

# 1 Jabr Model

For the OPF model construction we the network as directed graph  $(\mathbf{B}, \mathbf{L})$  where  $\mathbf{B}$  is the set of Buses and  $\mathbf{L} \subset \mathbf{B} \times \mathbf{B}$  is the set of branches of the network and for each adjacent buses  $k, m$  both  $(k, m)$  and  $(m, k)$  are in  $\mathbf{L}$ . So the line  $l$  adjacent to  $k, m$  is modeled by two edges in the arc  $\{(k, m), (m, k)\}$ .  $L$  can be partitioned in  $L_0$  and  $L_1$  with  $|L_0| = |L_1|$  where every line  $l$ , adjacent to the buses  $k, m$  and with a transformer at  $k$ , is oriented so that  $(k, m) \in L_0$  and  $(m, k) \in L_1$ . We also consider a set  $\mathcal{G}$  of generators, partitioned into (possibly empty) subsets  $\mathcal{G}_k$  for every bus  $k \in \mathbf{B}$ . We consider the following convex Jabr relaxation of the OPF problem:

$$\inf_{\substack{P_g^G, Q_g^G, c_{km}, \\ s_{km}, S_{km}, P_{km}, Q_{km}}} F(x) := \sum_{g \in \mathcal{G}} F_g(P_g^G) \quad (1)$$

Subject to:  $\forall km \in \mathbf{L}$

$$c_{km}^2 + s_{mk}^2 \leq c_{kk}c_{mm} \quad \text{Jabr constraint} \quad (2)$$

$$P_{km} = G_{kk}c_{kk} + G_{km}c_{km} + B_{km}s_{km} \quad (3)$$

$$Q_{km} = -B_{kk}c_{kk} - B_{km}c_{km} + G_{km}s_{km} \quad (4)$$

$$S_{km} = P_{km} + jQ_{km} \quad (5)$$

Power balance constraints:  $\forall k \in \mathbf{B}$

$$\sum_{km \in L} S_{km} + P_k^L + iQ_k^L = \sum_{g \in \mathcal{G}(k)} P_g^G + i \sum_{g \in \mathcal{G}(k)} Q_g^G \quad (6)$$

Power flow, Voltage, and Power generation limits:

$$P_{km}^2 + Q_{km}^2 \leq U_{km} \quad (7)$$

$$V_k^{\min^2} \leq c_{kk} \leq V_k^{\max^2} \quad (8)$$

$$P_g^{\min} \leq P_g^G \leq P_g^{\max} \quad (9)$$

$$c_{kk} \geq 0 \quad (10)$$

$$V_k^{\max} V_m^{\max} \geq c_{km} \geq 0 \quad (11)$$

$$-V_k^{\max} V_m^{\max} \leq s_{km} \leq V_k^{\max} V_m^{\max} \quad (12)$$

$$c_{km} = c_{mk}, \quad s_{km} = -s_{mk}. \quad (13)$$

This relaxation is in general not exact. We can recover exactness thanks to the following result:

**Proposition 1.** *Model (1) with the additional loop constraint (14) for every loop in a cycle basis of  $(\mathbf{B}, \mathbf{L})$  is exact, we refer to this new model as the Exact Jabr formulation*

$$\sum_{k=0}^{\lfloor n/2 \rfloor} \sum_{\substack{A \subset [n] \\ |A|=2k}} (-1)^k \prod_{h \in A} s_{k_h k_{h+1}} \prod_{h \in A^c} c_{k_h k_{h+1}} = \prod_{k=1}^n c_{k_i, k_i}. \quad (14)$$

In [cite](#), auxiliary branches were added to the network, dividing each loop in smaller loops, to decrease the degree of the polynomials defining the loop constraint. Then Mc Cormick linearization was applied. The problem with this approach is that one exiliary branch is added for every branch in the loop. This result suggests the following approaches to either find a feasible solution or move along the space of feasible solutions.

- Since the loop constraint is multilinear in it's variables, we can consider linear relaxations called *Flower inequalities*, which generalize che classical Mc Cormick relaxations of products of variables.
- Such relaxation is exact on tree Networks (also known as radial networks). Our objective is, given a network  $\mathcal{N} = (\mathbf{B}, \mathbf{L})$  which can also not be a tree, consider a radial subnetwork  $\mathcal{N}' = (\mathbf{B}, \mathbf{L}')$ , with  $\mathbf{L}' \subset \mathbf{L}$  and consider the Jabr model on  $\mathcal{N}'$ . This solution is not necessarily feasible for the original problem  $\mathcal{N}$ , our objective is to iteratively recover a feasible solution for  $\mathcal{N}$ . Since the Jabr relaxation is exact on  $\mathcal{N}'$  it follows that the constraints

2 are respected, the constraints which are violated are the flow constraints on the leaves. We can try to recover feasibility my moving along the solution to the Jabr and Loop constraints.

- Given a feasible solution, find feasible directions.

## 2 Linearization of loop constraints

To find feasible relaxations of the loop constraint we follow [cite](#). It must be noted that a major difference in our approach is that the OPF is not a multilinear optimization problem. So first we show that the same results in [cite](#) can be applied to the OPF.

Consider a set of multilinear constraints:

$$\sum_{I \in \mathcal{I}_j} c_I^j \prod_{v \in I_j} x_v \quad \forall I \leq b_j \quad \forall j \in \{1, 2, \dots, m\} \quad (15)$$

$$x_v \in [l_v, u_v] \quad \forall v \in V \quad (16)$$

Where  $V$  denotes the variables and  $\mathcal{I}_j \in \mathcal{P}(V)$ , for  $j = 1, \dots, m$  are the variables of the monomials appearing in the j-th homogenous constraint. A straight forward linearization is to introduce a variable  $z_I$  for every subset  $I$  of variables appearing in the constraints. Thus we obtain the following equivalent problem.

$$\sum_{I \in \mathcal{I}_j} c_I^j z_I \leq b_j \quad \forall j \in \{1, 2, \dots, m\} \quad (17)$$

$$z_I = \prod_{i \in I} x_i \quad \forall I \in \mathcal{E} := \cup_{j=1}^m \mathcal{I}_j \quad (18)$$

$$x_v \in [l_v, u_v] \quad \forall v \in V \quad (19)$$

By affine afformation we can assume the variables  $x_v$  to be in the form  $c_v \in [0, 1]$ . Note that such affine transformations need to be handled with care, we will cover this in subsection 2.1. Since constraint (17) is now linear, we are now interested in the linearization of the following set  $Pr := \{(x, z) \in [0, 1]^V \times [0, 1]^\mathcal{E} \mid z_I = \prod_{i \in I} x_i \forall I \in \mathcal{E}\}$ . If such constraints were the only ones, and if the cost was also multilinear, we would know that the solution would be on one of the vertices of the hypercube and the observation that follows would be trivially true. Since in the OPF the cost is not multilinear and there are other types of constraints we show that this is also a relaxation for  $Pr$ .

**Definition 1** (Standard form relaxation). *Let the polyhedral  $PrR$  be defined by the linear constraints (20a)-(20d).*

$$z_I \leq x_v \quad \forall v \in I \in \mathcal{E} \quad (20a)$$

$$z_I + \sum_{v \in I} (1 - x_v) \geq 1 \quad \forall I \in \mathcal{E} \quad (20b)$$

$$z_I \geq 0 \quad \forall I \in \mathcal{E} \quad (20c)$$

$$x_v \in [0, 1] \quad \forall v \in V \quad (20d)$$

G: fixalign-  
ment

The corresponding Standard Form Relaxation for problem with homogeonus cost and constraints if often very weak. As done in [cite](#) we augment 1 with *Flower Inequalities*, which are additional inequalities valid for  $Pr$ . Again the main difference with [cite: McCormick stikes back](#), is that we cannot restict the hypercuber  $C$  to its vertices becace other point could also be optimal for the OPF problem. Se we check the additional flower inequalities are still valid for  $Pr$ .

**Definition 2** (extendend flower inequalities.). *Let  $I \in \mathcal{E}$  and let  $J_1, \dots, J_k \in \mathcal{E} \cup \mathcal{S}$  be such that  $I \subset \bigcup_{i=1}^k J_i$  and  $I \cap J_i \neq \emptyset$  holds for  $i = 1, 2, \dots, k$ . The extended flower inequality with center  $I$  and petals  $J_1, \dots, J_k$  is defined as*

$$z_I + \sum_{i=1}^k (1 - z_{J_i}) \geq 1 \quad (21)$$

*The extended flower relaxation  $FR \subset [0, 1]^{\mathcal{E} \cup \mathcal{S}}$  are the elements  $x \in [0, 1]^{\mathcal{E} \cup \mathcal{S}}$  for which all the extended flower inequalities hold.*

**Proposition 2.** *For all  $x \in Pr$  and  $I \in \mathcal{E}$ ,  $J_1, \dots, J_k \in \mathcal{E} \cup \mathcal{S}$  such that  $I \subset \bigcup_{i=1}^k J_i$  and  $I \cap J_i \neq \emptyset$  for  $i = 1, 2, \dots, k$ . Then extended flower inequality (21) with center  $I$  and petals  $J_1, \dots, J_k$  holds for  $x$ . In particular  $Pr \subset FR$ .*

*Proof.* For  $|I| = 1$  this is trivially true. For  $|I| = n > 1$ , wlog  $I = \{1, \dots, n\}$ . We want to see that for any  $x \in C_{\cup_k J_k} := [0, 1]^{\cup_{k=1}^K J_k}$  we have  $a(x) = \prod_{i \in I} x_i + \sum_{k=1}^K (1 - \prod_{j \in J_k} x_j) - 1 \geq 0$ . Consider the face  $F = \{x \in [0, 1]^{\cup_{k=1}^K J_k} \mid x_1 = 0\}$ . Then  $C_{\cup_k J_k} = C_{\cup_k J_k} \cap (F + \langle e_1 \rangle)$ . Thus we only need to show that for every  $x \in F$  the function  $f_x(x_1) := a(x + x_1 e_1)$  is positive. This is an affine function, thus it is sufficient to show that it is positive at  $x_1 = 0$  and  $x_1 = 1$ . For  $x_1 = 0$  this is trivially true. For  $x_1 = 1$ , we have  $f_x(1) = \prod_{i \in I \setminus \{1\}} x_i + \sum_{k=1}^K (1 - \prod_{j \in J_k \setminus \{1\}} x_j) - 1 \geq 0$  by induction on  $|I|$ .  $\square$

By taking  $J_i = \{x_i\}$  for all  $x_i \in I$ , since  $z_{J_i} = x_i$ , we have:

**Corollary 2.1.** *The standard form relaxation as in definition 1 is a relaxation of  $Pr$ . That is  $Pr \subset PrR$ .*

G: ok, to write better

G: Il resto del paper McCormick strikes back dovrebbe valere anche qui, perchè parla della struttura dei rilassamenti, che non dipende da  $Pr$ .

## 2.1 Handling affine transformations

In the beginning of the sections, we assumed that the variables  $x_i \in [0, 1]$  because affine transformation of homogenous constraints remain homogenous. But it must be noted that for each non linear affine transformation, that is when the lower bound of the corresponding variable is not zero, the number of monomials increases. More precisely, given a monomial defined by  $I \in \mathcal{E}$ , let  $I' \subset I$  be the subset of variables in  $I$  for which a nonlinear transformation is applied. Then the monomial  $I$  is split into  $2^{|I'|+1}$  new monomials. When the size of such  $I'$  is large this greatly increases the number of auxiliary variables  $z_J$  which must be introduced. Thus applying many non linear affine transformation can be very costly and complicates the handling of the constraints. For this reason, instead of applying non linear affine transformation, for each variables  $v \in V$  such that  $x_v \in [l_v, u_v]$  and  $l_v * u_v \neq 0$ , we split the problem in two new subproblems having  $v_x \in [l_v, 0]$  and  $v_x \in [0, u_v]$  respectively. This way linear transformations can be applied in the subproblems. This creates many subproblems, many of which are unfeasible for the OPF, we diminish the number of subproblems we need to solve thanks to some unfeasibility conditions. Then, instead of solving each subproblem in a random order, we rewrite the subproblems as a unique mixed integer programming problem.

### Observation 3.

G: add observation that they cannot be all positive or all negative. Can we also say something more? maybe not

Let  $C = \{k_1, \dots, k_n\} \subset \mathbf{B}$  be a cycle. The variables  $s_h$  are in the form  $s_h \in [-u_{s_h}, u_{s_h}]$  where  $h = (k_i, k_{i+1})$  for all  $i = 1, \dots, n$ . We can then substitute  $s_h$  with  $u_h s'_h = s_h$  where  $s'_h \in [-1, 1]$ . We then define the sign variables

$\sigma_h \in \{0, 1\}$  for each  $h \in C$ , where  $\sigma_h = 0$  if  $s_h$  is negative and 1 if it is positive. We can now rewrite the loop constraint as:

$$\sum_{k=0}^{\lfloor n/2 \rfloor} \sum_{\substack{A \subset [n] \\ |A|=2k}} (-1)^k \left( \prod_{h \in A} (2\sigma_h - 1) u_h \right) z_A = z'_C \quad (22)$$

Where we substitute the monomial  $\prod_{h \in A} s_{k_h k_{h+1}} \prod_{h \in A^c} c_{k_h k_{h+1}}$  with  $z_A$  and the product  $\prod_{k=1}^n c_{k_i, k_i}$  with  $z'_C$ . For each even subset  $A \subset [n]$  we introduce the binary variable  $\lambda_A \in \{0, 1\}$  which is 0 if  $\prod_{h \in A} (2\sigma_h - 1)$  is  $-1$  and  $\lambda_A = 1$  otherwise. The loop constraint becomes:

$$\sum_{k=0}^{\lfloor n/2 \rfloor} \sum_{\substack{A \subset [n] \\ |A|=2k}} (-1)^k (2\lambda_A - 1) U_A z_A = z'_C \quad (23)$$

The product  $\lambda_A z_A$  can easily be linearized. To enforce the relation  $2\lambda_A - 1 = \prod_{h \in A} (2\delta_h - 1)$ , simply note that  $\lambda_A = 0$  if and only if there is an odd number of  $\delta_h$  equal to 0, that is, there exists  $m_A \in \mathbb{Z}$  such that:

$$\lambda_A + 2m_A = \sum_{h \in A} \delta_h \quad (24)$$

### 3 Other cuts

Let  $I$  a set of indices and  $x_v, v \in I$ , continuous variables such that  $x_v \in [l_v, u_v] \subset [-1, 1]$ . Let also the set  $I$  be partitioned in two set such that  $I = J \oplus K$  and

$$l_v > 0, \quad u_v = 1, \quad \forall v \in J, \quad (25a)$$

$$l_v = -u_v, \quad u_v < 1, \quad \forall v \in K. \quad (25b)$$

If we define  $z_I := \prod_{v \in I} x_v$  and  $I' := I \setminus \{v\}$ , then the following lower and upper bounds trivially hold:

$$z_I \leq x_v \prod_{v' \in I'} u_{v'}, \quad \forall v \in J, \quad (26a)$$

$$z_I \leq |x_v| \prod_{v' \in I'} u_{v'}, \quad \forall v \in K, \quad (26b)$$

$$z_I \geq -|x_v| \prod_{v' \in I'} u_{v'}, \quad \forall v \in K, \quad (26c)$$

$$z_I \geq x_v \prod_{v' \in I'} l_{v'}, \quad \forall v \in J, I' = J' \oplus K' : K' = \emptyset, \quad (26d)$$

$$z_I \geq -x_v \prod_{v' \in I'} u_{v'}, \quad \forall v \in J, I' = J' \oplus K' : K' \neq \emptyset. \quad (26e)$$

G: In realtà questo non è specifico all'OPF, va bene per tutti i vincoli omogenei e si può fare al posto di fare le trasformazioni affini!

**Lemma 4.** *The following inequality holds: **Questo considera l'iperpiano tangente nel punto avente coordinate  $u_v, u_v, \dots, u_v, \prod u_v$ . Si riesce a fare lo stesso per altri punti del cuboide? Possibile che qualcuno lo ha già fatto?***

$$z_I + \sum_{v \in I} c_v(u_v - x_v) \geq \prod_{v \in I} u_v, \quad c_v := \prod_{v' \in I \setminus \{v\}} u_{v'}. \quad (27)$$

*Proof.* Because we are dealing with a multilinear inequality, it is sufficient to verify that it holds for every vertex of the multidimensional rectangular cuboid

$$\mathfrak{C} := \prod_{v \in I} [l_v, u_v] \subset [-1, 1]^{|I|}.$$

For such a vertex  $x$ , we have either  $x_v = l_v$  or  $x_v = u_v$  for every  $v \in I$ . Define  $I_1 := \{v \in I \mid x_v = l_v\}$  and  $I_2 := \{v \in I \mid x_v = u_v\}$ , and  $J_1, J_2, K_1, K_2$  analogously. By defining  $k_1 := |K_1|$ , we then have

$$\begin{aligned} z_I + \sum_{v \in I} c_v(u_v - x_v) &= \prod_{v \in I_1} l_v \prod_{v \in I_2} u_v + \sum_{v \in I_1} c_v(u_v - x_v) + \sum_{v \in I_2} c_v(u_v - x_v) = \\ &= \prod_{v \in I_1} l_v \prod_{v \in I_2} u_v + \sum_{v \in I_1} c_v(u_v - l_v) = \\ &= (-1)^{k_1} \prod_{v \in K_1 \cup I_2} u_v \prod_{v \in J_1} l_v + \sum_{v \in J_1} c_v(1 - l_v) + 2 \sum_{v \in K_1} c_v u_v = \\ &= A + B + C. \end{aligned}$$

Now, we rewrite each of the three terms. First,

$$\begin{aligned} A &= (-1)^{k_1} \prod_{v \in K_1 \cup I_2} u_v \prod_{v \in J_1} l_v = (-1)^{k_1} \prod_{v \in K_1 \cup I_2} u_v \prod_{v \in J_1} u_v \prod_{v \in J_1} l_v = \\ &= (-1)^{k_1} \prod_{v \in I} u_v \prod_{v \in J_1} l_v, \end{aligned}$$

where the second equality holds because  $u_v = 1, \forall v \in J_1$ . Second,

$$\begin{aligned} B &= \sum_{v \in J_1} c_v(1 - l_v) = \sum_{v \in J_1} \left( \prod_{v' \in I \setminus \{v\}} u_{v'} \right) (1 - l_v) = \sum_{v \in J_1} \left( \prod_{v' \in I} u_{v'} \right) (1 - l_v) = \\ &= \left( \prod_{v \in I} u_v \right) \sum_{v \in J_1} (1 - l_v), \end{aligned}$$

where the third equality holds because  $u_v = 1 \forall v \in J_1$ . Finally,

$$\begin{aligned} C &= 2 \sum_{v \in K_1} c_v u_v = 2 \sum_{v \in K_1} \left( \prod_{v' \in I \setminus \{v\}} u_{v'} \right) u_v = 2 \sum_{v \in K_1} \left( \prod_{v' \in I} u_{v'} \right) = \\ &= 2k_1 \left( \prod_{v \in I} u_v \right). \end{aligned}$$

We then have

$$\begin{aligned} z_I + \sum_{v \in I} c_v(u_v - x_v) &= A + B + C = \\ &= \left( \prod_{v \in I} u_v \right) ((-1)^{k_1} \prod_{v \in J_1} l_v + \sum_{v \in J_1} (1 - l_v) + 2k_1). \end{aligned}$$

To conclude, we just need to prove that

$$(-1)^{k_1} \prod_{v \in J_1} l_v + \sum_{v \in J_1} (1 - l_v) + 2k_1 \geq 1,$$

but this is true because

$$\begin{aligned} (-1)^{k_1} \prod_{v \in J_1} l_v + \sum_{v \in J_1} (1 - l_v) + 2k_1 &= \\ &= ((-1)^{k_1} - 1) \prod_{v \in J_1} l_v + 2k_1 + \prod_{v \in J_1} l_v + \sum_{v \in J_1} (1 - l_v) = \\ &\geq ((-1)^{k_1} - 1) \prod_{v \in J_1} l_v + 2k_1 + 1 \geq (-1)^{k_1} + 2k_1 \geq 1, \end{aligned}$$

where the first inequality holds because  $\prod_{v \in J_1} l_v + \sum_{v \in J_1} (1 - l_v) \geq 1$  because of the standard multilinear relaxation. [cita](#), the second inequality holds because  $0 < l_v < 1$  and so  $0 \leq \prod_{v \in J_1} l_v < 1$ , and the last inequality holds because  $k_1 \geq 0$  integer.  $\square$

**Observation 5.** *Note that, with the same notation of the proof above, (27) is tight for every vertex of  $\mathfrak{C}$  for which  $|I_1| \leq 1$ .*

### 3.1 A new(?) class of constraints

We now consider when, given a vertex  $a$  of the cuboid  $\mathfrak{C}$ , we can define a separating hyperplane  $\pi$  for  $Pr$ , that is, when  $\pi : \mathbb{R}^n \rightarrow \mathbb{R}$  such that either  $\pi(x) \leq \prod_{v \in I} x_v$  for all  $x$  in  $\mathfrak{C}$  for all  $x$  in the vertex or  $\pi(x) \geq \prod_{v \in I} x_v$  for all  $x$  in  $\mathfrak{C}$ . Furthermore, we want a good cut, so we look for hyperplanes such that  $\pi(y) = \prod_{v \in I} y_v$  for all vertices  $y$  in  $\mathfrak{C}$ , adjacent to  $a$ . In this section we denote the vertex opposite to  $a$ ,  $a^{\text{op}}$ . Choosing a vertex, corresponds to picking for each interval  $v \in I$ , either the lower bound or the upper bound, so  $a^{\text{op}}$  is the vertex having as  $a_v^{\text{op}} = l_v$  if  $a_v = u_v$  and  $a_v^{\text{op}} = u_v$  otherwise. Thus by defining  $d_v := (a_v^{\text{op}} - a_v)e_v$ , a vertex  $x \in \mathfrak{C}$  corresponds to a unique  $J \subset I$  such that

$$x = a + \sum_{v \in J} d_v$$

for this reason we denote  $x$  as  $x_J$ . First we observe that since in  $\mathbb{R}^{n+1}$  fixed  $n+1$  affinely independent points there exists a unique hyperplane containing all these points, then there exists a unique hyperplane such that  $\pi(y) = \prod_{v \in I} y_v$  for all vertices  $y$  in  $\mathfrak{C}$ , adjacent to  $a$  and for  $y = x$ .

**Observation 6.** The hyperplane  $\pi_a(x) := \prod_{v \in I} a_v + \sum_{v \in I} C_v a_v (x_v - a_v)$ , where  $C_v := \prod_{v' \in I \setminus \{v\}} C_v$ , is the only hyperplane such that  $\pi(y) = \prod_{v \in I} y_v$  for all vertices  $y$  in  $\mathfrak{C}$ , adjacent to  $a$ .

We now look for conditions for when this uniquely defined hyperplane is also a separating hyperplane for  $Pr$ .

**Proposition 7.** The hyperplane  $\pi_a$  is a separating hyperplane for  $Pr$  if and only if either for all  $J \subset I$ ,  $J = \{j_1, \dots, j_s\}$ ,  $k = 1, \dots, s-1$  and  $J_k := \{j_1, \dots, j_k\}$ , the following holds:

$$\sum_{k=1}^{s-1} \left( \prod_{\substack{v \in I \\ v \neq j_k}} a_v - \prod_{\substack{v \in I \\ v \neq j_k}} x_v^{J_k} \right) (a_{j_s}^{\text{op}} - a_{j_s}) \geq 0 \quad (28)$$

or for all  $J \subset I$ ,  $J = \{j_1, \dots, j_s\}$ :

$$\sum_{k=1}^{s-1} \left( \prod_{\substack{v \in I \\ v \neq j_k}} a_v - \prod_{\substack{v \in I \\ v \neq j_k}} x_v^{J_k} \right) (a_{j_s}^{\text{op}} - a_{j_s}) \leq 0 \quad (29)$$

*Proof.* Let  $p(x) := \prod_{v \in I} x_v$ . Observe that for all  $J \subset I$  with  $|J| = 1$ , we have  $\pi(x) = p(x)$ . Now fix  $J \subset I$  and denote  $J_h = \{j_1, \dots, j_h\} \subset J$  for  $h = 1, \dots, s$ . Then we have:

$$\pi(x_J) = \sum_{h=1}^{s-1} \pi(x_{J_{h+1}}) - \pi(x_{J_h}) + \pi(x_{J_1}) = \sum_{h=1}^{s-1} \left( \prod_{\substack{v \in I \\ v \neq j_h}} a_v \right) (a_{j_h}^{\text{op}} - a_{j_h}) + p(x_{J_1}) \quad (30)$$

And similarly:

$$p(x_J) = \sum_{h=1}^{s-1} p(x_{J_{h+1}}) - p(x_{J_h}) + p(x_{J_1}) = \sum_{h=1}^{s-1} \left( \prod_{\substack{v \in I \\ v \neq j_h}} a_v \right) (a_{j_h}^{\text{op}} - a_{j_h}) + p(x_{J_1}) \quad (31)$$

From which the thesis follows.  $\square$

Since Inequality (30) needs to hold for all subsets of  $I$ , it is in general non-trivial to assess for which vertices  $a \in \mathfrak{C}$ , the hyperplane  $\pi_a$  serves as a separating hyperplane. However, vertices at which the product  $\pi$  attains its maximum (or minimum) value on the cuboid always define separating hyperplanes:

**Proposition 8.** If

$$\max_{x \in \mathfrak{C}} \prod_{v \in I} x_v = \prod_{v \in I} a_v \quad \text{or} \quad \min_{x \in \mathfrak{C}} \prod_{v \in I} x_v = \prod_{v \in I} a_v,$$

then  $\pi_a$  is a separating hyperplane. In particular in the first case we have  $\pi_a(x) \leq p(x)$  for all  $x$  in  $\mathfrak{C}$  and in the second case  $\pi_a(x) \geq p(x)$ .



*Proof.* Assume that  $\prod_{v \in I} a_v$  attains the maximum. The argument for the minimum case is analogous.

By Proposition 7, it suffices to verify that for all  $J \subset I$  and  $j \in J$ :

$$\left( \prod_{\substack{v \in I \\ v \neq j}} a_v - \prod_{\substack{v \in I \\ v \neq j}} x_v^J \right) (a_j^{\text{op}} - a_j) \leq 0.$$

First, consider the case  $\prod_{v \in I} a_v \geq 0$ :

If  $\prod_{\substack{v \in I \\ v \neq j}} a_v \geq 0$ , then  $a_j \geq 0$  and  $a_j \geq a_j^{\text{op}}$ . Since

$$a_j \prod_{\substack{v \in I \\ v \neq j}} a_v \geq a_j \prod_{\substack{v \in I \\ v \neq j}} x_v^J,$$

it follows that

$$\prod_{\substack{v \in I \\ v \neq j}} a_v \geq \prod_{\substack{v \in I \\ v \neq j}} x_v^J.$$

Hence,

$$\left( \prod_{\substack{v \in I \\ v \neq j}} a_v - \prod_{\substack{v \in I \\ v \neq j}} x_v^J \right) (a_j^{\text{op}} - a_j) \leq 0.$$

If  $\prod_{\substack{v \in I \\ v \neq j}} a_v \leq 0$ , then  $a_j \leq 0$  and  $a_j \leq a_j^{\text{op}}$ . Since

$$a_j \prod_{\substack{v \in I \\ v \neq j}} a_v \geq a_j \prod_{\substack{v \in I \\ v \neq j}} x_v^J,$$

we have

$$\prod_{\substack{v \in I \\ v \neq j}} a_v \geq \prod_{\substack{v \in I \\ v \neq j}} x_v^J,$$

and again

$$\left( \prod_{\substack{v \in I \\ v \neq j}} a_v - \prod_{\substack{v \in I \\ v \neq j}} x_v^J \right) (a_j^{\text{op}} - a_j) \leq 0.$$

Now consider the scenario where  $\prod_{v \in I} a_v < 0$ . In this case all signs are reversed accordingly and the argument is the same.

In all cases, the required inequality is satisfied. Hence, by Proposition 7,  $\pi_a$  is a separating hyperplane.  $\square$

We look for sufficient and necessary conditions for when if  $\pi_{\bar{a}}$  is a separating hyperplane, if  $a \in \mathfrak{C}$  is and adjacent vertex of  $a$ , then also  $\pi_a$  is a separating hyperplane.

**Proposition 9.** *If  $a$  is an adjacent vertex of  $\bar{a}$  and  $\pi_{\bar{a}}$  is a separating hyperplane for  $Pr$ , such that  $\pi_{\bar{a}}(x) \leq p(x)$  for all  $x$  in  $\mathfrak{C}$ , let  $d_j := \bar{a}_j^{op} - \bar{a}_j \geq 0$  for all  $j$ . Then  $\pi_a$  is also a separating hyperplane for  $Pr$  such that  $\pi_a(x) \leq p(x)$  if and only if*

$$C_v^a d_v \leq C_v^{\bar{a}} d_v \text{ for all } v \text{ in } J \setminus \bar{v} \quad (32)$$

*Conversely the proposition also works by changing the sign of all inequalities.*

*Proof.* Let  $\bar{v} \in [n]$  be such that  $\bar{a} - d_{\bar{v}} = a$ . First we observe that  $p(\bar{a}) = p(a) - C_{\bar{v}}^a d_{\bar{v}}$ , by definition of  $C_{\bar{v}}^a$ . Let  $x^J := \bar{a} + \sum_{j \in J} d_j$ . Then if  $\bar{v}$  is contained in  $J$ , we have:

$$\pi_a(x^J) = p(a) + \sum_{j \in J \setminus \bar{v}} C_v^a d_v \quad (33)$$

$$= p(\bar{a}) + C_{\bar{v}}^a d_{\bar{v}} + \sum_{j \in J \setminus \bar{v}} C_v^a d_v \quad (34)$$

$$\leq p(\bar{a}) + C_{\bar{v}}^{\bar{a}} d_{\bar{v}} + \sum_{j \in J \setminus \bar{v}} C_v^{\bar{a}} d_v = \pi_{\bar{a}}(x^J) \leq p(x^J) \quad (35)$$

Where the first inequality follows directly from the hypothesis. Similarly the same is done when  $\bar{v} \notin J$ :

$$\pi_a(x^J) = p(a) - C_{\bar{v}}^a d_{\bar{v}} + \sum_{j \in J} C_v^a d_v \quad (36)$$

$$= p(\bar{a}) + \sum_{j \in J} C_v^a d_v \quad (37)$$

$$\leq p(\bar{a}) + C_{\bar{v}}^{\bar{a}} d_{\bar{v}} + \sum_{j \in J} C_v^{\bar{a}} d_v = \pi_{\bar{a}}(x^J) \leq p(x^J) \quad (38)$$

Thus  $\pi_a$  is a separating hyperplane. Now we show that if the conditions doesn't hold than  $\pi_a$  is not a separating hyperplane. Consider  $v' \in I \setminus \bar{v}$  such that  $C_v^a d_v \leq C_v^{\bar{a}} d_v > 0$ , then we have:

$$\pi_a(a - d_{\bar{v}} + d_{v'}) = \pi_{\bar{a}}(\bar{a}) + C_{v'}^a d_{v'} > p(\bar{a}) + C_{v'}^{\bar{a}} d_{v'} = \quad (39)$$

$$= p(\bar{a} + d_{v'}) = p(a - d_{\bar{v}} + d_{v'}) \quad (40)$$

□

**Observation 10.** *If  $\bar{a}_{\bar{v}} \neq 0$ , Equation (32) is equivalent to  $\frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} C_v^{\bar{a}} = C_v^a \leq C_v^{\bar{a}}$  for all  $v$  in  $J \setminus \bar{v}$ .*

*Proof.* Since  $C_{\bar{v}}^a = \prod_{j \in I, j \neq \bar{v}} a_j = \prod_{j \in I, j \neq \bar{v}} \bar{a}_j = C_{\bar{v}}^{\bar{a}}$ , and

$$C_h^a = \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} \prod_{j \in I, j \neq \bar{v}} a_j = \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} \prod_{j \in I, j \neq \bar{v}} \bar{a}_j = \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} C_h^{\bar{a}}.$$

□

We observe that it could still be the case that, even if the assumption does not hold,  $\pi_{\bar{a}}$  could still be a separating hyperplane for  $Pr$ , but it may separate  $Pr$  from above instead of from below. In fact, this occurs whenever there are two adjacent vertices where one attains the maximum over the product and the other the minimum, as they both define supporting hyperplanes. We note that Condition (32) implies that if  $1 - \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} \leq 0$ , then  $p(\bar{a} + d_{\bar{v}}) \leq p(\bar{a})$ . Conversely, if  $1 - \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} \geq 0$ , then  $p(\bar{a} + d_{\bar{v}}) \geq p(\bar{a})$ . It is natural to examine how this condition behaves when  $\bar{a}$  attains the maximum over the product, as it defines a supporting hyperplane. In this case, it is true that  $p(\bar{a} + d_j) \leq p(\bar{a})$  for all  $j \in I \setminus \{\bar{v}\}$ . However, in general, we do not have  $1 - \frac{a_{\bar{v}}}{\bar{a}_{\bar{v}}} \leq 0$ . If  $\bar{a}_{\bar{v}} \geq 0$ , this is equivalent to  $d_{\bar{v}} \geq 0$ , which would imply  $p(\bar{a} + d_{\bar{v}}) \geq p(\bar{a})$ . Thus, the adjacent point still attains a maximum. On the other hand, if  $\bar{a}_{\bar{v}} \leq 0$ , then Condition (32) implies that  $p(\bar{a} + d_{\bar{v}}) \geq p(\bar{a})$ . Therefore, Proposition 9 indicates that the only adjacent vertices to a maximizing vertex which also support  $Pr$  from below are themselves maximizing vertices.

VW: scrivo delle cose qui sotto che magari possono tornare utili

$$f_a(x) = \prod_{v \in I} x_v + \sum_{v \in I} c_v(a_v - x_v) - \prod_{v \in I} a_v,$$

$$g_a(x) = \prod_{v \in I} x_v - \sum_{v \in I} c_v x_v$$

we are looking for  $a \in \mathfrak{C}$  such that either

$$\begin{aligned} f_a(x) &\leq 0 & \forall x \in \mathfrak{C}, \text{ or} \\ f_a(x) &\geq 0 & \forall x \in \mathfrak{C}, \end{aligned}$$

that is

$$\begin{aligned} g_a(x) &\leq g_a(a), & \forall x \in \mathfrak{C}, \text{ or} \\ g_a(x) &\geq g_a(a), & \forall x \in \mathfrak{C}. \end{aligned}$$

So we are looking for  $a$  such that the function  $g_a$  attains its maximum or minimum at  $a$ . Note that  $g_a(a) = (1 - |I|) \prod_{v \in I} a_v$ .

## 4 Bounds on Loop constraints violation

We want to confront different possible relaxations in order to pick the one which minimizes the violation of the loop constraint. The violation of the loop constraint comes from the fact that a solution  $x$  can violate the following equality:

$$z_I = \prod_{v \in I} x_v$$

We are thus interested in the following quantity,

$$\epsilon_I := \sup_{(z_I, x) \in PrR} |z_I - \prod_{v \in I} x_v|$$

VW: quindi secondo me, col fatto che  $I \leq 2$ , se  $|a_v| = u_v$  dovrebbe essere facile far vedere che quello è sempre il massimo o il minimo, dipende da quanti segni meno ci sono

To give a bound on the violation of the loop constraint. We give a lower bound on  $\epsilon_I$ :

**Proposition 11.** *Let  $I$  be a set of variables. Then*

$$\epsilon_I \geq \sup_{(z_i, x) \in \mathcal{C}(Pr)} |z_I - \prod_{v \in I} x_v| = U_I \left( \frac{1}{|I|} \right)^{\frac{1}{|I|-1}} \left( 1 - \frac{1}{|I|} \right),$$

where  $U_I := \prod_{v \in I} \max(|u_v|, |l_v|)$ .

*Proof.* We start with the case where  $l_v = 0$ . It can be easily (?) shown that the point which achieves the supremum is of the type  $(z_I, tu_{v_1}, \dots, tu_{v_k}, \dots)$ , where  $k = |I|$ , with  $z_I = t \prod_{v \in I} u_v$ . Thus, we calculate:

$$\sup_{t \in [0,1]} t \prod_{v \in I} u_v - \prod_{v \in I} tu_v = \sup_{t \in [0,1]} \prod_{v \in I} u_v (t - t^k).$$

The supremum is attained at  $t = \left( \frac{1}{|I|} \right)^{\frac{1}{|I|-1}}$ , and thus the error is

$$\prod_{v \in I} u_v \left( \frac{1}{|I|} \right)^{\frac{1}{|I|}} \left( 1 - \frac{1}{|I|} \right)$$

In general, for  $l_v$  possibly negative, we observe that the relaxation introduced in Section [ref](#) is not convex. However, if restricted to each quadrant, it is convex, and we can apply the same argument. The error is then larger than the maximum error of the convexification of the graph of the monomial over each quadrant, and thus the thesis follows.  $\square$

We now consider how the error on the monomial approximation influences the error on the loop constraint:

$$\epsilon_C := \left| \prod_{v \in V} c_{vv} - \sum_{k=0}^{\lfloor \frac{|C|}{2} \rfloor} \sum_{\substack{A \subset \mathcal{E}(C) \\ |A|=2k}} (-1)^k \prod_{e \in A} c_e \prod_{e \in A^c} s_e \right| \quad (44)$$

$$\leq |z_C^v + \epsilon_C^v + \sum_{k=0}^{\lfloor \frac{|C|}{2} \rfloor} \sum_{\substack{A \subset \mathcal{E}(C) \\ |A|=2k}} z_A + \epsilon_A| \quad (45)$$

$$\leq \left| \prod_{v \in V} \epsilon_C^v \right| + \sum_{k=0}^{\lfloor \frac{|C|}{2} \rfloor} \sum_{\substack{A \subset \mathcal{E}(C) \\ |A|=2k}} |\epsilon_A| \quad (46)$$

$$\leq \bar{\epsilon}_C + \sum_{k=0}^{\lfloor \frac{|C|}{2} \rfloor} \sum_{\substack{A \subset \mathcal{E}(C) \\ |A|=2k}} \bar{\epsilon}_C \cong 2^{|C|-1} \bar{\epsilon}_C \quad (47)$$

G: mhhh  
se  $l_v$  è più grande di zero l'errore è più piccolo di così.

As done in [cite](#), cycles can be decomposed into cycles of length 3 or 4 (resulting in McCormick relaxations of binomial), or larger cycles (resulting in generalized monomial relaxations). We determine the optimal length subcycle length to minimize the loop constraint violation. To do this, given the constraints induced by the subcycles of  $C$  we relate these to the loop constraint over  $C$  to confront the error. First, given  $C$ , decomposed in the cycles  $C_0, \dots, C_k$ , let  $\epsilon_{C_i}$  be the loop constraint violation over the subcycle  $C_i$ , and let  $\epsilon_{C_i}^s$  be the constraint violation respect to the constraint  $\prod_{v \in C_i} \sin(\sum_{e \in \mathcal{E}(C_i)} \theta_e) = 0$ . Lastly, we denote by  $LHS_{C_i}^c$  (resp.  $RHS_{C_i}^s$ ) the left hand side (right hand side) of the constraint  $\prod_{v \in C_i} c_{vv} \cos(\sum_{e \in \mathcal{E}(C_i)} \theta_e) = \prod_{v \in C_i} c_{vv}$ . Consider:

$$\prod_{v \in C} c_{vv} \cos\left(\sum_{e \in \mathcal{E}(C)} \theta_e\right) = \prod_{v \in C} c_{vv}$$

By expanding the cosine, and substituting  $\cos(\theta_e)|V_{e0}||V_{e1}|$  and  $\sin(\theta_e)|V_{e0}||V_{e1}|$ , by  $c_e$  and  $s_e$  respectively, we obtain the loop constraint. Alternatively, observe that:

$$\cos\left(\sum_{e \in \mathcal{E}(C)} \theta_e\right) = \cos\left(\sum_{i=0}^k \sum_{e \in C_i} \theta_e\right) = \cos\left(\sum_{i=0}^k \theta_{C_i}\right)$$

Where  $\theta_{C_i} := \sum_{e \in C_i} \theta_e$ . Thus, by expanding the last sum respect to the angles  $\theta_{C_i}$  and multiplying by  $\prod_{i=0}^k \prod_{v \in C_i} c_{vv}$ , we obtain the loop constraint expressed respect in function of the LHS of the loop constraints of the subcycles:

$$\sum_{h=0}^{\lfloor \frac{k}{2} \rfloor} (-1)^h \sum_{\substack{A \subset [k] \\ |A|=2h}} \prod_{i \in A} LHS_{C_i}^c \prod_{i \in A^c} LHS_{C_i}^s = \prod_{i=0}^k \prod_{v \in C_i} c_{vv}$$

Observe that  $LHS_{C_i}^c = RHS_{C_i}^c + \epsilon_{C_i}^s$  and  $LHS_{C_i}^s = \epsilon_{C_i}^s$ , and that dividing by  $\prod_{i=0}^k \prod_{v \in C_i} c_{vv}$  we obtain the expression of the loop constraint over  $C$ . Thus:

$$\frac{1}{\prod_{i=0}^k \prod_{v \in C_i} c_{vv}} \sum_{h=0}^{\lfloor \frac{k}{2} \rfloor} (-1)^h \sum_{\substack{A \subset [k] \\ |A|=2h}} \prod_{i \in A} (RHS_{C_i}^c + \epsilon_{C_i}^s) \prod_{i \in A^c} \epsilon_{C_i}^s = RHS_C$$

This sum can be divided in two sums, one corresponding to the left hand side of the loop constraint over  $C$ , and the other corresponding to the loop constraint violation, depending on  $\epsilon^c$  and  $\epsilon^s$ . By taking the absolute values, we obtain:

$$\epsilon_C \leq 2^{|k|-1} \bar{\epsilon}_C^A$$

Where  $\bar{\epsilon}_C^A$  is the average of the products in the sum. Then, since  $k = |C|/c$ , where  $c = |C_i|$  the optimal length of the subcycles is  $c = 42 * y$  with  $y$  to be determined. MHHHHH va scritto meglio