The cardinal of various monoids of transformations that preserve a uniform partition

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Abstract

In this paper we give formulas for the number of elements of the monoids $\mathcal{OR}_{m\times n}$ of all full transformations on a finite chain with mn elements that preserve a uniform m-partition and preserve or reverse the orientation and for its submonoids $\mathcal{OD}_{m\times n}$ of all order-preserving or order-reversing elements, $\mathcal{OP}_{m\times n}$ of all orientation-preserving elements, $\mathcal{O}_{m\times n}$ of all order-preserving elements, $\mathcal{O}^+_{m\times n}$ of all extensive order-preserving elements and $\mathcal{O}^-_{m\times n}$ of all co-extensive order-preserving elements.

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Introduction and preliminaries

For $n \in \mathbb{N}$, let X_n be a finite chain with n elements, say $X_n = \{1 < 2 < \cdots < n\}$. Following the standard notations, we denote by $\mathcal{PT}_n$ the monoid (under composition) of all partial transformations on X_n and by $\mathcal{T}_n$ and $\mathcal{I}_n$ its submonoids of all full transformations and of all injective partial transformations, respectively.

A transformation $\alpha \in \mathcal{PT}_n$ is said to be *extensive* (resp., *co-extensive*) if $x \le x\alpha$ (resp., $x\alpha \le x$), for all $x \in \mathrm{Dom}(\alpha)$. We denote by $\mathcal{T}^+_n$ (resp., $\mathcal{T}^-_n$) the submonoid of $\mathcal{T}_n$ of all extensive (resp., co-extensive) transformations.

A transformation $\alpha \in \mathcal{PT}_n$ is said to be *order-preserving* (resp., *order-reversing*) if $x \le y$ implies $x\alpha \le y\alpha$ (resp., $y\alpha \le x\alpha$), for all $x, y \in \mathrm{Dom}(\alpha)$. We denote by $\mathcal{PO}_n$ the submonoid of $\mathcal{PT}_n$ of all order-preserving partial transformations. As usual, we denote by $\mathcal{O}_n$ the monoid $\mathcal{PO}_n \cap \mathcal{T}_n$ of all full transformations that preserve the order. This monoid has been extensively studied since the sixties (e.g. see [2, 1, 20, 34, 7, 3, 31, 9]). In particular, in 1971, Howie [21] showed that the cardinal of $\mathcal{O}_n$ is $\binom{2n-1}{n-1}$ and later, jointly with Gomes, in [18] they proved that $|\mathcal{PO}_n| = \sum_{i=1}^n \binom{n}{i}\binom{n+i-1}{i} + 1$. See also Laradji and Umar papers [27] and [28].

Next, denote by $\mathcal{O}^+_n$ (resp., by $\mathcal{O}^-_n$) the monoid $\mathcal{T}^+_n \cap \mathcal{O}_n$ (resp., $\mathcal{T}^-_n \cap \mathcal{O}_n$) of all extensive (resp., co-extensive) order-preserving full transformations. The monoids $\mathcal{O}^+_n$ and $\mathcal{O}^-_n$ are isomorphic and it is well-known that the pseudovariety of $\mathscr{J}$-trivial monoids, which are the syntactic monoids of piecewise testable languages (see e.g. [30]), is generated by the family $\{\mathcal{O}^+_n \mid n \in \mathbb{N}\}$. Moreover, the cardinal of $\mathcal{O}^+_n$ (or $\mathcal{O}^-_n$) is the n^{th}-Catalan number, i.e. $|\mathcal{O}^+_n| = \frac{1}{n+1}\binom{2n}{n}$ (see [32]).

Regarding the injective counterpart of $\mathcal{O}_n$, i.e. the inverse monoid $\mathcal{POI}_n = \mathcal{PO}_n \cap \mathcal{I}_n$ of all injective order-preserving partial transformations, we have $|\mathcal{POI}_n| = \binom{2n}{n}$. This result was first presented by Garba in [17] (see also [7]).

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Now, being $\mathcal{POD}_n$ the submonoid of $\mathcal{PT}_n$ of all partial transformations that preserve or reverse the order, $\mathcal{OD}_n = \mathcal{POD}_n \cap \mathcal{T}_n$ and $\mathcal{PODI}_n = \mathcal{POD}_n \cap \mathcal{I}_n$ (the full and partial injective counterparts of $\mathcal{POD}_n$, respectively), Fernandes et al. [10, 11] proved that $|\mathcal{POD}_n| = \sum_{i=1}^{n} \binom{n}{i} \left(2\binom{n+i-1}{i} - n\right) + 1$, $|\mathcal{OD}_n| = 2\binom{2n-1}{n-1} - n$ and $|\mathcal{PODI}_n| = 2\binom{2n}{n} - n^2 - 1$.

Wider classes of monoids are obtained when we consider transformations that either preserve or reverse the orientation. Let $a = (a_1, a_2, \ldots, a_t)$ be a sequence of t, $t \geq 0$, elements from the chain X_n. We say that a is *cyclic* (resp., *anti-cyclic*) if there exists no more than one index $i \in \{1, \ldots, t\}$ such that $a_i > a_{i+1}$ (resp., $a_i < a_{i+1}$), where a_{t+1} denotes a_1. Let $\alpha \in \mathcal{T}_n$ and suppose that $\mathrm{Dom}(\alpha) = \{a_1, \ldots, a_t\}$, with $t \geq 0$ and $a_1 < \cdots < a_t$. We say that α is *orientation-preserving* (resp., *orientation-reversing*) if the sequence of its images $(a_1\alpha, a_2\alpha, \ldots, a_t\alpha)$ is cyclic (resp., anti-cyclic). This notions were introduced by McAlister in [29] and independently Catarino and Higgins in [6].

Denote by $\mathcal{POP}_n$ (resp., $\mathcal{POR}_n$) the submonoid of $\mathcal{PT}_n$ of all orientation-preserving (resp., orientation-preserving or orientation-reversing) transformations. The cardinalities of $\mathcal{POP}_n$ and $\mathcal{POR}_n$ were calculated by Fernandes et al. [12] and are $1 + (2^n - 1)n + \sum_{k=2}^{n} k\binom{n}{k}^2 2^{n-k}$ and $1 + (2^n - 1)n + 2\binom{n}{2}^2 2^{n-2} + \sum_{k=3}^{n} 2k\binom{n}{k}^2 2^{n-k}$, respectively. As usual, $\mathcal{OP}_n$ denotes the monoid $\mathcal{POP}_n \cap \mathcal{T}_n$ of all full transformations that preserve the orientation, $\mathcal{OR}_n$ denotes the monoid $\mathcal{POR}_n \cap \mathcal{T}_n$ of all full transformations that preserve or reserve the orientation and $\mathcal{POPI}_n$ and $\mathcal{PORI}_n$ denote the submonoids of $\mathcal{POP}_n$ and $\mathcal{POR}_n$, respectively, whose elements are the injective transformations. McAlister in [29], and independently Catarino and Higgins in [6], proved that $|\mathcal{OP}_n| = n\binom{2n-1}{n-1} - n(n-1)$ and $|\mathcal{OR}_n| = n\binom{2n}{n} - \frac{n^2}{2}(n^2 - 2n + 5) + n$. The monoids $\mathcal{OP}_n$ and $\mathcal{OR}_n$ were also studied by Arthur and Randoffnot Ruškuc in [5]. Regarding their injective counterparts, in [8], Fernandes established that $|\mathcal{POPI}_n| = 1 + \frac{n}{2}\binom{2n}{n}$ and, in [10], Fernandes et al. showed that $|\mathcal{PORI}_n| = 1 + n\binom{2n}{n} - \frac{n^2}{2}(n^2 - 2n + 3)$.

All these results are summarized in [13].

Now, let X be a set and denote by $\mathcal{T}(X)$ the monoid (under composition) of all full transformations on X. Let ρ be an equivalence relation on X and denote by $\mathcal{T}_\rho(X)$ the submonoid of $\mathcal{T}(X)$ of all transformations that preserve the equivalence relation ρ, i.e. $\mathcal{T}_\rho(X) = \{\alpha \in \mathcal{T}(X) \mid (a\alpha, b\alpha) \in \rho, \text{for all } (a, b) \in \rho\}$. This monoid was studied by Huisheng in [23] who determined its regular elements and described its Green's relations.

Let $m, n \in \mathbb{N}$. Of particular interest is the submonoid $\mathcal{T}_{m\times n} = \mathcal{T}_\rho(X_{mn})$ of $\mathcal{T}_{mn}$, with ρ the equivalence relation on X_{mn} defined by $\rho = (A_1 \times A_1) \cup (A_2 \times A_2) \cup \cdots \cup (A_m \times A_m)$, where $A_i = \{(i-1)n + 1, \ldots, in\}$, for $i \in \{1, \ldots, m\}$. Notice that the ρ-classes A_i, with $1 \leq i \leq m$, form a uniform m-partition of X_{mn}.

Regarding the rank of $\mathcal{T}_{m\times n}$, first, Huisheng [22] proved that it is at most 6 and, later on, Araújo and Schneider [4] improved this result by showing that, for $|X_{mn}| \geq 3$, the rank of $\mathcal{T}_{m\times n}$ is precisely 4.

Finally, denote by $\mathcal{OR}_{m\times n}$ the submonoid of $\mathcal{T}_{m\times n}$ of all orientation-preserving or orientation-reversing transformations, i.e. $\mathcal{OR}_{m\times n} = \mathcal{T}_{m\times n} \cap \mathcal{OR}_{mn}$. Similarly, let $\mathcal{OD}_{m\times n} = \mathcal{T}_{m\times n} \cap \mathcal{OD}_{mn}$, $\mathcal{OP}_{m\times n} = \mathcal{T}_{m\times n} \cap \mathcal{OP}_{mn}$ and $\mathcal{O}_{m\times n} = \mathcal{T}_{m\times n} \cap \mathcal{O}_{mn}$. Consider also the submonoids $\mathcal{O}^+_{m\times n} = \mathcal{O}_{m\times n} \cap \mathcal{T}^+_{mn}$ and $\mathcal{O}^-_{m\times n} = \mathcal{O}_{m\times n} \cap \mathcal{T}^-_{mn}$ of $\mathcal{O}_{m\times n}$ whose elements are the extensive transformations and the co-extensive transformations, respectively.

Example 0.1 Consider the following transformations of $\mathcal{T}_{12}$:

$$\alpha_1 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 9 & 11 & 10 & 12 & 1 & 3 & 3 & 2 & 5 & 5 & 7 & 8 \end{array}\right); \quad \alpha_2 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 8 & 8 & 8 & 6 & 6 & 5 & 5 & 5 & 12 & 12 & 11 & 10 \end{array}\right);$$

$$\alpha_3 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 11 & 11 & 10 & 10 & 10 & 9 & 9 & 9 & 4 & 3 & 3 & 1 \end{array}\right); \quad \alpha_4 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 7 & 7 & 7 & 8 & 8 & 8 & 5 & 5 & 5 & 6 & 6 & 7 \end{array}\right);$$

$$\alpha_5 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 1 & 1 & 1 & 2 & 3 & 3 & 4 & 4 & 10 & 11 & 11 & 11 \end{array}\right); \quad \alpha_6 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 5 & 5 & 6 & 6 & 6 & 7 & 7 & 8 & 10 & 11 & 11 & 12 \end{array}\right);$$

$$\alpha_7 = \left(\begin{array}{cccc|cccc|cccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 1 & 1 & 2 & 3 & 5 & 5 & 6 & 8 & 9 & 9 & 10 & 11 \end{array}\right); \quad \alpha_8 = \left(\begin{array}{cccccccccccc} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ 1 & 1 & 2 & 3 & 5 & 5 & 6 & 9 & 9 & 10 & 10 & 11 \end{array}\right).$$

Then, we have: $\alpha_1 \in \mathcal{T}_{3\times 4}$, but $\alpha_1 \notin \mathcal{OR}_{3\times 4}$; $\alpha_2 \in \mathcal{OR}_{3\times 4}$, but $\alpha_2 \notin \mathcal{OP}_{3\times 4}$; $\alpha_3 \in \mathcal{OD}_{3\times 4}$, but $\alpha_3 \notin \mathcal{O}_{3\times 4}$; $\alpha_4 \in \mathcal{OP}_{3\times 4}$, but $\alpha_4 \notin \mathcal{O}_{3\times 4}$; $\alpha_5 \in \mathcal{O}_{3\times 4}$, but $\alpha_5 \notin \mathcal{O}^+_{3\times 4}$ and $\alpha_5 \notin \mathcal{O}^-_{3\times 4}$; $\alpha_6 \in \mathcal{O}^+_{3\times 4}$; $\alpha_7 \in \mathcal{O}^-_{3\times 4}$; and, finally, $\alpha_8 \notin \mathcal{T}_{3\times 4}$.

Notice that, as $\mathcal{O}_n^-$ and $\mathcal{O}_n^+$, the monoids $\mathcal{O}_{m\times n}^-$ and $\mathcal{O}_{m\times n}^+$ are isomorphic [15]. Recall that in [25] Kunze proved that the monoid $\mathcal{O}_n$ is a quotient of a bilateral semidirect product of its subsemigroups $\mathcal{O}_n^-$ and $\mathcal{O}_n^+$. This result was generalized by the authors [15] by showing that $\mathcal{O}_{m\times n}$ also is a quotient of a bilateral semidirect product of its subsemigroups $\mathcal{O}_{m\times n}^-$ and $\mathcal{O}_{m\times n}^+$. See also [26, 14].

In [24] Huisheng and Dingyu described the regular elements and the Green's relations of $\mathcal{O}_{m\times n}$. On the other hand, the ranks of the monoids $\mathcal{O}_{m\times n}$, $\mathcal{O}_{m\times n}^+$ and $\mathcal{O}_{m\times n}^-$ were calculated by the authors in [15].

Regarding $\mathcal{OP}_{m\times n}$, a description of the regular elements and a characterization of the Green's relations were given by Sun et al. in [33]. Its rank was determined by the authors in [16], who also computed in the same paper the ranks of the monoids $\mathcal{OD}_{m\times n}$ and $\mathcal{OR}_{m\times n}$.

In this paper we calculate the cardinals of the monoids $\mathcal{OR}_{m\times n}$, $\mathcal{OP}_{m\times n}$, $\mathcal{OD}_{m\times n}$, $\mathcal{O}_{m\times n}$, $\mathcal{O}_{m\times n}^+$ and $\mathcal{O}_{m\times n}^-$. In order to achieve this objective, we use a wreath product description of $\mathcal{T}_{m\times n}$, due to Araújo and Schneider [4], that we recall in Section 1.

1 Wreath products of transformation semigroups

In [4] Araújo and Schneider proved that the rank of $\mathcal{T}_{m\times n}$ is 4, by using the concept of wreath product of transformation semigroups. This approach will also be very useful in this paper. Next, we recall some facts from [4, 15, 16].

First, we define the wreath product $\mathcal{T}_n \wr \mathcal{T}_m$ of $\mathcal{T}_n$ and $\mathcal{T}_m$ as being the monoid with underlying set $\mathcal{T}_n^m \times \mathcal{T}_m$ and multiplication defined by $(\alpha_1,\ldots,\alpha_m;\beta)(\alpha_1',\ldots,\alpha_m';\beta') = (\alpha_1\alpha_{1\beta}',\ldots,\alpha_m\alpha_{m\beta}';\beta\beta')$, for all $(\alpha_1,\ldots,\alpha_m;\beta),(\alpha_1',\ldots,\alpha_m';\beta')\in\mathcal{T}_n^m\times\mathcal{T}_m$.

Now, let $\alpha\in\mathcal{T}_{m\times n}$ and let $\beta=\alpha/\rho\in\mathcal{T}_m$ be the *quotient* map of α by ρ, i.e. for all $j\in\{1,\ldots,m\}$, we have $A_j\alpha\subseteq A_{j\beta}$. For each $j\in\{1,\ldots,m\}$, define $\alpha_j\in\mathcal{T}_n$ by $k\alpha_j=((j-1)n+k)\alpha-(j\beta-1)n$, for all $k\in\{1,\ldots,n\}$. Let $\overline{\alpha}=(\alpha_1,\alpha_2,\ldots,\alpha_m;\beta)\in\mathcal{T}_n^m\times\mathcal{T}_m$. With these notations, the function $\psi:\mathcal{T}_{m\times n}\longrightarrow\mathcal{T}_n\wr\mathcal{T}_m$, $\alpha\longmapsto\overline{\alpha}$, is an isomorphism (see [4, Lemma 2.1]).

Observe that, from this fact, we can immediately conclude that the cardinal of $\mathcal{T}_{m\times n}$ is $n^{nm}m^m$.

Example 1.1 Consider the transformation $\alpha = \left(\begin{array}{cccc|cccc|cccc} 1&2&3&4&5&6&7&8&9&10&11&12\\ 5&5&7&6&10&10&9&12&1&1&2&3\end{array}\right)\in\mathcal{T}_{3\times 4}$. Then, being $\beta=\begin{pmatrix}1&2&3\\2&3&1\end{pmatrix}$, $\alpha_1=\begin{pmatrix}1&2&3&4\\1&1&3&2\end{pmatrix}$, $\alpha_2=\begin{pmatrix}1&2&3&4\\2&2&1&4\end{pmatrix}$ and $\alpha_3=\begin{pmatrix}1&2&3&4\\1&1&2&3\end{pmatrix}$, we have $\overline{\alpha}=(\alpha_1,\alpha_2,\alpha_3;\beta)$.

Next, consider

$$\overline{\mathcal{O}}_{m\times n}=\{(\alpha_1,\ldots,\alpha_m;\beta)\in\mathcal{O}_n^m\times\mathcal{O}_m \mid j\beta=(j+1)\beta \text{ implies } n\alpha_j\le 1\alpha_{j+1}, \text{ for all } j\in\{1,\ldots,m-1\}\}.$$

Notice that, if $(\alpha_1,\ldots,\alpha_m;\beta)\in\overline{\mathcal{O}}_{m\times n}$ and $1\le i<j\le m$ are such that $i\beta=j\beta$, then $n\alpha_i\le 1\alpha_j$.

Proposition 1.2 [15] *The set $\overline{\mathcal{O}}_{m\times n}$ is a submonoid of $\mathcal{T}_n\wr\mathcal{T}_m$ (and of $\mathcal{O}_n\wr\mathcal{O}_m$) isomorphic to $\mathcal{O}_{m\times n}$.* ∎

On the other hand, being

$$\begin{aligned}\overline{\mathcal{O}}_{m\times n}^+ \;=\; \{(\alpha_1,\ldots,\alpha_m;\beta)\in\mathcal{O}_n^{m-1}\times\mathcal{O}_n^+\times\mathcal{O}_m^+ \mid & \; j\beta=(j+1)\beta \text{ implies } n\alpha_j\le 1\alpha_{j+1} \text{ and}\\ & \; j\beta=j \text{ implies } \alpha_j\in\mathcal{O}_n^+, \text{ for all } j\in\{1,\ldots,m-1\}\}\end{aligned}$$

and

$$\begin{aligned}\overline{\mathcal{O}}_{m\times n}^- \;=\; \{(\alpha_1,\ldots,\alpha_m;\beta)\in\mathcal{O}_n^-\times\mathcal{O}_n^{m-1}\times\mathcal{O}_m^- \mid & \; (j-1)\beta=j\beta \text{ implies } n\alpha_{j-1}\le 1\alpha_j \text{ and}\\ & \; j\beta=j \text{ implies } \alpha_j\in\mathcal{O}_n^-, \text{ for all } j\in\{2,\ldots,m\}\},\end{aligned}$$

we have:

Proposition 1.3 [15] *The set $\overline{\mathcal{O}}_{m\times n}^+$ [resp. $\overline{\mathcal{O}}_{m\times n}^-$] is a submonoid of $\mathcal{T}_n\wr\mathcal{T}_m$ (and of $\mathcal{O}_n\wr\mathcal{O}_m$) isomorphic to $\mathcal{O}_{m\times n}^+$ [resp. $\mathcal{O}_{m\times n}^-$].* ∎

A description of $\mathcal{OP}_{m\times n}$ in terms of wreath products is more elaborate. In fact, considering addition modulo m (in particular, $m+1=1$), we have:

Proposition 1.4 [16] *A $(m+1)$-tuple $(\alpha_1,\alpha_2,\dots,\alpha_m;\beta)$ of $\mathcal{T}_n^m \times \mathcal{T}_m$ belongs to $\mathcal{OP}_{m\times n}\psi$ if and only if it satisfies one of the following conditions:*

1. *β is a non-constant transformation of $\mathcal{OP}_m$,*
   for all $i\in\{1,\dots,m\}$, $\alpha_i\in\mathcal{O}_n$ and,
   for all $j\in\{1,\dots,m\}$, $j\beta=(j+1)\beta$ implies $n\alpha_j \le 1\alpha_{j+1}$;
2. *β is a constant transformation,*
   for all $i\in\{1,\dots,m\}$, $\alpha_i\in\mathcal{O}_n$ and
   there exists at most one index $j\in\{1,\dots,m\}$ such that $n\alpha_j > 1\alpha_{j+1}$;
3. *β is a constant transformation,*
   there exists one index $i\in\{1,\dots,m\}$ such that $\alpha_i\in\mathcal{OP}_n\setminus\mathcal{O}_n$ and, for all $j\in\{1,\dots,m\}\setminus\{i\}$, $\alpha_j\in\mathcal{O}_n$ and, for all $j\in\{1,\dots,m\}$, $n\alpha_j\le 1\alpha_{j+1}$.

Let $\alpha\in\mathcal{OP}_{m\times n}$. We say that α is of *type* i if $\alpha\psi$ satisfies the condition i. of the previous proposition, for $i\in\{1,2,3\}$.

2 The cardinals

In this section we use the previous bijections to obtain formulas for the number of elements of the monoids $\mathcal{O}_{m\times n}$, $\mathcal{O}^+_{m\times n}$, $\mathcal{O}^-_{m\times n}$, $\mathcal{OD}_{m\times n}$, $\mathcal{OP}_{m\times n}$ and $\mathcal{OR}_{m\times n}$.

In order to count the elements of $\mathcal{O}_{m\times n}$, on one hand, for each transformation $\beta\in\mathcal{O}_m$, we determine the number of sequences $(\alpha_1,\dots,\alpha_m)\in\mathcal{O}_n^m$ such that $(\alpha_1,\dots,\alpha_m;\beta)\in\overline{\mathcal{O}}_{m\times n}$ and, on the other hand, we notice that this last number just depends of the kernel of β (and not of β itself).

With this purpose, let $\beta\in\mathcal{O}_m$. Suppose that $\mathrm{Im}(\beta)=\{b_1<b_2<\cdots<b_t\}$, for some $1\le t\le m$, and define $k_i=|b_i\beta^{-1}|$, for $i=1,\dots,t$. Being β an order-preserving transformation, the sequence $(k_1,\dots,k_t)$ determines the kernel of β: we have $\{k_1+\cdots+k_{i-1}+1,\dots,k_1+\cdots+k_i\}\beta=\{b_i\}$, for $i=1,\dots,t$ (considering $k_1+\cdots+k_{i-1}+1=1$, with $i=1$). We define the *kernel type* of β as being the sequence $(k_1,\dots,k_t)$. Notice that $1\le k_i\le m$, for $i=1,\dots,t$, and $k_1+k_2+\cdots+k_t=m$.

Now, recall that the number of non-decreasing sequences of length k from a chain with n elements (which is the same as the number of k-combinations with repetition from a set with n elements) is $\binom{n+k-1}{k}=\binom{n+k-1}{n-1}$ (see [19], for example). Next, notice that, as a sequence $(\alpha_1,\dots,\alpha_k)\in\mathcal{O}_n^k$ satisfies the condition $n\alpha_j\le 1\alpha_{j+1}$, for all $1\le j\le k-1$, if and only if the concatenation sequence of the images of the transformations $\alpha_1,\dots,\alpha_k$ (by this order) is still a non-decreasing sequence, then we have $\binom{n+kn-1}{n-1}$ such sequences.

Since $(\alpha_1,\dots,\alpha_m;\beta)\in\overline{\mathcal{O}}_{m\times n}$ if and only if, for all $1\le i\le t$, $\alpha_{k_1+\cdots+k_{i-1}+1},\dots,\alpha_{k_1+\cdots+k_i}$ are k_i order-preserving transformations such that the concatenation sequence of their images (by this order) is still a non-decreasing sequence, then we have $\prod_{i=1}^t\binom{k_in+n-1}{n-1}$ elements in $\overline{\mathcal{O}}_{m\times n}$ whose $(m+1)$-component is β.

Finally, now it is also clear that if β and β' are two elements of $\mathcal{O}_m$ with the same kernel type then $(\alpha_1,\dots,\alpha_m;\beta)\in\overline{\mathcal{O}}_{m\times n}$ if and only if $(\alpha_1,\dots,\alpha_m;\beta')\in\overline{\mathcal{O}}_{m\times n}$. Thus, as the number of transformations $\beta\in\mathcal{O}_m$ with kernel type of length t $(1\le t\le m)$ coincides with the number of t-combinations (without repetition) from a set with m elements, it follows:

Theorem 2.1 $|\mathcal{O}_{m\times n}| = \displaystyle\sum_{\substack{1\le k_1,\dots,k_t\le m\\ k_1+\cdots+k_t=m\\ 1\le t\le m}} \binom{m}{t}\prod_{i=1}^{t}\binom{k_in+n-1}{n-1}.$ ■

The table below gives us an idea of the size of the monoid $\mathcal{O}_{m\times n}$.

$m \setminus n$	1	2	3	4	5	6
1	1	3	10	35	126	462
2	3	19	156	1555	17878	225820
3	10	138	2845	78890	2768760	115865211
4	35	1059	55268	4284451	454664910	61824611940
5	126	8378	1109880	241505530	77543615751	34003513468232
6	462	67582	22752795	13924561150	13556873588212	19134117191404027

In view of Theorem 2.1, finding the cardinal of $\mathcal{OD}_{m\times n}$ is not difficult. Indeed, consider the reflexion permutation $h = \begin{pmatrix} 1 & 2 & \cdots & mn-1 & mn \\ mn & mn-1 & \cdots & 2 & 1 \end{pmatrix}$. Observe that $h \in \mathcal{OD}_{m\times n}$ and, given $\alpha \in \mathcal{T}_{m\times n}$, we have $\alpha \in \mathcal{OD}_{m\times n}$ if and only if $\alpha \in \mathcal{O}_{m\times n}$ or $h\alpha \in \mathcal{O}_{m\times n}$. On the other hand, as clearly $|\mathcal{O}_{m\times n}| = |h\mathcal{O}_{m\times n}|$ and $|\mathcal{O}_{m\times n} \cap h\mathcal{O}_{m\times n}| = |\{\alpha \in \mathcal{O}_{m\times n} \mid |\operatorname{Im}(\alpha)| = 1\}| = mn$, it follows immediately that:

Theorem 2.2 $|\mathcal{OD}_{m\times n}| = 2|\mathcal{O}_{m\times n}| - mn = 2 \displaystyle\sum_{\substack{1\le k_1,\ldots,k_t\le m \\ k_1+\cdots+k_t=m \\ 1\le t\le m}} \binom{m}{t} \prod_{i=1}^{t} \binom{k_in+n-1}{n-1} - mn.$ ∎

Next, we describe a process to count the number of elements of $\mathcal{O}^+_{m\times n}$.

First, recall that the cardinal of $\mathcal{O}^+_n$ is the n^{th}-Catalan number, i.e. $|\mathcal{O}^+_n| = \frac{1}{n+1}\binom{2n}{n}$. See [32].

It is also useful to consider the following numbers: $\theta(n,i) = |\{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i\}|$, for $1 \le i \le n$. Clearly, we have $|\mathcal{O}^+_n| = \sum_{i=1}^n \theta(n,i)$. Moreover, for $2 \le i \le n-1$, we have $\theta(n,i) = \theta(n,i+1) + \theta(n-1,i-1)$. In fact, $\{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i\} = \{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i < 2\alpha\} \,\dot\cup\, \{\alpha \in \mathcal{O}^+_n \mid 1\alpha = 2\alpha = i\}$ and it is easy to show that the function which maps each transformation $\beta \in \{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i < 2\alpha\}$ into the transformation

$$\begin{pmatrix} 1 & 2 & \ldots & n \\ i+1 & 2\beta & \ldots & n\beta \end{pmatrix} \in \{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i+1\}$$

and the function which maps each transformation $\beta \in \{\alpha \in \mathcal{O}^+_{n-1} \mid 1\alpha = i-1\}$ into the transformation

$$\begin{pmatrix} 1 & 2 & 3 & \ldots & n-1 & n \\ i & i & 2\beta+1 & \ldots & (n-2)\beta+1 & (n-1)\beta+1 \end{pmatrix} \in \{\alpha \in \mathcal{O}^+_n \mid 1\alpha = 2\alpha = i\}$$

are bijections. Thus

$$\begin{aligned} \theta(n,i) &= |\{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i < 2\alpha\}| + |\{\alpha \in \mathcal{O}^+_n \mid 1\alpha = 2\alpha = i\}| \\ &= |\{\alpha \in \mathcal{O}^+_n \mid 1\alpha = i+1\}| + |\{\alpha \in \mathcal{O}^+_{n-1} \mid 1\alpha = i-1\}| \\ &= \theta(n,i+1) + \theta(n-1,i-1). \end{aligned}$$

Also, it is not hard to prove that $\theta(n,2) = \theta(n,1) = \sum_{i=1}^{n-1} \theta(n-1,i) = |\mathcal{O}^+_{n-1}|$.

Now, we can prove:

Lemma 2.3 *For all* $1 \le i \le n$, $\theta(n,i) = \frac{i}{n}\binom{2n-i-1}{n-i} = \frac{i}{n}\binom{2n-i-1}{n-1}$.

Proof. We prove the lemma by induction on n.

For $n=1$, it is clear that $\theta(1,1) = 1 = \frac{1}{1}\binom{2-1-1}{1-1}$.

Let $n \ge 2$ and suppose that the formula is valid for $n-1$.

Next, we prove the formula for n by induction on i. For $i=1$, as observed above, we have $\theta(n,1) = |\mathcal{O}^+_{n-1}| = \frac{1}{n}\binom{2n-2}{n-1}$. For $i=2$, we have $\theta(n,2) = \theta(n,1) = \frac{1}{n}\binom{2n-2}{n-1} = \frac{2}{n}\frac{(2n-2)!}{(n-1)!(n-1)!}\frac{n-1}{2n-2} = \frac{2}{n}\frac{(2n-3)!}{(n-1)!(n-2)!} = \frac{2}{n}\binom{2n-3}{n-1}$.

Now, suppose that the formula is valid for $i-1$, with $3 \le i \le n$. Then, using both induction hypothesis on i and on n in the second equality, we have $\theta(n,i) = \theta(n,i-1) - \theta(n-1,i-2) = \frac{i-1}{n}\binom{2n-i}{n-1} - \frac{i-2}{n-1}\binom{2n-i-1}{n-2} = \frac{i-1}{n}\frac{(2n-i)!}{(n-1)!(n-i+1)!} - \frac{i-2}{n-1}\frac{(2n-i-1)!}{(n-2)!(n-i+1)!} = \frac{i(n-i+1)}{n(2n-i)}\frac{(2n-i)!}{(n-1)!(n-i+1)!} = \frac{i}{n}\binom{2n-i-1}{n-1}$, as required. ∎

Recall that $(\alpha_1,\ldots,\alpha_m;\beta)\in\overline{\mathcal{O}}^+_{m\times n}$ if and only if $\beta\in\mathcal{O}^+_m$, $\alpha_m\in\mathcal{O}^+_n$, $\alpha_1,\ldots,\alpha_{m-1}\in\mathcal{O}_n$ and, for all $j\in\{1,\ldots,m-1\}$, $j\beta=(j+1)\beta$ implies $n\alpha_j\le 1\alpha_{j+1}$ and $j\beta=j$ implies $\alpha_j\in\mathcal{O}^+_n$.

Let $\beta\in\mathcal{O}^+_m$. As for the monoid $\mathcal{O}_{m\times n}$, we aim to count the number of sequences $(\alpha_1,\ldots,\alpha_m)\in\mathcal{O}^m_n$ such that $(\alpha_1,\ldots,\alpha_m;\beta)\in\overline{\mathcal{O}}^+_{m\times n}$.

Let $(k_1,\ldots,k_t)$ be the kernel type of β. Let $K_i=\{k_1+\cdots+k_{i-1}+1,\ldots,k_1+\cdots+k_i\}$, for $i=1,\ldots,t$. Then, β fixes a point in K_i if and only if it fixes $k_1+\cdots+k_i$, for $i=1,\ldots,t$. It follows that $(\alpha_1,\ldots,\alpha_m;\beta)\in\overline{\mathcal{O}}^+_{m\times n}$ if and only if, for all $1\le i\le t$:

1. If β does not fix a point in K_i, then $\alpha_{k_1+\cdots+k_{i-1}+1},\ldots,\alpha_{k_1+\cdots+k_i}$ are k_i order-preserving transformations such that the concatenation sequence of their images (by this order) is still a non-decreasing sequence (in this case, we have $\binom{k_in+n-1}{n-1}$ subsequences $(\alpha_{k_1+\cdots+k_{i-1}+1},\ldots,\alpha_{k_1+\cdots+k_i})$ allowed);

2. If β fixes a point in K_i, then $\alpha_{k_1+\cdots+k_{i-1}+1},\ldots,\alpha_{k_1+\cdots+k_i-1}$ are k_i-1 order-preserving transformations such that the concatenation sequence of their images (by this order) is still a non-decreasing sequence, $n\alpha_{k_1+\cdots+k_i-1}\le 1\alpha_{k_1+\cdots+k_i}$ and $\alpha_{k_1+\cdots+k_i}\in\mathcal{O}^+_n$ (in this case, we have $\sum_{j=1}^n\binom{(k_i-1)n+j-1}{j-1}\theta(n,j)$ subsequences $(\alpha_{k_1+\cdots+k_{i-1}+1},\ldots,\alpha_{k_1+\cdots+k_i})$ allowed).

Define

$$\mathfrak{d}(\beta,i)=\begin{cases}\binom{k_in+n-1}{n-1}, & \text{if } (k_1+\cdots+k_i)\beta\neq k_1+\cdots+k_i\\ \sum_{j=1}^n\frac{j}{n}\binom{2n-j-1}{n-1}\binom{(k_i-1)n+j-1}{j-1}, & \text{if } (k_1+\cdots+k_i)\beta=k_1+\cdots+k_i,\end{cases}$$

for all $1\le i\le t$.

Thus, we have:

Proposition 2.4 $|\mathcal{O}^+_{m\times n}|=\displaystyle\sum_{\beta\in\mathcal{O}^+_m}\prod_{i=1}^t\mathfrak{d}(\beta,i)$. ∎

Next, we obtain a formula for $|\mathcal{O}^+_{m\times n}|$ which does not depend of $\beta\in\mathcal{O}^+_m$.

Let β be an element of $\mathcal{O}^+_m$ with kernel type $(k_1,\ldots,k_t)$. Define $s_\beta=(s_1,\ldots,s_t)\in\{0,1\}^{t-1}\times\{1\}$ by $s_i=1$ if and only if $(k_1+\cdots+k_i)\beta=k_1+\cdots+k_i$, for all $1\le i\le t-1$.

Let $1\le t,k_1,\ldots,k_t\le m$ be such that $k_1+\cdots+k_t=m$ and let $(s_1,\ldots,s_t)\in\{0,1\}^{t-1}\times\{1\}$. Let $k=(k_1,\ldots,k_t)$ and $s=(s_1,\ldots,s_t)$. Define $\Delta(k,s)=|\{\beta\in\mathcal{O}^+_m\mid\beta\text{ has kernel type }k\text{ and }s_\beta=s\}|$.

In order to get a formula for $\Delta(k,s)$, we count the number of distinct restrictions to unions of partition classes of the kernel of transformations β of $\mathcal{O}^+_m$ with kernel type k and $s_\beta=s$ corresponding to maximal subsequences of consecutive zeros of s.

Let β be an element of $\mathcal{O}^+_m$ with kernel type k and $s_\beta=s$.

First, notice that, given $i\in\{1,\ldots,t\}$, if $s_i=1$ then $K_i\beta=\{k_1+\cdots+k_i\}$ and if $s_i=0$ then the (unique) element of $K_i\beta$ belongs to K_j, for some $i<j\le t$.

Next, let $i\in\{1,\ldots,t\}$ and $r\in\{1,\ldots,t-i\}$ be such that $s_j=0$, for all $j\in\{i,\ldots,i+r-1\}$, $s_{i+r}=1$ and, if $i>1$, $s_{i-1}=1$ (i.e. $(s_i,\ldots,s_{i+r-1})$ is a maximal subsequence of consecutive zeros of s). Then

$$(K_i\cup\cdots\cup K_{i+r-2}\cup K_{i+r-1})\beta\subseteq K_{i+1}\cup\cdots\cup K_{i+r-1}\cup(K_{i+r}\setminus\{k_1+\cdots+k_{i+r}\}).$$

Let $\ell_j=|K_{i+j}\cap(K_i\cup\cdots\cup K_{i+r-1})\beta|$, for $1\le j\le r$. Hence, we have $\ell_1,\ldots,\ell_{r-1}\ge 0$, $\ell_r\ge 1$, $\ell_1+\cdots+\ell_r=r$ and $0\le\ell_1+\cdots+\ell_j\le j$, for all $1\le j\le r-1$.

On the other hand, given $\ell_1,\ldots,\ell_r$ such that $\ell_1,\ldots,\ell_{r-1}\ge 0$, $\ell_r\ge 1$, $\ell_1+\cdots+\ell_r=r$ and $0\le\ell_1+\cdots+\ell_j\le j$, for all $1\le j\le r-1$, we have precisely $\binom{k_{i+1}}{\ell_1}\binom{k_{i+2}}{\ell_2}\cdots\binom{k_{i+r-1}}{\ell_{r-1}}\binom{k_{i+r}-1}{\ell_r}=\binom{k_{i+r}-1}{\ell_r}\prod_{j=1}^{r-1}\binom{k_{i+j}}{\ell_j}$ distinct restrictions to $K_i\cup\cdots\cup K_{i+r-1}$ of transformations β of $\mathcal{O}^+_m$, with kernel type k and $s_\beta=s$, such that

$\ell_j = |K_{i+j} \cap (K_i \cup \cdots \cup K_{i+r-1})\beta|$, for $1 \leq j \leq r$. It follow that the number of distinct restrictions to $K_i \cup \cdots \cup K_{i+r-1}$ of transformations β of $\mathcal{O}_m^+$ with kernel type k and $s_\beta = s$ is

$$\sum_{\substack{\ell_1+\cdots+\ell_r=r \\ 0\leq \ell_1+\cdots+\ell_j\leq j,\ 1\leq j\leq r-1 \\ \ell_1,\ldots,\ell_{r-1}\geq 0,\ \ell_r\geq 1}} \binom{k_{i+r}-1}{\ell_r} \prod_{j=1}^{r-1} \binom{k_{i+j}}{\ell_j}.$$

Now, let p be the number of distinct maximal subsequences of consecutive zeros of s. Clearly, if $p = 0$ then $\Delta(k, s) = 1$. Hence, suppose that $p \geq 1$ and let $1 \leq u_1 < v_1 < u_2 < v_2 < \cdots < u_p < v_p \leq t$ be such that

$$\{j \in \{1, \ldots, t\} \mid \ s_j = 0\} = \bigcup_{i=1}^{p} \{u_i, \ldots, v_i - 1\}$$

(i.e. $(s_{u_i}, \ldots, s_{v_i-1})$, with $1 \leq i \leq p$, are the p distinct maximal subsequences of consecutive zeros of s). Then, being $r_i = v_i - u_i$, for $1 \leq i \leq p$, we have

$$\Delta(k, s) = \prod_{i=1}^{p} \sum_{\substack{\ell_1+\cdots+\ell_{r_i}=r_i \\ 0\leq \ell_1+\cdots+\ell_j\leq j\ \ 1\leq j\leq r_i-1 \\ \ell_1,\ldots,\ell_{r_i-1}\geq 0,\ \ell_{r_i}\geq 1}} \binom{k_{u_i+r_i}-1}{\ell_{r_i}} \prod_{j=1}^{r_i-1} \binom{k_{u_i+j}}{\ell_j}.$$

Finally, notice that, if β and β' two elements of $\mathcal{O}_m^+$ with kernel type $k = (k_1, \ldots, k_t)$ such that $s_{\beta'} = s_\beta$, then $\mathfrak{d}(\beta, i) = \mathfrak{d}(\beta', i)$, for all $1 \leq i \leq t$. Thus, defining $\Lambda(k, s) = \prod_{i=1}^{t} \mathfrak{d}(\beta, i)$, where β is any transformation of $\mathcal{O}_m^+$ with kernel type k and $s_\beta = s$, we have:

Theorem 2.5 $|\mathcal{O}_{m\times n}^+| = |\mathcal{O}_{m\times n}^-| = \displaystyle\sum_{\substack{k=(k_1,\ldots,k_t) \\ 1\leq k_1,\ldots,k_t\leq m \\ k_1+\cdots+k_t=m \\ 1\leq t\leq m}} \sum_{s\in\{0,1\}^{t-1}\times\{1\}} \Delta(k, s)\Lambda(k, s).$ ■

The next table gives us an idea of the size of the monoid $\mathcal{O}_{m\times n}^+$ (or $\mathcal{O}_{m\times n}^-$).

$m \setminus n$	1	2	3	4	5	6
1	1	2	5	14	42	132
2	2	8	35	306	2401	21232
3	5	42	569	10024	210765	5089370
4	14	252	8482	410994	25366480	1847511492
5	42	1636	138348	18795636	3547275837	839181666224
6	132	11188	2388624	913768388	531098927994	415847258403464

Despite the unpleasant appearance, the previous formula allows us to calculate the cardinal of $\mathcal{O}_{m\times n}^+$, even for larger m and n. For instance, we have $|\mathcal{O}_{10\times 10}^+| = 4701675895106986289638897622139264555060675224\!4$.

In order to count the number of elements of the monoid $\mathcal{OP}_{m\times n}$, we begin by recalling that, for $k \in \mathbb{N}$, being g_k the k-cycle $\begin{pmatrix} 1 & 2 & \cdots & k-1 & k \\ 2 & 3 & \cdots & k & 1 \end{pmatrix} \in \mathcal{OP}_k$, each element $\alpha \in \mathcal{OP}_k$ admits a factorization $\alpha = g_k^j \gamma$, with $0 \leq j \leq k-1$ and $\gamma \in \mathcal{O}_k$, which is unique unless α is constant [6].

Next, consider the permutations (of $\{1, \ldots, mn\}$)

$$g = g_{mn} = \begin{pmatrix} 1 & 2 & \cdots & mn-1 & mn \\ 2 & 3 & \cdots & mn & 1 \end{pmatrix} \in \mathcal{OP}_{mn}$$

and

$$f = g^n = \left(\begin{array}{ccc|ccc|ccc} 1 & \cdots & n & n+1 & \cdots & mn-n & mn-n+1 & \cdots & mn \\ n+1 & \cdots & 2n & 2n+1 & \cdots & mn & 1 & \cdots & n \end{array} \right) \in \mathcal{OP}_{m\times n}.$$

Being α an element of $\mathcal{OP}_{m\times n} \setminus \mathcal{O}_{m\times n}$ of type 1 or 2 (see Proposition 1.4) and $j \in \{1, \ldots, m-1\}$ such that $(jn)\alpha > (jn+1)\alpha$, as $(jn+1)\alpha \leq \cdots \leq (mn)\alpha \leq 1\alpha \leq \cdots \leq (jn)\alpha$, it is clear that $f^j\alpha \in \mathcal{O}_{m\times n}$. Thus, each element α of $\mathcal{OP}_{m\times n}$ of type 1 or 2 admits a factorization $\alpha = f^j\gamma$, with $0 \leq j \leq m-1$ and $\gamma \in \mathcal{O}_{m\times n}$, which is unique unless α is constant. Notice that, this uniqueness follows immediately from Catarino and Higgins's result mentioned above. Therefore we have precisely $m(|\mathcal{O}_{m\times n}| - mn)$ non-constant transformations of $\mathcal{OP}_{m\times n}$ of types 1 and 2 and mn constant transformations (which are elements of type 2 of $\mathcal{OP}_{m\times n}$).

Now, let α be a transformation of $\mathcal{OP}_{m\times n}$ of type 3. As α is not constant, it can be factorized in a unique way as $g^r\gamma$, for some $r \in \{0, \ldots, mn-1\} \setminus \{jn \mid 0 \leq j \leq m-1\}$ and some non-constant order-preserving transformation γ from $\{1, \ldots, mn\}$ to A_i, for some $1 \leq i \leq m$. Since only elements of $\mathcal{OP}_{m\times n}$ of type 3 have factorizations of this form and the number of non-constant and non-decreasing sequences of length mn from a chain with n elements is equal to $\binom{mn+n-1}{n-1} - n$, we have precisely $m(mn-m)\left(\binom{mn+n-1}{n-1} - n\right)$ elements of type 3 in $\mathcal{OP}_{m\times n}$. Thus $|\mathcal{OP}_{m\times n}| = m|\mathcal{O}_{m\times n}| + m^2(n-1)\binom{mn+n-1}{n-1} - mn(mn-1)$ and so we obtain:

Theorem 2.6 $|\mathcal{OP}_{m\times n}| = m \displaystyle\sum_{\substack{1\leq k_1,\ldots,k_t\leq m \\ k_1+\cdots+k_t=m \\ 1\leq t\leq m}} \binom{m}{t} \prod_{i=1}^{t} \binom{k_in+n-1}{n-1} + m^2(n-1)\binom{mn+n-1}{n-1} - mn(mn-1).$ ∎

It follows a table that gives us an idea of the size of the monoid $\mathcal{OP}_{m\times n}$.

$m \setminus n$	1	2	3	4	5	6
1	1	4	24	128	610	2742
2	4	46	506	5034	51682	575268
3	24	447	9453	248823	8445606	349109532
4	128	4324	223852	17184076	1819339324	247307947608
5	610	42075	5555990	1207660095	387720453255	170017607919290
6	2742	405828	136530144	83547682248	81341248206546	114804703283314542

We finish this paper computing the cardinal of the monoid $\mathcal{OR}_{m\times n}$. Notice that, as for $\mathcal{OD}_{m\times n}$ and $\mathcal{O}_{m\times n}$, we have a similar relationship between $\mathcal{OR}_{m\times n}$ and $\mathcal{OP}_{m\times n}$. In fact, $\alpha \in \mathcal{OR}_{m\times n}$ if and only if $\alpha \in \mathcal{OP}_{m\times n}$ or $h\alpha \in \mathcal{OP}_{m\times n}$. Hence, since $|\mathcal{OP}_{m\times n}| = |h\mathcal{OP}_{m\times n}|$ and $\mathcal{OP}_{m\times n} \cap h\mathcal{OP}_{m\times n} = \{\alpha \in \mathcal{OP}_{m\times n} \mid |\mathrm{Im}(\alpha)| \leq 2\}$, we obtain $|\mathcal{OR}_{m\times n}| = 2|\mathcal{OP}_{m\times n}| - |\{\alpha \in \mathcal{OP}_{m\times n} \mid |\mathrm{Im}(\alpha)| = 2\}| - mn$.

It remains to calculate the number of elements of $A = \{\alpha \in \mathcal{OP}_{m\times n} \mid |\mathrm{Im}(\alpha)| = 2\}$.

First, we count the number of elements of A of types 2 and 3. Let α be such a transformation. Then, there exists $k \in \{1, \ldots, m\}$ such that $|\mathrm{Im}(\alpha)| \subseteq A_k$. Clearly, in this case, the number of distinct kernels allowed for α coincides with the number of distinct kernels allowed for transformations of $\mathcal{OP}_{mn}$ of rank 2, which is $\binom{mn}{2}$ (see [6]). On the hand, it is easy to check that we have $m\binom{n}{2}$ distinct images for α. Furthermore, for each such possible kernel and image, we have two distinct transformations of A. Hence, the total number of elements of A of types 2 and 3 is precisely $2m\binom{n}{2}\binom{mn}{2}$.

Finally, we determine the number of elements of A of type 1. Let $\alpha \in A$ be of type 1 and suppose that $\alpha\psi = (\alpha_1, \ldots, \alpha_m; \beta)$. Then β must have rank 2 and so, as $\beta \in \mathcal{OP}_m$, we have $2\binom{m}{2}^2$ distinct possibilities for β (see [6]). Moreover, for each $1 \leq i \leq m$, α_i must be a constant transformation of $\mathcal{O}_n$ and, for $1 \leq i, j \leq m$, if $i\beta = j\beta$ then $\alpha_i = \alpha_j$. Thus, for a fixed β, since β as rank 2, we have precisely n^2 sequences $(\alpha_1, \ldots, \alpha_m; \beta)$ allowed. Hence, A has $2n^2\binom{m}{2}^2$ distinct elements of type 1.

Therefore, $|\mathcal{OR}_{m\times n}| = 2|\mathcal{OP}_{m\times n}| - 2m\binom{n}{2}\binom{mn}{2} - 2n^2\binom{m}{2}^2 - mn = 2m|\mathcal{O}_{m\times n}| + 2m^2(n-1)\binom{mn+n-1}{n-1} - 2m\binom{n}{2}\binom{mn}{2} - 2n^2\binom{m}{2}^2 - mn(2mn-1)$ and so we get:

Theorem 2.7 $|\mathcal{OR}_{m\times n}| = 2m \sum_{\substack{1\le k_1,\ldots,k_t\le m\\ k_1+\cdots+k_t=m\\ 1\le t\le m}} \binom{m}{t}\prod_{i=1}^{t}\binom{k_in+n-1}{n-1} +$

$$+2m^2(n-1)\binom{mn+n-1}{n-1} - 2m\binom{n}{2}\binom{mn}{2} - 2n^2\binom{m}{2}^2 - mn(2mn-1). \blacksquare$$

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