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Finding a bounded mixed-integer solution to a system of dual network inequalities

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ABSTRACT

We show that using max-algebraic techniques it is possible to generate the set of all solutions to a system of inequalities $x_i - x_j \geq b_{ij}$, $i, j = 1, \ldots, n$ using n generators. This efficient description enables us to develop a pseudopolynomial algorithm which either finds a bounded mixed-integer solution, or decides that no such solution exists.

1. Introduction

This papers deals with the systems of inequalities of the form

$$x_i - x_j \geq b_{ij} \quad (i, j = 1, \ldots, n) \tag{1}$$

where $B = (b_{ij}) \in \mathbb{R}^{n\times n}$. In [19] the matrix of the left-hand side coefficients of this system is called the *dual network matrix*. It is the transpose of the constraint matrix of a circulation problem in a network (such as the maximum flow or minimum-cost flow problem) and inequalities of the form (1) therefore appear as dual inequalities for this type of problems. These facts motivate us to call (1) the *system of dual network inequalities* (SDNI). The aim of this paper is to show that using standard max-algebraic techniques it is possible to generate the set of all solutions to (1) (which is of size $n^2 \times n$) using n generators (Theorem 2.3). This description enables us then to find a *bounded mixed-integer solution* to the following system of dual network inequalities (BMISDNI), or to decide that there is no such solution:

$$x_i - x_j \geq b_{ij} \quad (i, j \in N)$$
$$u_j \geq x_j \geq l_j \quad (j \in N)$$
$$x_j \text{ integer} \quad (j \in J)$$

where $u = (u_1, \ldots, u_n)^{\mathrm{T}}, l = (l_1, \ldots, l_n)^{\mathrm{T}} \in \mathbb{R}^n$ and $J \subseteq N = \{1, \ldots, n\}$ are given. Note that without loss of generality u_j and l_j may be assumed to be integer for $j \in J$. This type of inequalities have been studied for instance in [19] where it has been proved that a related mixed-integer feasibility question is *NP*-complete. For similar problems see also [15,17].

We will show that in general, the application of max-algebra leads to a pseudopolynomial algorithm for solving BMISDNI. However, an explicit solution is proved in the case when B is integer (but still a mixed-integer solution is wanted). This implies that BMISDNI can be solved using $O(n^3)$ operations. Note that when $J = \emptyset$ then BMISDNI is polynomially solvable since it is a set of constraints of a linear program. When $J = N$ and B is integer then BMISDNI is also polynomially solvable since the matrix of the system is totally unimodular [16].

2. All solutions to SDNI

The system

$$x_i - x_j \geq b_{ij} \quad (i, j \in N)$$

is equivalent to

$$\max_{j\in N} \left(b_{ij} + x_j\right) \leq x_i \quad (i \in N).$$

If we denote $u \oplus v = \max(u, v)$ and $u \otimes v = u + v$ for $u, v \in \overline{\mathbb{R}} := \mathbb{R} \cup \{-\infty\}$ then this reads $\sum^{\oplus}_{j\in N} b_{ij} \otimes x_j \leq x_i$ for $i \in N$ or (if we extend the operations $\oplus$ and $\otimes$ to matrices and vectors), equivalently

$$B \otimes x \leq x. \tag{2}$$

Being motivated by this observation we first summarize some basic concepts and results of max-algebra and then we present our main results.

By *max-algebra* we understand the analogue of linear algebra developed for the pair of operations $(\oplus, \otimes)$, extended to matrices and vectors. That is if $A = (a_{ij})$, $B = (b_{ij})$ and $C = (c_{ij})$ are matrices of compatible sizes with entries from $\overline{\mathbb{R}}$, we write $C = A \oplus B$ if

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$c_{ij} = a_{ij} \oplus b_{ij}$ for all i, j and $C = A \otimes B$ if $c_{ij} = \sum_k^{\oplus} a_{ik} \otimes b_{kj} = \max_k (a_{ik} + b_{kj})$ for all i, j. If $\alpha \in \overline{\mathbb{R}}$ then $\alpha \otimes A = (\alpha \otimes a_{ij})$. If $\alpha \in \mathbb{R}$ then the symbol α^{-1} stands for $-\alpha$.

The following isotonicity lemma is easily verified:

Lemma 2.1. *If $A \in \overline{\mathbb{R}}^{n\times n}$ and $x, y \in \overline{\mathbb{R}}^n$ then $x \le y$ implies $A \otimes x \le A \otimes y$.*

The letter I will stand for any square matrix whose diagonal entries are 0 and off-diagonal entries are $-\infty$. If A is an $n \times n$ matrix and k is a positive integer then the iterated product $A \otimes A \otimes \cdots \otimes A$ in which the symbol A appears k-times will be denoted by A^k and $A^* = I \oplus A \oplus A^2 \oplus \cdots \oplus A^n$. Any set of the form

$$\{A \otimes z; z \in \mathbb{R}^n\}$$

is a finitely generated max-*algebraic linear subspace* (sometimes also called a *maxcone*) whose essentially unique basis can be found efficiently [7].

Given $A = (a_{ij}) \in \overline{\mathbb{R}}^{n\times n}$ the symbol D_A denotes the *associated digraph*, that is the arc-weighted digraph (N, E, w) where $E = \{(i, j); a_{ij} > -\infty\}$ and $w(i, j) = a_{ij}$ for all $(i, j) \in E$. If $\pi = (i_1, \ldots, i_p)$ is a path in D_A then we denote $w(\pi, A) = a_{i_1 i_2} + a_{i_2 i_3} + \cdots + a_{i_{p-1} i_p}$ if $p > 1$ and $-\infty$ if $p = 1$. The number $p-1$ is called the *length* of π and $w(\pi, A)$ the *weight* of π. It can be easily seen that A^k is the matrix of greatest weights of paths of length k between all pairs of nodes in D_A. If $i_1 = i_p$ but $p > 1$ then π is called a *cycle*; it is called *positive* if $w(\pi, A) > 0$.

Max-algebra has been studied by many authors and the reader is referred to [14,1] or [4] for more information about max-algebra, see also [9–11,18,20,8,13,12,2,3,5].

A basic problem in max-algebra, motivated for instance by the efforts to solve synchronisation problems in some industrial processes [9,1] is:

EIGENVECTOR [EV]: Given $A \in \overline{\mathbb{R}}^{n\times n}$ find all $x \in \overline{\mathbb{R}}^n, x \neq (-\infty, \ldots, -\infty)^{\mathrm{T}}$ such that $A \otimes x = \lambda \otimes x$ for some $\lambda \in \overline{\mathbb{R}}$.

EV has been studied since 1960s and can now be efficiently solved [10,11,8,1,14,4]. It is known that an $n \times n$ matrix may have up to n eigenvalues. The set of eigenvectors corresponding to a particular eigenvalue is a finitely generated max-algebraic linear subspace.

In this paper we only discuss finite (real matrices) but most of the results can be extended to matrices over $\overline{\mathbb{R}}$. If $A = (a_{ij}) \in \mathbb{R}^{n\times n}$ then A has a unique (max-algebraic) eigenvalue equal to the maximum cycle mean (notation $\lambda(A)$) of the associated digraph, that is

$$\lambda(A) = \max \frac{a_{i_1 i_2} + a_{i_2 i_3} + \cdots + a_{i_{p-1} i_p}}{p}$$

where the maximisation is taken over all p-tuples of indices from N, and $p = 1, 2, \ldots, n$. All eigenvectors are finite and the set of eigenvectors can easily be described. It follows from the definition of $\lambda(A)$ that $\lambda(A) \le 0$ means that there are no positive cycles in D_A. It is known [1,14] that in this case A^* is the matrix of greatest weights of paths between all pairs of nodes in D_A with added zero entries on the diagonal. This matrix can be found using standard $O(n^3)$ algorithms such as Floyd–Warshall's [16].

For $A \in \mathbb{R}^{n\times n}$ and $\mu \in \mathbb{R}$ we denote

$$\mathrm{Sol}(A, \mu) = \{x \in \mathbb{R}^n; A \otimes x \le \mu \otimes x\}.$$

Theorem 2.1 *([6], Cor.2.9). If $A \in \mathbb{R}^{n\times n}$ and $\mu \in \mathbb{R}$ then*

1. *$\mathrm{Sol}(A, \mu) \neq \emptyset$ if and only if $\lambda(A) \le \mu$.*
2. *If $\mathrm{Sol}(A, \mu) \neq \emptyset$ then*

   $$\mathrm{Sol}(A, \mu) = \{(\mu^{-1} \otimes A)^* \otimes z; z \in \mathbb{R}^n\}.$$

Remark 2.1. It is known that $\mathrm{Sol}(A, \mu)$ is actually the set of (max-algebraic) eigenvectors of the matrix

$$I \oplus \mu^{-1} \otimes A.$$

Max-algebra also works with *dual operations*: $u \oplus' v = \min(u, v)$ and $u \otimes' v = u \otimes v$ for $u, v \in \mathbb{R}$ (the operators $\otimes$ and $\otimes'$ coincide for reals). The *conjugate* of a square matrix $A = (a_{ij})$ is $A^\sharp = (-a_{ji})$.

Theorem 2.2 *([9]). If $A \in \mathbb{R}^{n\times n}$, $b \in \mathbb{R}^n$ and $z \in \mathbb{R}^n$ then*

$$A \otimes z \le b \quad \text{if and only if } z \le A^\sharp \otimes' b.$$

Corollary 2.1. *If $A \in \mathbb{R}^{n\times n}$ and $v \in \mathbb{R}^n$ then $A \otimes (A^\sharp \otimes' v) \le v$ and (by isotonicity) $A \otimes z \le A \otimes (A^\sharp \otimes' v)$ for every z satisfying $A \otimes z \le v$.*

We can now use Theorems 2.1 and 2.2 to describe all solutions to SDNI. In (2) we obviously have $\mu = 0$ and B plays the role of A. For simplicity we denote $\mathrm{Sol}(B, 0)$ by $\mathrm{Sol}(B)$. We start with an immediate transcription of Theorem 2.1.

Theorem 2.3. *If $B \in \mathbb{R}^{n\times n}$ then*

1. *$\mathrm{Sol}(B) \neq \emptyset$ if and only if $\lambda(B) \le 0$.*
2. *If $\mathrm{Sol}(B) \neq \emptyset$ then*

   $$\mathrm{Sol}(B) = \{B^* \otimes z; z \in \mathbb{R}^n\}.$$

Hence the set of all solutions to SDNI is a finitely generated max-algebraic linear subspace.

Corollary 2.2. *The set of all solutions x to SDNI satisfying $x \le u$ is*

$$\left\{B^* \otimes z; z \le (B^*)^\sharp \otimes' u\right\}$$

and if this set is non-empty then the vector $B^* \otimes ((B^*)^\sharp \otimes' u)$ is the greatest element of this set. Hence the inequality

$$l \le B^* \otimes \left((B^*)^\sharp \otimes' u\right)$$

is necessary and sufficient for the existence of a solution to SDNI satisfying $l \le x \le u$.

Proof. It follows from (2) and Theorem 2.3 part 2. that solutions to SDNI are exactly the vectors of the form $B^* \otimes z, z \in \mathbb{R}^n$. Therefore solutions to SDNI satisfying $x \le u$ are exactly the vectors $B^* \otimes z, B^* \otimes z \le u$. By Theorem 2.2 this means the same as $B^* \otimes z, z \le (B^*)^\sharp \otimes' u$ and the first part follows. For the second part realise that $B^* \otimes ((B^*)^\sharp \otimes' u)$ is by Corollary 2.1 the greatest solution to SDNI satisfying $x \le u$. ∎

3. Solving BMISDNI

We start by another corollary to Theorem 2.3.

Corollary 3.1. *A necessary condition for BMISDNI to have a solution is that $\lambda(B) \le 0$. If this condition is satisfied then the BMISDNI is equivalent to finding a vector $z \in \mathbb{R}^n$ such that*

$$l \le B^* \otimes z \le u$$

and

$$(B^* \otimes z)_j \quad \text{integer for } j \in J.$$

Remark 3.1. Recall that $\lambda(B) \le 0$ means there is no positive cycle in D_B and in what follows we will assume that this condition is satisfied.

Theorem 3.1. *Let $A \in \mathbb{R}^{n\times n}$, $b \in \mathbb{R}^n$ and $J \subseteq N$. Let $\tilde{b}$ be defined by*

$$\tilde{b}_j = \lfloor b_j \rfloor \quad \text{for } j \in J,$$
$$\tilde{b}_j = b_j \quad \text{for } j \notin J.$$

Then the following are equivalent:

1. *There exists a $z \in \mathbb{R}^n$ such that $l \leq A \otimes z \leq b$ and* $(A \otimes z)_j$ *integer for $j \in J$.*
2. *There exists a $z \in \mathbb{R}^n$ such that $l \leq A \otimes z \leq \tilde{b}$ and* $(A \otimes z)_j$ *integer for $j \in J$.*
3. *There exists a $z \in \mathbb{R}^n$ such that $l \leq A \otimes z \leq A \otimes \left(A^\sharp \otimes' \tilde{b}\right)$ and* $(A \otimes z)_j$ *integer for $j \in J$.*

Proof. 1. $\Longrightarrow$ 2.: If $(A \otimes z)_j \leq b_j$ and $(A \otimes z)_j$ is integer then $(A \otimes z)_j \leq \lfloor b_j \rfloor = \tilde{b}_j$ by the definition of the integer part.

2. $\Longrightarrow$ 1.: $\tilde{b}_j = \lfloor b_j \rfloor \leq b_j$ for $j \in J$ by definition and the statement follows.

2. $\Longrightarrow$ 3.: If $A \otimes z \leq \tilde{b}$ then by Theorem 2.2 $z \leq A^\sharp \otimes' \tilde{b}$ and by isotonicity (Lemma 2.1) $A \otimes z \leq A \otimes \left(A^\sharp \otimes' \tilde{b}\right)$.

3. $\Longrightarrow$ 2.: By Corollary 2.1 $A \otimes \left(A^\sharp \otimes' \tilde{b}\right) \leq \tilde{b}$ and so if $A \otimes z \leq A \otimes \left(A^\sharp \otimes' \tilde{b}\right)$ then also $A \otimes \left(A^\sharp \otimes' \tilde{b}\right) \leq \tilde{b}$. ∎

Theorem 3.1 enables us to compile the following algorithm.

Algorithm 3.1. BMISDNI

Input: $B \in \mathbb{R}^{n\times n}$, $u, l \in \mathbb{R}^n$ and $J \subseteq N$

Output: x satisfying the BMISDNI conditions or an indication that no such vector exists.

[1] $A := B^*, x := u$
[2] $x_j := \lfloor x_j \rfloor$ for $j \in J$
[3] $z := A^\sharp \otimes' x, x := A \otimes z$
[4] If $l \nleq x$ then stop (no solution)
[5] If $l \leq x$ and x_j integer for $j \in J$ then stop else go to [2]

Theorem 3.2. *Algorithm BMISDNI is correct and requires $O(n^3+n^2L)$ operations of addition, maximum, minimum, comparison and integer part, where*

$$L = \sum_{j\in J} \left(u_j - l_j\right).$$

Proof. If the algorithm terminates at step [4] then there is no solution by the repeated use of Theorem 3.1.

The sequence of vectors x constructed by this algorithm is non-increasing by Corollary 2.1 and hence $x = A \otimes z \leq u$ if it terminates at step [5]. The remaining requirements of the BMISDNI are satisfied explicitly due to the conditions in step [5].

Computational complexity: The calculation of B^* is $O(n^3)$ [16]. Each run of the loop [2]–[5] is $O(n^2)$. In every iteration at least one component of $x_j, j \in J$ decreases by one and the statement now follows from the fact that all x_j range between l_j and u_j. ∎

Example 3.1. Let

$$B = \begin{pmatrix} -2 & 2.7 & -2.1 \\ -3.8 & -1 & -5.2 \\ 1.6 & 3.5 & -3 \end{pmatrix}$$

$u = (5.2, 0.8, 7.4)^T$, $J = \{1, 3\}$ (l is not specified). The algorithm BMISDNI will find:

$$A = B^* = \begin{pmatrix} 0 & 2.7 & -2.1 \\ -3.6 & 0 & -5.2 \\ 1.6 & 4.3 & 0 \end{pmatrix}$$

$$x = (5, 0.8, 7)^T,$$

$$z = A^\sharp \otimes' x = \begin{pmatrix} 0 & 3.6 & -1.6 \\ -2.7 & 0 & -4.3 \\ 2.1 & 5.2 & 0 \end{pmatrix} \otimes' x = \begin{pmatrix} 4.4 \\ 0.8 \\ 6 \end{pmatrix}$$

$$x = A \otimes z = (4.4, 0.8, 6)^T.$$

Now $x_1 \notin \mathbb{Z}$ so the algorithm continues by another iteration: $x = (4, 0.8, 6)^T$,

$$z = A^\sharp \otimes' x = (4, 0.8, 6)^T$$

and

$$x = A \otimes z = (4, 0.8, 6)^T,$$

which is a solution to the BMISDNI (provided that $l \leq x$) since $x_1, x_3 \in \mathbb{Z}$ (otherwise there is no solution).

4. Solving BMISDNI for integer matrices

In this section we prove that a solution to the BMISDNI can be found explicitly if B is integer.

The following will be useful:

Theorem 4.1. *Let $A \in \mathbb{Z}^{n\times n}$, $b \in \mathbb{R}^n$ and $A \otimes x = b$ for some $x \in \mathbb{R}^n$. Let $J \subseteq N$ and $\tilde{b}$ be defined by*

$$\tilde{b}_j = \lfloor b_j \rfloor \quad \text{for } j \in J$$
$$\tilde{b}_j = b_j \quad \text{for } j \notin J.$$

Then there exists an $\tilde{x} \in \mathbb{R}^n$ such that

$$A \otimes \tilde{x} \leq \tilde{b}$$

and

$$\left(A \otimes \tilde{x}\right)_j = \tilde{b}_j \quad \text{for } j \in J.$$

Proof. Let $k \in J$ be such that $b_k \notin \mathbb{Z}$. Since $b_k = \max_{j\in N}\left(a_{kj} + x_j\right)$, the set

$$S_k = \{s;\, a_{ks} + x_s > \lfloor b_k \rfloor\}$$

is non-empty and $x_s \notin \mathbb{Z}$ for every $s \in S_k$ since A is integer. Let $x^{(1)}$ be the vector defined by $x_j^{(1)} = \lfloor x_j \rfloor$ for $j \in S_k$ and $x_j^{(1)} = x_j$ otherwise. Clearly $x^{(1)} \leq x$ and so $A \otimes x^{(1)} \leq A \otimes x$ by Lemma 2.1. Let $r \in N$ be such that $\max_{j\in N}\left(a_{rj} + x_j\right) \in \mathbb{Z}$ (if any). Then $a_{rs} + x_s < \max_{j\in N}\left(a_{rj} + x_j\right)$ for all $s \in S_k$ since $x_s \notin \mathbb{Z}$. Therefore $\max_{j\in N}\left(a_{rj} + x_j^{(1)}\right) = \max_{j\in N}\left(a_{rj} + x_j\right)$. At the same time $\max_{j\in N}\left(a_{kj} + x_j^{(1)}\right) = \lfloor b_k \rfloor$ yielding that the number of indices r such that $\max_{j\in N}\left(a_{rj} + x_j^{(1)}\right) = \lfloor b_r \rfloor$ has increased by at least one compared to x. If there is still an index $k \in J$ such that $S_k \neq \emptyset$ then we repeat this construction and obtain $x^{(2)}, x^{(3)}, \ldots$. Since the number of indices r for which $\max_{j\in N}\left(a_{rj} + x_j\right) \in \mathbb{Z}$ increases at every step, this process stops after a finite number of steps with a vector $\tilde{x}$ satisfying the conditions in the theorem statement. ∎

Corollary 4.1. *Under the assumptions of Theorem 4.1 and using the same notation, if* $\bar{x} = A^\sharp \otimes' \tilde{b}$ *then*

$$A \otimes \bar{x} \leq \tilde{b}$$

and

$$(A \otimes \bar{x})_j = \tilde{b}_j \quad \text{for } j \in J.$$

Proof. The inequality follows from Corollary 2.1. Let $\tilde{x}$ be the vector described in Theorem 4.1. By Theorem 2.2 we have $\tilde{x} \leq \bar{x}$ implying that

$$\tilde{b}_j = \left(A \otimes \tilde{x}\right)_j \leq (A \otimes \bar{x})_j \leq \tilde{b}_j \quad \text{for } j \in J$$

which concludes the proof. ■

Our main result is:

Theorem 4.2. *Let* $B \in \mathbb{Z}^{n\times n}$, $\lambda(B) \leq 0$, $A = B^*$, $b = A \otimes \left(A^\sharp \otimes' u\right)$ *and* $\tilde{b}$ *be defined by*

$$\tilde{b}_j = \lfloor b_j \rfloor \quad \text{for } j \in J$$

and

$$\tilde{b}_j = b_j \quad \text{for } j \notin J.$$

Then the BMISDNI has a solution if and only if

$$l \leq A \otimes \left(A^\sharp \otimes' \tilde{b}\right),$$

and $\hat{x} = A \otimes \left(A^\sharp \otimes' \tilde{b}\right)$ *is then the greatest solution (that is* $y \leq \hat{x}$ *for any solution* y*).*

Proof. Note first that A is an integer matrix and we therefore may apply Corollary 4.1 to A.

"If": By Corollary 2.1 $\hat{x} \leq \tilde{b} \leq b \leq u$. Let us take in Corollary 4.1 (and Theorem 4.1) $x = A^\sharp \otimes' u$. Then $\hat{x} = A \otimes \bar{x}$ and so $\hat{x}_j \in \mathbb{Z}$ for $j \in J$.

"Only if": Let y be a solution. Then $y = A \otimes w \leq u$ for some $w \in \mathbb{R}^n$, thus by Theorem 2.2

$$w \leq A^\sharp \otimes' u$$

and so

$$y = A \otimes w \leq A \otimes \left(A^\sharp \otimes' u\right) = b.$$

Since $y_j \in \mathbb{Z}$ for $j \in J$ we also have

$$A \otimes w = y \leq \tilde{b}.$$

Hence by Theorem 2.2

$$w \leq A^\sharp \otimes' \tilde{b}$$

and by Lemma 2.1 then

$$l \leq y = A \otimes w \leq A \otimes \left(A^\sharp \otimes' \tilde{b}\right) = \hat{x}.$$

We also have $\hat{x} \leq \tilde{b} \leq b \leq u$ by Corollary 2.1 and $\hat{x}_j \in \mathbb{Z}$ for $j \in J$ by Corollary 4.1 as above, hence $\hat{x}$ is the greatest solution. ■

Example 4.1. Let

$$B = \begin{pmatrix} -2 & 2 & -2 \\ -3 & -1 & -4 \\ 1 & 3 & -3 \end{pmatrix}$$

$u = (3.5, 0.8, 5.7)^T$, $J = \{1, 3\}$ (l is not specified). Theorem 4.2 provides:

$$A = B^* = \begin{pmatrix} 0 & 2 & -2 \\ -3 & 0 & -4 \\ 1 & 3 & 0 \end{pmatrix}$$

$$A^\sharp \otimes' u = \begin{pmatrix} 0 & 3 & -1 \\ -2 & 0 & -3 \\ 2 & 4 & 0 \end{pmatrix} \otimes' u = \begin{pmatrix} 3.5 \\ 0.8 \\ 4.8 \end{pmatrix}$$

$$b = A \otimes \left(A^\sharp \otimes' u\right) = \begin{pmatrix} 3.5 \\ 0.8 \\ 4.8 \end{pmatrix}$$

$$\tilde{b} = \begin{pmatrix} 3 \\ 0.8 \\ 4 \end{pmatrix}$$

$$\hat{x} = A \otimes \left(A^\sharp \otimes' \tilde{b}\right) = (3, 0.8, 4)^T.$$

By Theorem 4.2 $\hat{x}$ is the greatest solution to the BMISDNI provided that $l \leq \hat{x}$ (otherwise there is no solution).

5. A note on an application

As a by-product, this paper provides a solution technique for solving a scheduling-type of problems.

Consider a multiprocessor interactive system (of production, transportation, information technology, etc.) in which the individual processors work in stages and a processor, say P cannot start its work in a new stage until all or some of the processors have finished their activities necessary for P [10,11,14]. It is assumed that each of the processors $P_1, \ldots, P_n$ can work for all other processors simultaneously and that a processor starts all these activities as soon as it starts to work.

Let $x_i(r)$ denote the starting time of the rth stage on processor i $(i = 1, \ldots, n)$ and let a_{ij} denote the duration of the operation at which the jth processor prepares the component necessary for the ith processor in the $(r + 1)$st stage $(i, j = 1, \ldots, n)$. Then

$$x_i(r + 1) = \max(x_1(r) + a_{i1}, \ldots, x_n(r) + a_{in}) \quad (i = 1, \ldots, n;\ r = 0, 1, \ldots)$$

or, in max-algebraic notation

$$x(r + 1) = A \otimes x(r)(r = 0, 1, \ldots)$$

where $A = (a_{ij})$ is a *production matrix*. We say that the system is in a *steady state* [9] if it moves forward in regular steps, that is if for some λ we have $x(r + 1) = \lambda \otimes x(r)$ for all r. This implies $A \otimes x(r) = \lambda \otimes x(r)$ for all r. Therefore the system is in a steady state in all stages if and only if for some λ, the starting times vector $x(0)$ is a solution to

$$A \otimes x = \lambda \otimes x.$$

For practical reasons it may be necessary to find the starting times for the individual processors within given bounds, for instance $u_j \geq x_j \geq l_j$ for all j. If an eigenvector within these bounds does not exist then it may be interesting to find a subeigenvector, that is an x satisfying

$$A \otimes x \leq \lambda \otimes x \tag{3}$$

and $u_j \geq x_j \geq l_j$ for all j (in this case a new stage at any processor starts within a given time limit λ after the beginning of the previous stage). Solvability of (3) is answered by Theorem 2.1 and once this is affirmative it remains to solve

$$B \otimes x \leq x$$

$$l \leq x \leq u$$

where $B = \lambda^{-1} \otimes A$. The answer to this question is given in Corollary 2.2.

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References

[1] F.L. Baccelli, G. Cohen, G.-J. Olsder, J.-P. Quadrat, Synchronization and Linearity, John Wiley, Chichester, New York, 1992.
[2] R.B. Bapat, A max version of the Perron Frobenius theorem, Linear Algebra Appl. 275/276 (1998) 3–18.
[3] R.B. Bapat, Pattern properties and spectral inequalities in max algebra, SIAM J. Matrix Anal. Appl. 16 (1995) 964–976.
[4] P. Butkovic, Max-algebra: The linear algebra of combinatorics? Linear Algebra Appl. 367 (2003) 313–335.
[5] R.E. Burkard, P. Butkovic, Max algebra and the linear assignment problem, Math. Program. Ser. B 98 (2003) 415–429.
[6] P. Butkovic, H. Schneider, Applications of max-algebra to diagonal scaling of matrices, Electron. J. Linear Algebra 13 (2005) 262–273.
[7] P. Butkovic, H. Schneider, S. Sergeev, Generators, extremals and bases of max cones, Linear Algebra Appl. 421 (2007) 394–406.
[8] G. Cohen, D. Dubois, J.-P. Quadrat, M. Viot, A linear-system-theoretic view of discrete-event processes and its use for performance evaluation in manufacturing, IEEE Trans. Automat. Control AC-30 (3) (1985).
[9] R.A. Cuninghame-Green, Describing industrial processes with interference and approximating their steady-state behaviour, Oper. Res. Quarterly 13 (1962) 95–100.
[10] R.A. Cuninghame-Green, Minimax Algebra, in: Lecture Notes in Economics and Mathematical Systems, vol. 166, Springer, Berlin, 1979.
[11] R.A. Cuninghame-Green, Minimax Algebra and Applications, in: Advances in Imaging and Electron Physics, vol. 90, Academic Press, New York, 1995, pp. 1–121.
[12] S. Gaubert, Théorie des systèmes liné aires dans les dioïdes, Thèse, Ecole des Mines de Paris, 1992.
[13] M. Gondran, M. Minoux, Valeurs propres et vecteur propres dans les dioïdes et leur interprétation en théorie des graphes, Bulletin de la direction des etudes et recherches, Serie C, Mathematiques et Informatiques 2 (1977) 25–41.
[14] B. Heidergott, G.J. Olsder, J. van der Woude, Max plus at work: Modeling and analysis of synchronized systems, A Course on Max-Plus Algebra, PUP, 2006.
[15] D. Hochbaum, J. Naor, Simple and fast algorithms for linear and integer programs with two variables per inequality, SIAM J. Comput. 23 (6) (1994) 1179–1192.
[16] C.H. Papadimitriou, K. Steiglitz, Combinatorial Optimization-Algorithms and Complexity, Dover Publications, 1998.
[17] D.R. Shier, A decomposition algorithm for optimality problems in tree-structured networks, Discrete Math. 6 (1973) 175–189.
[18] N.N. Vorobjov, Extremal algebra of positive matrices, Elektronische Datenverarbeitung und Kybernetik 3 (1967) 39–71 (in Russian).
[19] M. Conforti, M. Di Summa, F. Eisenbrand, L. Wolsey, Network formulations of mixed-integer programs, CORE discussion paper 2006/117, Université Catholique de Louvain, Belgium.
[20] K. Zimmermann, Extremální algebra, *Výzkumná publikace Ekonomicko — matematické laboratoře při Ekonomickém ústavě ČSAV*, 46, Praha, 1976 (in Czech).