QUADRATIC 0–1 PROGRAMMING: TIGHTENING LINEAR OR QUADRATIC CONVEX REFORMULATION BY USE OF RELAXATIONS

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Abstract. Many combinatorial optimization problems can be formulated as the minimization of a 0–1 quadratic function subject to linear constraints. In this paper, we are interested in the exact solution of this problem through a two-phase general scheme. The first phase consists in reformulating the initial problem either into a compact mixed integer linear program or into a 0–1 quadratic convex program. The second phase simply consists in submitting the reformulated problem to a standard solver. The efficiency of this scheme strongly depends on the quality of the reformulation obtained in phase 1. We show that a good compact linear reformulation can be obtained by solving a continuous linear relaxation of the initial problem. We also show that a good quadratic convex reformulation can be obtained by solving a semidefinite relaxation. In both cases, the obtained reformulation profits from the quality of the underlying relaxation. Hence, the proposed scheme gets around, in a sense, the difficulty to incorporate these costly relaxations in a branch-and-bound algorithm.

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Résumé. Le problème de la minimisation d’une fonction quadratique en variables 0–1 sous contraintes linéaires permet de modéliser de nombreux problèmes d’Optimisation Combinatoire. Nous nous intéressons à sa résolution exacte par un schéma général en deux phases. La première phase permet de reformuler le problème de départ soit en un programme linéaire compact en variables mixtes soit en un programme quadratique convexe en variables 0–1. La deuxième phase consiste simplement à soumettre le problème reformulé à un solveur standard. L’efficacité de ce schéma est étroitement liée à la qualité de la reformulation obtenue à la fin de la phase 1. Nous montrons qu’une bonne reformulation linéaire compacte peut être obtenue par la résolution d’une relaxation linéaire. De même, une bonne reformulation quadratique convexe peut être obtenue par une relaxation semi-définie positive. Dans les deux cas, la reformulation obtenue tire profit de la qualité de la relaxation sur laquelle elle se base. Ainsi, le schéma proposé contourne, d’une certaine façon, la difficulté d’intégrer des relaxations, coûteuses en temps de calcul, dans un algorithme de branch-and-bound.

Keywords. Combinatorial optimization, quadratic 0–1 programming, linear reformulation, quadratic convex reformulation.

Mathematics Subject Classification. 90C10, 90C11, 90C20.

Introduction

Consider the following linearly-constrained zero-one quadratic program:

\[
Q_{01} : \min \left\{ F(x) = \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} q_{ij} x_i x_j : x \in X \right\}
\]

where \( X = \left\{ x : \sum_{i=1}^{n} a_k x_i = b_k, k = 1, \ldots, m; \sum_{i=1}^{n} a_{k,l} x_i \leq b_{l}', l = 1, \ldots, p; x \in \{0, 1\}^n \right\} \) is the feasible solution set of \( Q_{01} \) and \( q_i, q_{ij}, a_{k,l}, b_k, a_{k,l}', b_{l}' \) are real numbers.

Without loss of generality, we can assume that \( q_{ij} = q_{ji} \). We denote by \( \overline{X} \) the continuous-relaxation solution set of \( Q_{01} \). Set \( \overline{X} \) is obtained from \( X \) by replacing \( x \in \{0, 1\} \) with \( x \in [0, 1] \).

Problem \( Q_{01} \) is NP-hard [13]. It allows to formulate many Combinatorial Optimization problems such as graph bipartition, quadratic knapsack, and quadratic assignment. It also has several applications such as task allocation and capital budgeting. Due to its complexity, many heuristic solution methods have been proposed for it. For example, [4,15,21,23] apply tabu search for the unconstrained
problem, and local search heuristics are applied to graph bipartition problems in
[19,20].

Exact solution methods have also been proposed for solving Q01. In this paper,
we focus on two main approaches: linear reformulation and quadratic convex re-
formulation. Linear reformulation techniques transform Q01 into a mixed integer
linear program. The most frequently used linearization was first introduced by
Fortet in [11,12] and is sometimes called the classical linearization. It consists in
replacing each product $x_i x_j$ by a new variable $y_{ij}$ and adding a set of linear con-
straints that force $y_{ij}$ to be equal to $x_i x_j$, i.e. $y_{ij} \leq x_i$, $y_{ij} \geq x_i + x_j - 1$, $y_{ij} \geq 0$, and $y_{ij} = y_{ji}$ for all $i \neq j$. A strengthening of the classical linearization by a family
of valid inequalities was later proposed by Sherali et al. in [25,26]. They developed
a Reformulation and Linearization Technique (RLT). Using quite different ideas,
Glover [14] introduced an alternative linearization strategy that requires a much
smaller set of additional variables and constraints than the classical linearization
and RLT. This is why it is often called a compact linearization. Variants of this
compact linearization were further used by several authors [1,8,16].

Another class of exact solution methods aims at reformulating the objective
function of Q01 by a quadratic convex function. Doing this, solving the continu-
ous relaxation of the reformulated problem becomes tractable in polynomial time.
For example, Hammer and Rubin [17] devise a simple convexification method
based on a smallest eigenvalue computation. Later, Carter [9] then Billionnet and
Elloumi [5], Plateau et al. [24], and Billionnet et al. [6] study several families of
quadratic convex reformulations and provide theoretical and computational com-
parisons between these families. All the reformulations proposed in [5,6,24] are
based on an exact solution of a quadratic semidefinite program. Among these
reformulations, the one proposed in [6] and called QCR gives the provably best
bound by continuous relaxation.

In this paper, we introduce a positive compact linearization method and we
recall the quadratic convex reformulation method QCR [6]. We will focus on the
fact that each of these methods takes profit from a preprocessing phase. This
phase aims both at finding a suitable reformulation of the problem and at making
the further resolution process as efficient as possible. To achieve this last objective,
we use the common criterion that prefers reformulations yielding bounds that are
as tight as possible by continuous relaxation. We will show how we build a positive
linear compact reformulation once an RLT relaxation is solved and how it captures
the bound obtained by this relaxation. In a similar way, QCR is built once an
appropriate SDP relaxation is solved and it captures the bound obtained by SDP
relaxation.

The rest of the paper is organized as follows: Linear compact reformulations
and convex quadratic reformulations are presented in Section 1. In Section 2, we
show how to build a positive compact linearization from the RLT solution. In
Section 3, we show how to build a QCR reformulation from the solution of an
SDP relaxation. Section 4 is a conclusion.
Example. All along this paper, we will use the same example for illustration purposes: we consider the following 0–1 quadratic program $E$, which optimal value is $-65$:

$$
E: \begin{align*}
\text{Min } & \phi(x) = -9x_1 - 7x_2 + 2x_3 + 23x_4 + 12x_5 - 48x_1x_2 + 4x_1x_3 + 36x_1x_4 \\
& -24x_1x_5 - 7x_2x_3 + 36x_2x_4 - 84x_2x_5 + 40x_3x_4 + 4x_3x_5 - 88x_4x_5 \\
\text{s.t. } & x_1 - 2x_2 + 5x_3 + 2x_4 - 2x_5 \geq 2 \\
& x_1 + x_2 + x_4 + x_5 = 2 \\
& x_1, x_2, x_3, x_4, x_5 \in \{0, 1\}.
\end{align*}
$$

1. Reformulation of Quadratic 0–1 Programs

In the context of this paper, a reformulation of $Q01$ is any equivalent mathematical program $P$ with integer or mixed integer variables, that is either linear or quadratic convex. These equivalent reformulations are expected to preserve the feasible solution domain and the optimal value. Among all the possible reformulations, we choose two reformulation schemes that either use the same variables and constraints as program $Q01$ or require a small number of additional variables and constraints. Let us first recall the linear compact reformulation of Glover.

1.1. The compact linearization of Glover [14]

The linear reformulation method proposed in [14] aims to replace non-linear expressions of $Q01$ with a set of continuous variables. More precisely, take $z_j = \sum_{i=1, i \neq j}^{n} q_{ij} x_i$ and reformulate $Q01$ by:

$$
RL_g: \begin{align*}
\text{Min } & F(x) = \sum_{i=1}^{n} q_{ix_i} + \sum_{j=1}^{n} z_j \\
\text{s.t. } & \sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m \\
& \sum_{i=1}^{n} a_{\ell i} x_i \leq b_{\ell} \quad \ell = 1, \ldots, p \\
& L_j x_j \leq z_j \leq U_j x_j \quad j = 1, \ldots, n \\
& \sum_{i=1, i \neq j}^{n} q_{ij} x_i - U_j(1 - x_j) \leq z_j \quad j = 1, \ldots, n \\
& z_j \leq \sum_{i=1, i \neq j}^{n} q_{ij} x_i - L_j(1 - x_j) \quad j = 1, \ldots, n \\
x \in \{0, 1\}^n, z \in \mathbb{R}^n
\end{align*}
$$
where $L_j$ and $U_j$ are respectively lower and upper bounds of the linear functions $\sum_{i=1, i \neq j}^n q_{ij}x_i$, computed as:

$$L_j = \min \left\{ \sum_{i=1, i \neq j}^n q_{ij}x_i : x \in X \right\}$$

and

$$U_j = \max \left\{ \sum_{i=1, i \neq j}^n q_{ij}x_i : x \in X \right\}.$$ 

By optimality considerations, since coefficients of the $z_j$ variables in the objective function are positive, inequalities $z_j \leq U_j x_j$ and $z_j \leq \sum_{i=1, i \neq j}^n q_{ij}x_i - L_j (1 - x_j)$ can be discarded.

In the following, we present a family of compact linearizations that are inspired from Glover’s linearization. They are built from a first reformulation of the objective function as a constant plus a nonnegative function over $X$, as described below.

### 1.2. Positive linear compact reformulation

Suppose one has identified a constant $c$ and functions $L(x)$, $f_i(x)$, and $g_i(x)$ that are nonnegative on the relaxed domain $X$, and that satisfy:

$$\forall x \in X, F(x) = c + L(x) + \sum_{i=1}^n x_i f_i(x) + \sum_{i=1}^n (1 - x_i) g_i(x). \quad (1)$$

This first reformulation of $F(x)$ is always possible since a quadratic pseudoboolean function can be written as a constant plus a quadratic posiform. Function $\sum_{k=1}^K C_k T_k$ is a quadratic posiform if all coefficients $C_k$ are positive and every $T_k$ is a literal or the product of two literals. A literal is either a variable $x_i$ or its complement $(1 - x_i)$. Writing a quadratic pseudoboolean function as a constant, as large as possible, plus a posiform has addressed much interest in literature and we know it can be done by at least three different methods ([18] among others). For our example $E$, the largest constant equals -160 and we can write

$$\phi(x) = -160 + 41(1 - x_1) + 42(1 - x_2) + x_1 [48(1 - x_2) + 24(1 - x_3)] + 71x_2(1 - x_3) + x_3 (40x_4 + 3x_5) + x_4[7x_5 + 95(1 - x_5)] + (1 - x_2)[4(1 - x_3) + 36(1 - x_4)] + (1 - x_2)[7x_3 + 36(1 - x_4) + 13x_5] + (1 - x_3)(1 - x_5).$$

From the first reformulation (1), we can now build our positive compact linearization $RL_{comp}$. For $i = 1, ..., n$, we need an upper bound $\overline{f_i}$ (resp. $\overline{g_i}$) for function $f_i(x)$ (resp. $g_i(x)$) over the feasible solution set $X$. Let $RL_{comp}$ be the
following mixed 0–1 linear program:

\[
\text{RL}_{\text{comp}}: \text{Min} \quad F_L(x) = c + L(x) + \sum_{i=1}^{n} h_i + \sum_{i=1}^{n} h'_i
\]

s.t.
\[
\sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m
\]
\[
\sum_{i=1}^{n} a'_\ell x_i \leq b'_\ell \quad \ell = 1, \ldots, p
\]
\[
h_i \geq f_i(x) - \overline{f}_i(1 - x_i) \quad i = 1, \ldots, n
\]
\[
h'_i \geq g_i(x) - \overline{g}_i x_i \quad i = 1, \ldots, n
\]
\[
x \in \{0, 1\}^n
\]
\[
h_i \geq 0 \quad h'_i \geq 0 \quad i = 1, \ldots, n.
\]

The inequalities on \( h_i \) and \( h'_i \) impose that, for any optimal solution \( (x, h, h') \) for \( RL_{\text{comp}} \), if \( x_i = 0 \) then \( h_i = 0 \) and \( h'_i = g_i(x) \); if \( x_i = 1 \) then \( h_i = f_i(x) \) and \( h'_i = 0 \). Hence, variable \( h_i \) (resp. \( h'_i \)) is equal to \( x_if_i(x) \) (resp. \( (1 - x_i)g_i(x) \)).

The following property states the equivalence of \( Q_01 \) and our positive compact linearization \( RL_{\text{comp}} \):

**Proposition 1.1.** Problems \( Q_01 \) and \( RL_{\text{comp}} \) are equivalent in the sense that, from any optimal solution of the one, we can build a solution to the other, with the same objective value.

Program \( RL_{\text{comp}} \) has the \( n \) variables \( x_i \) and the \( m + p \) constraints of the initial program \( Q_01 \). In addition, it has \( 2n \) nonnegative variables \( h_i \) and \( h'_i \), and \( 2n \) additional constraints.

Other linear compact reformulations are reported in literature. Most of them are inspired from [14]. Our positive compact linearization can also be considered as a variation of [14] and has the advantage of working on a first reformulation of the objective function as a constant \( c \) plus a quadratic function, nonnegative over \( \overline{X} \). Hence, we can be sure that the lower bound computed by continuous relaxation of \( RL_{\text{comp}} \) is at least \( c \). Observe also that this last property holds for any correctly chosen values of the upper bounds \( \overline{f}_i \) et \( \overline{g}_i \) on functions \( f_i(x) \) and \( g_i(x) \).

### 1.3. Quadratic convex reformulation [6]

A quadratic convex reformulation of \( Q_01 \) consists in finding a quadratic convex function \( F_c(x) \) that satisfies \( F(x) = F_c(x) \) for any feasible solution \( x \) in \( X \). Hence,
the following problem $RQ_{\text{conv}}$ is equivalent to $Q_{01}$:

$$
RQ_{\text{conv}}: \text{Min } F_c(x) = q'_0 + \sum_{i=1}^{n} q'_i x_i + \sum_{i=1}^{n} \sum_{j=1}^{n} q'_{ij} x_i x_j
$$

s.t.

$$
\sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m
$$

$$
\sum_{i=1}^{n} a'_{\ell i} x_i \leq b'_\ell \quad \ell = 1, \ldots, p
$$

$x \in \{0, 1\}^n$.

Function $F_c$ is convex if and only if its Hessian matrix is positive semidefinite.

Such reformulation of $Q_{01}$ is always possible. One can for example use equality $x_i^2 = x_i$ satisfied by any binary variable $x_i$ in order to raise up the diagonal coefficients of matrix $Q = (q_{ij})$ by a large-enough constant. This diagonal perturbation can then immediately be balanced by the coefficients of the linear terms $q_i$. Based on this idea, a simple convex reformulation was already proposed in [17] and consists in a perturbation of the diagonal terms of $Q$ by its smallest eigenvalue. For our example $E$, the smallest eigenvalue of $Q$ equals $-56.88$ and $\phi_c(x)$ can be reformulated as $\phi_c(x) = \phi(x) + 56.88 \sum_{i=1}^{n} (x_i^2 - x_i)$ and the minimum of $\phi_c$ over $\mathcal{X}$ is equal to $-119.31$.

Problem $RQ_{\text{conv}}$ has precisely the same number of variables and constraints as problem $Q_{01}$.

1.4. A COMPARISON CRITERION FOR REFORMULATIONS

The linear and quadratic reformulations presented above have the following as a common property: solving their continuous relaxation is tractable in polynomial time, and is quick to compute. Indeed, the reformulated problem has, roughly speaking, the same size as the original problem $Q_{01}$. Hence a natural way to solve the mixed-01 reformulated problems is to submit them to standard solvers whose exact solution procedures are based on branch-and-bound and continuous relaxation. Further, we know that the efficiency of a branch-and-bound algorithm is strongly dependent upon the quality of the bound at the root of the branch-and-bound tree, computed as the optimal value of the continuous relaxation of the reformulated problem. This provides us with a criteria for comparing reformulations. We consider that the quality of a reformulation is given by the tightness of its continuous relaxation. Within a given reformulation scheme, reformulation $F1$ is better than reformulation $F2$ if the continuous relaxation of $F1$ leads to a tighter bound than the continuous relaxation of $F2$. 
2. Building a compact linear reformulation by use of the bound of a linear relaxation

2.1. The RLT-relaxation

The relaxation we use here in known in the literature under the name “RLT-level 1” [25,26]. It consists in adding quadratic valid inequalities to \( Q^{01} \) before a classical linearization step. The valid inequalities are obtained by multiplying every equality by \( x_i \) and every inequality by \( x_i \) and \((1 - x_i)\). Then, each product of two variables \( x_i x_j \) is replaced by a new real variable \( y_{ij} \). Linearization constraints ensure the validity of the substitution. Finally, a continuous relaxation step provides the following linear program \( PL_p \) that is precisely called the RLT-relaxation:

\[
PL_p : \text{Min } F(x, y) = \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} q_{ij} y_{ij}
\]

s.t. \[
\begin{align*}
\sum_{i=1}^{n} a_{ki} x_i &= b_k & k &= 1, \ldots, m \\
\sum_{i=1}^{n} a_{ki} y_{ij} &= b_k x_j & k &= 1, \ldots, m; j = 1, \ldots, n \\
y_{ij} &= y_{ji} & i &= 1, \ldots, n; j = 1, \ldots, n : j \neq i \\
y_{ii} &= x_i & i &= 1, \ldots, n \\
\sum_{i=1}^{n} a'_{\ell i} x_i &\leq b'_{\ell} & \ell &= 1, \ldots, p \tag{2} \\
\sum_{i=1}^{n} a'_{\ell i} y_{ij} &\leq b'_{\ell} x_j & \ell &= 1, \ldots, p; j = 1, \ldots, n \tag{3} \\
\sum_{i=1}^{n} a'_{\ell i} (x_i - y_{ij}) &\leq b'_{\ell} (1 - x_j) & \ell &= 1, \ldots, p; j = 1, \ldots, n \tag{4} \\
y_{ij} &\leq x_i & i &= 1, \ldots, n; j = 1, \ldots, n, j \neq i \tag{5} \\
x_i + x_j - y_{ij} &\leq 1 & i &= 1, \ldots, n - 1; j = i + 1, \ldots, n \tag{6} \\
x_i &\leq 1 & i &= 1, \ldots, n \tag{7} \\
x_i &\geq 0 & i &= 1, \ldots, n \\
y_{ij} &\geq 0 & i &= 1, \ldots, n; j = 1, \ldots, n, j \neq i.
\end{align*}
\]

This relaxation can be viewed as a strengthening trick for the classical linearization recalled in the Introduction. The bound computed by solving problem \( PL_p \) is
known to be quite efficient but rather time consuming because of the important size of \( PL_p \). This makes these bounds difficult to incorporate into a branch-and-bound algorithm.

Note that other ‘lift-and-project’ techniques are presented in the literature such as [2,3,22,25].

2.2. USING A DUAL SOLUTION OF \( PL_p \) IN ORDER TO BUILD A POSITIVE LINEAR COMPACT REFORMULATION

The following proposition shows how a reformulation of the objective function \( F(x) \), in the form (1), can be obtained from any dual solution of the RLT-relaxation.

**Proposition 2.1.** For any dual feasible solution of \( PL_p \), having objective value \( V \), there exists \( L(x) \), \( f_i(x) \), and \( g_i(x) \) such that,

\[
F(x) = V + L(x) + \sum_{i=1}^{n} x_i f_i(x) + \sum_{i=1}^{n} (1 - x_i) g_i(x)
\]

where \( L(x) \), \( f_i(x) \), and \( g_i(x) \) are linear functions, nonnegative over the relaxed set \( \mathbb{X} \).

**Proof.** (Use the Property in Appendix A) Let \( s_i \) (resp. \( s_{ij} \)) be the slack variables of the inequalities in the dual of \( PL_p \) associated to \( x_i \) (resp. \( y_{ij} \)). Given a dual feasible solution of \( PL_p \), having objective value \( V \), we take \( \bar{s}_i \) and \( \bar{s}_{ij} \), values of variables \( s_i \) and \( s_{ij} \), and the dual variables values \( \bar{v}^1 \) (resp. \( \bar{v}^2, \bar{v}^3, \bar{v}^4, \bar{v}^6 \)) associated to inequalities (2) (resp. (3), (4), (5), (6), (7)). We get,

For any feasible solution \( (x, y) \) of \( PL_p \):

\[
F(x, y) = V + \sum_{i=1}^{n} \bar{s}_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} \bar{s}_{ij} y_{ij} + \sum_{\ell=1}^{p} \bar{v}^1_{\ell} (b'_{\ell} - \sum_{i=1}^{n} a'_{\ell i} x_i)
\]

\[
+ \sum_{\ell=1}^{p} \sum_{j=1}^{n} \bar{v}^2_{\ell j} (b'_{\ell} x_j - \sum_{i=1}^{n} a'_{\ell i} y_{ij}) + \sum_{\ell=1}^{p} \sum_{j=1}^{n} \bar{v}^3_{\ell j} (b'_{\ell} (1 - x_j))
\]

\[
- \sum_{i=1}^{n} a'_{\ell i} (x_i - y_{ij}) + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} \bar{v}^4_{ij} (x_i - y_{ij})
\]

\[
+ \sum_{\ell=1}^{p} \sum_{j=1, j \neq i}^{n} \bar{v}^5_{ij} (1 + y_{ij} - x_i - x_j) + \sum_{i=1}^{n} \bar{v}^6_{i} (1 - x_i).
\]
For any \( x \in X \), there exists a unique \( y \) such that \((x, y)\) is a feasible solution to \( PL_p \). This \( y \) is defined as \( y_{ij} = x_i x_j \), and gives, for any \( x \in X \):

\[
F(x) = V + \sum_{i=1}^{n} s_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} s_{ij} x_i x_j + \sum_{\ell=1}^{p} \tilde{v}_{\ell i}^1 (b'_\ell - \sum_{i=1}^{n} a'_{i \ell} x_i) \\
+ \sum_{\ell=1}^{p} \sum_{j=1}^{n} \tilde{v}_{\ell j}^2 (b'_\ell - \sum_{i=1}^{n} a'_{i \ell} x_i) + \sum_{\ell=1}^{p} \sum_{j=1}^{n} \tilde{v}_{\ell j}^3 (1 - x_j)(b'_\ell - \sum_{i=1}^{n} a'_{i \ell} x_i) \\
+ \sum_{i=1}^{n} \tilde{v}_{i j}^4 (1 - x_j) + \sum_{i=1}^{n} \tilde{v}_{i j}^5 (1 - x_i) + \sum_{i=1}^{n} \tilde{v}_{i j}^6 (1 - x_i).
\]

Let:

\[
L(x) = \sum_{i=1}^{n} s_i x_i + \sum_{i=1}^{n} \tilde{v}_{i j}^6 (1 - x_i) + \sum_{\ell=1}^{p} \tilde{v}_{\ell i}^1 (b'_\ell - \sum_{i=1}^{n} a'_{i \ell} x_i)
\]

\[
f_i(x) = \sum_{j=1, j \neq i}^{n} s_{ij} x_j + \sum_{j=1, j \neq i}^{n} \tilde{v}_{i j}^4 (1 - x_j) + \sum_{\ell=1}^{p} \tilde{v}_{\ell i}^2 (b'_\ell - \sum_{j=1}^{n} a'_{j \ell} x_j)
\]

\[
g_i(x) = \sum_{j=i+1}^{n} \tilde{v}_{i j}^5 (1 - x_j) + \sum_{\ell=1}^{p} \tilde{v}_{\ell i}^3 (b'_\ell - \sum_{j=1}^{n} a'_{i j} x_j)
\]

observing that, for any \( x \in X \), the above functions are nonnegative, we obtain the reformulation of \( F(x) \) as (1), i.e.:

\[
\forall x \in X, \quad F(x) = V + L(x) + \sum_{i=1}^{n} x_i f_i(x) + \sum_{i=1}^{n} (1 - x_i) g_i(x). \quad \square
\]

Finally, we determine the upper bounds: \( \bar{f}_i = \max \{ f_i(x) : x \in X \} \) and \( \bar{g}_i = \max \{ g_i(x) : x \in X \} \) in order to get a positive linear compact reformulation associated to the given dual solution of \( PL_p \).

**Corollary 2.2.** For any dual solution of \( PL_p \) having objective value \( V \), we can build a positive linear compact reformulation which continuous relaxation value is at least \( V \). The best value of \( V \) is obviously obtained from an optimal solution.

Let us observe that Adams et al. [1] build a different compact linearization, more directly inspired from [14] and whose continuous relaxation is equal to the optimal value of \( PL_p \). An additional advantage of Corollary 2.2 is that it allows to reformulate the objective function \( F \) as the optimal value plus a nonnegative function over \( X \). This reformulation can be used for other exact or approximate solution approaches.
The optimal value of the continuous relaxation of \( RL \) has been solved: 
\[
\phi(x) = -67.52 + x_1 (109.83 x_4 + 30.07 x_5) + x_2 (129.90 x_4 + 3.52 (1 - x_3)) + x_3 (1.26 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)]) + x_4 (6.95 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)]) + x_5 (52.34 (1 - x_3) + 11.22 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)]) + (1 - x_2) (0.74 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)]).
\]

We can now define functions \( f_i(x) \) and \( g_i(x) \),
\[
\begin{align*}
  f_1(x) &= 109.83 x_4 + 30.07 x_5 \\
  f_2(x) &= 129.90 x_4 + 3.52 (1 - x_3) \\
  f_3(x) &= 1.26 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)] \\
  f_4(x) &= 6.95 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)] \\
  f_5(x) &= 52.34 (1 - x_3) + 11.22 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)] \\
  g_2(x) &= 0.74 [-2 - (-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5)]
\end{align*}
\]
compute the upper bounds,
\[
\mathcal{T}_1 = 139.90, \quad \mathcal{T}_2 = 133.42, \quad \mathcal{T}_3 = 7.56, \quad \mathcal{T}_4 = 41.7, \quad \mathcal{T}_5 = 67.32, \quad \mathcal{g}_2 = 4.44.
\]
and finally, build the following program \( RL_{compE} \):
\[
RL_{compE} : \text{Min} \quad \phi(x) = -67.52 + \sum_{i=1}^{5} h_i + h'_2
\]
\[
\begin{align*}
\text{s.t.} & \\
-x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5 & \leq -2 \\
x_1 + x_2 + x_4 + x_5 & = 2 \\
h_i & \geq f_i(x) - \mathcal{T}_i (1 - x_i) \quad i = 1, \ldots, 5 \\
h'_2 & \geq g_2(x) - \mathcal{g}_2 x_2 \\
x & \in \{0, 1\}^n \\
h_i & \geq 0 \quad i = 1, \ldots, 5 \\
h'_2 & \geq 0
\end{align*}
\]
The optimal value of the continuous relaxation of \( RL_{compE} \) is \(-67.52\).
In Appendix B we apply the linear compact reformulation of Glover [14] to the initial problem \( E \). Its continuous relaxation value is \(-106.84\) that is significantly lower than the continuous relaxation value of our positive linear compact reformulation.
3. BUILDING A QUADRATIC CONVEX REFORMULATION BY USE OF THE BOUND OF A SEMIDEFINITE RELAXATION

In this section, we recall the Quadratic Convex Reformulation (QCR) method introduced in [6]. As we will see, a parallel can be made with the linearization approach presented in Section 2.

3.1. A SEMIDEFINITE RELAXATION OF Q01

Let us consider again problem Q01. We multiply every equality constraint \( \sum_{i=1}^{n} a_{ki}x_i = b_k \) by \( x_i \) and then replace the products \( x_i x_j \) by variables \( X_{ij} \), we obtain the following equivalent problem:

\[
\begin{align*}
\text{Min} \quad & F(x) = \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} q_{ij} X_{ij} \\
\text{s.t.} \quad & \sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m \\
& \sum_{i=1}^{n} a_{ki} X_{ij} = b_k x_j \quad k = 1, \ldots, m; j = 1, \ldots, n \\
& \sum_{i=1}^{n} a'_{ki} x_i \leq b'_k \quad \ell = 1, \ldots, p \\
& X_{ij} = x_i x_j \quad i = 1, \ldots, n; j = 1, \ldots, n. \\
& x \in \{0, 1\}^n
\end{align*}
\]

The semidefinite relaxation consists in replacing the set of constraints \( X_{ij} = x_i x_j \) with the linear matrix inequality \( X - xx^t \succeq 0 \). By Schur’s Lemma, \( X - xx^t \succeq 0 \) is equivalent to \( \begin{pmatrix} 1 & x^t \\ x & X \end{pmatrix} \succeq 0 \).

The obtained SDP relaxation is the following:

\[
\text{SDP : Min} \quad \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n} \sum_{j=1, j \neq i}^{n} q_{ij} X_{ij}
\]

\[
\text{s.t.} \quad \sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m \\
\sum_{j=1}^{n} a_{kj} X_{ij} = b_k x_j \quad k = 1, \ldots, m; j = 1, \ldots, n \tag{8}
\]

\[
\sum_{i=1}^{n} a'_{ki} x_i \leq b'_k \quad \ell = 1, \ldots, p \\
X_{ii} = x_i \quad i = 1, \ldots, n \tag{9}
\]

\[
\begin{pmatrix} 1 & x^t \\ x & X \end{pmatrix} \succeq 0 \quad x \in \mathbb{R}^n, \ X \in S_n
\]
where $S_n$ is the set of $n \times n$ symmetric matrices.

### 3.2. Using an optimal solution to $SDP$ in order to build a quadratic reformulation

The QCR method consists in reformulating problem $Q_{01}$ by adding a combination of quadratic functions that vanish on the feasible solution set $X$. For any $\alpha \in \mathbb{R}^{m \times n}$ and $u \in \mathbb{R}^n$, let us consider the following quadratic function:

$$F_{\alpha,u}(x) = \sum_{i=1}^{n} q_i x_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} q_{ij} x_i x_j + \sum_{k=1}^{m} \left( \sum_{i=1}^{n} a_{ki} x_i \right) \left( \sum_{j=1}^{n} a_{kj} x_j - b_k \right) + \sum_{i=1}^{n} u_i \left( x_i^2 - x_i \right).$$

Function $F_{\alpha,u}$ is a reformulation of $F$ since for all $x \in X$, $F_{\alpha,u}(x)$ is equal to $F(x)$. We focus our interest on reformulations of $F$ by $F_{\alpha,u}$ where $F_{\alpha,u}(x)$ is convex over $\mathbb{R}^n$. Once $F(x)$ is transformed into a convex function, the reformulated problem can be solved by mixed integer convex quadratic programming. Our objective now is to find values for parameters $\alpha \in \mathbb{R}^{m \times n}$ and $u \in \mathbb{R}^n$ such that $F_{\alpha,u}(x)$ is convex on the one hand and the optimal value of the continuous relaxation of the reformulated problem is maximized on the other hand. It was proved in [6] that solving the above semidefinite relaxation $SDP$ allows to deduce optimal values for parameters $\alpha$ and $u$. More precisely, the optimal values $u^*_i$ of $u_i$ ($i = 1, \ldots, n$) are given by the optimal values of the dual variables associated with constraints (9) and the optimal values $a^*_i$ of $a_{ik}$ ($i = 1, \ldots, n; k = 1, \ldots, m$) are given by the optimal values of the dual variables associated to constraints (8).

The resulting quadratic convex reformulation is then:

$$RQ_{conv}: \text{Min } F_{\alpha^*,u^*}(x)$$

s.t.

$$\begin{align*}
\sum_{i=1}^{n} a_{ki} x_i &= b_k & k = 1, \ldots, m \\
\sum_{i=1}^{n} a'_{i\ell} x_i &\leq b'_\ell & \ell = 1, \ldots, p.
\end{align*}$$

$$x \in \{0,1\}^n$$

It is proved in [6] that $v_{SDP}$, the optimal value to $SDP$ is equal to the optimal value of the continuous relaxation of $RQ_{conv}$.

**Remark 3.1.** In a similar way as in the linear reformulation, we reformulate the objective function $F(x)$ as a constant plus a convex quadratic function that is nonnegative for any feasible solution $x \in \mathcal{X}$. Indeed, let $g(x) = F_{\alpha^*,u^*}(x) - v_{SDP}$, we have $F(x) = v_{SDP} + g(x)$ and $g(x) \geq 0 \forall x \in \mathcal{X}$. 
Example. The SDP relaxation of our example $E$ is:

$$SDP_{E}: \text{Min} \ -9x_1 - 7x_2 + 2x_3 + 23x_4 + 12x_5 - 48X_{12} + 4X_{13} + 36X_{14}$$
$$-24X_{15} - 7X_{23} + 36X_{24} - 84X_{25} + 40X_{34} + 4X_{35} - 88X_{45}$$

s.t.
$$x_1 - 2x_2 + 5x_3 + 2x_4 - 2x_5 \geq 2$$
$$x_1 + x_2 + x_4 + x_5 = 2$$
$$X_{12} + X_{14} + X_{15} = x_1 \leftarrow \alpha_1^*$$
$$X_{12} + X_{24} + X_{25} = x_2 \leftarrow \alpha_2^*$$
$$X_{13} + X_{23} + X_{34} + X_{35} = 2x_3 \leftarrow \alpha_3^*$$
$$X_{14} + X_{24} + X_{45} = x_4 \leftarrow \alpha_4^*$$
$$X_{15} + X_{25} + X_{45} = x_5 \leftarrow \alpha_5^*$$
$$X_{11} = x_1 \leftarrow u_1^*$$
$$X_{22} = x_2 \leftarrow u_2^*$$
$$X_{33} = x_3 \leftarrow u_3^*$$
$$X_{44} = x_4 \leftarrow u_4^*$$
$$X_{55} = x_5 \leftarrow u_5^*$$

$$\begin{pmatrix} 1 & x^t \end{pmatrix} \succeq 0,$$
$$x \in \mathbb{R}^5, \ X \in S_5$$

The optimal solution value of $SDP_{E}$ equals –81.38. It is also the optimal solution value of the continuous relaxation of the reformulated problem $RQ_{conv}$. Parameters $u^*$ and $\alpha^*$ that allow to build $RQ_{conv}$ are obtained from the optimal solution of $SDP_{E}$:

$$RQ_{conv}: \text{min} \ \phi(x) + (11.2x_1 + 26.3x_2 - 15x_3 - 21.8x_4 + 42.32x_5)$$
$$+ (x_1 + x_2 + x_4 + x_5 - 2) + 17.24(x_1^2 - x_1) + 0.34(x_2^2 - x_2)$$
$$+ 24.9(x_3^2 - x_3) + 132.74(x_4^2 - x_4) - 15.38(x_5^2 - x_5)$$

s.t.
$$x_1 - 2x_2 + 5x_3 + 2x_4 - 2x_5 \geq 2$$
$$x_1 + x_2 + x_4 + x_5 = 2$$

$$x \in \{0, 1\}^n.$$  

4. Conclusion

Nowadays, efficient mathematical programming solvers are available to solve mixed-integer linear or convex quadratic problems. Consequently, try to use them for the general 0–1 quadratic problem is attractive. For that, a preprocessing phase is necessary in order to reformulate the initial problem into a tractable form. The efficiency of this exact solution approach strongly depends on the quality of the bound given by the continuous relaxation of the reformulation and also on the size of this reformulation. For both classes of solvers – mixed-integer linear or
mixed-integer convex quadratic – we have proposed a concise reformulation technique that incorporates the optimal values of tight linear or positive semidefinite relaxations. A first computational comparison of the quadratic versus the linear approach was carried out for a task allocation problem and is reported in [10]. Other experimental results considering one of the two approaches are presented in [1,5–7] and show the efficiency of these methods. Future research topics include obtaining reformulations based on even tighter relaxations.

APPENDIX A

Let \( P \) be the following linear program:

\[
P: \text{Min } f(x) = \sum_{i=1}^{n} c_i x_i \\
\text{s.t. } \sum_{i=1}^{n} a_{ki} x_i = b_k \quad k = 1, \ldots, m \\
\sum_{i=1}^{n} a_{\ell i} x_i \leq b_{\ell} \quad \ell = 1, \ldots, p \\
x_i \geq 0 \quad i = 1, \ldots, n
\]

and let \( D \) be its dual problem:

\[
D: \text{Max } g(u, v) = \sum_{k=1}^{m} (-b_k) u_k + \sum_{\ell=1}^{p} (-b_{\ell}) v_{\ell} \\
\text{s.t. } \sum_{k=1}^{m} (-a_{ki}) u_k + \sum_{\ell=1}^{p} (-a_{\ell i}) v_{\ell} \leq c_i \quad i = 1, \ldots, n \\
u_k \in \mathbb{R} ; v_{\ell} \geq 0
\]

Proposition. Let \( s_i, i = 1, \ldots, n \) be the non-negative slack variables associated to constraints (10) and let \((\tilde{u}, \tilde{v}, \tilde{s})\) be a feasible solution for the dual problem \( D \). Then, for any feasible solution \( x \) of the primal \( P \), we have:

\[
f(x) = g(\tilde{u}, \tilde{v}) + \sum_{\ell=1}^{p} \tilde{v}_{\ell}(b_{\ell} - \sum_{i=1}^{n} a_{\ell i} x_i) + \sum_{i=1}^{n} \tilde{s}_i x_i.
\]

Proof. By definition of the slack variables \( s_i \):

\[
c_i = \sum_{k=1}^{m} (-a_{ki}) \tilde{u}_k + \sum_{\ell=1}^{p} (-a_{\ell i}) \tilde{v}_{\ell} + \tilde{s}_i.
\]

We can now use the last identity in the expression of \( f(x) \).
We get, for any vector $x$:

$$f(x) = \sum_{i=1}^{n} \sum_{k=1}^{m} (-a_{ki}) \tilde{u}_k + \sum_{\ell=1}^{p} (-a'_{\ell i}) \tilde{v}_\ell + \tilde{s}_i x_i$$

$$= \sum_{k=1}^{m} \tilde{u}_k (- \sum_{i=1}^{n} a_{ki} x_i) + \sum_{\ell=1}^{p} \tilde{v}_\ell (- \sum_{i=1}^{n} a'_{\ell i} x_i) + \sum_{i=1}^{n} \tilde{s}_i x_i$$

$$= \sum_{k=1}^{m} (-b_k) \tilde{u}_k + \sum_{\ell=1}^{p} (-b'_\ell) \tilde{v}_\ell + \sum_{k=1}^{m} \tilde{u}_k (b_k - \sum_{i=1}^{n} a_{ki} x_i)$$

$$+ \sum_{\ell=1}^{p} \tilde{v}_\ell (b'_\ell - \sum_{i=1}^{n} a'_{\ell i} x_i) + \sum_{i=1}^{n} \tilde{s}_i x_i$$

$$= g(\tilde{u}, \tilde{v}) + \sum_{k=1}^{m} \tilde{u}_k (b_k - \sum_{i=1}^{n} a_{ki} x_i) + \sum_{\ell=1}^{p} \tilde{v}_\ell (b'_\ell - \sum_{i=1}^{n} a'_{\ell i} x_i) + \sum_{i=1}^{n} \tilde{s}_i x_i$$

now, for any feasible solution $x$ to $P$, we have $b_k - \sum_{i=1}^{n} a_{ki} x_i = 0$, and then:

$$f(x) = g(\tilde{u}, \tilde{v}) + \sum_{\ell=1}^{p} \tilde{v}_\ell (b'_\ell - \sum_{i=1}^{n} a'_{\ell i} x_i) + \sum_{i=1}^{n} \tilde{s}_i x_i.$$  

Observe that for any feasible solution $x$, $b'_k - \sum_{i=1}^{n} a'_{\ell i} x_i \geq 0$, $x_i \geq 0$ and coefficients $\tilde{v}_\ell$ et $\tilde{s}_i$ are $\geq 0$.  

□

**APPENDIX B**

Recall our example $E$ presented all along the paper:

$$E : \text{Min } \phi(x) = -9x_1 - 7x_2 + 2x_3 + 23x_4 + 12x_5 - 48x_1 x_2 + 4x_1 x_3 + 36x_1 x_4 - 24x_1 x_5 - 7x_2 x_3 + 36x_2 x_4 - 84x_2 x_5 + 40x_3 x_4 + 4x_3 x_5 - 88x_4 x_5$$

s.t.

$$x_1 - 2x_2 + 5x_3 + 2x_4 - 2x_5 \geq 2$$
$$x_1 + x_2 + x_4 + x_5 = 2$$
$$x_1, x_2, x_3, x_4, x_5 \in \{0, 1\}.$$
Let us apply the classical linearization to it:

\[
\begin{align*}
\text{Min} & \quad -9x_1 - 7x_2 + 23x_4 + 12x_5 - 48y_{12} + 4y_{13} + 36y_{14} \\
& \quad -24y_{15} - 7y_{23} + 36y_{24} - 84y_{25} + 40y_{34} + 4y_{35} - 88y_{45} \\
\text{s.t.} & \quad -x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5 \leq -2 \\
& \quad x_1 + x_2 + x_4 + x_5 = 2 \\
& \quad y_{ij} \leq x_i \quad \text{for } i < j \quad q_{ij} < 0 \\
& \quad y_{ij} \leq x_j \quad \text{for } i < j \quad q_{ij} < 0 \\
& \quad 1 - x_i - x_j + y_{ij} \geq 0 \quad \text{for } i < j \quad q_{ij} > 0 \\
& \quad y_{ij} \geq 0 \quad \text{for } i < j \quad q_{ij} > 0 \\
& \quad x_1, \ldots, x_5 \in \{0, 1\}.
\end{align*}
\]

The optimal solution value equals \(-115\).

If one applies the compact linearization of Glover [14] to \(E\) (see Sect. 1.1), we get the following linear program:

\[
\begin{align*}
\text{Min} & \quad -9x_1 - 7x_2 + 23x_4 + 12x_5 + z_1 + z_2 + z_3 + z_4 + z_5 \\
\text{s.t.} & \quad -x_1 + 2x_2 - 5x_3 - 2x_4 + 2x_5 \leq -2 \\
& \quad x_1 + x_2 + x_4 + x_5 = 2 \\
& \quad z_1 \geq -22x_1 \\
& \quad z_1 \geq -24x_2 + 2x_3 + 18x_4 - 12x_5 - 20(1 - x_1) \\
& \quad z_2 \geq -69.5x_2 \\
& \quad z_2 \geq -24x_1 - 3.5x_3 + 18x_4 - 42x_5 - 14.5(1 - x_2) \\
& \quad z_3 \geq -1.5x_3 \\
& \quad z_3 \geq 2x_1 - 3.5x_2 + 20x_4 + 2x_5 - 22(1 - x_3) \\
& \quad z_4 \geq -24x_4 \\
& \quad z_4 \geq 18x_1 + 18x_2 + 20x_3 - 44x_5 - 56(1 - x_4) \\
& \quad z_5 \geq -84x_5 \\
& \quad z_5 \geq -12x_1 - 42x_2 + 2x_3 - 44x_4 + 10(1 - x_5) \\
& \quad x_1, \ldots, x_5 \in \{0, 1\}
\end{align*}
\]

which optimal value of the continuous relaxation equals \(-106.84\).

Below, we summarize the optimal values of different relaxations associated with example \(E\):

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References


