

FULL FRIENDLY INDEX SETS OF SLENDER AND FLAT CYLINDER GRAPHS

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ABSTRACT. Let $G = (V, E)$ be a connected simple graph. A labeling $f : V \rightarrow \mathbb{Z}_2$ induces an edge labeling $f^* : E \rightarrow \mathbb{Z}_2$ defined by $f^*(xy) = f(x) + f(y)$ for each $xy \in E$. For $i \in \mathbb{Z}_2$, let $v_f(i) = |f^{-1}(i)|$ and $e_f(i) = |f^{*-1}(i)|$. A labeling f is called friendly if $|v_f(1) - v_f(0)| \leq 1$. The full friendly index set of G consists all possible differences between the number of edges labeled by 1 and the number of edges labeled by 0. In recent years, full friendly index sets for certain graphs were studied, such as tori, grids $P_2 \times P_n$, and cylinders $C_m \times P_n$ for some n and m . In this paper we study the full friendly index sets of cylinder graphs $C_m \times P_2$ for $m \geq 3$, $C_m \times P_3$ for $m \geq 4$ and $C_3 \times P_n$ for $n \geq 4$. The results in this paper complement the existing results in literature, so the full friendly index set of cylinder graphs are completely determined.

1. Introduction

Let $G = (V, E)$ be a simple connected graph. A vertex labeling $f : V \rightarrow \mathbb{Z}_2$ induces an edge labeling $f^* : E \rightarrow \mathbb{Z}_2$, given by

$$f^*(xy) := f(x) + f(y),$$

where $xy \in E$. For $i \in \mathbb{Z}_2$, define $v_f(i) = |f^{-1}(i)|$ and $e_f(i) = |(f^*)^{-1}(i)|$, i.e., $v_f(i)$ is the number of vertices labeled by i and $e_f(i)$ is the number of edges labeled by i . A vertex labeling f is said to be *friendly* if

$$|v_f(1) - v_f(0)| \leq 1.$$

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For a friendly labeling f of a graph G the *friendly index* of G with respect to f , denoted by $i_f(G)$, is defined to be

$$i_f(G) := e_f(1) - e_f(0).$$

The *friendly index set* [2] $\text{FI}(G)$ of G is defined to be

$$\text{FI}(G) = \{i_f(G) \mid f \text{ is a friendly labeling of } G\}.$$

In [7] Shiu-Kwong generalize the friendly index set to the *full friendly index set* $\text{FFI}(G)$:

$$\text{FFI}(G) = \{i_f(G) \mid f \text{ is a friendly labeling of } G\}.$$

Friendly index of some graphs are studied in [4, 3, 5, 6]. Let $m \geq 3$ and $n \geq 2$. Denote by C_m an m -cycle and P_n an n -path. The full friendly index sets are studied in the case of a torus $C_m \times C_n$ [8, 9], a cylinder $C_m \times P_n$ for $m, n \geq 4$ [10, 11] and a grid $P_2 \times P_n$ [7]. In this paper we study the full friendly index sets of cylinder graphs $C_m \times P_2$ for $m \geq 3$, $C_m \times P_3$ for $m \geq 4$ and $C_3 \times P_n$ for $n \geq 4$. Together with [10, 11] the full friendly index sets of cylinder graphs $C_m \times P_n$ for arbitrary m and n are completely determined.

Henceforth the term “labeling” on a graph G means a vertex labeling from $V(G)$ to \mathbb{Z}_2 .

2. Notation and preliminary results

We refer to [1] for general notions of graphs. Let $m \geq 3$ and $n \geq 2$. Denote by C_m an m -cycle and P_n an n -path. The Cartesian product $C_m \times P_n$ is a cylinder graph with mn vertices labeled by u_{ij} (or $u_{i,j}$), where $1 \leq i \leq m$ and $1 \leq j \leq n$. The size of $C_m \times P_n$ is $2mn - m$. Two vertices u_{ij} and u_{hk} of $C_m \times P_n$ are adjacent if either

$$\begin{aligned} i = h \text{ and } j = k \pm 1, \text{ or} \\ j = k \text{ and } i \equiv h \pm 1 \pmod{m} \end{aligned}$$

We recall some results of the extremely friendly index of $C_m \times P_n$ in [10].

Theorem 2.1. [10, Theorem 2.4] *If f is a friendly labeling of $C_m \times P_n$, then*

$$i_f(C_m \times P_n) \leq \begin{cases} 2mn - m - 2n, & \text{if } m \text{ is odd;} \\ 2mn - m, & \text{if } m \text{ is even.} \end{cases}$$

Theorem 2.2. [10, Theorems 3.2–3.5] *Let f be a friendly labeling of $C_m \times P_n$.*

(1) *Suppose n is even.*

(a) *If $m \leq 2n$, then $i_f(C_m \times P_n) \geq 3m - 2mn$.*

(b) *If $m \geq 2n$, then*

$$i_f(C_m \times P_n) \geq \begin{cases} 4n + m + 2 - 2mn, & \text{if } m \text{ is odd;} \\ 4n + m - 2mn, & \text{if } m \text{ is even.} \end{cases}$$

(2) *Suppose n is odd.*

- (a) If $m \leq 2n - 1$, then $i_f(C_m \times P_n) \geq 3m + 4 - 2mn$.
 (b) If $m \geq 2n - 2$, then

$$i_f(C_m \times P_n) \geq \begin{cases} 4n + m + 2 - 2mn, & \text{if } m \text{ is odd;} \\ 4n + m - 2mn, & \text{if } m \text{ is even.} \end{cases}$$

3. Non-existence of friendly indices of $C_m \times P_n$

In the previous section we recall the upper bound and the lower bound of the friendly index of the graph $C_m \times P_n$. In this section we prove that some integers lying between the upper bound and the lower bound cannot be the friendly index of $C_m \times P_n$.

We begin with some elementary observations.

Lemma 3.1. *Let f be a friendly labeling of $C_m \times P_2 = (V, E)$. Then*

$$v_f(1) \equiv m \pmod{2}.$$

Proof. Since the degree of each of the vertices of $C_m \times P_2$ is 3, it follows that

$$e_f(1) \equiv \sum_{e \in E} f^*(e) = \sum_{v \in V} \deg(v)f(v) = \sum_{v \in V} 3f(v) \equiv 3v_f(1) \equiv v_f(1) \pmod{2}.$$

Since f is a friendly labeling, it follows that $v_f(0) = v_f(1) = m$. Thus $v_f(1) \equiv m \pmod{2}$. □

Theorem 3.2. [11, Theorem 2.1] *For even m with $m \geq 4$ and $n \geq 2$, there is no friendly labeling f of $C_m \times P_n$ such that $e_f(1) = 2mn - m - p$, where $p = 1, 2, 3$.*

Let G be a graph and $f : V \rightarrow \mathbb{Z}_2$ a vertex labeling of G . A subgraph H of G is said to be *mixed* with respect to f if there are two vertices $u, v \in V(H)$ such that $f(u) = 1$ and $f(v) = 0$. An edge $e \in E(G)$ is called a k -edge if $f^*(e) = k$, where $k \in \mathbb{Z}_2$.

Clearly, mixed cycles and mixed paths contain at least two 1-edges and one 1-edge, respectively. Let $k \in \mathbb{Z}_2$. A cycle C is called a k -pure cycle, where $k \in \mathbb{Z}_2$, with respect to f if $f(u) = k$ for all $u \in V(C)$. We define k -pure path in a similar fashion.

A path in $C_m \times P_n$ of the form $u_{i1}u_{i2} \cdots u_{in}$ is called a *vertical path* for each fixed $1 \leq i \leq m$. A cycle in $C_m \times P_n$ of the form $u_{1j}u_{2j} \cdots u_{mj}u_{1j}$ is called a *horizontal cycle* for each fixed $1 \leq j \leq n$.

Lemma 3.3. [11, Lemma 2.2] *For even m , if $C_m \times P_n$ contains a vertical mixed path under a friendly labeling f , then the number of vertical mixed paths is at least two.*

Lemma 3.4. [7, Corollary 5] *Let f be a labeling of a graph G that contains a cycle C as its subgraph. If C contains a 1-edge, then the number of 1-edges in C is a positive even number.*

Lemma 3.5. *Let $m \geq 6$ be even. If $C_m \times P_3$ contains a horizontal pure cycle (either a 1-pure cycle or a 0-pure cycle) and a horizontal mixed cycle with respect to a friendly labeling f , then $e_f(1) \geq 8$.*

Proof. Let r be the number of horizontal 1-pure cycles and s the number of horizontal 0-pure cycles. Since f is a friendly labeling, it follows that $0 \leq r, s \leq 1$. There are two cases.

- (1) Suppose $r = 1$ and $s = 0$. Then there are two horizontal mixed cycles, each of which has at least two 1-edges. Since $v_f(0) = \frac{3m}{2}$, there are at least $\frac{3m}{4}$ mixed vertical paths. Thus $e_f(1) \geq 4 + \frac{3m}{4} > 8$. Hence $e_f(1) \geq 9$. The case $r = 0$ and $s = 1$ is similar.
- (2) Suppose $r = 1 = s$. Then there is one horizontal mixed cycle, and all vertical paths are mixed. Thus

$$e_f(1) \geq 2 + m \geq 2 + 6 = 8.$$

□

Proposition 3.6. *Let $m \geq 6$ be even. There is no friendly labeling f of $C_m \times P_3$ such that $e_f(1) = 7$.*

Proof. Let a be the number of horizontal mixed cycles and b the number of vertical mixed paths of $C_m \times P_3$. Note that $a \neq 0$ by friendliness, and $b \neq 1$ by Lemma 3.3. If $a = 1$ or 2 , then $e_f(1) \geq 8$ by Lemma 3.5.

Suppose $a = 3$. If $b = 0$, then by Lemma 3.4 each horizontal mixed cycle contains at least two 1-edges. Thus $e_f(1) \geq 2 + 2 + 2 = 6$. Note that in this case $e_f(1)$ cannot be an odd integer by the same reason. If $b \geq 2$, then $e_f(1) \geq 2 + 2 + 2 + b \geq 8$, where the 2's follows from the reason as above.

Combining all these cases together we conclude that $e_f(1) \neq 7$. □

Lemma 3.7. [11, Lemma 2.3] *Let n be even. If $C_m \times P_n$ contains a horizontal mixed cycle with respect to a friendly labeling f , then the number of horizontal mixed cycles is at least two.*

Lemma 3.8. [11, Lemma 2.4] *Let $n \geq 4$ be even and $3 \leq m \leq 2n$. If $C_m \times P_n$ contains a horizontal pure cycle and a horizontal mixed cycle with respect to a friendly labeling f , then*

$$e_f(1) \geq \begin{cases} m + 4, & \text{if } m \text{ is odd;} \\ m + 3, & \text{if } m \text{ is even and } m = 2n; \\ m + 4, & \text{if } m \text{ is even and } m \leq 2n - 2. \end{cases}$$

Lemma 3.9. *Let $n \geq 4$ be even. There is no friendly labeling f of $C_3 \times P_n$ such that $e_f(1) = 4, 5$.*

Proof. Let a be the number of horizontal mixed cycles and b the number of vertical mixed paths. If $b = 0$, then all three vertical paths are pure and therefore $|v_f(1) - v_f(0)| \geq n \geq 4$, contradicting to the assumption that f is a friendly labeling. Thus $b \neq 0$. We consider the following three cases for a .

- (1) Suppose $a = 0$. Then all three vertical paths are identical. Thus $e_f(1)$ is a multiple of 3, so $e_f(1) \neq 4, 5$.
- (2) Suppose $1 \leq a < n$. Then $C_3 \times P_n$ contains a horizontal mixed cycles and at least one pure cycle. By Lemma 3.8 we have $e_f(1) \geq 3 + 4 = 7$.
- (3) Suppose $a = n$. Since $b \geq 1$, it follows from Lemma 3.4 that $e_f(1) \geq 2n + b \geq 8 + 1 = 9$.

Combining all these cases together we conclude that $e_f(1) \neq 4, 5$. □

4. Elementary operations on vertex labeling

In this section we prove some results that will be useful in studying the full friendly index set of $C_m \times P_n$.

Let f be a labeling of $C_m \times P_n$. An $n \times m$ matrix A_f , whose (j, i) -entry is defined by $(A_f)_{ji} = f(u_{ij})$, is called the labeling matrix of $C_m \times P_n$ under f . For convenience, we write f for A_f . Let $[a, b] = \{i \in \mathbb{Z} \mid a \leq i \leq b\}$. We denote by $O_{p,q}$ and $J_{p,q}$ the $p \times q$ zero matrix and the $p \times q$ matrix whose entries are 1 respectively.

For a given matrix A , define a row operation σ_i on A by shifting the i -th row of A to the right by 1 entry (the last entry of the i -th row shifts to the first entry). Denote by $\sigma_i(A)$ the resulting matrix.

Proposition 4.1. Consider $C_m \times P_2$ with a labeling f represented by the matrix

$$f = \begin{pmatrix} J_{2, \lfloor m/2 \rfloor} & O_{2, \lceil m/2 \rceil} \end{pmatrix}.$$

For $0 \leq j \leq \lfloor m/2 \rfloor$, let $f_j = \sigma_1^j(f)$, where $\sigma_1^j := \overbrace{\sigma_1 \circ \cdots \circ \sigma_1}^j$. Then $e_{f_j}(1) = 4 + 2j$.

Proof. Note that f is friendly for even m but not for odd m . Note also that shifting the vertex labeling of first horizontal cycle will not change the number of 1-edges in the horizontal cycle; it will only change the number of 1-edges in the vertical paths.

Note that $f = f_0$ and $e_f(1) = 4$. Clearly

$$f_1 = \begin{pmatrix} 0 & 1 & \cdots & 1 & 1 & 0 & \cdots & 0 \\ 1 & \underbrace{1 \cdots 1}_{\lfloor m/2 \rfloor - 1} & 0 & \underbrace{0 \cdots 0}_{\lfloor m/2 \rfloor - 1} \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} J_{2, \lfloor m/2 \rfloor - 1} \begin{pmatrix} 1 \\ 0 \end{pmatrix} O_{2, \lceil m/2 \rceil - 1}.$$

Thus there are two more 1-edges in the vertical paths. It is easy to see that $e_{f_j}(1) - e_{f_{j-1}}(1) = 2$ for each $1 \leq j \leq \lfloor m/2 \rfloor + 1$. Thus $e_{f_j}(1) = 4 + 2j$.

Proposition 4.2. Consider $C_m \times P_2$.

(1) Let f be a friendly labeling of $C_m \times P_2$ represented by

$$\begin{pmatrix} 1 & 1 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \end{pmatrix}.$$

Interchange the labeling of the $2j$ -th column of the above matrix for all $1 \leq j \leq k$, and denote by f_k the resulting labeling with $f_0 := f$. Then $e_f(1) = m$ and $e_{f_k}(1) = m + 4k$ for each $0 \leq k \leq \lfloor m/2 \rfloor$.

(2) Let g be a friendly labeling of $C_m \times P_2$ represented by

$$\begin{pmatrix} 1 & \cdots & 1 & \boxed{1 \ 0 \ 1} \\ 0 & \cdots & 0 & \boxed{0 \ 0 \ 1} \end{pmatrix}.$$

Interchange the labeling of the $2j$ -th column of the above matrix for all $1 \leq j \leq k$, and denote by g_k the resulting labeling with $g_0 := g$. Then $e_g(1) = m + 2$ and $e_{g_k}(1) = m + 2 + 4k$ for each $0 \leq k \leq \lfloor m/2 \rfloor - 2$.

Proof. Note that interchanging the labeling of the columns will only change the number of 1-edges in the horizontal cycles and will not change the number of 1-edges of the vertical paths.

- (1) It is obvious that $e_f(1) = m$. Note that f_1 is obtained by interchanging the second column of the labeling f , and the resulting matrix is

$$\begin{pmatrix} 1 & 0 & 1 & \cdots & 1 \\ 0 & 1 & 0 & \cdots & 0 \end{pmatrix}.$$

Thus four more 1-edges are obtained from the horizontal cycles. It is easy to see that $e_{f_k}(1) - e_{f_{k-1}}(1) = 4$ for all $1 \leq k \leq \lfloor m/2 \rfloor$. Thus $e_{f_k}(1) = m + 4k$.

- (2) Similar to the above proof. □

For a friendly labeling f of a graph G , we have

$$e_f(1) - e_f(0) = 2e_f(1) - |E(G)|.$$

To compute $\text{FFI}(G)$, it suffices to compute the set

$$a(G) = \{e_f(1) \mid f \text{ is a friendly labeling of } G\}.$$

Then $\text{FFI}(G) = \{2i - |E(G)| \mid i \in a(G)\}$.

By substituting m by $2m$ and $2m + 1$ in Proposition 4.2 we have

Corollary 4.3. For $m \geq 2$

$$\{2m + 2i \mid i \in [0, 2m] \setminus \{2m - 1\}\} = \{2i \mid i \in [m, 3m] \setminus \{3m - 1\}\} \subseteq a(C_{2m} \times P_2),$$

and for $m \geq 1$

$$\{2m + 1 + 2i \mid i \in [0, 2m]\} = \{2i + 1 \mid i \in [m, 3m]\} \subseteq a(C_{2m+1} \times P_2).$$

The following lemma is obvious.

Lemma 4.4. Let f be a friendly labeling on $C_4 \times P_3$ represented by

$$\begin{pmatrix} 1 & 0 & 1 & 0 \\ * & 1 & 0 & * \\ 1 & 0 & 1 & 0 \end{pmatrix},$$

where $*$ is either 1 or 0. Interchange the $(1, 2)$ -entry with $(1, 3)$ -entry of f (or the $(3, 2)$ -entry with $(3, 3)$ -entry, not both) decreases $e_f(1)$ by 4. Interchange the $(1, 2)$ -entry with $(1, 3)$ -entry and the $(3, 2)$ -entry with $(3, 3)$ -entry decreases $e_f(1)$ by 8.

Proposition 4.5. Consider the labeling $f = \begin{pmatrix} J_{\lfloor n/2 \rfloor, 3} \\ O_{\lfloor n/2 \rfloor, 3} \end{pmatrix}$ on $C_3 \times P_n$. Interchange the $(\lfloor n/2 \rfloor - i + 1, 3)$ -entry with the $(\lfloor n/2 \rfloor + i, 1)$ -entry of f for each $1 \leq i \leq k$, where $k \leq \lfloor n/2 \rfloor - 1$, and denote by f_k the resulting labeling. Then $e_f(1) = 3$ and $e_{f_k}(1) = 3 + 4k$.

Proof. Note that f is friendly for even n but not for odd n . Note also that $e_f(1) = 3$. After interchanging the $(\lfloor n/2 \rfloor, 3)$ -entry with the $(\lfloor n/2 \rfloor + 1, 1)$ -entry from f , we have the following matrix

$$f_1 = \begin{pmatrix} J_{\lfloor n/2 \rfloor - 1, 3} \\ 1 & 1 & 0 \\ 1 & 0 & 0 \\ O_{\lfloor n/2 \rfloor - 1, 3} \end{pmatrix}.$$

From the above matrix we see that $e_{f_1}(1) = 7 = 3 + 4$. After interchanging the $(\lfloor n/2 \rfloor - 1, 3)$ -entry with the $(\lfloor n/2 \rfloor + 2, 1)$ -entry from f_1 , we have

$$f_2 = \begin{pmatrix} J_{\lfloor n/2 \rfloor - 2, 3} \\ 1 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \\ O_{\lfloor n/2 \rfloor - 2, 3} \end{pmatrix}.$$

From the above matrix we see that $e_{f_2}(1) = 11 = e_{f_1}(1) + 4$. It is easy to see that $e_{f_k}(1) - e_{f_{k-1}}(1) = 4$ for each $k \leq \lfloor n/2 \rfloor - 1$, and therefore $e_{f_k}(1) = 3 + 4k$. \square

5. Realizing the full friendly index set

In this section we realize all the potential friendly indices of $C_m \times P_n$ for some n and m .

In the following we determine for $a(C_m \times P_2)$ for $m \geq 4$, $a(C_m \times P_3)$ for $m \geq 4$ and $a(C_3 \times P_n)$ for $n \geq 4$.

Theorem 5.1. For $m \geq 2$, we have

$$a(C_{2m} \times P_2) = \{2i \mid i \in [2, 3m] \setminus \{3m - 1\}\}.$$

Proof. Let ϕ be any friendly labeling of $C_{2m} \times P_2$. By Theorem 2.1 and (1)(b) of Theorem 2.2, we have

$$6m \geq i_\phi(C_{2m} \times P_2) \geq 8 - 6m.$$

On the other hand, we have

$$i_\phi(C_{2m} \times P_2) = 2e_\phi(1) - |E(C_{2m} \times P_2)| = 2e_\phi(1) - 6m.$$

It follows that $6m \geq e_\phi(1) \geq 4$.

Let f be the labeling of $C_{2m} \times P_2$ of Proposition 4.1. Note that f is friendly. By Proposition 4.1 we have $\{2i \mid i \in [2, m + 2]\} \subseteq a(C_{2m} \times P_2)$. The result follows from Corollary 4.3. \square

Theorem 5.2. For $m \geq 2$, we have

$$a(C_{2m+1} \times P_2) = \{2i + 1 \mid i \in [2, 3m]\}.$$

Proof. Let ϕ be any friendly labeling of $C_{2m+1} \times P_2$. By Theorem 2.1 and (1)(b) of Theorem 2.2, we have

$$6m - 1 \geq i_\phi(C_{2m} \times P_2) \geq 7 - 6m.$$

It follows that $6m + 1 \geq e_\phi(1) \geq 5$.

Let f be a labeling on $C_{2m+1} \times P_2$ represented by the matrix

$$\left(J_{2,m} \begin{bmatrix} 0 \\ 1 \end{bmatrix} O_{2,m} \right).$$

Note that f is a friendly labeling of $C_{2m+1} \times P_2$ and $e_f(1) = 5$. By applying the procedure in Proposition 4.1 we have $e_{f_j}(1) = 5 + 2j$ for $0 \leq j \leq m$. Thus $\{2i + 1 \mid i \in [2, m + 2]\} \subseteq a(C_{2m+1} \times P_2)$. The result follows from Corollary 4.3. \square

Theorem 5.3. For $m \geq 3$, we have

$$a(C_{2m} \times P_3) = \{6, 10m\} \cup [8, 10m - 4].$$

Proof. Let ϕ be any friendly labeling of $C_{2m} \times P_3$. By Theorem 2.1 and (2)(b) of Theorem 2.2, we have

$$10m \geq i_\phi(C_{2m} \times P_3) \geq 12 - 10m.$$

That means $10m \geq e_\phi(1) \geq 6$. By Theorem 3.2, $e_\phi(1) \notin \{10m - 1, 10m - 2, 10m - 3\}$.

Let f be a labeling on $C_{2m} \times P_3$ represented by the matrix $\begin{pmatrix} J_{3,m} & O_{3,m} \end{pmatrix}$. Note that f is a friendly labeling of $C_{2m} \times P_2$ and $e_f(1) = 6$. Let $f_j = \sigma_3^j(f)$ for $0 \leq j \leq m$. Similar to the proof of Proposition 4.1, we have $e_{f_j}(1) = 6 + 2j$ for $0 \leq j \leq m$. Thus $\{2i \mid i \in [3, m + 3]\} \subseteq a(C_{2m} \times P_3)$. The matrix representing f_m is given by

$$\begin{pmatrix} J_{2,m} & O_{2,m} \\ O_{1,m} & J_{1,m} \end{pmatrix}.$$

Consider $\sigma_1^j(f_m)$ for $0 \leq j \leq m$. Similar to the proof of Proposition 4.1 we see that $\{2i \mid i \in [m + 3, 2m + 3]\} \subseteq a(C_{2m} \times P_3)$.

Consider another labeling g of $C_{2m} \times P_3$ represented by the matrix

$$\left(J_{3,m-1} \begin{bmatrix} 1 & 1 \\ 0 & 0 \\ 1 & 0 \end{bmatrix} O_{3,m-1} \right).$$

Note that g is a friendly labeling and $e_g(1) = 9$. Consider $\sigma_1^j(g)$ for $0 \leq j \leq m - 1$. Similar to the proof of Proposition 4.1, we have $\{2i + 1 \mid i \in [4, m + 3]\} \subseteq a(C_{2m} \times P_3)$. Let $\tilde{g} = \sigma_1^{m-1}(g)$. Consider $\sigma_3^j(\tilde{g})$ for $0 \leq j \leq m - 1$. Similarly we have $\{2i + 1 \mid i \in [m + 3, 2m + 2]\} \subseteq a(C_{2m} \times P_3)$.

Combining the above cases, we have $\{6\} \cup [8, 4m + 6] \subseteq a(C_{2m} \times P_3)$.

By Theorem 2.1 we have $e_\phi(1) \leq 10m$ for any friendly labeling ϕ . Let h be a labeling of $C_{2m} \times P_3$ whose matrix representation is given by

$$\begin{pmatrix} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & \cdots & 0 & 1 & 0 & 1 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 \end{pmatrix}.$$

Then h is a friendly labeling and $e_h(1) = 10m$.

Case 1: Suppose $m = 2k$ for some $k \geq 2$. Then we can subdivide the above matrix into k submatrices (blocks) of size 3×4 starting from the first column. Apply the procedure in Lemma 4.4 to the first row and the third row in each of these blocks consecutively, we see that $\{4i \mid i \in [3k, 5k]\} \subseteq a(C_{2m} \times P_3)$.

Consider the labelings p , q and r whose matrix representations are of the form

$$\begin{aligned} p &= \begin{pmatrix} \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 0 & 1 & 0 \\ \boxed{0 & 1 & 0 & 1} & \cdots & \boxed{0 & 1 & 0 & 1} & 0 & 0 & 0 & 1 \\ \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 1 & 1 & 0 \end{pmatrix}, \\ q &= \begin{pmatrix} \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 0 & 1 & 0 \\ \boxed{0 & 1 & 0 & 1} & \cdots & \boxed{0 & 1 & 0 & 1} & 0 & 0 & 1 & 1 \\ \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 1 & 0 & 0 \end{pmatrix}, \\ r &= \begin{pmatrix} \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 0 & 1 & 0 \\ \boxed{0 & 1 & 0 & 1} & \cdots & \boxed{0 & 1 & 0 & 1} & 0 & 1 & 0 & 0 \\ \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} & 1 & 1 & 1 & 0 \end{pmatrix}. \end{aligned}$$

Note that p , q and r are friendly labelings of $C_{2m} \times P_3$ and $e_p(1) = 20k - 5$, $e_q(1) = 20k - 6$ and $e_r(1) = 20k - 7$. By applying the procedure of Lemma 4.4 to the first $k - 1$ blocks of all these matrices consecutively, we see that $\{4i + 3 \mid i \in [3k, 5k - 2]\}$, $\{4i + 2 \mid i \in [3k, 5k - 2]\}$ and $\{4i + 1 \mid i \in [3k, 5k - 2]\}$ are subsets of $a(C_{2m} \times P_3)$.

Combining the above four cases, we have $[6m, 10m - 4] \cup \{10m\} \subseteq a(C_{2m} \times P_3)$.

Let s be a friendly labeling of $C_{2m} \times P_3$ whose matrix representation is given by

$$s = \begin{pmatrix} \boxed{1 & 0 & 1 & 0} & \cdots & \boxed{1 & 0 & 1 & 0} \\ \boxed{1 & 1 & 0 & 0} & \cdots & \boxed{1 & 1 & 0 & 0} \\ \boxed{0 & 1 & 1 & 0} & \cdots & \boxed{0 & 1 & 1 & 0} \end{pmatrix}.$$

Note that $e_s(1) = 6m$. By applying a similar procedure in Lemma 4.4 to the first row of each block of s consecutively, we see that $\{4i \mid i \in [2k, 3k]\} \subseteq a(C_{2m} \times P_3)$.

Consider the labelings t , u and v of $C_{2m} \times P_3$ whose matrix representations are given by

$$t = \begin{pmatrix} \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \cdots & \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{matrix} \end{pmatrix},$$

$$u = \begin{pmatrix} \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \cdots & \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \end{matrix} \end{pmatrix},$$

$$v = \begin{pmatrix} \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \cdots & \boxed{\begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 \end{matrix}} & \begin{matrix} 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 \end{matrix} \end{pmatrix}.$$

Note that t , u and v are friendly labelings of $C_{2m} \times P_3$ and $e_t(1) = 6m + 2$, $e_u(1) = 6m + 1$ and $e_v(1) = 6m - 1$. By applying a similar procedure of Lemma 4.4 to the first row of each boxed block of these matrices, we see that $\{4i+2 \mid i \in [2k+1, 3k]\}$, $\{4i+1 \mid i \in [2k+1, 3k]\}$ and $\{4i+3 \mid i \in [2k, 3k-1]\}$ are subsets of $a(C_{2m} \times P_3)$.

Combining the above four cases, we have $[4m+3, 6m+2] \subseteq a(C_{2m} \times P_3)$. The theorem holds for even m by considering all the above cases.

Case 2: Suppose $m = 2k + 1$ for some $k \geq 1$. We shall keep the labelings h , p , q , r , s , t , u and v for $m = 2k$. Let

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 1 & 0 \\ 1 & 0 \\ 1 & 0 \end{pmatrix}.$$

We construct a labeling \bar{h} similar to h in Case 1 by inserting the sub-matrix A into h as the last two columns. Then $e_{\bar{h}}(1) = 20k + 10 = 10m$. Similar to Case 1 (i.e., apply the procedure in Lemma 4.4 to the first k blocks consecutively), we have $\{4i + 10 \mid i \in [3k, 5k]\}$.

Construct labelings \bar{p} , \bar{q} and \bar{r} by inserting the sub-matrix A into p , q and r between the last fifth and the last fourth column, respectively. Then $e_{\bar{p}}(1) = 20k + 5$, $e_{\bar{q}}(1) = 20k + 4$ and $e_{\bar{r}}(1) = 20k + 3$. Similar to Case 1, after combining the above four cases, we have $[6m + 4, 10m - 4] \cup \{10m\} \subseteq a(C_{2m} \times P_3)$. Denote by \bar{p}_{k-1} the labeling after the procedure in Lemma 4.4 is applied $k - 1$ times. Then $e_{\bar{p}_{k-1}}(1) = 20k + 5 - 8(k - 1) = 12k + 13$. By swapping the entries of the first row of A in \bar{p}_{k-1} , we see that $e(1) = 12k + 9 = 6m + 3$.

Similarly, let \bar{s} be obtained from s by inserting the sub-matrix B as the last two columns. We also construct labelings \bar{t} , \bar{u} and \bar{v} by inserting the sub-matrix B into t , u and v between the last fifth and last the fourth column, respectively. Then $e_{\bar{s}}(1) = 12k + 6$, $e_{\bar{t}}(1) = 12k + 8$, $e_{\bar{u}}(1) = 12k + 7$ and $e_{\bar{v}}(1) = 12k + 5$. Similar to Case 1, we will obtain $\{4m + 5\} \cup [4m + 7, 6m + 2] \subseteq a(C_{2m} \times P_3)$. Note that $4m + 6$ is covered before defining the labeling h .

The theorem now holds for odd m . □

Theorem 5.4. For $m \geq 2$, we have

$$a(C_{2m+1} \times P_3) = [7, 10m + 2].$$

Proof. For $m = 2k$, let f_j be the labelings of $C_{2m} \times P_3$ defined in the proof of Theorem 5.3, $0 \leq j \leq m$.

Let \bar{f}_j be the labeling obtained from f_j by inserting the sub-matrix $A = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$ as the last column.

Note that \bar{f}_j is friendly. Similar to the proof of Theorem 5.3 we have $\{7 + 2i \mid 0 \leq i \leq 2m\} \setminus \{9\} \subseteq$

$a(C_{2m+1} \times P_3)$. If we replace the sub-matrix A in \bar{f}_j by B , where $B = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$, then it is easy to see

that $\{8 + 2i \mid 0 \leq i \leq 2m\} \subseteq a(C_{2m+1} \times P_3)$. On the other hand, it is easy to see that $e_{\sigma_1^1(\bar{f}_0)}(1) = 9$. Combining all these cases we have $[7, 4m + 8] \subseteq a(C_{2m+1} \times P_3)$.

Consider the labeling h represented by the following matrix

$$\left(\begin{array}{cccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 1 & \cdots & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \end{array} \right).$$

Note that h is a friendly labeling of $C_{2m+1} \times P_3$ and $e_h(1) = 10m + 2$. Apply the procedure in Lemma 4.4 to the first row and the third row in each of first k blocks consecutively, we see that $\{10m + 2 - 4i \mid 0 \leq i \leq 2k\} \subseteq a(C_{2m+1} \times P_3)$. Consider the labelings p , q and r represented by the matrices

$$p = \left(\begin{array}{cccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & \cdots & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \end{array} \right),$$

$$q = \left(\begin{array}{cccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & \cdots & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \end{array} \right),$$

$$r = \left(\begin{array}{cccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & \cdots & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \end{array} \right).$$

They are friendly and $e_p(1) = 10m + 1$, $e_q(1) = 10m$, and $e_r(1) = 10m - 1$. Similarly, apply the procedure in Lemma 4.4 to p , q and r we see that $\{10m + 1 - 4i \mid 0 \leq i \leq 2k\}$ and $\{10m - 4i \mid 0 \leq i \leq 2k\}$ and $\{10m - 1 - 4i \mid 0 \leq i \leq 2k\}$ are subsets of $a(C_{2m+1} \times P_3)$. Combining these four cases we see that $[6m - 1, 10m + 2] \subseteq a(C_{2m+1} \times P_3)$.

Consider the labelings

$$\begin{aligned}
 t &= \left(\begin{array}{ccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & \cdots & 0 & 1 & 1 & 0 & 1 \end{array} \right), \\
 u &= \left(\begin{array}{ccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 & \cdots & 0 & 1 & 1 & 0 & 1 \end{array} \right), \\
 v &= \left(\begin{array}{ccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & \cdots & 0 & 1 & 1 & 0 & 0 \end{array} \right), \\
 w &= \left(\begin{array}{ccc|ccc|c} 1 & 0 & 1 & 0 & \cdots & 1 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 0 & \cdots & 1 & 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 & \cdots & 0 & 1 & 1 & 0 & 0 \end{array} \right).
 \end{aligned}$$

These are friendly labelings and $e_t(1) = 6m + 4$, $e_u(1) = 6m + 3$, $e_v(1) = 6m + 2$ and $e_w(1) = 6m + 1$. Similar to the proof of Case 1 of Theorem 5.3, we see that $[4m + 1, 6m + 4] \subseteq a(C_{2m+1} \times P_3)$.

By considering all the above cases, the theorem holds when m is even. When m is odd, one can prove the theorem similar to the proof of Case 2 of Theorem 5.3. Thus the theorem holds for all $m \geq 2$. \square

Theorem 5.5. For $n \geq 3$, we have

$$a(C_3 \times P_{2n}) = \{3\} \cup [6, 10n - 3].$$

Proof. Let ϕ be any friendly labeling of $C_3 \times P_{2n}$. By Lemma 3.9, Theorem 2.1 and (1)(a) of Theorem 2.2, we have $10n - 3 \geq e_\phi(1) \geq 3$ and $e_\phi(1) \neq 4, 5$.

Obviously, $q = \begin{pmatrix} O_{1,3} \\ J_{n,3} \\ O_{n-1,3} \end{pmatrix}$ is a friendly labeling of $C_3 \times P_{2n}$ and $e_q(1) = 6$.

Let f be the labeling of $C_3 \times P_{2n}$ in Proposition 4.5. It is a friendly labeling and $e_f(1) = 3$. By applying the procedure in Proposition 4.5 to f we see that $\{4k + 3 \mid k \in [0, n - 1]\} \subseteq a(C_3 \times P_{2n})$.

Consider the labelings g , h and ℓ of $C_3 \times P_{2n}$ represented by the matrices

$$g = \begin{pmatrix} 1 & 1 & 0 \\ J_{n-1,3} \\ 1 & 0 & 0 \\ O_{n-1,3} \end{pmatrix}, \quad h = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ J_{n-2,3} \\ 1 & 0 & 0 \\ O_{n-1,3} \end{pmatrix}, \quad \ell = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ J_{n-2,3} \\ 1 & 1 & 0 \\ O_{n-1,3} \end{pmatrix}.$$

Note that g , h and ℓ are friendly and $e_g(1) = 8$, $e_h(1) = 9$ and $e_\ell(1) = 10$ respectively. For the labelings g and h , interchange the $(n - i + 1, 3)$ -entry with the $(n + i, 3)$ -entry for $1 \leq i \leq k$ if $n \geq 4$, where $k \leq n - 3$. The resulting labelings are denoted by g_k and h_k , respectively.

For the labeling g , we have

$$\{8 + 4k \mid 0 \leq k \leq n - 3\} \subseteq a(C_3 \times P_{2n}).$$

Extend the above procedure to the labeling g to $k = n - 2$ and $k = n - 1$. It is easy to see that $e_{g_{n-2}}(1) = 8 + 4(n - 2) = 4n$ and $e_{g_{n-1}}(1) = 8 + 4(n - 2) + 2 = 4n + 2$. Thus

$$\{8 + 4k \mid 0 \leq k \leq n - 2\} \cup \{4n + 2\} \subseteq a(C_3 \times P_{2n}).$$

For the labeling h , we have

$$\{9 + 4k \mid 0 \leq k \leq n - 3\} \subseteq a(C_3 \times P_{2n}).$$

For the labeling ℓ , first interchange the $(n, 3)$ -entry with the $(n + 2, 1)$ -entry, and then interchange the $(n + 1 - i, 3)$ -entry with the $(n + i, 3)$ -entry consecutively, for $2 \leq i \leq n - 3$ if $n \geq 5$. Then we see that

$$\{10 + 4i \mid 0 \leq i \leq n - 3\} \subseteq a(C_3 \times P_{2n}).$$

Combining all the above cases, we see that $\{3\} \cup [6, 4n] \cup \{4n + 2\} \subseteq a(C_3 \times P_{2n})$.

The matrix representing the labeling f_{n-1} is given by

$$\begin{pmatrix} J_{1,3} \\ A \\ B \\ O_{1,3} \end{pmatrix}, \text{ where } A = \begin{pmatrix} J_{n-1,2} & O_{n-1,1} \end{pmatrix} \text{ and } B = \begin{pmatrix} J_{n-1,1} & O_{n-1,2} \end{pmatrix}.$$

For $2 \leq k \leq n - 1$ and $n + 1 \leq k \leq 2n - 2$, shift consecutively the k -th row to the right by one unit if k is even, and to the left by one unit if k odd. Applying this procedure we get

$$\begin{aligned} \{2i - 1 \mid i \in [2n, 4n - 4]\} &\subseteq a(C_3 \times P_{2n}) \text{ when } n \text{ is odd;} \\ \{2i - 1 \mid i \in [2n, 4n - 3]\} \setminus \{6n - 3\} &\subseteq a(C_3 \times P_{2n}) \text{ when } n \text{ is even.} \end{aligned}$$

To realize the value $6n - 3$ for even n , we make a special labeling as follows. Apply the above procedure up to shifting the $(n - 1)$ -th row, and then shift the $(n + 1)$ -th row to the right by 1 unit.

The matrix representing the labeling g_{n-1} is given by

$$g_{n-1} = \begin{pmatrix} A \\ 1 & 0 & 1 \\ B \\ 0 & 0 & 0 \end{pmatrix}, \text{ where } A = \begin{pmatrix} J_{n,2} & O_{n,1} \end{pmatrix}, B = \begin{pmatrix} O_{n-2,2} & J_{n-2,1} \end{pmatrix}.$$

For $1 \leq k \leq n - 1$, shift consecutively the k -th row to the right by 1 unit if k is odd, and to the left by 1 unit if k is even. It is easy to see that each operation increases $e(1)$ by 2. After these procedures, if $n \geq 5$, then we interchange the $(n + 2, 3)$ -entry with the $(n + 3, 2)$ -entry, the $(n + 3, 3)$ -entry with the

$(n+4, 1)$ -entry, the $(n+4, 3)$ -entry with the $(n+5, 2)$ -entry, the $(n+5, 3)$ -entry with the $(n+6, 1)$ -entry, etc., up to interchanging the entry in the $(2n-3)$ -th row with the entry in the $(2n-2)$ -th row. Again, it is easy to see that each interchange increases $e(1)$ by 2. Thus

$$\{4n+2+2k \mid 1 \leq k \leq 2n-5\} \subseteq a(C_3 \times P_{2n}).$$

Let p be the labeling whose matrix representation is given by

$$\begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ \vdots & & \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}.$$

For $1 \leq k \leq n+2$, shift consecutively the k -th row to the right by 1 unit if k is odd, and to the left by 1 unit if k is even. It is easy to see that each shift decreases $e(1)$ by 2. The resulting labeling is denoted by p_k and let $p_0 = p$. Thus

$$\{10n-3-2k \mid 0 \leq k \leq n+2\} \subseteq a(C_3 \times P_{2n}).$$

By swapping the $(2n-1, 3)$ -entry and $(2n, 3)$ -entry of p_k for $0 \leq k \leq n+2$, it decreases $e(1)$ by 1. So we get

$$\{10n-4-2k \mid 0 \leq k \leq n+2\} \subseteq a(C_3 \times P_{2n}).$$

The theorem follows from considering all the above cases. \square

Theorem 5.6. For $n \geq 2$, $a(C_3 \times P_{2n+1}) = [5, 10n+2]$.

Proof. By Theorem 2.1 and (2) of Theorem 2.2 we have $10n+2 \geq e_\phi(1) \geq 5$ for any friendly labeling ϕ of $C_3 \times P_{2n+1}$.

Let $f = \begin{pmatrix} J_{n,3} \\ 1 & 0 & 0 \\ O_{n,3} \end{pmatrix}$. Then f is friendly and $e_f(1) = 5$. Interchanging the $(n-i+1, 3)$ -entry with the $(n+i+1, 1)$ -entry for $1 \leq i \leq k$ for each k ($1 \leq k \leq n-1$). The resulting labeling is denoted by f_k . We see that $\{4k+1 \mid k \in [1, n]\} \subseteq a(C_3 \times P_{2n+1})$.

Let g , h and ℓ be labelings of $C_3 \times P_{2n+1}$ whose matrix representations are given by

$$g = \begin{pmatrix} 1 & 1 & 0 \\ J_{n,3} \\ O_{n,3} \end{pmatrix}, \quad h = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 0 \\ J_{n-1,3} \\ O_{n,3} \end{pmatrix}, \quad \ell = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 1 & 0 \\ J_{n-1,3} \\ O_{n,3} \end{pmatrix}.$$

Note that g , h and ℓ are friendly, and $e_g(1) = 6$, $e_h(1) = 7$ and $e_\ell(1) = 8$. For the labeling g , interchange the $(k, 3)$ -entry with the $(n + k, 3)$ -entry consecutively for $2 \leq k \leq n$. The resulting labeling is denoted by g_k . It is easy to see that each interchange increases $e(1)$ by 4. Thus

$$\{6 + 4k \mid 0 \leq k \leq n - 1\} \subseteq a(C_3 \times P_{2n+1}).$$

For the labelings h and ℓ , interchange the $(k, 3)$ -entry with the $(n - 1 + k, 3)$ -entry consecutively for $3 \leq k \leq n$ if $n \geq 3$. It is easy to see that each interchange increases $e(1)$ by 4. Thus

$$\{7 + 4k \mid 0 \leq k \leq n - 2\} \subseteq a(C_3 \times P_{2n+1}).$$

$$\{8 + 4k \mid 0 \leq k \leq n - 2\} \subseteq a(C_3 \times P_{2n+1}).$$

Combining the above results, we have $[5, 4n + 2] \subseteq a(C_3 \times P_{2n+1})$.

Consider

$$f_n = \begin{pmatrix} J_{1,3} \\ A \\ B \\ O_{1,3} \end{pmatrix}, \text{ where } A = \begin{pmatrix} J_{n-1,2} & O_{n-1,1} \end{pmatrix}, B = \begin{pmatrix} J_{n,1} & O_{n,2} \end{pmatrix}.$$

For $k \in [2, 2n - 1] \setminus \{n\}$, shift consecutively the k -th row to the left by 1 unit if k is odd, and to the right by 1 unit if k is even. Applying this procedure we get

$$\begin{aligned} \{4n + 1 + 2i \mid i \in [0, 2n - 3]\} &\subseteq a(C_3 \times P_{2n+1}) \text{ when } n \text{ is odd;} \\ \{4n + 1 + 2i \mid i \in [0, 2n - 2]\} \setminus \{6n - 1\} &\subseteq a(C_3 \times P_{2n+1}) \text{ when } n \text{ is even.} \end{aligned}$$

To realize the value $6n - 1$ for even n , we make a special labeling as follows. Apply the above procedure up to shifting the $(n - 1)$ -th row, and then shift the n -th row to the right by 1 unit.

Consider the labeling

$$g_n = \begin{pmatrix} A \\ B \end{pmatrix}, \text{ where } A = \begin{pmatrix} J_{n,2} & O_{n,1} \end{pmatrix}, B = \begin{pmatrix} J_{1,3} & O_{n-1,2} & J_{n-1,2} \\ O_{1,3} \end{pmatrix}.$$

For $1 \leq k \leq 2n - 1$, shift consecutively the k -th row to the right by 1 unit if k is odd, and to the left by 1 unit if k is even. It is easy to see that each shift increases $e(1)$ by 2, except shifting the n -th row and the $(n + 1)$ -th row which preserve $e(1)$. Thus

$$\{4n + 2 + 2i \mid i \in [0, 2n - 3]\} \subseteq a(C_3 \times P_{2n+1}).$$

Let p be the labeling whose matrix representation is given by

$$\begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ \vdots & & \\ 1 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 1 \end{pmatrix}.$$

Similar to the procedure for the matrix p in Theorem 5.5, we have

$$[8n - 3, 10n + 2] \subseteq a(C_3 \times P_{2n+1}).$$

The theorem follows from considering all the above cases. \square

By constructing labelings directly, it is easy to obtain that $a(C_4 \times P_3) = [6, 16] \cup \{20\}$, $a(C_3 \times P_2) = \{3, 5, 7\}$, $a(C_3 \times P_3) = [5, 12]$ and $a(C_3 \times P_4) = \{3\} \cup [6, 17]$.

We summarize the full friendly index sets of cylinder graphs $C_m \times P_2$ for $m \geq 3$, $C_m \times P_3$ for $m \geq 3$, and $C_3 \times P_n$ for $n \geq 4$, as follows.

Theorem 5.7. *The full friendly index set of $C_m \times P_n$ is given by*

$$\text{FFI}(C_m \times P_2) = \{4i - 3m \mid i \in [2, 3m/2 - 2] \cup \{3m/2\}\} \text{ if } m \geq 4 \text{ is even.}$$

$$\text{FFI}(C_m \times P_2) = \{4i - 3m + 2 \mid i \in [2, (3m - 1)/2]\} \text{ if } m \geq 5 \text{ is odd.}$$

$$\text{FFI}(C_m \times P_3) = \{2i - 5m \mid i \in \{6, 5m\} \cup [8, 5m - 3]\} \text{ if } m \geq 6 \text{ is even.}$$

$$\text{FFI}(C_m \times P_3) = \{2i - 5m \mid i \in [7, 5m - 2]\} \text{ if } m \geq 5 \text{ is odd.}$$

$$\text{FFI}(C_3 \times P_n) = \{2i - 10n - 3 \mid i \in \{3\} \cup [6, 5n - 3]\} \text{ if } n \geq 4 \text{ is even.}$$

$$\text{FFI}(C_3 \times P_n) = \{2i - 10n - 3 \mid i \in [5, 5n + 2]\} \text{ if } n \geq 5 \text{ is odd.}$$

$$\text{FFI}(C_3 \times P_2) = \{-3, 1, 5\}.$$

$$\text{FFI}(C_3 \times P_3) = \{2i - 15 \mid i \in [5, 12]\}.$$

$$\text{FFI}(C_4 \times P_3) = \{2i - 20 \mid i \in [6, 16] \cup \{20\}\}.$$

Together with [10, 11] (the results are listed as follows), the full friendly index set of $C_m \times P_n$, for all m and n , are completely determined.

For $m, n \geq 4$, $\text{FFI}(C_m \times P_n)$ is given by

$$\begin{aligned} & \{ -2mn + m + 2i \mid i \in [2n + 2, 2mn - m - 4] \cup \{2n, 2mn - m\} \} \\ & \quad \text{for } m \geq 2n + 2 \text{ and } m, n \text{ are even;} \\ & \{ -2mn + m + 2i \mid i \in [m + 4, 2mn - m - 4] \cup \{m + 2, 2mn - m\} \} \\ & \quad \text{for } m \leq 2n - 2, m \text{ is even and } n \text{ is odd;} \\ & \{ -2mn + m + 2i \mid i \in [2n + 2, 2mn - m - 4] \cup \{2n, 2mn - m\} \} \\ & \quad \text{for } m \geq 2n \text{ and } m \text{ is even and } n \text{ is odd;} \\ & \{ -2mn + m + 2i \mid i \in [m + 4, 2mn - m - n] \cup \{m\} \} \\ & \quad \text{for } m \leq 2n - 3, m \text{ is odd and } n \text{ is even;} \\ & \{ -2mn + m + 2i \mid i \in [m + 2, 2mn - m - n] \cup \{m\} \} \\ & \quad \text{for } m = 2n - 1 \text{ and } n \text{ is even;} \\ & \{ -2mn + m + 2i \mid i \in [2n, 2mn - m - n] \} \\ & \quad \text{for } m \geq 2n + 1 \text{ and } m \text{ is odd and } n \text{ is even;} \\ & \{ -2mn + m + 2i \mid i \in [m + 4, 2mn - m - n] \cup \{m + 2\} \} \\ & \quad \text{for } m \leq 2n - 3 \text{ and } m, n \text{ are odd;} \\ & \{ -2mn + m + 2i \mid i \in [2n + 1, 2mn - m - n] \} \\ & \quad \text{for } m \geq 2n - 1 \text{ and } m, n \text{ are odd.} \end{aligned}$$

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