
\Longrightarrow & & -D_i^\top u + \begin{pmatrix} w_0 \\ w \end{pmatrix}^\top \begin{pmatrix} -D_i^\top r \\ A_i(x) - V^\top D_i \end{pmatrix} \leq 0 & \qquad \forall \begin{pmatrix} w_0 \\ w \end{pmatrix} \in W,\ i = 1,\dots,L \\
\Longleftrightarrow & & -D_i^\top u + \delta^*\left(\begin{pmatrix} -D_i^\top r \\ A_i(x) - V^\top D_i \end{pmatrix} \middle| W \right) \leq 0 & \qquad i = 1,\dots,L \\
\Longleftrightarrow & & \begin{cases} -D_i^\top u + \left(-D_i^\top r\right) f\left(\frac{A_i(x) - V^\top D_i}{-D_i^\top r}\right) \leq 0 \\ -D_i^\top r \geq 0 \end{cases} & \qquad i = 1,\dots,L,
\end{aligned}$$

which is exactly (11b). Because the decision rule (39) is a more general decision rule than the decision rule used in Theorem 2, which equals (39) for $r = 0$, it follows that (11) is a tighter conservative approximation than (10). □

Proof of Theorem 6. Because f is a closed convex function we have that

$$f(z) = f^{**}(z) = \sup_{w \in \operatorname{dom} f^*} \left\{ z^\top w - f^*(w) \right\}.$$

Substituting this into (P) yields

$$\begin{aligned}
& & \forall \zeta \in U \ :\ f\left(A(x)\zeta + b(x)\right) \leq 0 & \\
\Longleftrightarrow & & \forall \zeta \in U \ :\ \sup_{w \in \operatorname{dom} f^*} \left\{ \left(A(x)\zeta + b(x)\right)^\top w - f^*(w) \right\} \leq 0 & \\
\Longleftrightarrow & & \sup_{\zeta \in U} \left\{ \sup_{w \in \operatorname{dom} f^*} \left\{ \left(A(x)^\top w\right)^\top \zeta + b(x)^\top w - f^*(w) \right\} \right\} \leq 0 & \\
\Longleftrightarrow & & \sup_{(w_0, w) \in W} \left\{ \sup_{\zeta \in U} \left\{ \left(A(x)^\top w\right)^\top \zeta \right\} + b(x)^\top w + w_0 \right\} \leq 0 & \qquad (41) \\
\Longleftrightarrow & & \sup_{(w_0, w) \in W} \left\{ \inf_{\substack{\lambda \in \mathbb{R}^q_+ \\ \{u_\ell\}_\ell}} \left\{ \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + b(x)^\top w + w_0 \mid A(x)^\top w \leq \sum_{\ell=1}^q u_\ell \right\} \right\} \leq 0 & \qquad (42) \\
\Longleftrightarrow & & \forall (w_0, w) \in W,\ \exists \lambda \in \mathbb{R}^q_+, \{u_\ell\}_\ell \subset \mathbb{R}^p :\ \begin{cases} \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + b(x)^\top w + w_0 \leq 0 \\ A(x)^\top w \leq \sum_{\ell=1}^q u_\ell \end{cases} &
\end{aligned}$$

where (41) and (42) are equivalent because of strong duality for convex optimization problems, which applies because $\operatorname{ri}(U) \neq \emptyset$. □

Proof of Theorem 7. We know from Theorem 6 that (P) is equivalent to (30). Here, we restrict the adjustable variables $(\lambda, \{u_\ell\}_\ell)$ to be a static decision rule, which yields

$$\begin{aligned}
& & \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + b(x)^\top w + w_0 \leq 0 & \qquad \forall (w_0, w) \in W \\
\Longrightarrow & & \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + \sup_{(w_0, w) \in W} \left\{ b(x)^\top w + w_0 \right\} \leq 0 & \\
\Longleftrightarrow & & \sum_{\ell=1}^q \lambda_\ell h_\ell^*(u_\ell/\lambda_\ell) + f\left(b(x)\right) \leq 0, &
\end{aligned}$$

where the last equivalence follows from the definition of the conjugate. For the second constraint we find

$$\begin{aligned}
& & A_i(x)^\top w &\leq \sum_{\ell=1}^{q} u_{i\ell} & & \forall w \in \operatorname{dom} f^*,\ i = 1, \ldots, L \\
&\implies & \delta^*\left(A_i(x) \mid \operatorname{dom} f^*\right) &\leq \sum_{\ell=1}^{q} u_{i\ell} & & i = 1, \ldots, L \\
&\iff & f_\infty\left(A_i(x)\right) &\leq \sum_{\ell=1}^{q} u_{i\ell} & & i = 1, \ldots, L,
\end{aligned}$$

where the last equivalence follows from (2). □

C Proof of Conically Representable Perspective

We use the definition of conically representable from Serrano (2015), that is, a function $f : \mathbb{R}^n \to \mathbb{R}$ is conically representable if its epigraph can be written as

$$\begin{aligned}
\operatorname{Epi} f &= \{(x,t) \mid f(x) \leq t\} \\
&= \{(x,t) \mid \exists u \in \mathbb{R}^m,\ S(x,u,t) = 0,\ T(x,u,t) \in \mathcal{K}\},
\end{aligned}$$

where $S : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R} \to \mathbb{R}^{k_1}$ and $T : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R} \to \mathbb{R}^{k_2}$ are affine mappings and $\mathcal{K}$ is a cone.

Theorem 8. *If f is conically representable, so is its perspective (fv).*

Proof. Let S, T be the affine mappings that define the conic representation of f and let $\mathcal{K}$ be the corresponding cone. Define $S^{per} : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R} \times \mathbb{R}_{++} \to \mathbb{R}^{k_1}$ and $T^{per} : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R} \times \mathbb{R}_{++} \to \mathbb{R}^{k_2}$ by

$$S^{per}(x,u,t,v) = vS\left(\frac{x}{v}, \frac{u}{v}, \frac{t}{v}\right), \qquad T^{per}(x,u,t,v) = vT\left(\frac{x}{v}, \frac{u}{v}, \frac{t}{v}\right).$$

Clearly, S^{per} and T^{per} are affine mappings. Moreover we find

$$\begin{aligned}
\operatorname{Epi}(fv) &= \left\{(x,v,t) \;\middle|\; vf\left(\frac{x}{v}\right) \leq t\right\} \\
&= \left\{(x,v,t) \;\middle|\; \left(\frac{x}{v}, \frac{t}{v}\right) \in \operatorname{Epi} f\right\} \\
&= \left\{(x,v,t) \;\middle|\; \exists u \in \mathbb{R}^m,\ S\left(\frac{x}{v}, u, \frac{t}{v}\right) = 0,\ T\left(\frac{x}{v}, u, \frac{t}{v}\right) \in \mathcal{K}\right\} \\
&= \left\{(x,v,t) \;\middle|\; \exists u \in \mathbb{R}^m,\ S\left(\frac{x}{v}, \frac{u}{v}, \frac{t}{v}\right) = 0,\ T\left(\frac{x}{v}, \frac{u}{v}, \frac{t}{v}\right) \in \mathcal{K}\right\} \\
&= \{(x,v,t) \mid \exists u \in \mathbb{R}^m,\ S^{per}(x,u,t,v) = 0,\ T^{per}(x,u,t,v) \in \mathcal{K}\},
\end{aligned}$$

which concludes the proof. □

D Progressive Approximation

As all sets of constraints described in Section 2.2 are conservative approximations to our original constraint (P), they can yield suboptimal solutions. In particular, we propose linear decision rules to solve (7), which is equivalent to (P), of which we know they generally do not guarantee to solve adjustable robust optimization problems to optimality (Ben-Tal et al., 2004). Moreover, as our adjustable formulation (7) exhibits left-hand side uncertainty, that is, the uncertain parameter w directly interacts with decision variables x, little is known with regard to the approximative power of linear decision rules.

In this section, therefore, we focus on finding a good progressive approximation to (P) such that we can gauge the quality of the conservative approximations we propose. A simple method detailed by Zhen et al. (2017) to obtain such approximation is to only require (P) to hold for a finite subset of scenarios from the uncertainty set U. The approximation is then given by

$$f\left(A(x)\zeta^{(k)} + b(x)\right) \leq 0 \qquad k = 1, \ldots, K, \tag{43}$$

where $\left\{\zeta^{(1)}, \ldots, \zeta^{(K)}\right\} \subseteq U$. We note that these constraints are exactly as computationally tractable as the original constraint without uncertainty. In fact, because we assume a polyhedral set U and f is convex, (43) is equivalent to (P) if $\left\{\zeta^{(1)}, \ldots, \zeta^{(K)}\right\}$ contains all extreme points of U. Generally, U has prohibitively many extreme points though, and we must resort to some other way of finding scenarios $\zeta^{(1)}, \ldots, \zeta^{(K)}$.

We can apply the same reasoning as above to (7) to find an approximation:

$$\text{For } k = 1, \ldots, K, \quad \exists \lambda^{(k)} \in \mathbb{R}^q : \begin{cases} w_0^{(k)} + b(x)^\top w^{(k)} + d^\top \lambda^{(k)} \leq 0 \\ D^\top \lambda^{(k)} \geq A(x)^\top w^{(k)}, \end{cases}$$

where $\left\{ \begin{pmatrix} w_0^{(1)} \\ w^{(1)} \end{pmatrix}, \ldots, \begin{pmatrix} w_0^{(K)} \\ w^{(K)} \end{pmatrix} \right\} \subset W$ and $\lambda^{(k)} \in \mathbb{R}^q$ is a non-adjustable variable. Recall that

$$W = \left\{ \begin{pmatrix} w_0 \\ w \end{pmatrix} : w_0 + f^*(w) \leq 0 \right\},$$

which generally has infinitely many extreme points.

An approach to find a small and efficient set of scenarios for two-stage fixed-recourse robust constraints is suggested by Hadjiyiannis et al. (2011). For any feasible solution $\hat{x}$ and linear decision rule $\hat{\lambda} = \hat{u} + \hat{V}w + \hat{r}w_0$, we find scenarios that are worst-case for the constraints in (7). We then hope that these scenarios are also worst-case for the actual optimal solution x^*, λ^* of (7). For our problem, this means that we obtain scenarios

$$\begin{pmatrix} \bar{w}_0 \\ \bar{w} \end{pmatrix} = \operatorname{argmax}_{\begin{pmatrix} w_0 \\ w \end{pmatrix} \in W} \left\{ d^\top \left(\hat{u} + \hat{V}w + \hat{r}w_0\right) + b(\hat{x})^\top w + w_0 \right\},$$

as well as the worst-case scenarios from (7b). An extension proposed by Zhen et al. (2017) is to use these $L+1$ scenarios to also obtain scenarios $\zeta^{(1)}, \ldots, \zeta^{(L+1)}$ by solving

$$\bar{\zeta}^{(k)} = \operatorname{argmax}_{\zeta \in U} \left\{ \left(A(\hat{x})\zeta + b(\hat{x})\right)^\top \bar{w}^{(k)} \right\}.$$

We note that similarly to this approach, we can also obtain worst-case scenarios $\bar{w}$ based on a linear decision rule solving (10). For more details, we refer to the papers by Hadjiyiannis et al. (2011) and Zhen et al. (2017).

E Proof of Equivalence of Quadratic and Conic Quadratic Approximations

Proof of Theorem 5. Let $x \in \mathbb{R}^n$ be such that there exist $u \in \mathbb{R}^q$, $V \in \mathbb{R}^{q \times p}$ and $r \in \mathbb{R}^q$ that satisfy (18). We claim choosing $u^* = \frac{1}{2}(u - r)$, $V_0^* = \frac{1}{2}V_0$ and $r^* = \frac{1}{2}(u + V_0 + r)$ means that (x, u^*, V, V_0^*, r^*)

satisfies (19). First suppose $1 + d^\top r > 0$. Then we find from (18a):

$$
\begin{aligned}
& & d^\top u + \left(1 + d^\top r\right)\left[\frac{d^\top V V^\top d}{\left(1 + d^\top r\right)^2} + \frac{d^\top V_0}{1 + d^\top r}\right] &\leq g(x) \\
\iff & & d^\top u + d^\top V_0 + \frac{d^\top V V^\top d}{1 + d^\top r} &\leq g(x) \\
\iff & & d^\top V V^\top d + \left(1 + d^\top r\right)\left(d^\top \left(u + V_0\right) - g(x)\right) &\leq 0 \\
\iff & & d^\top V V^\top d + \left[\frac{1}{2}\left(1 + d^\top r + d^\top \left(u + V_0\right) - g(x)\right)\right]^2 & \\
& & - \left[\frac{1}{2}\left(1 + d^\top r - d^\top \left(u + V_0\right) + g(x)\right)\right]^2 &\leq 0 \\
\iff & & d^\top V V^\top d + \left[\frac{1}{2}\left(1 + d^\top r + d^\top \left(u + V_0\right) - g(x)\right)\right]^2 & \\
& & \leq \left[\frac{1}{2}\left(1 + d^\top r - d^\top \left(u + V_0\right) + g(x)\right)\right]^2 & \\
\iff & & \left\| \begin{matrix} V^\top d \\ \frac{1}{2}\left(d^\top \left(u + V_0\right) + d^\top r + 1 - g(x)\right) \end{matrix} \right\|_2 &\leq \frac{1}{2}\left(d^\top r - d^\top \left(u + V_0\right)\right) + \frac{1 + g(x)}{2} \qquad (45) \\
\iff & & d^\top \left(\frac{1}{2}\left(u + V_0 - r\right)\right) + \left\| \begin{matrix} V^\top d \\ d^\top \left(\frac{1}{2}\left(u + V_0 + r\right)\right) + \frac{1 - g(x)}{2} \end{matrix} \right\|_2 &\leq \frac{1 + g(x)}{2} \\
\iff & & d^\top u^* + d^\top V_0^* + \left\| \begin{matrix} V^\top d \\ d^\top r^* + \frac{1 - g(x)}{2} \end{matrix} \right\|_2 &\leq \frac{1 + g(x)}{2},
\end{aligned}
$$

where we use the fact that $\frac{1}{2}\left(1 + d^\top r - d^\top \left(u + V_0\right) + g(x)\right) > 0$ for the equivalence in (45). This can be seen directly from (18a) and the realization that $d^\top V V^\top d \geq 0$ because it is a square. Suppose, on the other hand, that $1 + d^\top r = 0$. Then by our definition of the perspective function (18a) is equivalent to

$$
d^\top u + f_\infty \begin{pmatrix} V^\top d \\ V_0^\top d \end{pmatrix} \leq g(x) \iff \begin{cases} d^\top u + d^\top V_0 \leq g(x) \\ V^\top d = \mathbf{0}. \end{cases}
$$

Using this we find:

$$
\begin{aligned}
d^\top u^* + d^\top V_0^* + \left\| \begin{matrix} V^\top d \\ d^\top r^* + \frac{1 - g(x)}{2} \end{matrix} \right\|_2 &= \frac{1}{2} d^\top \left(u - r\right) + \frac{1}{2} d^\top V_0 + \frac{1}{2} d^\top \left(u + V_0 + r\right) + \frac{1 - g(x)}{2} \\
&= d^\top u + d^\top V_0 + \frac{1 - g(x)}{2} \\
&\leq g(x) + \frac{1 - g(x)}{2} \\
&= \frac{1 + g(x)}{2}.
\end{aligned}
$$

We have thus shown that (x, u^*, V, V_0^*, r^*) satisfies (19a).

Similarly, we can show for any $i = 1, \dots, L$ that if $-D_i^\top r > 0$ it holds that

$$
\begin{aligned}
& \left(-D_i^\top r\right) \left[\frac{\left(H_i(x) - V^\top D_i\right)^\top \left(H_i(x) - V^\top D_i\right)}{\left(-D_i^\top r\right)^2} + \frac{h_i(x) - D_i^\top V_0}{-D_i^\top r} \right] \leq D_i^\top u \\
\iff \quad & \frac{\left(H_i(x) - V^\top D_i\right)^\top \left(H_i(x) - V^\top D_i\right)}{-D_i^\top r} + h_i(x) - D_i^\top u - D_i^\top V_0 \leq 0 \\
\iff \quad & \left(H_i(x) - V^\top D_i\right)^\top \left(H_i(x) - V^\top D_i\right) + \left(1 + d^\top r\right) \left(h_i(x) - D_i^\top u - D_i^\top V_0\right) \leq 0 \\
\iff \quad & \left(H_i(x) - V^\top D_i\right)^\top \left(H_i(x) - V^\top D_i\right) + \left[\frac{1}{2}\left(-D_i^\top r + h_i(x) - D_i^\top u - D_i^\top V_0\right)\right]^2 \\
& \qquad - \left[\frac{1}{2}\left(-D_i^\top r - h_i(x) + D_i^\top u + D_i^\top V_0\right)\right]^2 \leq 0 \\
\iff \quad & \left(H_i(x) - V^\top D_i\right)^\top \left(H_i(x) - V^\top D_i\right) + \left[\frac{1}{2}\left(-D_i^\top r + h_i(x) - D_i^\top u - D_i^\top V_0\right)\right]^2 \\
& \qquad \leq \left[\frac{1}{2}\left(-D_i^\top r - h_i(x) + D_i^\top u + D_i^\top V_0\right)\right]^2 \\
\iff \quad & \left\| \begin{matrix} H_i(x) - V^\top D_i \\ \frac{1}{2}\left(-D_i^\top u - D_i^\top V_0 - D_i^\top r + h_i(x)\right) \end{matrix} \right\|_2 \leq \frac{1}{2}\left(D_i^\top u + D_i^\top V_0 - D_i^\top r\right) - \frac{1}{2} h_i(x) \\
\iff \quad & \frac{h_i(x)}{2} + \left\| \begin{matrix} H_i(x) - V^\top D_i \\ \frac{h_i(x)}{2} - D_i^\top \left(\frac{1}{2}\left(u + V_0 + r\right)\right) \end{matrix} \right\|_2 \leq D_i^\top \left(\frac{1}{2}\left(u - r\right)\right) + D_i^\top \left(\frac{1}{2} V_0\right) \\
\iff \quad & \frac{h_i(x)}{2} + \left\| \begin{matrix} \frac{h_i(x)}{2} - D_i^\top r^* \\ H_i(x) - V^\top D_i \end{matrix} \right\|_2 \leq D_i^\top u^* + D_i^\top V_0^*.
\end{aligned}
$$

Moreover, if $-D_i^\top r = 0$, it holds that

$$
f_\infty \begin{pmatrix} H_i(x) - V^\top D_i \\ h_i(x) - D_i^\top V_0 \end{pmatrix} \leq D_i^\top u \iff \begin{cases} h_i(x) - D_i^\top V_0 \leq D_i^\top u \\ \quad H_i(x) - V^\top D_i = \mathbf{0}, \end{cases}
$$

from which it also follows that (x, u^*, V, V_0^*, r^*) satisfies (19b).

Now, let $x \in \mathbb{R}^n$ such that there exist $u^* \in \mathbb{R}^q$, $V \in \mathbb{R}^{q \times p}$, $V_0^* \in \mathbb{R}^q$ and $r^* \in \mathbb{R}^q$ that satisfy (19). We claim choosing $u = u^* + r^* - V_0^*$, $V_0 = 2V_0^*$ and $r = r^* - u^* - V_0^*$ means that (x, u, V, V_0, r) satisfies (18).

First of all, note that we defined u, V_0 and r exactly such that they are the inverse of the equations used before for u^*, V_0^* and r^*. As all steps in the derivation above are two-way implications, it directly follows that (x, u, V, V_0, r) satisfies (18). □

F Equivalence of Sum-of-Max Reformulations

Substituting linear decision rules of the form $y_i(\zeta) = u + V\zeta$ in (23), yields the following robust counterpart:

$$\begin{cases} d^\top z_0 + \sum_{i=1}^m u_i \le 0 & & \text{(46a)} \\ D^\top z_0 \ge \sum_{i=1}^m V_i^\top & & \text{(46b)} \\ d^\top z_{ik} - u_i + b_k(x) \le 0 & \forall k \in K_i,\ \ i = 1, \dots, m & \text{(46c)} \\ D^\top z_{ik} \ge A_k(x)^\top - V_i^\top & \forall k \in K_i,\ \ i = 1, \dots, m & \text{(46d)} \\ z_{ik} \ge 0 & \forall k \in K_i,\ \ i = 1, \dots, m & \text{(46e)} \\ z_0 \ge 0. & & \text{(46f)} \end{cases}$$

Here, $z_0 \in \mathbb{R}_+^q$ is the dual variable corresponding to the robust counterpart of (23a) and $z_{ik} \in \mathbb{R}_+^q$ are the dual variables corresponding to the robust counterpart of (23b). Moreover, $A_k(x)$ is the k-th row of $A(x)$ and V_i is the i-th row of V in this notation.

If we continue, on the other hand, from (10), with f defined by (20), and introducing auxiliary variables z_{ij} for $i = 1, \dots, m$, $j = 0, \dots, L$, to model the sum of maxima, we obtain the following formulation:

$$\begin{cases} d^\top u + \sum_{i=1}^m z_{i0} \le 0 & & \text{(47a)} \\ D^\top u \ge \sum_{i=1}^m z_i & & \text{(47b)} \\ d^\top V_k - z_{i0} + b_k(x) \le 0 & \forall k \in K_i,\ \ i = 1, \dots, m & \text{(47c)} \\ D^\top V_k \ge A_k(x)^\top - z_i & \forall k \in K_i,\ \ i = 1, \dots, m. & \text{(47d)} \end{cases}$$

Here, $z_i = \begin{bmatrix} z_{i1} & \dots & z_{iL} \end{bmatrix}^\top$ and $A_k(x)$ is the k-th row of $A(x)$, while V_k is the k-th column of V.

Although the interpretation and naming of variables differs in the conservative approximations (46) and (47), there is only one true difference. In (46) $z_{ik} \in \mathbb{R}^q$ for all $k \in K_i$, $i = 1, \dots, m$, while the corresponding variable $V \in \mathbb{R}^{q \times p}$ does not necessarily have the same dimension. The problems are thus only equivalent when all K_i are pair-wise disjoint, such that $\sum_{i=1}^m |K_i| = p$. We can, without loss of generality, formulate any sum-of-max constraint such that this holds, by appropriately defining $A(x)$ and $b(x)$. This implies that the two approaches are in fact equivalent.