

# EXTENSION AND GENERALIZATION INEQUALITIES INVOLVING THE KHATRI-RAO PRODUCT OF SEVERAL POSITIVE MATRICES

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Recently, there have been many authors, who established a number of inequalities involving Khatri-Rao and Hadamard products of two positive matrices. In this paper, the results are established in the following three ways. First, we find generalization of the inequalities involving Khatri-Rao product using results given by Liu (1999), Mond and Pečarić (1997), Cao et al. (2002), Chollet (1997), and Visick (2000). Second, we recover and develop some results of Visick. Third, the results are extended to the case of Khatri-Rao product of any finite number of matrices. These results lead to inequalities involving Hadamard product, as a special case.

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## 1. Introduction

Consider matrices  $A$  and  $B$  of order  $m \times n$  and  $p \times q$ , respectively. Let  $A = [A_{ij}]$  be partitioned with  $A_{ij}$  of order  $m_i \times n_j$  as the  $(i, j)$ th block submatrix and let  $B = [B_{kl}]$  be partitioned with  $B_{kl}$  of order  $p_k \times q_l$  as the  $(k, l)$ th block submatrix ( $m = \sum_{i=1}^t m_i$ ,  $n = \sum_{j=1}^d n_j$ ,  $p = \sum_{k=1}^u p_k$ ,  $q = \sum_{l=1}^v q_l$ ). For simplicity, we say that  $A$  and  $B$  are *compatible partitioned* if  $A = [A_{ij}]_{i,j=1}^t$  and  $B = [B_{ij}]_{i,j=1}^t$  are square matrices of order  $m \times m$  and partitioned, respectively, with  $A_{ij}$  and  $B_{ij}$  of order  $m_i \times m_j$  ( $m = \sum_{i=1}^t m_i = \sum_{j=1}^t m_j$ ).

Let  $A \otimes B$ ,  $A \circ B$ ,  $A \ominus B$ , and  $A * B$  be the Kronecker, Hadamard, Tracy-Singh, and Khatri-Rao products, respectively, of  $A$  and  $B$ . The definitions of the mentioned four matrix products are given by Liu in [5, 6] as follows:

(i) *Kronecker product*

$$A \otimes B = [a_{ij}B]_{ij}, \quad (1.1)$$

where  $A = [a_{ij}]$ ,  $B = [b_{kl}]$  are scalar matrices of order  $m \times n$  and  $p \times q$ , respectively,  $a_{ij}B$  is of order  $p \times q$ , and  $A \otimes B$  of order  $mp \times nq$ ;

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### (ii) Hadamard product

$$A \circ B = [a_{ij}b_{ij}]_{ij} = B \circ A, \quad (1.2)$$

where  $A = [a_{ij}]$ ,  $B = [b_{ij}]$  are scalar matrices of order  $m \times n$ ,  $a_{ij}b_{ij}$  is a scalar, and  $A \circ B$  is of order  $m \times n$ ;

### (iii) Tracy-Singh product

$$A \Theta B = [A_{ij} \Theta B]_{ij} = [[A_{ij} \otimes B_{kl}]_{kl}]_{ij}, \quad (1.3)$$

where  $A = [A_{ij}]$ ,  $B = [B_{kl}]$  are partitioned matrices of order  $m \times n$  and  $p \times q$ , respectively,  $A_{ij}$  is of order  $m_i \times n_j$ ,  $B_{kl}$  of order  $p_k \times q_l$ ,  $A_{ij} \otimes B_{kl}$  of order  $m_i p_k \times n_j q_l$ ,  $A_{ij} \Theta B$  of order  $m_i p \times n_j q$  ( $m = \sum_{i=1}^t m_i$ ,  $n = \sum_{j=1}^d n_j$ ,  $p = \sum_{k=1}^u p_k$ ,  $q = \sum_{l=1}^v q_l$ ), and  $A \Theta B$  of order  $mp \times nq$ ;

### (iv) Khatri-Rao product

$$A * B = [A_{ij} \otimes B_{ij}]_{ij}, \quad (1.4)$$

where  $A = [A_{ij}]$ ,  $B = [B_{ij}]$  are partitioned matrices of order  $m \times n$  and  $p \times q$ , respectively,  $A_{ij}$  is of order  $m_i \times n_j$ ,  $B_{kl}$  of order  $p_i \times q_j$ ,  $A_{ij} \otimes B_{ij}$  of order  $m_i p_i \times n_j q_j$  ( $m = \sum_{i=1}^t m_i$ ,  $n = \sum_{j=1}^d n_j$ ,  $p = \sum_{i=1}^t p_i$ ,  $q = \sum_{j=1}^d q_j$ ), and  $A * B$  of order  $M \times N$  ( $M = \sum_{i=1}^t m_i p_i$ ,  $N = \sum_{j=1}^d n_j q_j$ ).

In general,  $A \Theta B \neq B \Theta A$ ,  $A \otimes B \neq B \otimes A$ ,  $A * B \neq B * A$ , but if  $A = [a_{ij}]$  is a scalar matrix and  $B = [B_{ij}]$  is a partitioned matrix, then  $A * B = B * A$ . Additionally, Liu [5] shows that the Khatri-Rao product can be viewed as a generalized Hadamard product and the Tracy-Singh product as a generalized Kronecker product, as follows:

(1) for a nonpartitioned matrix  $A$ , their  $A \Theta B$  is  $A \otimes B$ , that is,

$$A \Theta B = [a_{ij} \Theta B]_{ij} = [[a_{ij} \otimes B_{kl}]_{kl}]_{ij} = [[a_{ij} B_{kl}]_{kl}]_{ij} = [a_{ij} B]_{ij} = A \otimes B; \quad (1.5)$$

(2) for nonpartitioned matrices  $A$  and  $B$  of order  $m \times n$ , their  $A * B$  is  $A \circ B$ , that is,

$$A * B = [a_{ij} \otimes b_{ij}]_{ij} = [a_{ij} b_{ij}]_{ij} = A \circ B. \quad (1.6)$$

The Khatri-Rao and Tracy-Singh products are related by the following relation [5, 6]:

$$A * B = Z_1^T (A \Theta B) Z_2, \quad (1.7)$$

where  $A = [A_{ij}]$  is partitioned with  $A_{ij}$  of order  $m_i \times n_j$  and  $B = [B_{kl}]$  is partitioned with  $B_{kl}$  of order  $p_k \times q_l$  ( $m = \sum_{i=1}^t m_i$ ,  $n = \sum_{j=1}^d n_j$ ,  $p = \sum_{k=1}^u p_k$ ,  $q = \sum_{l=1}^v q_l$ ),  $Z_1$  is an  $mp \times r$  ( $r = \sum_{i=1}^t m_i p_i$ ) matrix of zeros and ones, and  $Z_2$  is an  $nq \times s$  ( $s = \sum_{j=1}^d n_j q_j$ ) matrix

of zeros and ones such that  $Z_1^T Z_1 = I_r$ ,  $Z_2^T Z_2 = I_s$  ( $I_r$  and  $I_s$  are  $r \times r$  and  $s \times s$  identity matrices, resp.).

In particular, if  $m = n$  and  $p = q$ , then there exists an  $mp \times r$  ( $r = \sum_{i=1}^t m_i p_i$ ) matrix  $Z$  such that  $Z^T Z = I_r$  ( $I_r$  is an  $r \times r$  identity matrix) and

$$A * B = Z^T (A \oplus B) Z. \tag{1.8}$$

Here

$$Z = \begin{bmatrix} Z_1 & & \\ & \ddots & \\ & & Z_t \end{bmatrix}, \tag{1.9}$$

where each  $Z_i = [0_{i1} \cdots 0_{ii-1} I_{m_i p_i} 0_{ii+1} \cdots 0_{in}]^T$  is a real matrix of zeros and ones, and  $0_{ik}$  is a  $m_i p_i \times m_i p_k$  zero matrix for any  $k \neq i$ . Note also that  $Z_i^T Z_i = I$  and

$$Z_i^T (A_{ij} \oplus B) Z_j = Z_i^T (A_{ij} \otimes B_{kl})_{kl} Z_j = A_{ij} \otimes B_{ij}, \quad i, j = 1, 2, \dots, t. \tag{1.10}$$

In [5–8], the authors proved a number of equalities and inequalities involving Khatri-Rao and Hadamard products of two matrices. Here we extend these results in three ways. First, we establish new attractive equalities and inequalities involving Khatri-Rao product of matrices. Second, we recover and develop some results of Visick, for example, [8, Theorem 11, page 54]. This does not follow simply from the work of Visick. Third, the results are extended to the case of Khatri-Rao products of any finite number of matrices. This result leads to inequalities involving Hadamard product, as a special case.

We use the following notations:

- (i)  $M_{m,n}$ —the set of all  $m \times n$  matrices over the complex number field  $\mathbb{C}$  and when  $m = n$ , we write  $M_m$  instead of  $M_{m,m}$ ;
- (ii)  $A^T, A^*, A^+, A^{-1}$ —the transpose, conjugate transpose, Moore-Penrose inverse, and inverse of matrix  $A$ , respectively.

For Hermitian matrices  $A$  and  $B$ , the relation  $A > B$  means that  $A - B > 0$  is a positive definite and the relation  $A \geq B$  means  $A - B \geq 0$  is a positive semidefinite. Given a positive definite matrix  $A$ , its positive definite square root is denoted by  $A^{1/2}$ . We use the known fact “for positive definite matrices  $A$  and  $B$ , the relation  $A \geq B$  implies  $A^{1/2} \geq B^{1/2}$ ” which is called the *Löwner-Heinz theorem*.

## 2. Some notations and preliminary results

Let  $A$  be a positive definite  $m \times m$  matrix. The *spectral decomposition* of matrix  $A$  assures that there exists a unitary matrix  $U$  such that

$$A = U^* D U = U^* \text{diag}(\lambda_i) U, \quad U^* U = I_m, \tag{2.1}$$

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where  $D = \text{diag}(\lambda_i) = \text{diag}(\lambda_1, \dots, \lambda_m)$  is the diagonal matrix with diagonal entries  $\lambda_i$  ( $\lambda_i$  are the positive eigenvalues of  $A$ ). For any real number  $r$ ,  $A^r$  is defined by

$$A^r = U^* D^r U = U^* \text{diag}(\lambda_i^r) U. \quad (2.2)$$

If  $A \in M_{m,n}$  is any matrix with  $\text{rank}(A) = s$ , the *singular value decomposition* of  $A$  assures that there are unitary matrices  $U \in M_m$  and  $V \in M_n$  such that

$$A = U \Sigma V^*. \quad (2.3)$$

Here  $\Sigma = \begin{bmatrix} W & 0 \\ 0 & 0 \end{bmatrix} \in M_{m,n}$ , where  $W = \text{diag}(\zeta_1, \dots, \zeta_s) \in M_s$  is the diagonal matrix with diagonal entries  $\zeta_i$  ( $i = 1, 2, \dots, s$ ) and  $\zeta_1 \geq \zeta_2 \geq \dots \geq \zeta_s > 0$  are the singular values of  $A$ , that is,  $\zeta_1 \geq \zeta_2 \geq \dots \geq \zeta_s > 0$  are positive square roots of positive eigenvalues of  $A^*A$  and  $AA^*$ . The *Moore-Penrose inverse* of  $A$  is defined by

$$A^+ = V \begin{bmatrix} W^{-1} & 0 \\ 0 & 0 \end{bmatrix} U^* \in M_{n,m}, \quad (2.4)$$

where  $W^{-1} = \text{diag}(\zeta_1^{-1}, \zeta_2^{-1}, \dots, \zeta_s^{-1}) \in M_s$  is the diagonal matrix with diagonal entries  $\zeta_i^{-1}$  ( $i = 1, 2, \dots, s$ ).  $A^+$  is a unique matrix which satisfies the following conditions:

$$AA^+A = A, \quad A^+AA^+ = A^+, \quad (AA^+)^* = AA^+, \quad (A^+A)^* = A^+A. \quad (2.5)$$

For any compatible partitioned matrices  $A, B, C$ , and  $D$ , we will make a frequent use of the following properties of the Tracy-Singh product (see e.g., [1, 3, 5, 10]):

- (a)  $(A \Theta B)(C \Theta D) = (AC) \Theta (BD)$  if  $AC$  and  $BD$  are well defined;
- (b)  $(A \Theta B)^r = A^r \Theta B^r$  if  $A \in M_m, B \in M_n$  are positive semidefinite matrices and  $r$  is any real number;
- (c)  $(A \Theta B)^* = A^* \Theta B^*$ ;
- (d)  $(A \Theta B)^+ = A^+ \Theta B^+$ .

If  $A \in M_m$  and  $B \in M_n$  are positive semidefinite matrices, then (see, [3, 10])

- (e)  $A \Theta B \geq 0$ ;
- (f)  $\lambda_1(A \Theta B) = \lambda_1(A)\lambda_1(B)$ ,  $\lambda_{mn}(A \Theta B) = \lambda_m(A)\lambda_n(B)$ ,

where  $\lambda_1(A)$ ,  $\lambda_m(A)$  are the largest and smallest eigenvalues, respectively, of a matrix  $A$ , and  $\lambda_1(B)$ ,  $\lambda_n(B)$  are the largest and smallest eigenvalues, respectively, of a matrix  $B$ .

The Khatri-Rao and Tracy-Singh products of  $k$  matrices  $A_i$  ( $1 \leq i \leq k, k \geq 2$ ) will be denoted by  $\prod_{i=1}^k *A_i = A_1 * A_2 * \dots * A_k$  and  $\prod_{i=1}^k \Theta A_i = A_1 \Theta A_2 \Theta \dots \Theta A_k$ , respectively.

For a finite number of matrices  $A_i$  ( $i = 1, 2, \dots, k$ ), the properties (a)–(d) become as in Lemma 2.1 and the connection between the Khatri-Rao and Tracy-Singh products in (1.7) and (1.8) becomes as in Lemma 2.2.

LEMMA 2.1. Let  $A_i$  and  $B_i$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be compatible partitioned matrices. Then

(i)

$$\left( \prod_{i=1}^k \ominus A_i \right) \left( \prod_{i=1}^k \ominus B_i \right) = \left( \prod_{i=1}^k \ominus (A_i B_i) \right) \quad (2.6)$$

if  $A_i B_i$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) are well defined;

(ii)

$$\left( \prod_{i=1}^k \ominus A_i \right)^+ = \prod_{i=1}^k \ominus A_i^+, \quad k = 2, 3, \dots; \quad (2.7)$$

(iii)

$$\left( \prod_{i=1}^k \ominus A_i \right)^* = \prod_{i=1}^k \ominus A_i^*, \quad \left( \prod_{i=1}^k * A_i \right)^* = \prod_{i=1}^k * A_i^*, \quad k = 2, 3, \dots; \quad (2.8)$$

(iv)

$$\left( \prod_{i=1}^k \ominus A_i \right)^r = \prod_{i=1}^k \ominus A_i^r \quad \text{if } A_i \in M_{m(i)} \quad (1 \leq i \leq k, k \geq 2) \quad (2.9)$$

are positive semidefinite matrices and  $r$  is any real number;

(v)

$$\left( \prod_{i=1}^k (A_i \ominus B_i) \right) = \left( \prod_{i=1}^k A_i \right) \ominus \left( \prod_{i=1}^k B_i \right), \quad k = 2, 3, \dots \quad (2.10)$$

*Proof.* The proof is immediately derived by induction on  $k$ . □

LEMMA 2.2. Let  $A_i = [A_{gh}^{(i)}] \in M_{m(i),n(i)}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g, h)$ th block submatrix ( $m = \prod_{i=1}^k m(i)$ ,  $n = \prod_{i=1}^k n(i)$ ,  $r = \sum_{j=1}^t \prod_{i=1}^k m_j(i)$ ,  $s = \sum_{j=1}^t \prod_{i=1}^k n_j(i)$ ,  $m(i) = \sum_{j=1}^t m_j(i)$ ,  $n(i) = \sum_{j=1}^t n_j(i)$ ). Then there exist two real matrices  $Z_1$  of order  $m \times r$  and  $Z_2$  of order  $n \times s$  such that  $Z_1^T Z_1 = I_r$ ,  $Z_2^T Z_2 = I_s$  ( $Z_1, Z_2$  are real matrices of zeros and ones) and

$$\prod_{i=1}^k * A_i = Z_1^T \left( \prod_{i=1}^k \ominus A_i \right) Z_2, \quad k = 2, 3, \dots, \quad (2.11)$$

where  $I_r$  and  $I_s$  are identity matrices of order  $r \times r$  and  $s \times s$ , respectively. In particular, if

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$m(i) = n(i)$  ( $1 \leq i \leq k, k \geq 2$ ), then there exists an  $m \times r$  matrix  $Z$  of zeros and ones such that  $Z^T Z = I_r$ ,

$$\prod_{i=1}^k *A_i = Z^T \left( \prod_{i=1}^k \Theta A_i \right) Z, \quad k = 2, 3, \dots, \quad (2.12)$$

and  $ZZ^T$  is an  $m \times m$  diagonal matrix of zeros and ones, so

$$0 \leq ZZ^T \leq I_m, \quad (2.13)$$

where  $m = \prod_{i=1}^k m(i)$ .

*Proof.* The special case in (2.12) of Lemma 2.2 is proved in [3, Corollary 2.2] and (2.13) follows immediately by the definition of matrix  $Z$ . We give proof of the general case in (2.11) of Lemma 2.2 for the sake of convenience. We proceed by induction on  $k$ . If  $k = 2$ , then (2.11) is true by (1.7). Now suppose (2.11) holds for the Khatri-Rao product of  $k$  matrices, that is, there exist an  $m \times r$  matrix  $P_{kr}$  of zeros and ones and an  $n \times s$  matrix  $R_{ks}$  of zeros and ones such that  $P_{kr}^T P_{kr} = I_r$ ,  $R_{ks}^T R_{ks} = I_s$ , and

$$\prod_{i=1}^k *A_i = P_{kr}^T \left( \prod_{i=1}^k \Theta A_i \right) R_{ks}, \quad k = 2, 3, \dots \quad (2.14)$$

We will prove that it is true for the Khatri-Rao product of  $k+1$  matrices. Then by (1.7), there exist an  $m(1)r \times r$  matrix  $Q_1$  of zeros and ones and an  $n(1)s \times s$  matrix  $Q_2$  of zeros and ones such that  $Q_1^T Q_1 = I_r$ ,  $Q_2^T Q_2 = I_s$ , and

$$\begin{aligned} \prod_{i=1}^{k+1} *A_i &= A_1 * \left( \prod_{i=2}^{k+1} *A_i \right) = Q_1^T \left( A_1 \Theta \prod_{i=2}^{k+1} *A_i \right) Q_2 = Q_1^T \left\{ A_1 \Theta \left( P_{kr}^T \left( \prod_{i=2}^{k+1} \Theta A_i \right) R_{ks} \right) \right\} Q_2 \\ &= Q_1^T \left\{ \left( I_{m(1)} A_1 I_{n(1)} \right) \Theta \left( P_{kr}^T \left( \prod_{i=2}^{k+1} \Theta A_i \right) R_{ks} \right) \right\} Q_2 \\ &= Q_1^T \left( I_{m(1)} \Theta P_{kr}^T \right) \left\{ A_1 \Theta \left( \prod_{i=2}^{k+1} \Theta A_i \right) \right\} \left( I_{n(1)} \Theta R_{ks} \right) Q_2 \\ &= Q_1^T \left( I_{m(1)} \Theta P_{kr}^T \right) \left( \prod_{i=1}^{k+1} \Theta A_i \right) \left( I_{n(1)} \Theta R_{ks} \right) Q_2. \end{aligned} \quad (2.15)$$

Letting  $Z_1 = (I_{m(1)} \Theta P_{kr}) Q_1$  and  $Z_2 = (I_{n(1)} \Theta R_{ks}) Q_2$ , the inductive step is complete. Here  $Q_1 = P_{2r} = P_r$ ,  $Q_1 = R_{2s} = R_s$ , and it is a simple matter to verify that

$$\begin{aligned} Z_1 &= (I_{m(1)} \Theta P_{kr}) P_r = P_{(k+1)r}, & Z_1^T &= P_r^T (I_{m(1)} \Theta P_{kr}^T) = P_{(k+1)r}^T, \\ Z_2 &= (I_{n(1)} \Theta R_{ks}) R_s = R_{(k+1)s}, & Z_2^T &= R_s^T (I_{n(1)} \Theta R_{ks}^T) = R_{(k+1)s}^T. \end{aligned} \quad (2.16)$$

Note that

$$\begin{aligned}
 Z_1^T Z_1 &= P_r^T (I_{m(1)} \ominus P_{kr}^T) (I_{m(1)} \ominus P_{kr}) P_r = Q_1^T (I_{m(1)} \ominus P_{kr}^T) (I_{m(1)} \ominus P_{kr}) Q_1 \\
 &= Q_1^T (I_{m(1)} I_{m(1)} \ominus P_{kr}^T P_{kr}) Q_1 \\
 &= Q_1^T (I_{m(1)} \ominus I_r) Q_1 \quad (I_{m(1)} \ominus I_r = I_{m(1)r}) \\
 &= Q_1^T (I_{m(1)r}) Q_1 = Q_1^T Q_1 = I_r.
 \end{aligned}
 \tag{2.17}$$

Similarly, it is easy to verify that  $Z_2^T Z_2 = I_s$ . □

LEMMA 2.3. Let  $\alpha$  be a nonempty subset of the set  $\{1, 2, \dots, m\}$  and let  $A \in M_m$  be a positive semidefinite matrix. Then (see Chollet [4])

(i) if either  $-1 \leq r \leq 0$  or  $1 \leq r \leq 2$ , then

$$A^r(\alpha) \geq A(\alpha)^r, \quad \forall \alpha; \tag{2.18}$$

(ii) if  $0 \leq r \leq 1$ , then

$$A^r(\alpha) \leq A(\alpha)^r, \quad \forall \alpha, \tag{2.19}$$

where  $A(\alpha)$  is the principal submatrix of  $A$  whose entries are in the intersection of the rows and columns of  $A$  specified by  $\alpha$ .

LEMMA 2.4. Let  $X_j > 0$  ( $j = 1, 2, \dots, k$ ) be  $n \times n$  matrices with eigenvalues in the interval  $[w, W]$  and  $U_j$  ( $j = 1, 2, \dots, k$ ) are  $r \times m$  matrices such that  $\sum_{j=1}^k U_j U_j^* = I$ . Then (see Mond and Pečarić [7])

(i) for every real  $p > 1$  and  $p < 0$ ,

$$\sum_{j=1}^k U_j X_j^p U_j^* \leq \mu \left\{ \sum_{j=1}^k U_j X_j U_j^* \right\}^p, \tag{2.20}$$

where

$$\mu = \frac{\delta^p - \delta}{(p-1)(\delta-1)} \left( \frac{p-1}{p} \frac{\delta^p - 1}{\delta^p - \delta} \right)^p, \quad \delta = \frac{W}{w}. \tag{2.21}$$

While for  $0 < p < 1$ , the reverse inequality holds in (2.20);

(ii) for every real  $p > 1$  and  $p < 0$ ,

$$\left\{ \sum_{j=1}^k U_j X_j^p U_j^* \right\} - \left\{ \sum_{j=1}^k U_j X_j U_j^* \right\}^p \leq \gamma \{I\}, \tag{2.22}$$

where

$$\gamma = \frac{Ww^p - wW^p}{W-w} + (p-1) \left( \frac{1}{p} \frac{W^p - w^p}{W-w} \right)^{p/(p-1)}. \tag{2.23}$$

While for  $0 < p < 1$ , the reverse inequality holds in (2.22).

### 3. New applications and results

Based on the basic results in Section 2 and the general connection between the Khatri-Rao and Tracy-Singh products in Lemma 2.2, we generalize and derive some equalities and inequalities in works of Visick [8, Corollary 3, Theorem 4], Chollet [4], and Mond and Pečarić [7] with respect to the Khatri-Rao product and extend these results to any finite number of matrices. These results lead to inequalities involving Hadamard products, as a special case.

**THEOREM 3.1.** *Let  $A_i = [A_{gh}^{(i)}] \in M_{m(i),n(i)}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g, h)$ th block submatrix ( $m = \prod_{i=1}^k m(i)$ ,  $n = \prod_{i=1}^k n(i)$ ) and let  $Z_1$  and  $Z_2$  be the real matrices of zeros and ones that satisfy (2.11). Then*

- (i) *there exists an  $m \times (m - r)$  matrix  $Q_{(m)}$  of zeros and ones such that the block matrix  $\Omega = [Z_1 \ Q_{(m)}]$  is an  $m \times m$  permutation matrix.  $Q_{(m)}$  is not unique but for any such choice of  $Q_{(m)}$ ,*

$$Z_1^T Q_{(m)} = 0, \quad Q_{(m)}^T Q_{(m)} = I_{m-r}, \quad Q_{(m)} Q_{(m)}^T + Z_1 Z_1^T = I_m \quad (3.1)$$

- (ii) *for any  $m \times n$  matrix  $L$ ,*

$$Z_1^T L L^* Z_1 \geq (Z_1^T L Z_2) (Z_1^T L Z_2)^* \geq 0. \quad (3.2)$$

*Proof.* Though the proof is quite similar to the proof of [8, Corollary 3(iii) and (vii)] for Hadamard product, we give proof for the sake of convenience.

(i) It is evident from the structure of  $Z_1$  that it may be considered as part of an  $m \times m$  permutation matrix  $\Omega = [Z_1 \ Q_{(m)}]$ , where  $Q_{(m)}$  is an  $m \times (m - r)$  matrix of zeros and ones. For example, when  $k = 2$ , then  $Q_{(2)}$  is not unique (see, [8, page 49]). Using the properties of a permutation matrix together with the definition of  $\Omega = [Z_1 \ Q_{(m)}]$ , we have

$$\begin{aligned} I_m &= \Omega \Omega^T = \begin{bmatrix} Z_1 & Q_{(m)} \end{bmatrix} \begin{bmatrix} Z_1^T \\ Q_{(m)}^T \end{bmatrix} = Q_{(m)} Q_{(m)}^T + Z_1 Z_1^T, \\ I_m &= \begin{bmatrix} I_r & 0 \\ 0 & I_{m-r} \end{bmatrix} = \Omega^T \Omega = \begin{bmatrix} Z_1^T \\ Q_{(m)}^T \end{bmatrix} \begin{bmatrix} Z_1 & Q_{(m)} \end{bmatrix} = \begin{bmatrix} Z_1^T Z_1 & Z_1^T Q_{(m)} \\ Q_{(m)}^T Z_1 & Q_{(m)}^T Q_{(m)} \end{bmatrix}. \end{aligned} \quad (3.3)$$

From these come the required results in (i), that is,

$$Z_1^T Q_{(m)} = 0, \quad Q_{(m)}^T Q_{(m)} = I_{m-r}, \quad Q_{(m)} Q_{(m)}^T + Z_1 Z_1^T = I_m. \quad (3.4)$$

- (ii) By (2.13) of Lemma 2.2, we have  $I_n \geq Z_2 Z_2^T \geq 0$  and so

$$Z_1^T L L^* Z_1 \geq Z_1^T L Z_2 Z_2^T L^* Z_1 = (Z_1^T L Z_2) (Z_1^T L Z_2)^* \geq 0. \quad (3.5)$$

We now generalize [8, Theorem 4] to the case of Khatri-Rao product involving a finite number of matrices.  $\square$



**THEOREM 3.2.** Let  $A_i = [A_{gh}^{(i)}] \in M_{m,n}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g,h)$ th block submatrix. Let  $Z_1$  be an  $m^k \times r$  matrix of zeros and ones that satisfies (2.12) and let  $Q_{(n)}$  be an  $n^k \times (n^k - s)$  matrix of zeros and ones that satisfies (3.1). Then

$$\begin{aligned} \prod_{i=1}^k *(A_i A_i^*) &= \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^* + Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} Q_{(n)}^T \left( \prod_{i=1}^k \Theta A_i \right)^* Z_1 \\ &= \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^* + \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} \right) \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} \right)^*, \end{aligned} \quad (3.6)$$

and hence

$$\prod_{i=1}^k *(A_i A_i^*) \geq \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^*, \quad k = 2, 3, \dots \quad (3.7)$$

*Proof.* From Lemma 2.1(i) and (iii), we have

$$\prod_{i=1}^k \Theta(A_i A_i^*) = \left( \prod_{i=1}^k \Theta A_i \right) \left( \prod_{i=1}^k \Theta A_i \right)^*. \quad (3.8)$$

But by Theorem 3.1(i), there exist an  $n^k \times s$  matrix  $Z_2$  of zeros and ones that satisfies (2.12) and an  $n^k \times (n^k - s)$  matrix  $Q_{(n)}$  of zeros and ones that satisfies (3.1) such that  $Z_2 Z_2^T + Q_{(n)} Q_{(n)}^T = I_{n^k}$  and

$$\begin{aligned} \prod_{i=1}^k \Theta(A_i A_i^*) &= \left( \prod_{i=1}^k \Theta A_i \right) (Z_2 Z_2^T + Q_{(n)} Q_{(n)}^T) \left( \prod_{i=1}^k \Theta A_i \right)^* \\ &= \left( \prod_{i=1}^k \Theta A_i \right) (Z_2 Z_2^T) \left( \prod_{i=1}^k \Theta A_i \right)^* + \left( \prod_{i=1}^k \Theta A_i \right) (Q_{(n)} Q_{(n)}^T) \left( \prod_{i=1}^k \Theta A_i \right)^*. \end{aligned} \quad (3.9)$$

Since  $A_i$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) are rectangular partitioned matrices of order  $m \times n$ , then due to (2.11) of Lemma 2.2 there exist two real matrices  $Z_1$  and  $Z_2$  of zeros and ones of order  $m^k \times r$  and  $n^k \times s$ , respectively, such that

$$\prod_{i=1}^k *A_i = Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2, \quad k = 2, 3, \dots \quad (3.10)$$

But because  $A_i A_i^*$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) are square matrices of order  $m \times m$ , then due to (2.12) of Lemma 2.2 there exists a real matrix  $Z_1$  of zeros and ones of order  $m^k \times r$  such that

$$\prod_{i=1}^k *(A_i A_i^*) = Z_1^T \left( \prod_{i=1}^k \Theta(A_i A_i^*) \right) Z_1, \quad k = 2, 3, \dots \quad (3.11)$$

Due to (3.9), (3.10), and (3.11), we have

$$\begin{aligned}
 \prod_{i=1}^k *(A_i A_i^*) &= Z_1^T \left( \prod_{i=1}^k \Theta(A_i A_i^*) \right) Z_1 = Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2 Z_2^T \left( \prod_{i=1}^k \Theta A_i \right)^* Z_1 \\
 &\quad + Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) (Q_{(n)} Q_{(n)}^T) \left( \prod_{i=1}^k \Theta A_i \right)^* Z_1 \\
 &= \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2 \right) \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2 \right)^* \\
 &\quad + Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) (Q_{(n)} Q_{(n)}^T) \left( \prod_{i=1}^k \Theta A_i \right)^* Z_1 \\
 &= \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^* + Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} Q_{(n)}^T \left( \prod_{i=1}^k \Theta A_i \right)^* Z_1 \\
 &= \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^* + \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} \right) \left( Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} \right)^*.
 \end{aligned} \tag{3.12}$$

□

If we put  $k = 2$  in Theorem 3.2, we obtain the following corollary.

**COROLLARY 3.3.** *Let  $A_i = [A_{gh}^{(i)}] \in M_{m,n}$  ( $1 \leq i \leq 2$ ) be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g, h)$ th block submatrix. Let  $Z_1$  be an  $m^2 \times r$  matrix of zeros and ones that satisfies (1.8) and let  $Q_{(n)}$  be an  $n^2 \times (n^2 - s)$  matrix of zeros and ones that satisfies (3.1). Then*

$$A_1 A_1^* * A_2 A_2^* = (A_1 * A_2) (A_1 * A_2)^* + Z_1^T (A_1 \Theta A_2) Q_{(n)} Q_{(n)}^T (A_1 \Theta A_2)^* Z_1, \tag{3.13}$$

and hence

$$A_1 A_1^* * A_2 A_2^* \geq (A_1 * A_2) (A_1 * A_2)^*. \tag{3.14}$$

**COROLLARY 3.4.** *Let  $A_i = [A_{gh}^{(i)}] \in M_{m,n}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g, h)$ th block submatrix. Let  $Z_1$  be an  $m^k \times r$  matrix of zeros and ones that satisfies (2.12) and let  $Q_{(n)}$  be an  $n^k \times (n^k - s)$  matrix of zeros and ones that satisfies (3.1). Then the following statements are equivalent:*

(i)

$$\prod_{i=1}^k *(A_i A_i^*) = \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *A_i \right)^*, \quad k = 2, 3, \dots; \tag{3.15}$$

(ii)

$$Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Q_{(n)} = 0, \quad k = 2, 3, \dots; \tag{3.16}$$

(iii)

$$\prod_{i=1}^k *(A_i X_i) = \left( \prod_{i=1}^k *(A_i) \right) \left( \prod_{i=1}^k *(X_i) \right), \quad \text{for } X_i \in M_{n,m} \ (1 \leq i \leq k, k \geq 2). \quad (3.17)$$

*Proof.* To arrive from (i) to (ii), notice that (i) holds if and only if the last term of (3.6) is zero, which is equivalent to  $Z_1^T (\prod_{i=1}^k \Theta A_i) Q_{(n)} = 0$ . To arrive from (ii) to (iii), notice that (ii) may be rewritten as  $Z_1^T (\prod_{i=1}^k \Theta A_i) Q_{(n)} Q_{(n)}^T = 0$ . By Theorem 3.1(i), there exist an  $n^k \times s$  matrix  $Z_2$  of zeros and ones that satisfies (2.12) and an  $n^k \times (n^k - s)$  matrix  $Q_{(n)}$  of zeros and ones that satisfies (3.1) such that  $Q_{(n)} Q_{(n)}^T = I_{n^k} - Z_2 Z_2^T$ , this becomes

$$Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) = Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2 Z_2^T. \quad (3.18)$$

By postmultiplying by  $(\prod_{i=1}^k \Theta X_i) Z_1$  for any of the  $n \times m$  matrices  $X_i \ (1 \leq i \leq k)$ , we have

$$Z_1^T \left( \prod_{i=1}^k \Theta (A_i X_i) \right) Z_1 = Z_1^T \left( \prod_{i=1}^k \Theta A_i \right) Z_2 Z_2^T \left( \prod_{i=1}^k \Theta X_i \right) Z_1, \quad (3.19)$$

which is (iii) by (2.11) and (2.12) of Lemma 2.2. To arrive from (iii) to (i), assume (iii) holds for all  $n \times m$  matrices  $X_i \ (1 \leq i \leq k)$ . It must therefore be true for  $X_i = A_i^* \ (1 \leq i \leq k)$ , which is condition (i). Hence (iii) implies (3.6) which is (i).  $\square$

If we put  $k = 2$  in Corollary 3.4, we obtain the following corollary.

**COROLLARY 3.5.** *Let  $A_i = [A_{gh}^{(i)}] \in M_{m,n} \ (1 \leq i \leq 2)$  be partitioned matrices with  $A_{gh}^{(i)}$  as the  $(g, h)$ th block submatrix. Let  $Z_1$  be an  $m^2 \times r$  matrix of zeros and ones that satisfies (1.8) and let  $Q_{(n)}$  be an  $n^2 \times (n^2 - s)$  matrix of zeros and ones that satisfies (3.1). Then the following statements are equivalent:*

(i)

$$A_1 A_1^* * A_2 A_2^* = (A_1 * A_2) (A_1 * A_2)^*; \quad (3.20)$$

(ii)

$$Z_1^T (A_1 \Theta A_2) Q_{(n)} = 0; \quad (3.21)$$

(iii)

$$A_1 X_1 * A_2 X_2 = (A_1 * A_2) (X_1 * X_2), \quad \text{for } X_1, X_2 \in M_{n,m}. \quad (3.22)$$

**THEOREM 3.6.** *Let  $A_i \geq 0 \ (1 \leq i \leq k, k \geq 2)$  be  $n \times n$  compatible partitioned matrices. Then*

(i) *if either  $-1 \leq r \leq 0$  or  $1 \leq r \leq 2$ , then*

$$\prod_{i=1}^k * A_i^r \geq \left( \prod_{i=1}^k * A_i \right)^r; \quad (3.23)$$

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(ii) if  $0 \leq r \leq 1$ , then

$$\prod_{i=1}^k *A_i^r \leq \left( \prod_{i=1}^k *A_i \right)^r. \quad (3.24)$$

*Proof.* If we put  $s = 1$ , replace  $r$  by  $1/r$  and  $A_i$  by  $A_i^r$  in [3, Theorem 3.1(i)], we obtain (i). But, if we put  $s = -1$ , replace  $r$  by  $1/-r$  and  $A_i$  by  $A_i^{-r}$  in [3, Theorem 3.1(i)], we obtain (ii).  $\square$

*Remark 3.7.* It is easy to give another proof of Theorem 3.6 by replacing  $A$  by  $\prod_{i=1}^k \Theta A_i$  in Lemma 2.3 and applying (2.12) of Lemma 2.2.

**THEOREM 3.8.** *Let  $A_i > 0$  be compatible partitioned matrices such that  $\prod_{i=1}^k \Theta A_i > 0$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ). Let  $W$  and  $w$  be the largest and smallest eigenvalues of  $\prod_{i=1}^k \Theta A_i$ , respectively. Then*

(i) for every real  $p > 1$  and  $p < 0$ ,

$$\prod_{i=1}^k *A_i^p \leq \mu \left( \prod_{i=1}^k *A_i \right)^p, \quad k = 2, 3, \dots, \quad (3.25)$$

where

$$\mu = \frac{\delta^p - \delta}{(p-1)(\delta-1)} \left( \frac{p-1}{p} \frac{\delta^p - 1}{\delta^p - \delta} \right)^p, \quad \delta = \frac{W}{w}. \quad (3.26)$$

While for every  $0 < p < 1$ , the reverse inequality holds in (3.25);

(ii) for every real  $p > 1$  and  $p < 0$ ,

$$\prod_{i=1}^k *A_i^p - \left( \prod_{i=1}^k *A_i \right)^p \leq \gamma I, \quad k = 2, 3, \dots, \quad (3.27)$$

where

$$\gamma = \frac{Ww^p - wW^p}{W-w} + (p-1) \left( \frac{1}{p} \frac{W^p - w^p}{W-w} \right)^{p/(p-1)}. \quad (3.28)$$

While for every  $0 < p < 1$ , the reverse inequality holds in (3.27).

*Proof.* This theorem follows from [3, Theorem 3.1(ii) and (iii)]. We give proof for the sake of convenience. In (2.20) and (2.22) of Lemma 2.4, set  $k = 1$  and replace  $U$  by  $Z^T$ ,  $U^*$  by  $Z$ , and  $X$  by  $\prod_{i=1}^k \Theta A_i$ , where  $Z$ , is the selection matrix of zeros and ones that satisfies (2.12). By using Lemma 2.1(iv), we establish Theorem 3.8.  $\square$

From (3.25), we have the following special cases:

(i) for  $p = 2$ , we have

$$\prod_{i=1}^k *A_i^2 \leq \left\{ \frac{(W+w)^2}{4wW} \right\} \left( \prod_{i=1}^k *A_i \right)^2, \quad k = 2, 3, \dots; \quad (3.29)$$

(ii) for  $p = -1$ , we have

$$\prod_{i=1}^k *A_i^{-1} \leq \left\{ \frac{(W+w)^2}{4wW} \right\} \left( \prod_{i=1}^k *A_i \right)^{-1}, \quad k = 2, 3, \dots \tag{3.30}$$

From (3.27), we have the following special cases:

(i) for  $p = 2$ , we have

$$\prod_{i=1}^k *A_i^2 - \left( \prod_{i=1}^k *A_i \right)^2 \leq \frac{1}{4} (W-w)^2 \{I\}, \quad k = 2, 3, \dots; \tag{3.31}$$

(ii) for  $p = -1$ , we have

$$\prod_{i=1}^k *A_i^{-1} - \left( \prod_{i=1}^k *A_i \right)^{-1} \leq \left\{ \frac{\sqrt{W} - \sqrt{w}}{wW} \right\} I, \quad k = 2, 3, \dots \tag{3.32}$$

#### 4. Further developments and applications

Due to *Albert's theorem* in [2] and [9, Theorem 6.13], for a partitioned matrix  $\begin{bmatrix} A & B \\ B^* & D \end{bmatrix}$  with a positive (semi) definite matrix  $A \in M_m$ ,

$$\begin{bmatrix} A & B \\ B^* & D \end{bmatrix} \geq 0 \quad \text{iff } D \geq B^* A^+ B, \tag{4.1}$$

for any positive semidefinite matrix  $D \in M_n$ . It is also known that if matrix  $A$  is square and nonsingular, then  $A^+ = A^{-1}$  and  $\begin{bmatrix} A & B \\ B^* & D \end{bmatrix} \geq 0$  if and only if  $D \geq B^* A^{-1} B$ .

Let  $Z_1$  and  $Z_2$  be the real matrices of zeros and ones of order  $m \times r$  and  $n \times s$ , respectively, that satisfy (2.11) in Lemma 2.2. Now another way to use Lemma 2.2 to generate inequalities involving the Khatri-Rao product is by using the following obvious inequality:

$$TT^* = \begin{bmatrix} T_1 \\ T_2 \end{bmatrix} \begin{bmatrix} T_1^* & T_2^* \end{bmatrix} = \begin{bmatrix} T_1 T_1^* & T_1 T_2^* \\ T_2 T_1^* & T_2 T_2^* \end{bmatrix} \geq 0, \tag{4.2}$$

where  $T_1$  and  $T_2$  are  $n \times l$  and  $m \times l$  matrices, respectively. Note that  $T_1 T_1^*$  and  $T_2 T_2^*$  are positive semidefinite (positive definite) matrices for every (nonsingular) complex matrices  $T_1$  and  $T_2$ . This leads to

$$\begin{bmatrix} Z_2^T & 0 \\ 0 & Z_1^T \end{bmatrix} \begin{bmatrix} T_1 T_1^* & T_1 T_2^* \\ T_2 T_1^* & T_2 T_2^* \end{bmatrix} \begin{bmatrix} Z_2 & 0 \\ 0 & Z_1 \end{bmatrix} = \begin{bmatrix} Z_2^T T_1 T_1^* Z_2 & Z_2^T T_1 T_2^* Z_1 \\ Z_1^T T_2 T_1^* Z_2 & Z_1^T T_2 T_2^* Z_1 \end{bmatrix} \geq 0, \tag{4.3}$$

if and only if

$$Z_1^T T_2 T_2^* Z_1 \geq (Z_1^T T_2 T_1^* Z_2) (Z_2^T T_1 T_1^* Z_2)^+ (Z_2^T T_1 T_2^* Z_1). \tag{4.4}$$

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Therefore (4.4) can be considered to be more general than (3.2). In order to prove this we set  $T_1 = I$  and  $T_2 = L$  in (4.4), we have

$$\begin{aligned} Z_1^T L L^* Z_1 &\geq (Z_1^T L I^* Z_2) (Z_2^T I I^* Z_2)^+ (Z_2^T I L^* Z_1) \\ &= (Z_1^T L Z_2) (Z_2^T Z_2)^+ (Z_2^T L^* Z_1) \quad (Z_2^T Z_2 = I) \\ &= (Z_1^T L Z_2) (Z_1^T L Z_2)^*. \end{aligned} \quad (4.5)$$

Returning to (4.4) and (3.2), it can be easily seen that various other choices of the matrices  $T_1$ ,  $T_2$ , and  $L$  are possible which lead to quite different inequalities involving Khatri-Rao products. However, there exist some inequalities that do not seem to follow directly from (1.7) or (2.11), but follow easily from (4.4) and (3.2). Based on (4.4) and (3.2) we generalize some inequalities in works of Visick [8, Corollary 13, Remark in page 56, Theorems 11, 17, and 20] and establish some new inequalities involving Khatri-Rao products of several positive matrices.

**THEOREM 4.1.** *Let  $A_1$  and  $A_2$  be compatible partitioned matrices. Then*

$$\begin{aligned} A_1 A_1^* * A_2 A_2^* + A_2 A_2^* * A_1 A_1^* + A_1 A_2^* * A_2 A_1^* + A_2 A_1^* * A_1 A_2^* \\ \geq (A_1 * A_2 + A_2 * A_1) ((A_1 * A_2)^* + (A_2 * A_1)^*). \end{aligned} \quad (4.6)$$

*Proof.* Set  $T_1 = I \ominus I$  and  $T_2 = A_1 \ominus A_2 + A_2 \ominus A_1$ . Then calculations show that

$$\begin{aligned} T_2 T_2^* &= A_1 A_1^* \ominus A_2 A_2^* + A_2 A_2^* \ominus A_1 A_1^* + A_1 A_2^* \ominus A_2 A_1^* + A_2 A_1^* \ominus A_1 A_2^*, \\ T_2 T_1^* &= A_1 \ominus A_2 + A_2 \ominus A_1, \quad T_1 T_2^* = (A_1 \ominus A_2)^* + (A_2 \ominus A_1)^*, \quad T_1 T_1^* = I \ominus I. \end{aligned} \quad (4.7)$$

Substituting these into (4.4) and using (1.7), we get (4.6).  $\square$

**COROLLARY 4.2.** *Let  $A_i$  ( $1 \leq i \leq 2$ ) be Hermitian compatible partitioned matrices. Then*

(i)

$$A_1^2 * A_2^2 \geq (A_1 * A_2)^2; \quad (4.8)$$

(ii)

$$A^2 * A^{-2} \geq (A * A^{-1})^2 \quad \text{if } A \text{ is nonsingular}; \quad (4.9)$$

(iii)

$$I * A^2 \geq (I * A)^2. \quad (4.10)$$

*Proof.* (i) Set  $A_1^* = A_1$  and  $A_2^* = A_2$  in (3.14) of Corollary 3.3, we get (4.8).

(ii) Set  $A_1 = A$  and  $A_2 = A^{-1}$  in (4.8), we get (4.9).

(iii) Set  $A_1 = I$  and  $A_2 = A$  in (4.8), we get (4.10).  $\square$

**COROLLARY 4.3.** *Let  $A_i > 0$  ( $1 \leq i \leq 2$ ) be compatible partitioned matrices. Then*

$$(A_1^2 * A_2^2)^{1/2} \geq A_1 * A_2. \quad (4.11)$$

*Proof.* It follows immediately by (4.8) and Löwner-Heinz theorem.  $\square$

**THEOREM 4.4.** *Let  $A_i \geq 0$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be compatible partitioned matrices and let  $A_i^0 = A_i^{1/2} A_i^{+1/2} = A_i^{+1/2} A_i^{1/2}$  ( $1 \leq i \leq k$ ). Then*

$$\begin{aligned} & 2 \left( \prod_{i=1}^k *A_i^0 \right) + \left( A_1 * \prod_{i=2}^k *A_i^+ \right) + \left( A_1^+ * \prod_{i=2}^k *A_i \right) \\ & \geq \left( A_1 * \prod_{i=2}^k *A_i^0 + A_1^0 * \prod_{i=2}^k *A_i \right) \left( \prod_{i=1}^k *A_i \right)^+ \left( A_1 * \prod_{i=2}^k *A_i^0 + A_1^0 * \prod_{i=2}^k *A_i \right). \end{aligned} \tag{4.12}$$

*Proof.* Since  $A_i \geq 0$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ), then  $A_i^* = A_i$ . Set  $T_1 = \prod_{i=1}^k \ominus A_i^{1/2}$  and  $T_2 = A_1^{1/2} \ominus \prod_{i=2}^k \ominus A_i^{+1/2} + A_1^{+1/2} \ominus \prod_{i=2}^k \ominus A_i^{1/2}$ . Since  $A_i^{1/2} A_i^{1/2} = A_i$ ,  $A_i^{+1/2} A_i^{+1/2} = A_i^+$ , and  $A_i^0 = A_i^{1/2} A_i^{+1/2} = A_i^{+1/2} A_i^{1/2}$  ( $1 \leq i \leq k$ ), then calculations show that

$$\begin{aligned} T_2 T_2^* &= 2 \left( \prod_{i=1}^k \ominus A_i^0 \right) + \left( A_1 \ominus \prod_{i=2}^k \ominus A_i^+ \right) + \left( A_1^+ \ominus \prod_{i=2}^k \ominus A_i \right), & T_1 T_1^* &= \prod_{i=1}^k \ominus A_i, \\ T_2 T_1^* &= \left( A_1 \ominus \prod_{i=2}^k \ominus A_i^0 + A_1^0 \ominus \prod_{i=2}^k \ominus A_i \right), & T_1 T_2^* &= \left( A_1 \ominus \prod_{i=2}^k \ominus A_i^0 + A_1^0 \ominus \prod_{i=2}^k \ominus A_i \right). \end{aligned} \tag{4.13}$$

Substituting these into (4.4) and using Lemma 2.2, we get (4.12).  $\square$

If we put  $k = 2$  and replace  $A_i$  by  $A_i^r$  ( $1 \leq i \leq 2$ ) in Theorem 4.4, we obtain the following theorem.

**THEOREM 4.5.** *Let  $A_1 \geq 0$ ,  $A_2 \geq 0$  be compatible partitioned and let  $r$  be any nonzero real number such that  $A_1^0 = A_1^{r/2} A_1^{+r/2} = A_1^{+r/2} A_1^{r/2}$  and  $A_2^0 = A_2^{r/2} A_2^{+r/2} = A_2^{+r/2} A_2^{r/2}$ . Then*

$$\begin{aligned} & 2A_1^0 * A_2^0 + A_1^r * A_2^{+r} + A_1^{+r} * A_2^r \\ & \geq (A_1^r * A_2^0 + A_1^0 * A_2^r) (A_1^r * A_2^r)^+ (A_1^r * A_2^0 + A_1^0 * A_2^r). \end{aligned} \tag{4.14}$$

If  $A_1 > 0$ ,  $A_2 > 0$  in Theorem 4.5, we obtain the following theorem.

**THEOREM 4.6.** *Let  $A_1 > 0$ ,  $A_2 > 0$  be compatible partitioned and let  $I$  be a compatible partitioned identity matrix. Then for any nonzero real number  $r$ ,*

$$2I + A_1^r * A_2^{-r} + A_1^{-r} * A_2^r \geq (A_1^r * I + I * A_2^r) (A_1^r * A_2^r)^{-1} (A_1^r * I + I * A_2^r). \tag{4.15}$$

If we put  $r = 1$  and  $A_1 = A_2$  in Theorem 4.6, we obtain the following theorem.

**THEOREM 4.7.** *Let  $A > 0$  be compatible partitioned and let  $I$  be a compatible partitioned identity matrix. Then*

$$2I + A * A^{-1} + A^{-1} * A \geq (A * I + I * A) (A * A)^{-1} (A * I + I * A). \tag{4.16}$$

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In particular, if  $I$  is a nonpartitioned identity matrix, then

$$2I + A * A^{-1} + A^{-1} * A \geq 4(I * A)(A * A)^{-1}(I * A). \quad (4.17)$$

**THEOREM 4.8.** Let  $A_1 > 0$  and  $A_2 > 0$  be compatible partitioned matrices. Then for any nonzero real number  $r$

$$A_1^r * A_2^{-r} + A_1^{-r} * A_2^r + 2I \geq (A_1^{r/2} * A_2^{-r/2} + A_1^{-r/2} * A_2^{r/2})^2. \quad (4.18)$$

In particular, if  $A_1 = A_2 = A$ , Then

$$A^r * A^{-r} + A^{-r} * A^r + 2I \geq (A^{r/2} * A^{-r/2} + A^{-r/2} * A^{r/2})^2. \quad (4.19)$$

*Proof.* Since  $A_1 > 0$  and  $A_2 > 0$ , then  $A_1^* = A_1$  and  $A_2^* = A_2$ . Set  $L = A_1^{r/2} \Theta A_2^{-r/2} + A_1^{-r/2} \Theta A_2^{r/2}$ . Compute

$$\begin{aligned} Z_1^T L L^* Z_1 &= Z_1^T L L Z_1 = Z_1^T (A_1^{r/2} \Theta A_2^{-r/2} + A_1^{-r/2} \Theta A_2^{r/2}) (A_1^{r/2} \Theta A_2^{-r/2} + A_1^{-r/2} \Theta A_2^{r/2}) Z_1 \\ &= Z_1^T (A_1^r \Theta A_2^{-r}) Z_1 + Z_1^T (I \Theta I) Z_1 + Z_1^T (I \Theta I) Z_1 + Z_1^T (A_1^{-r} \Theta A_2^r) Z_1 \\ &= A_1^r * A_2^{-r} + 2I + A_1^{-r} * A_2^r. \end{aligned} \quad (4.20)$$

Similarly,

$$\begin{aligned} (Z_1^T L Z_2) (Z_1^T L Z_2)^* &= (Z_1^T L Z_2)^2 = \{Z_1^T (A_1^{r/2} \Theta A_2^{-r/2} + A_1^{-r/2} \Theta A_2^{r/2}) Z_2\}^2 \\ &= (A_1^{r/2} * A_2^{-r/2} + A_1^{-r/2} * A_2^{r/2})^2. \end{aligned} \quad (4.21)$$

Substituting (4.20) and (4.21) into (3.2), we get (4.18).  $\square$

From (4.18), we have the following special cases:

(i) for  $r = 1$ , we have

$$A_1^* A_2^{-1} + A_1^{-1} * A_2 + 2I \geq (A_1^{1/2} * A_2^{-1/2} + A_1^{-1/2} * A_2^{1/2})^2; \quad (4.22)$$

(ii) for  $r = 2$ , we have

$$A_1^2 * A_2^{-2} + A_1^{-2} * A_2^2 + 2I \geq (A_1 * A_2^{-1} + A_1^{-1} * A_2)^2. \quad (4.23)$$



From (4.19), we have the following special cases:

(i) for  $r = 1$ , we have

$$A * A^{-1} + A^{-1} * A + 2I \geq (A^{1/2} * A^{-1/2} + A^{-1/2} * A^{1/2})^2; \quad (4.24)$$

(ii) for  $r = 2$ , we have

$$A^2 * A^{-2} + A^{-2} * A^2 + 2I \geq (A * A^{-1} + A^{-1} * A)^2. \quad (4.25)$$

**THEOREM 4.9.** *Let  $A_1 \geq 0, A_2 \geq 0$  be compatible partitioned and let  $I$  be a compatible partitioned identity matrix. Then*

$$A_1^2 \infty A_2^2 + 2(A_1 * A_2) \geq (A_1 \infty A_2)^2, \quad (4.26)$$

where  $A_1 \infty A_2 = A_1 * I + I * A_2$  is called the Khatri-Rao sum.

*Proof.* Set  $L = A_1 \nabla A_2 = A_1 \Theta I + I \Theta A_2$  (Tracy-Singh sum). Since  $A_1 \geq 0$  and  $A_2 \geq 0$ , then  $A_1^* = A_1$  and  $A_2^* = A_2$ . Calculations show that

$$\begin{aligned} Z_1^T LL^* Z_1 &= Z_1^T LLZ_1 = Z_1^T (A_1 \Theta I + I \Theta A_2) (A_1 \Theta I + I_2 \Theta A_2) Z_1 \\ &= A_1^2 * I + I * A_2^2 + 2(A_1 * A_2) = A_1^2 \infty A_2^2 + 2(A_1 * A_2). \end{aligned} \quad (4.27)$$

Similarly,

$$\begin{aligned} (Z_1^T LZ_2) (Z_1^T LZ_2)^* &= \{Z_1^T (A_1 \Theta I + I \Theta A_2) Z_2\} \{Z_1^T (A_1 \Theta I + I \Theta A_2) Z_2\}^* \\ &= (A_1 * I + I * A_2)^2 = (A_1 \infty A_2)^2. \end{aligned} \quad (4.28)$$

Substituting (4.27) and (4.28) into (3.2), we get (4.26). □

**THEOREM 4.10.** *Let  $A_1 > 0$  and  $A_2 > 0$  be compatible partitioned matrices. Then for any positive real number  $r$ ,*

$$\begin{aligned} r(A_1^2 * A_2^2) + (A_1 A_2 * A_2 A_1) + (A_2 A_1 * A_1 A_2) + \frac{1}{r}(A_2^2 * A_1^2) \\ \geq r(A_1 * A_2)^2 + (A_1 * A_2)(A_2 * A_1) + (A_2 * A_1)(A_1 * A_2) + \frac{1}{r}(A_2 * A_1)^2. \end{aligned} \quad (4.29)$$

*Proof.* Set  $L = \varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1$ , where  $\varepsilon_1$  and  $\varepsilon_2$  are both positive. Since  $A_1 > 0$  and  $A_2 > 0$ , then  $A_1^* = A_1$  and  $A_2^* = A_2$ . Compute

$$\begin{aligned} Z_1^T LL^* Z_1 &= Z_1^T LLZ_1 = Z_1^T (\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1) (\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1) Z_1 \\ &= Z_1^T \{ \varepsilon_1^2 (A_1^2 \Theta A_2^2) + \varepsilon_1 \varepsilon_2 (A_1 A_2 \Theta A_2 A_1) + \varepsilon_1 \varepsilon_2 (A_2 A_1 \Theta A_1 A_2) + \varepsilon_2^2 (A_2^2 \Theta A_1^2) \} Z_1 \\ &= \{ \varepsilon_1^2 (A_1^2 * A_2^2) + \varepsilon_1 \varepsilon_2 (A_1 A_2 * A_2 A_1) + \varepsilon_1 \varepsilon_2 (A_2 A_1 * A_1 A_2) + \varepsilon_2^2 (A_2^2 * A_1^2) \}. \end{aligned} \quad (4.30)$$

Similarly,

$$\begin{aligned}
 (Z_1^T LZ_2)(Z_1^T LZ_2)^* &= \{Z_1^T(\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1)Z_2\} \{Z_1^T(\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1)Z_2\}^* \\
 &= \{Z_1^T(\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1)Z_2\} \{Z_1^T(\varepsilon_1 A_1 \Theta A_2 + \varepsilon_2 A_2 \Theta A_1)Z_2\} \\
 &= \{(\varepsilon_1 A_1 * A_2 + \varepsilon_2 A_2 * A_1)\}^2 \\
 &= \varepsilon_1^2 (A_1 * A_2)^2 + \varepsilon_1 \varepsilon_2 (A_1 * A_2)(A_2 * A_1) \\
 &\quad + \varepsilon_1 \varepsilon_2 (A_2 * A_1)(A_1 * A_2) + \varepsilon_2^2 (A_2 * A_1)^2.
 \end{aligned} \tag{4.31}$$

Substituting (4.30) and (4.31) into (3.2), we have

$$\begin{aligned}
 &\{\varepsilon_1^2 (A_1^2 * A_2^2) + \varepsilon_1 \varepsilon_2 (A_1 A_2 * A_2 A_1) + \varepsilon_1 \varepsilon_2 (A_2 A_1 * A_1 A_2) + \varepsilon_2^2 (A_2^2 * A_1^2)\} \\
 &\geq \{\varepsilon_1^2 (A_1^* A_2)^2 + \varepsilon_1 \varepsilon_2 (A_1 * A_2)(A_2 * A_1) + \varepsilon_1 \varepsilon_2 (A_2 * A_1)(A_1 * A_2) + \varepsilon_2^2 (A_2^* A_1)^2\}.
 \end{aligned} \tag{4.32}$$

Set  $r = \varepsilon_1/\varepsilon_2$ , we get (4.29). □

*Remark 4.11.* Let  $A_i$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) be compatible partitioned matrices. Then (3.7) can be proved by setting  $T_1 = \prod_{i=1}^k \Theta I$  and  $T_2 = \prod_{i=1}^k \Theta A_i$ . Calculations show that

$$T_2 T_2^* = \prod_{i=1}^k \Theta A_i A_i^*, \quad T_2 T_1^* = \prod_{i=1}^k \Theta A_i, \quad T_1 T_2^* = \left( \prod_{i=1}^k \Theta A_i \right)^*, \quad T_1 T_1^* = \prod_{i=1}^k \Theta I. \tag{4.33}$$

Substituting these into (4.4) and using (2.11), we get (3.7).

*Remark 4.12.* Let  $A_i$  ( $1 \leq i \leq 2$ ) be compatible partitioned matrices. Then (3.14) can be proved by putting  $k = 2$  in Remark 4.11.

*Remark 4.13.* All results obtained in Sections 3 and 4 are quite general. These results lead to inequalities involving Hadamard product, as a special case, for nonpartitioned matrices  $A_i$  ( $i = 1, 2, \dots, k$ ,  $k \geq 2$ ) with the Hadamard product and Kronecker product replacing the Khatri-Rao product and Tracy-Singh product, respectively.

Now we utilize the commutativity of the Hadamard product to develop, for instance, (3.7) of Theorem 3.2. This result leads to the following inequality involving Hadamard product, as a special case:

$$\prod_{i=1}^k \circ (A_i A_i^*) \geq \left( \prod_{i=1}^k \circ (A_i) \right) \left( \prod_{i=1}^k \circ A_i \right)^*. \tag{4.34}$$

It is possible to develop (4.34) in a different direction from (3.6). For example, Visick [8, Theorem 11, page 54] proved that if  $A_1, A_2 \in M_{m,n}$  and  $s \in [-1, 1]$ , then

$$A_1 A_1^* \circ A_2 A_2^* + s(A_1 A_2^* \circ A_2 A_1^*) \geq (1+s)(A_1 \circ A_2)(A_1 \circ A_2)^*. \tag{4.35}$$

We will extend this inequality to the case of products involving any finite number of matrices.

If the Tracy-Singh and Khatri-Rao products are replaced by the Kronecker and Hadamard products in Lemma 2.2, respectively, we obtain the following corollary.

**COROLLARY 4.14.** *Let  $A_i \in M_{m,n}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ). Then*

$$\prod_{i=1}^k \circ A_i = P_{km}^T \left( \prod_{i=1}^k \otimes A_i \right) P_{kn}, \tag{4.36}$$

where  $P_{km} = (E_{11}^{(m)} \ 0^{(m)} \dots \ 0^{(m)} \ E_{22}^{(m)} \ 0^{(m)} \dots \ 0^{(m)} \ \dots \ 0^{(m)} \ \dots \ 0^{(m)} \ E_{mm}^{(m)})^T$  is of order  $m^k \times m$ ,  $0^{(m)}$  is an  $m \times m$  matrix with all entries equal to zero, and  $E_{ij}^{(m)}$  is an  $m \times m$  matrix of zeros except for a one in the  $(i, j)$ th position.

**THEOREM 4.15.** *Let  $A_i \in M_{m,n}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ). Then for any real scalars  $\alpha_1, \alpha_2, \dots, \alpha_k$  which are not all zero,*

$$\begin{aligned} & (\alpha_1^2 + \dots + \alpha_k^2) \left( \prod_{i=1}^k \circ (A_i A_i^*) \right) + \left( \sum_{r=1}^{k-1} \mu_r \prod_{w=1}^k \circ (A_w A_{(w+r)'}^*) \right) \\ & \geq (\alpha_1 + \dots + \alpha_k)^2 \left( \prod_{i=1}^k \circ A_i \right) \left( \prod_{i=1}^k \circ A_i \right)^*, \end{aligned} \tag{4.37}$$

where  $\mu_r = \sum_{w=1}^k \alpha_w \alpha_{(w+r)'}$  and  $w + r \equiv (w + r)' \pmod k$  with  $1 \leq (w + r)' \leq k$ .

*Proof.* Let

$$L = \alpha_1 (A_1 \otimes A_2 \otimes \dots \otimes A_k) + \alpha_2 (A_2 \otimes \dots \otimes A_k \otimes A_1) + \dots + \alpha_k (A_k \otimes A_1 \otimes \dots \otimes A_{k-1}), \tag{4.38}$$

where  $A_i \in M_{m,n}$  ( $1 \leq i \leq k$ ,  $k \geq 2$ ) and  $\alpha_1, \alpha_2, \dots, \alpha_k$  are real scalars which are not all zero. Taking indices “mod  $k$ ,” Lemma 2.1(i), (iii) (by setting  $\otimes$  instead of  $\Theta$ ) give

$$\begin{aligned} LL^* &= \sum_{i=1}^k \alpha_i (A_i \otimes A_{i+1} \otimes \dots \otimes A_{i-1}) \sum_{i=1}^k \alpha_i (A_i^* \otimes A_{i+1}^* \otimes \dots \otimes A_{i-1}^*) \\ &= \alpha_1^2 (A_1 A_1^* \otimes \dots \otimes A_k A_k^*) + \dots + \alpha_k^2 (A_k A_k^* \otimes A A_1^* \otimes \dots \otimes A_k A_{k-1}^*) \\ &\quad + \sum_{i \neq j} \alpha_i \alpha_j (A_i A_j^* \otimes A_{j+1} A_{j+1}^* \otimes \dots \otimes A_{j-1} A_{j-1}^*). \end{aligned} \tag{4.39}$$

Now the application of (4.36) and the commutativity of the Hadamard product yield

$$P_{km}^T LL^* P_{km} = (\alpha_1^2 + \dots + \alpha_k^2) \left( \prod_{i=1}^k \circ (A_i A_i^*) \right) + \left( \sum_{r=1}^{k-1} \mu_r \prod_{w=1}^k \circ (A_w A_{(w+r)'}^*) \right), \tag{4.40}$$

where  $\mu_r = \sum_w \alpha_w \alpha_{(w+r)'}$  and  $w + r \equiv (w + r)' \pmod k$  with  $1 \leq (w + r)' \leq k$ .

Also by (4.36) and the commutativity of the Hadamard product, we obtain

$$\begin{aligned}
 (P_{km}^T L P_{kn}) &= P_{km}^T \{ \alpha_1 (A_1 \otimes A_2 \otimes \cdots \otimes A_k) + \alpha_2 (A_2 \otimes \cdots \otimes A_k \otimes A_1) \\
 &\quad + \cdots + \alpha_k (A_k \otimes A_1 \otimes \cdots \otimes A_{k-1}) \} P_{kn} \\
 &= \alpha_1 P_{km}^T (A_1 \otimes A_2 \otimes \cdots \otimes A_k) P_{kn} + \alpha_2 P_{km}^T (A_2 \otimes \cdots \otimes A_k \otimes A_1) P_{kn} \\
 &\quad + \cdots + \alpha_k P_{km}^T (A_k \otimes A_1 \otimes \cdots \otimes A_{k-1}) P_{kn} \\
 &= \alpha_1 (A_1 \circ A_2 \circ \cdots \circ A_k) + \alpha_2 (A_2 \circ \cdots \circ A_k \circ A_1) \\
 &\quad + \cdots + \alpha_k (A_k \circ A_1 \circ \cdots \circ A_{k-1}) \\
 &= (\alpha_1 + \cdots + \alpha_k) \left( \prod_{i=1}^k \circ A_i \right), \\
 (P_{km}^T L P_{kn})^* &= (\alpha_1 + \cdots + \alpha_k) \left( \prod_{i=1}^k \circ A_i \right)^*.
 \end{aligned} \tag{4.41}$$

Now

$$(P_{km}^T L P_{kn}) (P_{km}^T L P_{kn})^* = (\alpha_1 + \cdots + \alpha_k)^2 \left( \prod_{i=1}^k \circ A_i \right) \left( \prod_{i=1}^k \circ A_i \right)^*. \tag{4.42}$$

Since  $P_{km}^T L L^* P_{km} \geq (P_{km}^T L P_{kn}) (P_{km}^T L P_{kn})^*$  by (3.2) and from (4.40) and (4.42), we get (4.37).  $\square$

Now, we examine some special cases briefly.

In order to see that (4.37) really is an extension in (4.34), it is sufficient to set  $\alpha_1 = 1$  and  $\alpha_2 = \cdots = \alpha_k = 0$ . Thus we recover the result of Visick in (4.35) which we mentioned before the statement of Corollary 4.14. Let  $k = 2$ , then  $\mu_1 = \sum_{w=1}^2 \alpha_w \alpha_{(w+1)'}$  with  $w + 1 \equiv (w + 1)' \pmod{2}$ , that is,  $\mu_1 = 2\alpha_1\alpha_2$ . Then Theorem 4.15 asserts that

$$(\alpha_1^2 + \alpha_2^2) (A_1 A_1^* \circ A_2 A_2^*) + 2\alpha_1 \alpha_2 (A_1 A_2^* \circ A_2 A_1^*) \geq (\alpha_1 + \alpha_2)^2 (A_1 \circ A_2) (A_1 \circ A_2)^*. \tag{4.43}$$

Simplification gives

$$A_1 A_1^* \circ A_2 A_2^* + s (A_1 A_2^* \circ A_2 A_1^*) \geq (1 + s) (A_1 \circ A_2) (A_1 \circ A_2)^* \tag{4.44}$$

for any  $s \in [-1, 1]$ , just as we wanted. Finally, we present an attractive inequality using three matrices. Let  $k = 3$ ,  $\alpha_1 = 1$ ,  $\alpha_2 = \alpha_3 = -1/2$ . Theorem 4.15 asserts that

$$A_1 A_1^* \circ A_2 A_2^* \circ A_3 A_3^* \geq \frac{1}{2} \{ A_1 A_2^* \circ A_2 A_3^* \circ A_3 A_1^* + A_2 A_1^* \circ A_3 A_2^* \circ A_1 A_3^* \}. \tag{4.45}$$

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