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Partitioning Harary graphs into connected subgraphs containing prescribed vertices

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Abstract

A graph G is *arbitrarily partitionable* (AP for short) if for every partition (τ_1, \dots, τ_p) of $|V(G)|$ there exists a partition (V_1, \dots, V_p) of $V(G)$ such that each V_i induces a connected subgraph of G with order τ_i . If, additionally, k of these subgraphs ($k \leq p$) each contains an arbitrary vertex of G prescribed beforehand, then G is *arbitrarily partitionable under k prescriptions* (AP+ k for short). Every AP+ k -graph on n vertices must be $(k+1)$ -connected, and have thus at least $\lceil \frac{n(k+1)}{2} \rceil$ edges. We show that there exist AP+ k -graphs on n vertices and $\lceil \frac{n(k+1)}{2} \rceil$ edges for every $k \geq 1$ and $n \geq k$.

Keywords: arbitrarily partitionable graph, partition under prescriptions, Harary graph.

1 Introduction

We denote by $V(G)$ and $E(G)$ the sets of vertices and edges, respectively, of a graph G . The *order* (resp. *size*) of G is the cardinality of the set $V(G)$ (resp. $E(G)$). If X is a subset of $V(G)$, then $G[X]$ denotes the subgraph of G induced by X .

In the late 1970s, Györi and Lovász independently proved the following well-known result.

Theorem 1 (Györi [4] and Lovász [6], independently) *If G is a k -connected graph, then, given k pairwise distinct vertices (v_1, \dots, v_k) of G and k positive integers (τ_1, \dots, τ_k) adding up to $|V(G)|$, there exists a partition (V_1, \dots, V_k) of $V(G)$ such that $v_i \in V_i$, the subgraph $G[V_i]$ is connected and $|V_i| = \tau_i$ for every $i \in [1, k]$.*

In this paper, we consider a more general partition problem resulting from the combination of the notion of *arbitrarily partitionable* graphs [1] with the constraint of prescribing a set of vertices from Theorem 1. Let G be a connected graph of order n . A sequence $\tau = (\tau_1, \dots, \tau_p)$ of positive integers is *admissible for G* if it performs a partition of n , that is if $\sum_{i=1}^p \tau_i = n$. If, additionally, we can partition $V(G)$ into p parts (V_1, \dots, V_p) such that each V_i induces a connected subgraph of G with order τ_i , then τ is *realizable in G* , and the partition (V_1, \dots, V_p) is a *realization of τ in G* . If every admissible sequence for G is also realizable in G , then G is *arbitrarily partitionable* (AP for short). The interested reader is referred to [1, 2, 7] for a review of some results on AP-graphs.

Now suppose that we still want to partition G into an arbitrary number, say p , of connected subgraphs G_1, \dots, G_p of prescribed orders, but in such a way that each connected subgraph

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$G_i \in \{G_1, \dots, G_k\}$, with $k \leq p$, contains some vertex v_i of G arbitrarily chosen. To model this additional requirement, the definition of AP-graphs can be strengthened as follows [3]. A k -prescription of G is a subset $P = (v_1, \dots, v_k)$ of k distinct vertices of G . We say that a sequence (τ_1, \dots, τ_p) with $p \geq k$ elements is *realizable in G under P* if there exists a realization (V_1, \dots, V_p) of τ in G such that for every $i \in [1, k]$, the vertex v_i belongs to V_i . Notice that we have adopted the convention that the sizes associated to the prescribed vertices are located at the beginning of the sequence. We now say that G is (p, k) -partitionable if every sequence admissible for G consisting of exactly p elements is realizable in G under every k -prescription. Finally, G is *arbitrarily partitionable under k prescriptions* (AP+ k for short) if G is (p, k) -partitionable for every $p \in [k, n]$.

According to these definitions, an AP+0-graph is an AP-graph. Stated differently, Theorem 1 says that every k -connected graph is (k, k) -partitionable. Hence, throughout this paper, we mainly consider (p, k) -partitions with $p > k$. For any $k \geq 1$, the set of complete graphs on at least k vertices is a trivial class of AP+ k -graphs, each of them having the largest possible number of edges. In this work, we will focus on *optimal AP+ k -graphs*, that is AP+ k -graphs having the least possible number of edges.

This paper is organized as follows. In Section 2, we introduce some notations and preliminary results which are useful to prove, in Sections 3 and 4, respectively, some results on the partitioning of powers of paths and cycles under many prescriptions. In Section 5, these results are then used to show that, for every $k \neq 2$, every $(k+1)$ -connected Harary graph is an optimal AP+ k -graph. We finally show, in Section 6, that 3-connected Harary graphs are not necessarily AP+2, and provide another class of optimal AP+2-graphs instead.

2 Definitions, notation, and preliminary results

A subgraph H of a graph G is a *spanning subgraph* of G if $V(H) = V(G)$. We will also say that G is *spanned by H* . Given a graph G and an integer $k \geq 1$, the k^{th} power of G , denoted by G^k , is the graph with the same vertex set as G , two of its vertices being adjacent if they are at distance at most k in G . Let P_n (resp. C_n) denote the path (resp. the cycle) on n vertices, and $\{v_0, \dots, v_{n-1}\}$ its set of vertices. For convenience, the vertices v_0 and v_{n-1} of P_n are called the *first vertex* and the *last vertex* of P_n , respectively. We use the same terminology to deal with the vertices of P_n^k (resp. C_n^k) according to its natural spanning path P_n (resp. spanning cycle C_n).

Let $k \geq 1$ and $n \geq k$ be any two integers. The k -connected Harary graph on n vertices, denoted by $H_{k,n}$, has vertex set $\{v_0, \dots, v_{n-1}\}$ and the following edges:

- if $k = 2r$ is even, then two vertices v_i and v_j are linked if and only if $i - r \leq j \leq i + r$;
- if $k = 2r + 1$ is odd and n is even, then $H_{k,n}$ is obtained by joining v_i and $v_{i+\frac{n}{2}}$ in $H_{2r,n}$ for every $i \in [0, \frac{n}{2} - 1]$;
- if $k = 2r + 1$ and n are odd, then $H_{k,n}$ is obtained from $H_{2r,n}$ by first linking v_0 to both $v_{\lfloor \frac{n}{2} \rfloor}$ and $v_{\lceil \frac{n}{2} \rceil}$, and then each vertex v_i to $v_{i+\lceil \frac{n}{2} \rceil}$ for every $i \in [1, \lfloor \frac{n}{2} \rfloor - 1]$;

where the subscripts are taken modulo n . Three examples of Harary graphs are given in Figure 1. When k is odd, the neighbours of a vertex v of $H_{k,n}$ which are at distance strictly more than k from v in its spanning C_n are called the *antipodal neighbours* of v . Clearly, v has at most two antipodal neighbours in $H_{k,n}$. In particular, v has exactly two antipodal neighbours if and only if $i = 0$, and k and n are both odd. A *diagonal edge* of $H_{k,n}$ is an edge linking two antipodal neighbours of $H_{k,n}$.

If G is a graph with a natural ordering of its vertices (like powers of paths and cycles, or Harary graphs), then, for any vertex v of G , we denote by v^+ (resp. v^-) the neighbour of v following v (resp. preceding v) in this ordering.

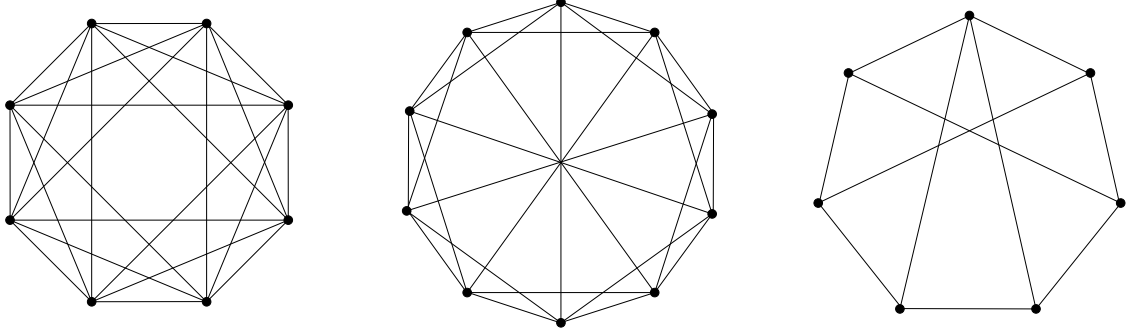


Figure 1: The Harary graphs $H_{6,8}$, $H_{5,10}$ and $H_{3,7}$

One of the first important property of AP-graphs is the following one.

Proposition 2 *If a graph G admits a spanning AP-subgraph (resp. a spanning $AP+k$ -subgraph for some $k \geq 1$), then G is AP (resp. $AP+k$).*

Recall that a graph is *traceable* if it admits a Hamiltonian path. Since every path is obviously AP, the previous proposition implies that every traceable graph is AP.

We now point out the following property of $AP+k$ -graphs, from which we deduce the size of an optimal $AP+k$ -graph.

Observation 3 *Every $AP+k$ -graph is $(k+1)$ -connected. Therefore, an optimal $AP+k$ -graph has $\lceil \frac{n(k+1)}{2} \rceil$ edges.*

Indeed, if there exist p vertices v_1, \dots, v_p , where $p \leq k$, such that $G - \{v_1, \dots, v_p\}$ is disconnected into q connected components on n_1, \dots, n_q vertices, respectively, with $n_1 \geq \dots \geq n_q$, then the sequence $(1, \dots, 1, n_1 + 1, (\sum_{i=2}^q n_i) - 1)$ cannot be realized in G under (v_1, \dots, v_p) . Since an edge-minimal $(k+1)$ -connected graph has size $\lceil \frac{n(k+1)}{2} \rceil$, this is the size of an optimal $AP+k$ -graph.

Baudon *et al.* [3] proved that, for every $k \geq 1$, there exist non complete $AP+k$ -graphs, namely the powers of paths and the powers of cycles:

Theorem 4 (Baudon et al. [3]) *The graph P_n^{k+1} is $AP+k$ for every $k \geq 0$ and $n \geq k+1$. The graph C_n^k is $AP+(2k-1)$ for every $k \geq 1$ and $n \geq 2k$.*

Since the number of edges of P_n^{k+1} is $(k+1)(n - (k+1)) + \sum_{i=1}^k i$, this graph has more edges than an optimal $AP+k$ -graph having the same number of vertices. However, C_n^k is $2k$ -regular and hence is an edge-minimal $2k$ -connected graph. According to Observation 3, it follows that the set of k^{th} powers of cycles is a set of optimal $AP+(2k-1)$ -graphs.

3 Partitioning P_n^k under strictly more than $k-1$ prescriptions

In this section, we point out, in terms of prescribed vertices location, some situations in which it is possible to partition the graph P_n^k under strictly more than $k-1$ prescriptions.

Lemma 5 ([3]) *Let $P = (v_{i_1}, \dots, v_{i_k})$ be a k -prescription of P_n^k with $k \geq 1$, $n \geq k$ and $0 \leq i_1 < \dots < i_k \leq n-1$. If $i_1 = 0$ or $i_k = n-1$, then every partition $\tau = (\tau_1, \dots, \tau_p)$ of n with $p \geq k$ elements is realizable in P_n^k under P .*

Lemma 6 *Let $P = (v_{i_1}, \dots, v_{i_{k+1}})$ be a $(k+1)$ -prescription of $G = P_n^k$ with $k \geq 1$, $n \geq k$ and $0 \leq i_1 < \dots < i_{k+1} \leq n-1$. If $i_1 = 0$ and $i_{k+1} = n-1$, then every partition $\tau = (\tau_1, \dots, \tau_p)$ of n with $p \geq k+1$ elements is realizable in G under P .*

Proof. We prove this claim by induction on k . For $k = 1$, the result is obvious; thus, we now suppose that $k \geq 2$ and that the claim holds for every k' such that $k' < k$. If $\tau_1 \leq i_2$, then a correct realization of τ in G under P is (V_1, \dots, V_p) where $V_1 = \{v_0, \dots, v_{\tau_1-1}\}$ and (V_2, \dots, V_p) is a realization of (τ_2, \dots, τ_p) in $G - V_1$ under the prescription $(v_{i_2}, \dots, v_{i_{k+1}})$. This realization necessarily exists according to Lemma 5 since $v_{i_{k+1}}$ is the last vertex of $G - V_1$.

Suppose now that $\tau_1 > i_2$. Observe that $[0, k-1] - (\bigcup_{j=2}^k i_j \pmod k)$ is not empty, and let us denote by r one of these values. The subset V_1 of the realization is constructed as follows. It first contains all the vertices between v_0 and v_{i_2-1} , that is $V_1 \supseteq \{v_0, \dots, v_{i_2-1}\}$. We then add the vertex v_j to V_1 , where $j \in [i_2 + 1, i_2 + k - 1]$ is such that $j \equiv r \pmod k$. Finally, as long as $|V_1| < \tau_1$ and we do not reach v_{n-1} , we repeatedly add to V_1 the vertex at distance k on the right from the last one added to V_1 (v_{j+k}, v_{j+2k} , etc.). According to our choice of r , these vertices are not prescribed ones and, at any moment of this procedure, the subgraph $G - V_1$ is spanned by the $(k-1)^{\text{th}}$ power of a path and the subgraph $G[V_1]$ is connected.

Thus, on the one hand, if $|V_1| = \tau_1$ holds after the procedure, then (V_1, \dots, V_p) is a correct realization of τ under P , where (V_2, \dots, V_p) is a realization of (τ_2, \dots, τ_p) in $G - V_1$ under the prescription $(v_{i_2}, \dots, v_{i_{k+1}})$ which necessarily exists by the induction hypothesis since v_{i_2} and $v_{i_{k+1}}$ are the first and last vertices of $G - V_1$.

On the other hand, if $|V_1| < \tau_1$ holds once the procedure is achieved, then each vertex from $V(G) - V_1$ has a neighbour in V_1 . Hence, we can obtain a correct realization $(V_1 \cup V_1', V_2, \dots, V_p)$ of τ in G under P , where (V_2, \dots, V_p, V_1') is a realization of $(\tau_2, \dots, \tau_p, \tau_1 - |V_1|)$ in $G - V_1$ under the prescription $(v_{i_2}, \dots, v_{i_{k+1}})$. Once again, such a realization necessarily exists in this subgraph according to the induction hypothesis. \blacksquare

Lemma 7 *Let $P = (v_{i_1}, \dots, v_{i_k})$ be a k -prescription of $G = P_n^k$ with $k \geq 1$, $n \geq k$ and $0 \leq i_1 < \dots < i_k \leq n-1$. If $i_k \neq i_1 + k - 1$, then every partition $\tau = (\tau_1, \dots, \tau_p)$ of n with $p \geq k$ elements is realizable in P_n^k under P .*

Proof. If $x = \sum_{j=k+1}^p \tau_j \leq i_1$, then a correct realization of τ in G under P is (V_1, \dots, V_p) where (V_{k+1}, \dots, V_p) is an arbitrary realization of $(\tau_{k+1}, \dots, \tau_p)$ in the traceable subgraph $G[\{v_0, \dots, v_{x-1}\}]$, and (V_1, \dots, V_k) is a realization of (τ_1, \dots, τ_k) in $G - \{v_0, \dots, v_{x-1}\}$ under P obtained using Theorem 1.

Suppose now that $x > i_1$. On the one hand, if $\tau_1 > i_1$, then a correct realization of τ in G under P is $(V_1' \cup V_1'', V_2, \dots, V_p)$, where $V_1' = \{v_0, \dots, v_{i_1-1}\}$ and (V_1'', V_2, \dots, V_p) is a realization of $(\tau_1 - i_1, \tau_2, \dots, \tau_p)$ in $G - V_1'$ under P obtained via Lemma 5. On the other hand, if $\tau_1 \leq i_1$, then let V_1 be a subset of $\{v_0, \dots, v_{i_1}\}$ obtained as follows. First, we let $V_1 = \{v_{i_1}\}$ and we then repeatedly add to V_1 the vertex located at distance 2 on the left of the last vertex added to V_1 as long as $|V_1| < \tau_1$ and v_0 is not reached. If there is no vertex at distance 2 on the left of the last vertex added to V_1 , then we add to V_1 every remaining vertex from $\{v_0, \dots, v_{i_1-1}\} - V_1$ from left to right until V_1 has size τ_1 . Let $X = \{v_0, \dots, v_{i_1-1}\} - V_1$. Notice that, at the end of the previous procedure, $G[V_1]$ is connected, $G[X]$ is traceable, and $v_{i_1-1} \in X$. Now, if there exists $y \in [k+1, p]$ such that $\sum_{j=k+1}^y \tau_j = |X|$, then a correct realization of τ in G under P is (V_1, \dots, V_p) where (V_{k+1}, \dots, V_y) is a realization of $(\tau_{k+1}, \dots, \tau_y)$ in $G[X]$ and $(V_2, \dots, V_k, V_{y+1}, \dots, V_p)$ is a realization of $(\tau_2, \dots, \tau_k, \tau_{y+1}, \dots, \tau_p)$ in $G - \{v_1, \dots, v_{i_1}\}$ under $\{v_{i_2}, \dots, v_{i_k}\}$ obtained using Lemma 5.

Theorem 1. On the contrary, if for some y we have $\sum_{j=k+1}^{y-1} \tau_j < |X|$ and $\sum_{j=k+1}^y \tau_j > |X|$, then let $\tau_y' = |X| - \sum_{j=k+1}^{y-1} \tau_j$, $\tau_y'' = \tau_y - \tau_y'$, and $v_\alpha \notin P$ be the nearest neighbour of v_{i_1-1} located on the right of v_{i_1} . Such a vertex necessarily exists since otherwise this would imply that our k prescribed vertices are located consecutively along G . Moreover, v_α is the first vertex of $G - \{v_0, \dots, v_{i_1}\}$ if $v_{i_1}^+ \neq v_{i_2}$. We then obtain a desired realization $(V_1, \dots, V_{y-1}, V_y' \cup V_y'', V_{y+1}, \dots, V_p)$ of τ in G under P , where $(V_y', V_{k+1}, \dots, V_{y-1})$ is a realization of $(\tau_y', \tau_{k+1}, \dots, \tau_{y-1})$ in $G[X]$ under (v_{i_1-1}) , and $(V_2, \dots, V_k, V_y'', V_{y+1}, \dots, V_p)$ is a realization of $(\tau_2, \dots, \tau_k, \tau_y'', \tau_{y+1}, \dots, \tau_p)$ in $G[\{v_{i_1+1}, \dots, v_{n-1}\}]$ under $(v_{i_2}, \dots, v_{i_k}, v_\alpha)$. Those two realizations exist according to Lemma 5. \blacksquare

4 Partitioning C_n^k under $2k$ prescriptions

We now prove, for any $k \geq 1$ and $n \geq 2k$, that C_n^k can be partitioned under $2k$ prescriptions when the prescribed vertices are "conveniently" located in C_n^k . Since the Harary graph $H_{2k+1,n}$ is spanned by C_n^k , these results imply that, in some situations, we can deduce a partitioning of $H_{2k+1,n}$ under $2k$ prescriptions using a spanning subgraph argument.

We first introduce some notations. Suppose that $G = C_n^k$ for some $k \geq 1$ and $n \geq 2k$, and that we want to realize the sequence $\tau = (\tau_0, \dots, \tau_{p-1})$ in G under $P = (v_{i_0}, \dots, v_{i_{2k-1}})$, with $p \geq 2k$ and $0 \leq i_0 < \dots < i_{2k-1} \leq n-1$. For every $j \in [0, 2k-1]$, we denote by d_j the value $i_j - i_{j-1} - 1$. In particular, we have $n = 2k + \sum_{j=0}^{2k-1} d_j$. Given two distinct integers $x, y \in [0, 2k-1]$ such that $x < y$, the *garden of the prescribed vertices* v_{i_x}, \dots, v_{i_y} in G is defined as $G_{x,y} = \{v_{i_{x-1}}^+, \dots, v_{i_{y+1}}^-\}$ and is the maximum subset of consecutive vertices of G containing no other prescribed vertices than v_{i_x}, \dots, v_{i_y} . In particular, $|G_{x,y}| = (y - x + 1) + \sum_{j=x}^{y+1} d_j$. We say that the prescribed vertices v_{i_x}, \dots, v_{i_y} are *saturated for τ in their garden* if $\sum_{j=x}^y \tau_j > |G_{x,y}|$, that is if the parts associated to the prescribed vertices v_{i_x}, \dots, v_{i_y} of a realization of τ in G under P must contain some vertices of $V(G) - G_{x,y}$.

Lemma 8 *Let $P = (v_{i_0}, \dots, v_{i_{2k-1}})$ be a $2k$ -prescription of $G = C_n^k$ with $k \geq 1$, $n \geq 2k$ and $0 \leq i_0 < \dots < i_{2k-1} \leq n-1$, and $\tau = (\tau_0, \dots, \tau_{p-1})$ be an admissible sequence for G with $p \geq 2k$. For any $x \in [0, 2k-1]$, if the prescribed vertices $v_{i_x}, \dots, v_{i_{x+k-1}}$ are saturated for τ in their garden, then neither the prescribed vertices $v_{i_{x+1}}, \dots, v_{i_{x+k}}$ nor $v_{i_{x+k+1}}, \dots, v_{i_x}$ are saturated in their respective garden.*

Proof. Let us consider, without loss of generality, that $x = 0$. If the prescribed vertices $v_{i_0}, \dots, v_{i_{k-1}}$ are saturated for τ in $G_{0,k-1}$, then we have:

$$\sum_{j=0}^{k-1} \tau_j > k + \sum_{j=0}^k d_j,$$

and

$$\sum_{j=k}^{2k-1} \tau_j < k + \sum_{j=k+1}^{2k-1} d_j.$$

If the prescribed vertices v_{i_1}, \dots, v_{i_k} are also saturated for τ in $G_{1,k}$, then

$$\sum_{j=1}^k \tau_j > k + \sum_{j=1}^{k+1} d_j,$$

and

$$\tau_0 + \sum_{j=k+1}^{2k-1} \tau_j < k + d_0 + \sum_{j=k+2}^{2k-1} d_j,$$

which implies that both $n_1 - n_{k+1} > d_1 - d_{k+2}$ and $n_1 - n_{k+1} < d_1 - d_{k+2}$ hold, a contradiction.

If we now suppose that $v_{i_{k+1}}, \dots, v_{i_0}$ are saturated for τ in $G_{k+1,0}$, then

$$\sum_{j=1}^k \tau_j < k + \sum_{j=2}^k d_j,$$

and

$$\tau_0 + \sum_{j=k+1}^{2k-1} \tau_j > k + d_0 + d_1 + \sum_{j=k+1}^{2k-1} d_j,$$

and we thus get that both

$$\left(\sum_{j=1}^{k-1} \tau_j\right) - \left(\sum_{j=k+1}^{2k-1} \tau_j\right) > \left(\sum_{j=2}^k d_j\right) - \left(\sum_{j=k-1}^{2k-1} d_j\right)$$

and

$$\left(\sum_{j=1}^{k-1} \tau_j\right) - \left(\sum_{j=k+1}^{2k-1} \tau_j\right) < \left(\sum_{j=2}^k d_j\right) - \left(\sum_{j=k-1}^{2k-1} d_j\right)$$

hold, again a contradiction. \blacksquare

In what follows, a *maximal block* B of P in C_n^k is a maximal subset $B \subseteq P$ of consecutive vertices of C_n^k . In particular, if $\{v_{i_q}, \dots, v_{i_{q+\alpha}}\}$ is a maximal block of P in C_n^k , then neither $v_{i_q}^-$ nor $v_{i_{q+\alpha}}^+$ are prescribed vertices.

Lemma 9 *Let $P = (v_{i_0}, \dots, v_{i_{2k-1}})$ be a $2k$ -prescription of $G = C_n^k$ with $k \geq 1$, $n \geq 2k$ and $0 \leq i_1 < \dots < i_k \leq n-1$. If there exists exactly one maximal block B of P in G of size at least k , then every partition $\tau = (\tau_0, \dots, \tau_{p-1})$ of n with $p \geq 2k$ elements is realizable in G under P .*

Proof. Let us suppose, without loss of generality, that $v_{i_0}, \dots, v_{i_{k-1}}$ belong to B . We distinguish two subcases depending on whether $v_{i_0}, \dots, v_{i_{k-1}}$ are saturated for τ in their garden or not.

Case 1: The prescribed vertices $v_{i_0}, \dots, v_{i_{k-1}}$ are not saturated for τ in $G_{0,k-1}$.

Let X be a subset of $\sum_{j=0}^{k-1} \tau_j$ consecutive vertices of $G_{0,k-1}$ such that $X \cap P = \{v_{i_0}, \dots, v_{i_{k-1}}\}$. According to Theorem 1, there exists a realization (V_0, \dots, V_{k-1}) of $(\tau_0, \dots, \tau_{k-1})$ in $G[X]$ under the prescription $(v_{i_0}, \dots, v_{i_{k-1}})$ since this subgraph is k -connected. Now observe that a realization (V_k, \dots, V_{p-1}) of $(\tau_k, \dots, \tau_{p-1})$ in $G - X$ under the prescription $(v_{i_k}, \dots, v_{i_{2k-1}})$ necessarily exists since $G - X$ is isomorphic to the k^{th} power of a path and we supposed that the prescribed vertices perform only one maximal block of size at least k in G . This implies that either v_{i_k} is the first vertex of $G - X$, $v_{i_{2k-1}}$ is the last vertex of $G - X$, or the prescribed vertices $v_{i_k}, \dots, v_{i_{2k-1}}$ are not consecutive in $G - X$. In the first two cases, the realization is obtained thanks to Lemma 5, and it follows from Lemma 7 in the third case. Finally, observe that (V_0, \dots, V_{p-1}) is a correct realization of τ in G under P .

Case 2: The prescribed vertices $v_{i_0}, \dots, v_{i_{k-1}}$ are saturated for τ in $G_{0,k-1}$.

By Lemma 8, we know that neither v_{i_1}, \dots, v_{i_k} nor $v_{i_{k+1}}, \dots, v_{i_0}$ are saturated for τ in $G_{1,k}$ and $G_{k+1,0}$, respectively. Hence, only two cases may occur.

Case 2.a. If there exists a subset X' of $\sum_{j=1}^k \tau_j$ consecutive vertices of $G_{1,k}$ such that $P \cap X' = \{v_{i_1}, \dots, v_{i_k}\}$, then, since v_{i_0} is the last vertex of $G - X'$, all the conditions are met to apply the procedure used in *Case 1* with v_{i_1}, \dots, v_{i_k} and X' to get the desired realization. A similar realization can be obtained analogously if the assumption above holds for $v_{i_{k+1}}, \dots, v_{i_0}$ and their garden $G_{k+1,0}$.

Case 2.b. Suppose now that both $\sum_{j=1}^k \tau_j < k + \sum_{j=2}^k d_j$ and $\tau_0 + \sum_{j=k+1}^{2k-1} \tau_j < k + d_0 + \sum_{j=k+2}^{2k-1} d_j$ hold. Let $X = \{v_{i_1}, \dots, v_{i_k}\}$. If there exists a $x \in [2k, p-1]$ such that $(\sum_{j=1}^k \tau_j) + (\sum_{j=2k}^x \tau_j) = |X|$ then we can partition G into two graphs $G[X]$ and $G - X$ and obtain a whole realization of τ in G under P by considering realizations of $(\tau_1, \dots, \tau_k, \tau_{2k}, \dots, \tau_x)$ in $G[X]$ under $(v_{i_1}, \dots, v_{i_k})$ and of $(\tau_0, \tau_{k+1}, \dots, \tau_{2k-1}, \tau_{x+1}, \dots, \tau_{p-1})$ in $G - X$ under $(v_{i_0}, v_{i_{k+1}}, \dots, v_{i_{2k-1}})$ which necessarily exist since the conditions of Lemma 5 are satisfied in both cases (v_{i_0} is the last vertex of $G - X$ and v_{i_1} is the first vertex of $G[X]$). Finally, (V_0, \dots, V_{p-1}) is a realization of τ in G under P .

If such a x does not exist, then let $x \in [2k, p-1]$ be such that $(\sum_{j=1}^k \tau_j) + (\sum_{j=2k}^{x-1} \tau_j) < |X|$ and $(\sum_{j=1}^k \tau_j) + (\sum_{j=2k}^x \tau_j) > |X|$, and let $\tau'_x = |X| - [(\sum_{j=1}^k \tau_j) + (\sum_{j=2k}^{x-1} \tau_j)]$ and $\tau''_x = \tau_x - \tau'_x$. Since we supposed that there is only one maximal block of P in G with size at least k and

v_{i_0} and v_{i_1} are adjacent according to the natural ordering of $V(G)$, there exist $\alpha \in [i_1, i_k]$ and $\beta \in [i_k + 1, i_k + k - 1]$ such that v_α and v_β are adjacent and are not prescribed vertices (otherwise there would exist a second maximal block of P in G with size at least k since v_{i_1}, \dots, v_{i_k} are not saturated for τ in their garden). In particular, let us choose v_β in such a way that the distance between v_α and v_β is the smallest possible according to the natural ordering of $V(G)$. We get that either v_β or $v_{i_{k+1}}$ is the first vertex of $G - X$.

Finally, we obtain the desired realization of τ in G under P as follows. First, let $(V_1, \dots, V_k, V'_x, V_{2k}, \dots, V_{x-1})$ be a realization of $(\tau_1, \dots, \tau_k, \tau'_x, \tau_{2k}, \dots, \tau_{x-1})$ in $G[X]$ under $(v_{i_1}, \dots, v_{i_k}, v_\alpha)$. Then, let $(V_0, V_{k+1}, \dots, V_{2k-1}, V''_x, V_{x+1}, \dots, V_{p-1})$ be a realization of $(\tau_0, \tau_{k+1}, \dots, \tau_{2k-1}, \tau''_x, \tau_{x+1}, \dots, \tau_{p-1})$ in $G - X$ under $(v_{i_0}, v_{i_{k+1}}, \dots, v_{i_{2k-1}}, v_\beta)$. These two realizations necessarily exist according to Lemma 6. Moreover, the subgraph $G[V'_x \cup V''_x]$ is connected since $v_\alpha v_\beta \in E(G)$; therefore, we eventually get that $(V_0, \dots, V_{x-1}, V'_x \cup V''_x, V_{x+1}, \dots, V_{p-1})$ is a correct realization of τ in G under P . \blacksquare

Lemma 10 *Let $P = (v_{i_0}, \dots, v_{i_{2k-1}})$ be a $2k$ -prescription of $G = C_n^k$ with $k \geq 1$, $n \geq 2k$ and $0 \leq i_1 < \dots < i_k \leq n - 1$. If there does not exist a maximal block of P in G of size at least k , then every partition $\tau = (\tau_0, \dots, \tau_{p-1})$ of n with $p \geq 2k$ elements is realizable in G under P .*

Proof. We can suppose, without loss of generality, that neither $v_{i_0}, \dots, v_{i_{k-1}}$ nor $v_{i_k}, \dots, v_{i_{2k-1}}$ are saturated for τ in $G_{0,k-1}$ and $G_{k,2k-1}$, respectively. Indeed, if one of these conditions holds, then this cannot be simultaneously the case for v_{i_1}, \dots, v_{i_k} nor $v_{i_{k+1}}, \dots, v_{i_{2k-1}}, v_{i_0}$ in their respective garden according to Lemma 8; we could thus easily relabel our prescribed vertices and part sizes so that the above assertion holds.

We distinguish the following two subcases.

Case 1. If we can find a subset X of $\sum_{j=0}^{k-1} \tau_j$ consecutive vertices of $G_{0,k-1}$ such that $P \cap X = \{v_{i_0}, \dots, v_{i_{k-1}}\}$, then we can obtain a correct realization of τ in G under P in a same way as what we did in *Case 2.a* of Lemma 9. A similar argument holds if there exists a satisfying subset X included in the garden of $v_{i_k}, \dots, v_{i_{2k-1}}$.

Case 2. The last case which may happen is the one where both $\sum_{j=0}^{k-1} \tau_j < k + \sum_{j=1}^{k-1} d_j$ and $\sum_{j=k}^{2k-1} \tau_j < k + \sum_{j=k+1}^{2k-1} d_j$ hold, and neither v_{i_0} and $v_{i_{2k-1}}$ nor $v_{i_{k-1}}$ and v_{i_k} are consecutive vertices of G (otherwise, we could use the arguments of *Case 2.b* of Lemma 9 to deduce a realization of τ in G under P). We can suppose that there does not exist $x \in [2k, p - 1]$ such that $\sum_{j=0}^{k-1} \tau_j + \sum_{j=2k}^x \tau_j = k + \sum_{j=1}^{k-1} d_j$ or $\sum_{j=k}^{2k-1} \tau_j + \sum_{j=2k}^x \tau_j = k + \sum_{j=k+1}^{2k-1} d_j$ for otherwise we could find a realization of τ in G under P using Lemma 7 since there is no maximal block of P in G with size at least k . We explain below how to deduce a realization of τ in G under P .

If $\tau_0 + \tau_{2k-1} \geq d_0 + 2$, then we can obtain a correct realization of τ in G under P as follows. Let $V'_0 = \{v_{i_0-1}, v_{i_0-2}, \dots, v_\alpha\}$ and $V'_{2k-1} = \{v_{i_{2k-1}+1}, v_{i_{2k-1}+2}, \dots, v_\alpha^-\}$ where $|V'_0| < \tau_0$, $|V'_{2k-1}| < \tau_{2k-1}$, and $\alpha \in [i_{2k-1} + 1, i_0 - 1]$. Then, consider a realization $(V''_0, V_1, \dots, V_{2k-2}, V''_{2k-1}, V_{2k}, \dots, V_{p-1})$ of the sequence $(\tau_0 - |V'_0|, \tau_1, \dots, \tau_{2k-2}, \tau_{2k-1} - |V'_{2k-1}|, \tau_{2k}, \dots, \tau_{p-1})$ in the subgraph $G[\{v_{i_0}, \dots, v_{i_{2k-1}}\}]$ under P obtained in the same way as what we did for *Case 2.b* (that is by doing as if v_{i_0} and $v_{i_{2k-1}}$ were consecutive vertices of G). Such a realization necessarily exists since we supposed that there is no maximal block of P in G with size at least k . Finally, observe that the realization $(V'_0 \cup V''_0, V_1, \dots, V_{2k-2}, V'_{2k-1} \cup V''_{2k-1}, V_{2k}, \dots, V_{p-1})$ is a correct realization of τ in G under P .

Now, if $\tau_0 + \tau_{2k-1} < d_0 + 2$, then $\tau_0 - 1 \geq \lfloor \frac{d_0(k-1)}{k} \rfloor$ and $\tau_{2k-1} - 1 \geq \lfloor \frac{d_0(k-1)}{k} \rfloor$ cannot hold simultaneously since otherwise we would get a contradiction. Let $Z = \{v_{i_{2k-1}}^+, \dots, v_{i_0}^-\}$ and suppose that $\tau_0 - 1 < \lfloor \frac{d_0(k-1)}{k} \rfloor$; thus, there exists a subset V_0 of $Z \cup \{v_{i_0}\}$ such that $G[V_0]$ is connected on τ_0 vertices, V_0 contains the vertex v_{i_0} but does not contain neither $v_{i_{2k-1}}^+$ nor $v_{i_0}^-$, and the subgraph $G[Z - V_0]$ is traceable.

Once again, we can suppose that there does not exist $x \in [2k, p - 1]$ such that $\sum_{j=1}^{k-1} \tau_j + \sum_{j=2k}^x \tau_j = |G_{1,k-1}|$ since otherwise we could easily deduce a realization of τ in G under P using

Lemmas 5 and 6 (recall that $v_{i_k}, \dots, v_{i_{2k-1}}$ are not saturated for τ in their garden). Thus, let $x \in [2k, p-1]$ be such that $\sum_{j=1}^{k-1} \tau_j + \sum_{j=2k}^{x-1} \tau_j < |G_{1,k-1}|$ and $\sum_{j=1}^{k-1} \tau_j + \sum_{j=2k}^x \tau_j > |G_{1,k-1}|$, and let $\tau'_x = |G_{1,k-1}| - \sum_{j=1}^{k-1} \tau_j - \sum_{j=2k}^{x-1} \tau_j$ and $\tau''_x = \tau_x - \tau'_x$. For the sake of the proof, let us also denote τ_p instead of τ''_x . Since $G_{1,k-1}$ only includes $k-1$ prescribed vertices, then we can obtain a realization $(V_1, \dots, V_{k-1}, V'_x, V_{2k}, \dots, V_{x-1})$ of $(\tau_1, \dots, \tau_{k-1}, \tau'_x, \tau_{2k}, \dots, \tau_{x-1})$ in $G[G_{1,k-1}]$ under $(v_{i_1}, \dots, v_{i_{k-1}}, v_\alpha)$ where v_α is a non-prescribed vertex of $G_{1,k-1}$ neighbouring $v_{i_0}^-$. Such a vertex necessarily exists since there are no maximal block of P of size at least k in G ; in particular, choose $v_\alpha = v_{i_0}^+$ if $v_{i_1} \neq v_{i_0}^+$. The previous realization exists by Lemma 5.

For the same reasons as above, let us suppose that there does not exist $y \in [x+1, p]$ such that $\sum_{j=k}^{2k-1} \tau_j + \sum_{j=x+1}^y \tau_j = k + \sum_{j=k+1}^{2k-1} d_j$. Then denote by $y \in [x+1, p]$ the least integer such that $\sum_{j=k}^{2k-1} \tau_j + \sum_{j=x+1}^{y-1} \tau_j < k + \sum_{j=k+1}^{2k-1} d_j$ and $\sum_{j=k}^{2k-1} \tau_j + \sum_{j=x+1}^y \tau_j > k + \sum_{j=k+1}^{2k-1} d_j$. Next, let us split τ_y into two elements τ'_y and τ''_y as above, and use the arguments above once again to obtain a realization $(V_k, \dots, V_{2k-1}, V'_y, V_{x+1}, \dots, V_{y-1})$ of $(\tau_k, \dots, \tau_{2k-1}, \tau'_y, \tau_{x+1}, \dots, \tau_{y-1})$ in $G[\{v_{i_k}, \dots, v_{i_{2k-1}}\}]$ under $(v_{i_k}, \dots, v_{i_{2k-1}}, v_\beta)$ where v_β is a non-prescribed vertex of $\{v_{i_k}, \dots, v_{i_{2k-1}}\}$ neighbouring $v_{i_{2k-1}}^+$. This realization exists by Lemma 6 since v_{i_k} and $v_{i_{2k-1}}$ are the first and last vertices of $G[\{v_{i_k}, \dots, v_{i_{2k-1}}\}]$, respectively.

On the one hand, if $y = p$, then it means that the element τ_x was split into three elements τ'_x , τ'_y and τ''_y . In this case, the realization $(V_0, \dots, V_{x-1}, V'_x \cup V'_y \cup Z, V_{y+1}, \dots, V_{p-1})$ is a correct realization of τ in G under P . On the other hand, if $y < p$, then, since $G[Z - V_0]$ is spanned by a path whose first and last vertices are $v_{i_{2k-1}}^+$ and $v_{i_0}^-$, respectively, by Lemma 6 there exists a realization $(V''_x, V''_y, V_{y+1}, \dots, V_{p-1})$ of $(\tau''_x, \tau''_y, \tau_{y+1}, \dots, \tau_{p-1})$ in $G[Z - V_0]$ under $(v_{i_0}^-, v_{i_{2k-1}}^+)$. By construction, $G[V'_x \cup V''_x]$ and $G[V'_y \cup V''_y]$ both induce a connected subgraph of G . It follows that $(V_0, \dots, V_{x-1}, V'_x \cup V''_x, V_{x+1}, \dots, V_{y-1}, V'_y \cup V''_y, V_{y+1}, \dots, V_{p-1})$ is a realization of τ in G under P . \blacksquare

5 Partitioning Harary graphs under prescriptions

Harary graphs are known to be graphs having the smallest possible size regarding their connectivity [5]. They trivially have the property of being AP since they are Hamiltonian; thus, one could wonder about the maximum number of prescribed vertices we can allow while partitioning them. In particular, can we always prescribe k vertices when partitioning a $(k+1)$ -connected Harary graph? If this is the case, then such a graph will also be an optimal AP+ k -graph.

We investigate, in this section, the question for the three different constructions of Harary graphs, according to the parities of both n and k .

5.1 Construction 1: k is even

For every $k \geq 2$ and $n \geq 2k$ such that k is even, $H_{k,n}$ is isomorphic to $C_n^{\frac{k}{2}}$ which is AP+ $(k-1)$ according to Theorem 4. Thus, the following result derives directly.

Corollary 11 *For every even $k \geq 2$ and $n \geq 2k$, the Harary graph $H_{k,n}$ is AP+ $(k-1)$.*

5.2 Construction 2: k is odd and n is even

Let $k \geq 2$ and $n \geq 2$ be two integers such that k is odd and n is even. By construction, $H_{2k+1,n}$ is spanned by $H_{2k,n}$ and thus is AP+ $(2k-1)$ according to Corollary 11. Although this number of prescribed vertices is good since $H_{2k+1,n}$ is $(2k+1)$ -connected, the connectivity of this graph suggests that we could up to one more prescribed vertex while partitioning it (see Observation 3).

Before proving that $H_{2k+1,n}$ is actually AP+ $2k$, we first introduce the following lemma which deals with the traceability of a graph composed by two linked squares of paths.

Lemma 12 *If G is a graph such that $V(G) = V_1 \cup V_2$, the subgraphs $G[V_1]$ and $G[V_2]$ are both spanned by the square of a path, and there exists an edge joining one vertex of V_1 and one of V_2 , then G is traceable.*

Proof. Let v_1, \dots, v_{n_1} and u_1, \dots, u_{n_2} denote the vertices of $G[V_1]$ and $G[V_2]$, from left to right, and v_α and u_β be two vertices of G such that $v_\alpha u_\beta \in E(G)$. Consider the following subpaths of G :

- $P = v_1 v_2 \dots v_{\alpha-1}$;
- $Q = \begin{cases} v_{\alpha+1} v_{\alpha+3} \dots v_{n_1-1} v_{n_1} v_{n_1-2} v_{n_1-4} \dots v_{\alpha+2} & \text{if } n_1 - \alpha \text{ is even,} \\ v_{\alpha+1} v_{\alpha+3} \dots v_{n_1} v_{n_1-1} v_{n_1-3} \dots v_{\alpha+2} & \text{otherwise;} \end{cases}$
- $R = \begin{cases} u_{\beta+2} u_{\beta+4} \dots u_{n_2} u_{n_2-1} u_{n_2-3} \dots u_{\beta+1} & \text{if } n_2 - \beta \text{ is even,} \\ u_{\beta+2} u_{\beta+4} \dots u_{n_2-1} u_{n_2} u_{n_2-2} u_{n_2-4} \dots u_{\beta+1} & \text{otherwise;} \end{cases}$
- $S = u_{\beta-1} u_{\beta-2} \dots u_1$.

It is then easy to check that $PQv_\alpha u_\beta RS$ is a Hamiltonian path of G . ■

We now prove the main result of this section.

Theorem 13 *For every odd $k \geq 2$ and even $n \geq 2k + 1$, the Harary graph $H_{2k+1, n}$ is $AP+2k$.*

Proof. Let $G = H_{2k+1, n}$ be the $(2k + 1)$ -connected Harary graph on n vertices. We prove that every partition $\tau = (\tau_0, \dots, \tau_{p-1})$ of n with $p \geq 2k + 1$ elements is realizable in G under every prescription $P = (v_{i_0}, \dots, v_{i_{2k-1}})$ with $0 \leq i_0 < \dots < i_{2k-1} \leq n - 1$. We distinguish three cases depending on whether there exists a realization of τ in C_n^k under P or not. Since C_n^k is a spanning subgraph of G , such a realization would also be a realization of τ in G under P .

Case 1. First observe that if there exists exactly one maximal block of P in G with size at least k , then we can obtain a correct realization of τ in G under P by considering a realization of τ in C_n^k under P . Such a realization necessarily exists according to Lemma 9.

Case 2. Similarly, if there does not exist a maximal block of P in G with size at least k , then we can use Lemma 10 to deduce a realization of τ in C_n^k under P . This realization is also a realization of τ in G under P .

Case 3. The last case we have to consider is the one where there exist two maximal blocks B_1 and B_2 of P in G with size exactly k . In this case, the prescribed vertices disconnect the graph into two components linked by some diagonal edges. Indeed, without loss of generality, let us suppose that $B_1 = \{v_{i_0}, \dots, v_{i_{k-1}}\}$ and $B_2 = \{v_{i_k}, \dots, v_{i_{2k-1}}\}$; necessarily, the antipodal neighbours of $v_{i_0}^-$ and $v_{i_{k-1}}^+$ do not both belong to P since otherwise there would exist a maximal block of P in G with size at least $k + 2$. Let us denote by v_α and v_β two antipodal neighbours of G such that $v_\alpha, v_\beta \notin B_1 \cup B_2$, $\alpha \in [i_{k-1} + 1, i_k - 1]$ and $\beta \in [i_{2k-1} + 1, i_0 - 1]$. Besides, let $a_1 = \alpha - i_{k-1} - 1$, $a_2 = i_k - \alpha - 1$, $a_3 = i_0 - \beta - 1$ and $a_4 = \beta - i_{2k-1} - 1$ denote the number of consecutive vertices between B_1 , B_2 and the two vertices v_α and v_β according to the natural ordering of $V(G)$.

If $\sum_{j=0}^{k-1} \tau_j \leq a_1 + a_3 + k$ and $\sum_{j=k}^{2k-1} \tau_j \leq a_2 + a_4 + k$, then we can find two subsets X and Y of consecutive vertices of G such that $|X| = \sum_{j=0}^{k-1} \tau_j$, $|Y| = \sum_{j=k}^{2k-1} \tau_j$, $\{v_{i_0}, \dots, v_{i_{k-1}}\} \subseteq X$, $\{v_{i_k}, \dots, v_{i_{2k-1}}\} \subseteq Y$, and $v_\alpha, v_\beta \notin X \cup Y$. Since $G[X]$ and $G[Y]$ are both isomorphic to the k^{th} power of a path, then using Theorem 1 we can deduce two realizations (V_0, \dots, V_{k-1}) and (V_k, \dots, V_{2k-1}) of $(\tau_0, \dots, \tau_{k-1})$ and $(\tau_k, \dots, \tau_{2k-1})$ in $G[X]$ and $G[Y]$ under the prescriptions $(v_{i_0}, \dots, v_{i_{k-1}})$ and $(v_{i_k}, \dots, v_{i_{2k-1}})$. Moreover, since $k \geq 2$, $G - (X, Y)$ is traceable according to Lemma 12, there exists a realization (V_{2k}, \dots, V_{p-1}) of $(\tau_{2k}, \dots, \tau_{p-1})$ in $G - (X, Y)$. Finally, (V_0, \dots, V_{p-1}) is a correct realization of τ in G under P .

Let us now suppose that, without loss of generality, $\sum_{j=0}^{k-1} \tau_j > a_1 + a_3 + k$ and $\sum_{j=k}^{2k-1} \tau_j < a_2 + a_4 + k$. If $\sum_{j=0}^{2k-1} \tau_j \geq a_1 + a_2 + 2k + 1$, then we can find two subsets of consecutive vertices $X, Y \subseteq V(G)$ such that, for some $\gamma \in [i_{k-1} + 1, i_k - 1]$, $v_\gamma \in X$, $v_\gamma^+ \in Y$, $\{v_{i_0}, \dots, v_{i_{k-1}}\} \subseteq X$, $\{v_{i_k}, \dots, v_{i_{2k-1}}\} \subseteq Y$, $|X| = \sum_{j=0}^{k-1} \tau_j$ and $|Y| = \sum_{j=k}^{2k-1} \tau_j$. By Theorem 1, we know that there exists a realization (V_0, \dots, V_{k-1}) of $(\tau_0, \dots, \tau_{k-1})$ in $G[X]$ under the prescription $(v_{i_0}, \dots, v_{i_{k-1}})$, and a realization (V_k, \dots, V_{2k-1}) of $(\tau_k, \dots, \tau_{2k-1})$ in $G[Y]$ under $(v_{i_k}, \dots, v_{i_{2k-1}})$. Finally, $G - (X, Y)$ is isomorphic to the k^{th} power of a path, and thus there exists a realization (V_{2k}, \dots, V_p) of the remaining sequence $(\tau_{2k}, \dots, \tau_{p-1})$ in it. We get that (V_0, \dots, V_{p-1}) is a realization of τ in G under P .

If it is not possible to choose the subsets X and Y in such a way that they have two neighbouring consecutive vertices along the arc of size $a_1 + a_2 + 1$ of G , then we can necessarily find two such subsets along the arc of size $a_3 + a_4 + 1$ of G . Indeed, in such a situation we have $\sum_{j=0}^{k-1} \tau_j > a_1 + a_3 + k$ by hypothesis, but $\sum_{j=0}^{k-1} \tau_j < a_1 + a_2 + k + 1$. This implies that $a_2 \geq a_3$, and, since $a_1 + a_3 = a_2 + a_4$, that $a_1 \geq a_4$. Hence, we get $\sum_{j=0}^{k-1} \tau_j > a_4 + a_3 + k$ and it is therefore possible to choose the two subsets X and Y along the arc of size $a_3 + a_4 + 1$ of G to deduce a realization of τ in G under P . ■

5.3 Construction 3: k and n are odd

The Harary graph $G = H_{2k+1, n+1}$, where $k \geq 2$ and $n + 1 \geq 2k + 1$ are odd, is spanned by C_n^k . Thus, it follows, according to Lemmas 9 and 10, that there always exists a realization of τ in G under a $2k$ -prescription which admits at most one maximal block in G with size at least k . Moreover, $H_{2k+1, n}$ and $H_{2k+1, n+1}$ differ by their diagonal edges, but the arguments we used to prove *Case 3* of Theorem 13 also hold when considering $H_{2k+1, n+1}$ instead of $H_{2k+1, n}$.

Thus, we can directly derive the following result.

Theorem 14 *For every odd $k \geq 2$ and odd $n \geq 2k + 1$, the Harary graph $H_{2k+1, n}$ is AP+2k.*

6 On the existence of optimal AP+2-graphs

The proof of Theorems 13 and 14 relies on the fact that some particular subgraphs of a Harary graph $H_{k, n}$ necessarily satisfy the conditions of Lemma 12 when $k \neq 3$. Although, one can easily check that this lemma cannot be used when $H_{k, n}$ is not connected enough, in particular when $k = 3$. Hence, our proof cannot be used directly to prove that a Harary graph $H_{3, n}$ is AP+2 for some n .

Besides, these graphs are not all AP+2 anyway:

Observation 15 *For every $n \equiv 2 \pmod{4}$, the Harary graph $H_{3, n}$ is not AP+2.*

Indeed, let $n \equiv 2 \pmod{4}$ and $G = H_{3, n}$. One can check that the subgraph $G - \{v_0, v_2\}$ does not admit a perfect matching. Therefore, the sequence $(1, 1, 2, \dots, 2)$ is not realizable in G under (v_0, v_2) .

In order to prove that there actually exist optimal AP+2-graphs, we introduce a new class of 3-connected graphs.

Definition 16 Let $n \geq 4$. The graph Pr_n is constructed as follows:

- If n is even, Pr_n is obtained from the cycle C_n , whose vertices are successively denoted by $u, w_1^1, \dots, w_{\frac{n-2}{2}}^1, v, w_{\frac{n-2}{2}}^2, \dots, w_1^2$, by adding it the edge uv and all edges $w_i^1 w_i^2$, for every $i \in [1, \frac{n-2}{2}]$.
- If n is odd, Pr_n is obtained by first removing the edges $w_1^1 w_1^2$ and $w_{\frac{n-3}{2}}^1 w_{\frac{n-3}{2}}^2$ from Pr_{n-1} , and then adding it a new vertex o linked to $w_1^1, w_1^2, w_{\frac{n-3}{2}}^1$, and $w_{\frac{n-3}{2}}^2$.

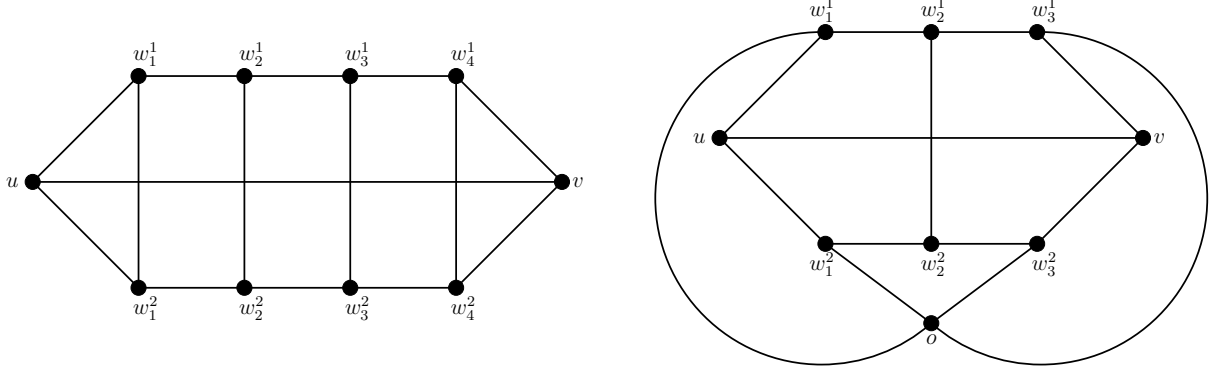


Figure 2: The graphs Pr_{10} and Pr_9

The two graphs Pr_9 and Pr_{10} are drawn in Figure 2.

For every $n \geq 4$, the graph Pr_n is 3-connected and has the least possible number of edges, that is $\lceil \frac{3n}{2} \rceil$. To now prove that such a graph is AP+2, we consider the following sufficient condition for a graph to be AP+2 which is easier to determine for Pr graphs. Recall that a graph G is *Hamiltonian-connected* if, for every two distinct vertices u and v of G , there exists a Hamiltonian path in G with endvertices u and v .

Lemma 17 *If a graph G is Hamiltonian-connected, then G is AP+2.*

This lemma obviously holds since, by Lemma 6, we can partition P_n under every 2-prescription (u, v) as long as u and v are the endvertices of P_n .

Before showing that $G = Pr_n$ is Hamiltonian-connected for every $n \geq 4$, we first introduce some notations to deal with the vertices of such a graph. Let $q = \frac{n-2}{2}$ if n is even (resp. $q = \frac{n-3}{2}$ if n is odd); given two distinct integers x and y in $[1, q]$ (resp. in $[2, q-1]$) such that $x < y$, we denote by $P_{x,y}^{\nearrow}(G)$ and $P_{x,y}^{\searrow}(G)$ the paths of G defined as follows.

$$P_{x,y}^{\nearrow}(G) = \begin{cases} w_x^2 w_x^1 & \text{if } x = y, \\ w_x^2 w_x^1 P_{x+1,y}^{\searrow}(G) & \text{otherwise.} \end{cases}$$

$$P_{x,y}^{\searrow}(G) = \begin{cases} w_x^1 w_x^2 & \text{if } x = y, \\ w_x^1 w_x^2 P_{x+1,y}^{\nearrow}(G) & \text{otherwise.} \end{cases}$$

The paths $P_{x,y}^{\nwarrow}(G)$ and $P_{x,y}^{\swarrow}(G)$ of G are defined analogously from right to left when $x > y$. For every $\alpha \in \{1, 2\}$, we additionally define $P_{x,y}^{\alpha, \rightarrow}(G)$ for $x < y$ (resp. $P_{x,y}^{\alpha, \leftarrow}(G)$ for $x > y$) to be the path $w_x^\alpha w_{x+1}^\alpha \dots w_y^\alpha$ of G (resp. the path $w_x^\alpha w_{x-1}^\alpha \dots w_y^\alpha$ of G). For convenience, let us assume that $P_{x,y}^{\nearrow}(G) = \emptyset$, $P_{x,y}^{\searrow}(G) = \emptyset$ and $P_{x,y}^{\alpha, \rightarrow}(G) = \emptyset$ (resp. $P_{x,y}^{\nwarrow}(G) = \emptyset$, $P_{x,y}^{\swarrow}(G) = \emptyset$ and $P_{x,y}^{\alpha, \leftarrow}(G) = \emptyset$) whenever x or y do not belong to the interval above or when $x > y$ (resp. when $x < y$). Using these notations, we get, for instance, that $uP_{1,4}^{1, \rightarrow}(Pr_{10})vP_{4,1}^{2, \leftarrow}(Pr_{10})$ and $uP_{1,4}^{\nearrow}(Pr_{10})v$ are Hamiltonian paths of Pr_{10} .

We are now ready to prove that every Pr_n graph is Hamiltonian-connected, and thus AP+2 according to Lemma 17.

Proposition 18 *For every $n \geq 4$, the graph Pr_n is Hamiltonian-connected.*

Proof. Let $G = Pr_n$, and $q = \frac{n-2}{2}$ if n is even, $q = \frac{n-3}{2}$ otherwise. Table 1 (resp. Table 2) exhibits, given two distinct vertices s and t of G , a Hamiltonian path P of G whose endvertices are s and t when n is even (resp. n is odd). In Table 1 (resp. Table 2), it is assumed that $1 \leq i \leq q$ when j is not defined (resp. $1 < i < q$), and $0 \leq i < j \leq q$ otherwise (resp. $1 < i < j < q$). All the Hamiltonian paths which do not appear in these two tables can be deduced from other Hamiltonian paths using the symmetries of G . ■

s	t	P
u	v	$uP_{1,q}^{\nearrow}(G)v$
u	w_i^1	$uP_{1,i-1}^{\nearrow}(G)w_i^2P_{i+1,q}^{2,\rightarrow}(G)vP_{q,i}^{1,\leftarrow}(G)$ if $i-1$ is even $uP_{1,i-1}^{\searrow}(G)w_i^2P_{i+1,q}^{2,\rightarrow}(G)vP_{q,i}^{1,\leftarrow}(G)$ otherwise
w_i^1	w_j^1	$P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,1}^{\nwarrow}(G)uvP_{q,j}^{\swarrow}(G)$ if $q-j$ is even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,1}^{\nwarrow}(G)uvP_{q,j}^{\swarrow}(G)$ otherwise
w_i^1	w_j^2	$P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,1}^{\nwarrow}(G)uvP_{q,j}^{\swarrow}(G)$ if $q-j$ is even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,1}^{\nwarrow}(G)uvP_{q,j}^{\swarrow}(G)$ otherwise

Table 1: Proof that Pr_n is Hamiltonian-connected for every $n \geq 4$ even

s	t	P
o	u	$oP_{1,q}^{1,\rightarrow}(G)vP_{q,1}^{2,\leftarrow}(G)u$
o	w_1^1	$ow_q^1vw_q^2P_{q-1,2}^{\nwarrow}w_1^2uw_1^1$ if q is even $ow_q^2vw_q^1P_{q-1,2}^{\swarrow}w_1^2uw_1^1$ otherwise
o	w_i^1	$ow_1^1uw_1^2P_{2,i-1}^{\nearrow}(G)w_i^2P_{i+1,q}^{2,\rightarrow}(G)vP_{q,i}^{1,\leftarrow}(G)$ if i is even $ow_1^2uw_1^1P_{2,i-1}^{\searrow}(G)w_i^2P_{i+1,q}^{2,\rightarrow}(G)vP_{q,i}^{1,\leftarrow}(G)$ otherwise
u	v	$uP_{1,q}^{2,\rightarrow}(G)oP_{1,q}^{1,\rightarrow}(G)v$
u	w_1^1	$uvP_{q,1}^{2,\leftarrow}(G)oP_{q,1}^{1,\leftarrow}(G)$
u	w_q^1	$uvP_{q,1}^{2,\leftarrow}(G)oP_{1,q}^{1,\rightarrow}(G)$
u	w_i^1	$uP_{1,i-1}^{1,\rightarrow}(G)P_{i-1,1}^{2,\leftarrow}(G)ow_q^2vw_q^1P_{q-1,i}^{\swarrow}(G)$ if $q-i$ is even $uP_{1,i-1}^1(G)P_{i-1,1}^{2,\leftarrow}(G)ow_q^1vw_q^2P_{q-1,i}^{\nwarrow}(G)$ otherwise
w_1^1	w_1^2	$w_1^1uvP_{q,2}^{1,\leftarrow}(G)P_{2,q}^{2,\rightarrow}(G)ow_1^2$
w_1^1	w_q^1	$P_{1,q-1}^{1,\rightarrow}(G)P_{q-1,1}^{2,\leftarrow}(G)uvw_q^2ow_q^1$
w_1^1	w_q^2	$w_1^1ow_1^2uvP_{q,2}^{1,\leftarrow}(G)P_{2,q}^{2,\rightarrow}(G)$
w_i^1	w_j^1	$P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^2uw_1^1ow_q^2vw_q^1P_{q-1,j}^{\swarrow}(G)$ if i and $q-j$ are even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^1uw_1^2ow_q^2vw_q^1P_{q-1,j}^{\swarrow}(G)$ if i is odd and $q-j$ is even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^2uw_1^1ow_q^1vw_q^2P_{q-1,j}^{\nwarrow}(G)$ if i is even and $q-j$ is odd $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^1uw_1^2ow_q^1vw_q^2P_{q-1,j}^{\nwarrow}(G)$ if i and $q-j$ are odd
w_i^1	w_j^2	$P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^2uw_1^1ow_q^1vw_q^2P_{q-1,j}^{\nwarrow}(G)$ if i and $q-j$ are even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^1uw_1^2ow_q^1vw_q^2P_{q-1,j}^{\nwarrow}(G)$ if i is odd and $q-j$ is even $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^2uw_1^1ow_q^2vw_q^1P_{q-1,j}^{\swarrow}(G)$ if i is even and $q-j$ is odd $P_{i,j-1}^{1,\rightarrow}(G)P_{j-1,i}^{2,\leftarrow}(G)P_{i-1,2}^{\nwarrow}(G)w_1^1uw_1^2ow_q^2vw_q^1P_{q-1,j}^{\swarrow}(G)$ if i and $n-j$ are odd

Table 2: Proof that Pr_n is Hamiltonian-connected for every $n \geq 5$ odd

Corollary 19 For every $n \geq 4$, the graph Pr_n is $AP+2$.

7 Conclusions

We summarize Corollaries 11 and 19 and Theorems 13 and 14 in this concluding theorem.

Theorem 20 For every $k \geq 1$ and $n \geq k$, there exist optimal $AP+k$ -graphs on n vertices.

According to Observation 3, we know that the number of optimal $AP+k$ -graphs is upper bounded by the number of edge-minimal $(k+1)$ -connected graphs. However, it seems difficult

to make an estimation on the number of optimal AP+ k -graphs in general.

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