

# Globally convergent decomposition algorithm for risk parity problem in portfolio selection

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## 1 Introduction

## 2 Preliminary background

Let us consider the following optimization problem:

$$\min_{x,y} f(x,y) \tag{1a}$$

$$\text{s.t. } l \leq x \leq u \tag{1b}$$

$$\mathbf{1}^T x = 1 \tag{1c}$$

where  $x \in \mathbb{R}^n$ ,  $y \in \mathbb{R}^k$ ,  $f$  continuously differentiable,  $l, u \in \mathbb{R}^n$  with  $l < u$  and  $\mathbf{1} \in \mathbb{R}^n$  is all composed by ones.

Now we define the feasible set  $\mathcal{F}$  of Problem (1):

$$\mathcal{F} = \{(x, y) \in \mathbb{R}^{n+k} : \mathbf{1}^T x = 1, l \leq x \leq u\}. \tag{2}$$

Since the constraints of Problem (1) respect constraints qualification conditions, a feasible point  $(x, y)$  is a stationary point, if the Karush-Kuhn-Tucker (KKT) conditions are satisfied.

Let  $L(x, y, \lambda, \mu, \gamma)$  the Lagrangian function associated to Problem (1) then we can write KKT conditions.

**Proposition 2.1 (Optimality conditions (Necessary))** *Let  $(x^*, y^*) \in \mathbb{R}^{n+k}$ , with  $(x^*, y^*) \in \mathcal{F}$ , a local optimum for Problem (1). Then there exist three multipliers  $\lambda^* \in \mathbb{R}^n$ ,  $\mu^* \in \mathbb{R}^n$ ,  $\gamma^* \in \mathbb{R}$  such that:*

$$\begin{aligned} \nabla_x L(x^*, y^*, \lambda^*, \mu^*, \gamma^*) &= \nabla_x F(x^*, y^*) + \lambda^* - \mu^* + \gamma^* = 0 \\ \nabla_x L(x^*, y^*, \lambda^*, \mu^*, \gamma^*) &= \nabla_y F(x^*, y^*) = 0 \\ \lambda_i^* (l - x_i^*) &= 0, \quad \forall i \\ \mu_i^* (x_i^* - u) &= 0, \quad \forall i \\ \lambda^*, \mu^* &\geq 0 \end{aligned} \tag{3}$$

From the first condition we have:

$$\nabla_x f(x^*, y^*) - \lambda^* + \mu^* + \gamma^* = 0 \quad (4)$$

Then there are three possible cases:

$$\frac{\partial F(x^*, y^*)}{dx_i} = \begin{cases} -\mu_i^* - \gamma & x_i^* = u \\ -\gamma + \lambda_i^* & x_i^* = l \\ -\gamma & l < x_i^* < u \end{cases} \quad (5)$$

Then if  $x_j^* > l$ :

$$\frac{\partial f(x^*)}{dx_j} \leq \frac{\partial f(x^*)}{dx_i}, \forall i \quad (6)$$

Let  $(x, y) \in \mathcal{F}$ , we define a set of all feasible direction in  $(x, y)$ :

$$\mathcal{D}(x, y) = \{d \in \mathbb{R}^{n+k} : \mathbf{1}^T d_x = 0, d_i \geq 0 \forall i \in L(x), d_i \leq 0 \forall i \in U(x)\} \quad (7)$$

where:

$$\begin{aligned} L(x) &= \{i : x_i = l\} \\ U(x) &= \{i : x_i = u\} \end{aligned} \quad (8)$$

## 2.1 Set of sparse feasible directions

Because of  $y$  is unconstrained, we pay attention only on the  $x$  variable to find a feasible descent direction w.r.t.  $x$ . In our case we want to build a set of sparse feasible direction in order to justify our decomposition approach.

Let  $(x, y) \in \mathcal{F}$  non stationary w.r.t.  $x$ , then it's easy to see that

$$L(x) \neq \{1, \dots, n\} \quad (9)$$

hence  $\exists i$  such that  $x_i > 0$  and  $j \neq i$  such that:

$$\frac{\partial f(x^*)}{dx_i} > \frac{\partial f(x^*)}{dx_j}, \quad (10)$$

Now we define a direction  $d^{i,j} \in \mathbb{R}^n$  with only two non-zero components such that:

$$d_h^{i,j} = \begin{cases} 1, & h = j \\ -1, & h = i \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

**Proposition 2.2** *Let  $(x, y)$  a feasible point for Problem (1). Then the direction  $d^{i,j}$  is feasible and descent direction in  $x$ .*

**Proof** For the feasibility it is enough to see that  $\mathbf{1}^T d^{i,j} = 1 - 1 = 0$ . Then we can apply sufficient conditions for descent direction in  $x$ , such that:

$$\nabla_x f(x, y)^T d^{i,j} = \frac{\partial f(x)}{dx_j} - \frac{\partial f(x)}{dx_i} < 0;$$

As always, we should choose the steepest descent direction composed by only two non-zero components. This can be done computing the *Most Violating Pair*  $(i, j)$  such that  $x_i > 0$  and:

$$(i, j) \in \arg \min_{l, m} \left\{ \frac{\partial f(x^*)}{\partial x_l} - \frac{\partial f(x^*)}{\partial x_m} \right\} \quad (12)$$

If one doesn't want to use decomposition methods, he can define a direction  $d_{xy} \in \mathbb{R}^{n+k}$  such that:

$$d_{xy} = \{d^{i,j}, -\nabla_y f(x, y)\} \quad (13)$$

## 2.2 Armijo-Type Line Search Algorithm

In this section, we briefly describe the well-known Armijo-type line search along a feasible descent direction. The procedure will be used in the decomposition method presented in the next section. Let  $d^k \in \mathcal{D}(x_k)$   $x^k \in \mathcal{F}$ . In particular we choose  $d^k = d_k^{i,j}$  with MVP  $(i(k), j(k))$ . We denote by  $\Delta_k$  the maximum feasible step along  $d^k$ .

It is easy to see that:

$$\Delta_k = \min\{x_{j(k)}^k - l, u - x_{i(k)}^k\}$$

Then at iteration  $k + 1$  we have:

$$x_{j(k)}^{k+1} = \begin{cases} l & \alpha_k = x_{j(k)}^k - l \\ x_{j(k)}^k - u + x_{i(k)}^k & \alpha_k = u - x_{i(k)}^k \end{cases}$$

and:

$$x_{i(k)}^{k+1} = \begin{cases} x_{j(k)}^k - l + x_{i(k)}^k & \alpha_k = x_{j(k)}^k - l \\ u & \alpha_k = u - x_{i(k)}^k \end{cases}$$

## 2.3 Exact Line Search

When we move along the direction  $d^{i^*, j^*}$ , defined in (11), we modify only 2 variables  $(x_{i^*}, x_{j^*})$  leaving the others unchanged. Thus, we can see our  $f(x, y)$  as a function of two components, i.e. we can rewrite Problem (1) as

$$\min_{x_{i^*}, x_{j^*}} f(x_{i^*}, x_{j^*}) \quad (14a)$$

$$\text{s.t. } l_{i^*} \leq x_{i^*} \leq u_{i^*} \quad (14b)$$

$$l_{j^*} \leq x_{j^*} \leq u_{j^*} \quad (14c)$$

$$x_{i^*} + x_{j^*} = 1 - \underbrace{\sum_{h \neq i^*, j^*} x_h}_c \quad (14d)$$

Thanks to the last constraint, we can substitute  $x_{i^*} = c - x_{j^*}$  and then we obtain

$$\min_{x_{j^*}} f(x_{j^*}) \quad (15a)$$

$$\text{s.t. } x_{i^*} = c - x_{j^*} \quad (15b)$$

$$ll_{j^*} = \max\{l_{j^*}, c - u_{i^*}\} \leq x_{j^*} \leq \min\{u_{j^*}, c - l_{i^*}\} = uu_{j^*} \quad (15c)$$

Because the domain is  $I = [ll_{j^*}, uu_{j^*}]$ , if  $f(x_{j^*})$  is continuous in  $I$ , then  $f$  has a minimum in  $I$ . If  $f(x_{j^*})$  is differentiable in  $I$  we can compute  $f'(x_{j^*})$ . Let  $R = \{r \mid f'(r) = 0, r \in I\}$  be set of the real feasible roots of  $f'$ . Each  $r \in R$  can be a local maximum, minimum or flex; if  $R = \{\emptyset\}$ , then the minimum of  $f$  is on the extreme points of  $I$ .

Let  $r^* = \arg \min_{r \in R} f(r)$ , then the optimal step  $\alpha^*$  along the direction  $d^{i^*, j^*}$  is

$$\alpha^* = x_{j^*} - r^* > 0 \quad (16)$$

*TODO: problema di notazione,  $x_{j^*}$  rappresenta il valore della componente  $j^*$  del vettore  $x$  prima della ricerca di linea*

### 3 A decomposition framework

The algorithm follows the Gauss-Seidel scheme with 2 blocks of variables ( $x$  and  $y$ ). At each iteration, we optimize  $f$  w.r.t. one block of variables, considering the other block fixed.

The  $y$ -block of variables is unconstrained, so we can find

$$y^{(k+1)} = \arg \min_{y \in \mathbb{R}^m} f(x^{(k)}, y) \quad (17)$$

using the first-order necessary condition, i.e. *TODO: ma questo vale se  $f$  è convessa rispetto ad  $y$*

$$\nabla_y f(x^{(k)}, y^{(k)}) = 0 \quad (18)$$

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#### Algorithm 1: Decomposition Algorithm

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**Data:** Given the initial feasible guess  $(x^{(0)}, y^{(0)})$

- 1 Set  $k = 0$
  - 2 **while** (*not convergence*) **do**
  - 3     Compute  $y^{(k+1)}$  as in (17)
  - 4     Compute  $\nabla_x f(x^{(k)}, y^{(k+1)})$
  - 5     Choose indexes  $i^*(k), j^*(k)$  using the Gauss-Southwell rules
  - 6     Choose a step  $\alpha^{(k)}$  along the direction  $d^{i^*(k), j^*(k)}$
  - 7     Set  $x^{(k+1)} = x^{(k)} + \alpha^{(k)} d^{i^*(k), j^*(k)}$
  - 8     Set  $k = k + 1$
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- 4 Convergence analysis
- 5 Computational experiments



