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Research Paper

The Locating Chromatic Number of the Cyclic Chain Graph

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Abstract
The locating chromatic number of graph G ($\chi_L(G)$) combines the idea of the partition dimension and the chromatic number by considering the locations of the vertices of graph G. Let (C_{n_i}, m) be a cyclic chain graph, namely a group of blocks in the form of a cycle graph $C_{n_1}^{(1)}, C_{n_2}^{(2)}, \cdots, C_{n_i}^{(i)}$. The n_i is the number of vertices on the i-th cycle, and m is the number of cycles, for $n_i \geq 3$, $1 \leq i \leq m$, and $m \geq 2$, and the vertex $v_{i,\lceil n_i/2\rceil+1}$ in $C_{n_i}^{(i)}$ is identified with the vertex $v_{i,\lceil n_i/2\rceil+1}$ in $C_{n_{i+1}}^{(i+1)}$. In this research, we determine $\chi_L(C_{n_i}, m)$ for $n_i \geq 3$, $1 \leq i \leq m$, and $m \geq 2$.

Keywords
Color Code, Cyclic Chain Graph, Locating Chromatic Number

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1. INTRODUCTION

Let $G = (V, E)$ be a connected graph, where two adjacent vertices have distinct colors. Let Π be a set of ordered vertices. The color codes of a vertex v in G are represented by $c_\Pi(v) = (d(v, S_1), d(v, S_2), \ldots, d(v, S_k))$, where $d(v, S_i) = \min\{d(v, x) \mid x \in S_i\}$ for $1 \leq i \leq k$, with S_i being the set of vertices with color number i. If $c_\Pi(v_i) \neq c_\Pi(v_j)$ for $i \neq j$, then c is the k-locating coloring of G, denoted by $\chi_L(G)$.

Chartrand et al. (2002) determined the locating chromatic number of certain graph classes, such as paths P_n for $n \geq 3$, cycles C_n for $n \geq 3$, and trees P_n for $n \geq 5$. Up to this time, a significant amount of research has been conducted on the topic of determining the chromatic number of connected graphs, such as the characterization of all cycle-related graphs with locating chromatic number three (Asmiati and Baskoro, 2012), characterization of some Petersen graphs $P(n, k)$ with $\chi_L(P_{n,k}) = 4$ or $\chi_L(P_{n,k}) = 5$ (Asmiati et al., 2017),), the new operation on generalized Petersen graph $N_{P(m,1)}$ (Irawan and Istiani, 2024), and characterization of trees with $\chi_L(T) = 3$ (Tri Baskoro, 2013). Sakri and Abbas (2024) corrected the theorem regarding the characterization of some Petersen graphs by Asmiati et al. (2017).

Recently, the split graph of cycle for $n \leq 3$ (Prawinasti et al., 2021), the connected graph in The Midle graph of (Aouf et al., 2024), the m-shadow (Sudarsana et al., 2022), the power of paths and cycles (Ghanem et al., 2019). The path P_n graph, C_n cycle graph, $K_(1, n)$ star graph, W_n wheel graph, G_n gear graph and H_n helm graph, the certain barbell graph (Asmiati et al., 2018), the book graph (Inayah et al., 2021), the halin graphs (Purwasih et al., 2017), the pseudotrees graph (Alcon et al., 2020), and the origami graphs (Irawan et al., 2021). Moreover, the graph of corona product (Syofyan et al., 2024), the some of Buckminsterfullerene-type graphs (Putri et al., 2021) and the locating number four in some modified Path with Cycle (Damayanti et al., 2021).

The locating chromatic number of tree graphs has been the subject of numerous studies, such as, improve algorithm the locating chromatic number of trees (Baskoro and Primaskun, 2021), calculating upper bound of trees (Assiyatun et al., 2020; Furuya and Matsumoto, 2019) and $X_L(T) = 4$ (Haryeni and Baskoro, 2022).

Regarding the disconnected graphs, Welyyanti et al. (2019) investigated the locating chromatic number of disconnected graphs, such as $H = kP_n \cup \ell C_m$. Welyyanti et al. (2017) discussed graphs with two homogeneous components, and Welyyanti et al. (2021) studied graphs of the form $H = xP_\ell \cup yK_{1,m} \cup zC_n \cup S_{m,n}$.

Based on the research, there is no researcher who has studied the locating chromatic number of cyclic chain graphs. A cyclic chain graph, denoted as (C_{n_i}, m), is a set of blocks constructed by cycles $C_{n_1}^{(1)}, C_{n_2}^{(2)}, \ldots, C_{n_i}^{(i)}$. Here, n_i is the number of vertices in the i-th cycle and m is the number of cycles, with $n_i \geq 3$, $1 \leq i \leq m$, and $m \geq 2$. The vertex $v_{i,\lceil n_i/2\rceil+1}$ in $C_{n_i}^{(i)}$ is identified with the vertex $v_{i+1,1}$ in $C_{n_{i+1}}^{(i+1)}$.

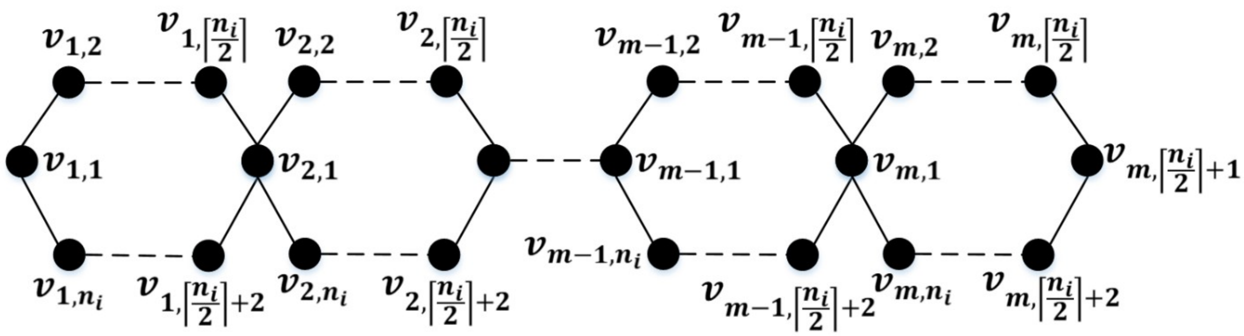

Figure 1. The Graph $C_{n_i,m}$ is Defined for $n_i \geq 3$, $m \geq 2$, and $1 \leq i \leq m$.

Table 1. Color Codes Each Vertices of $(C_{n,m})$ for $n \geq 4$

Vertices	$c_n(v_{i,j})$	Note
$v_{1,1}$	$(0, 1, 2, \lceil\frac{n}{2}\rceil)$	
$v_{i,1}$	$(\lceil\frac{n}{2}\rceil, i, 1, 1, 0)$	$i \geq 2$
$v_{i,j}$	$(j-1, 0, 1, (\lceil\frac{n}{2}\rceil+1)-j)$	$i \geq 2,\ j$ even, $2 \leq j \leq \lceil\frac{n}{2}\rceil$
$v_{i,j}$	$(j-1, 1, 0, (\lceil\frac{n}{2}\rceil+1)-j)$	$i \geq 2,\ j$ odd, $2 \leq j \leq \lceil\frac{n}{2}\rceil$
$v_{i,j}$	$((n+1)-j, 1, 0, j-(\lceil\frac{n}{2}\rceil+1))$	$i \geq 2,\ j$ even, $\lceil\frac{n}{2}\rceil+2 \leq j \leq n$
$v_{i,j}$	$((n+1)-j, 0, 1, j-(\lceil\frac{n}{2}\rceil+1))$	$i \geq 2,\ j$ odd, $\lceil\frac{n}{2}\rceil+2 \leq j \leq n$
$v_{i,j}$	$((i-1)\lceil\frac{n}{2}\rceil+(j-1), 0, 1, j-1)$	$i \geq 2,\ j$ even, $2 \leq j \leq \lceil\frac{n}{4}\rceil$
$v_{i,j}$	$((i-1)\lceil\frac{n}{2}\rceil+(j-1), 1, 0, j-1)$	$i \geq 2,\ j$ odd, $2 \leq j \leq \lceil\frac{n}{4}\rceil$
$v_{i,j}$	$((i-1)\lceil\frac{n}{2}\rceil+(j-1), 0, 1, (\lceil\frac{n}{2}\rceil+1)-j)$	$i \geq 2,\ \lceil\frac{n}{4}\rceil < j \leq \lceil\frac{n}{2}\rceil$
$v_{i,j}$	$((i-1)\lceil\frac{n}{2}\rceil+(j-1), 1, 0, (\lceil\frac{n}{2}\rceil+1)-j)$	$i \geq 2,\ \lceil\frac{n}{4}\rceil < j \leq \lceil\frac{n}{2}\rceil$
$v_{i,k}$	$(((i-1)\frac{n}{2}+1)+(n-k+1), 1, 0, (k-\frac{n}{2}+1))$	$i \geq 2,\ n, k$ even, $\frac{n}{2}+2 \leq k \leq \lceil\frac{3n}{4}\rceil+1$
$v_{i,k}$	$((i-1)\frac{n}{2}+1+(n-k+1),\ 0, 1,\ (k-\frac{n}{2}+1))$	$i \geq 2,\ n,\ k$ even, $\frac{n}{2}+2 \leq k \leq \lceil\frac{3n}{4}\rceil+1$
$v_{i,k}$	$((i-1)\lceil\frac{n}{2}\rceil+(n-k),\ 1, 0,\ k-\lceil\frac{n}{2}\rceil+1)$	$i \geq 2,\ n$ odd, k odd, $\lceil\frac{n}{2}\rceil+2 \leq k \leq \lceil\frac{3n}{4}\rceil+1$
$v_{i,k}$	$((i-1)\lceil\frac{n}{2}\rceil+(n-k),\ 0, 1,\ k-\lceil\frac{n}{2}\rceil+1)$	$i \geq 2,\ n,\ k$ odd, $\lceil\frac{n}{2}\rceil+2 \leq k \leq \lceil\frac{3n}{4}\rceil+1$
$v_{i,k}$	$((i-1)\lceil\frac{n}{2}\rceil+(n-k),\ 1, 0,\ n+1-k)$	$i \geq 2,\ n$ odd, $\lceil\frac{3n}{4}\rceil+1 < k \leq n$
$v_{i,k}$	$((i-1)\frac{n}{2}+(n-k+1),\ 0, 1,\ n+1-k)$	$i \geq 2,\ n$ even, $\lceil\frac{3n}{4}\rceil+1 < k \leq n$
$v_{i,k}$	$((i-1)\frac{n}{2}+(n-k+1),\ 1, 0,\ n+1-k)$	$i \geq 2,\ n$ odd, $\lceil\frac{3n}{4}\rceil+1 < k \leq n$
$v_{i,k}$	$((i-1)\lceil\frac{n}{2}\rceil+(n-k),\ 0, 1,\ n+1-k)$	$i \geq 2,\ n,\ k$ odd, $\lceil\frac{3n}{4}\rceil+1 < k \leq n$

Therefore, this research aimsed to determine the locating chromatic number of a cyclic chain graph (C_{n_i}, m), $1 \leq i \leq m$, $m \geq 2$, $n_i \geq 3$, with two cases: (1)The value of each n_i is the same, so $n_1 = n_2 = n_m = n$ and (2) $n_i = i + 2$, for $1 \leq i \leq m$.

2. EXPERIMENTAL SECTION

2.1 Methods

Methods the research is a literary analysis aimed at determining the locating chromatic number of a cyclic chain graph. The investigation begins by defining the topic to be addressed, followed by a description of the cyclic chain graph denoted by $(c_(n_i), m)$.

The set of vertices and edges in the graph (C_{n_i}, m) for $1 \leq i \leq m$, $m \leq 2$, and $n_i \leq 3$, are given in Equations (1) and (2).

$$V(C_{n_i}; m) = \left\{v_{i,j} \,\middle|\, 1 \leq i \leq m,\ 1 \leq j \leq \left\lfloor\frac{n_i}{2}\right\rfloor\right\} \cup \left\{v_{i,k} \,\middle|\, 1 \leq i \leq m,\ \left\lfloor\frac{n_i}{2}\right\rfloor + 2 \leq k \leq n_i\right\} \cup \left\{v_{m,\lfloor\frac{n_i}{2}\rfloor+1}\right\} \quad (1)$$

$$E(C_{n_i}; m) = \left\{v_{i,j}v_{i,j+1} \,\middle|\, 1 \leq i \leq m,\ 1 \leq j \leq \left\lfloor\frac{n_i}{2}\right\rfloor\right\} \cup \left\{v_{i,k}v_{i,k+1} \,\middle|\, 1 \leq i \leq m,\ \left\lfloor\frac{n_i}{2}\right\rfloor + 2 \leq k \leq n_i - 1\right\} \cup \left\{v_{i,\lfloor\frac{n_i}{2}\rfloor}v_{i+1,1},\ v_{i,\lfloor\frac{n_i}{2}\rfloor+2}v_{i+1,1} \,\middle|\, 1 \leq i \leq m-1\right\} \cup \left\{v_{m,\lfloor\frac{n_i}{2}\rfloor}v_{m,\lfloor\frac{n_i}{2}\rfloor+1},\ v_{m,\lfloor\frac{n_i}{2}\rfloor+1}v_{m,\lfloor\frac{n_i}{2}\rfloor+2}\right\} \quad (2)$$

Table 2. Color Codes of Vertices in $(C^m_{n_i}, m)$, $n_i = i + 2,\ 1 \le i \le m$ and $m \ge 2$

Vertices	$\mathbf{c_n(v_{ij})}$	Note
$v_{1,1}$	$(0, 1, 2, 1)$	
$v_{1,2}$	$(1, 0, 2, 0)$	
$v_{i,j}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (j-2), 0, 1, j-1\right)$	$i \ge 2,\ j$ even, $1 \le j \le \left\lceil \frac{n_i}{4} \right\rceil$
$v_{i,j}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (j-2), 0, 1, (\left\lceil \frac{n_i}{2} \right\rceil + 1) - j\right)$	$i \ge 2,\ j$ even, $\left\lceil \frac{n_i}{4} \right\rceil < j \le \left\lceil \frac{n_i}{2} \right\rceil$
$v_{i,j}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (j-2), 1, 0, j-1\right)$	$i \ge 2,\ j$ odd, $1 \le j \le \left\lceil \frac{n_i}{4} \right\rceil$
$v_{i,j}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (j-2), 1, 0, (\left\lceil \frac{n_i}{2} \right\rceil + 1) - j\right)$	$i \ge 2,\ j$ odd, $\left\lceil \frac{n_i}{4} \right\rceil < j \le \left\lceil \frac{n_i}{2} \right\rceil$
$v_{i,k}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (n_i - k), 1, 0, k - (\left\lceil \frac{n_i}{2} \right\rceil + 1)\right)$	$i \ge 2,\ k$ even, $\left\lceil \frac{n_i}{2} \right\rceil + 2 \le k \le \left\lceil \frac{3n_i}{4} \right\rceil + 1$
$v_{i,k}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor + (n_i - k), 0, 1, k - \left\lceil \frac{n_i}{2} \right\rceil\right)$	$i \ge 2,\ k$ odd, $\left\lceil \frac{n_i}{2} \right\rceil + 2 \le k \le \left\lceil \frac{3n_i}{4} \right\rceil + 1$
$v_{i,k}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor, 1, 0, (n_i + 1) - k\right)$	$i \ge 2,\ k$ even, $\left\lceil \frac{3n_i}{4} \right\rceil + 1 < k \le n_i$
$v_{i,k}$	$\left(\left\lfloor \frac{n_i-1}{2} \right\rfloor, 0, 1, (n_i + 1) - k\right)$	$i \ge 2,\ k$ odd, $\left\lceil \frac{3n_i}{4} \right\rceil + 1 < k \le n_i$

Next, create a coloring c and partition II on $V(c(n_i), m)$, then calculate $X_L(c(n_i), m)$. Step four, prove the cyclic chain graph 's chromatic number. The last, we get the results based on examining the proved theorems.

3. RESULTS AND DISCUSSION

Theorem 3.1 Let (C_{n_i}, m) be a cyclic chain graph for $n_1 = n_2 = \cdots = n_m = n$ and $m \ge 2$, with the vertex and edge sets defined in Equations (1) and (2), as illustrated in Figure 1. Then:

$$\chi_L(C_n, m) = \begin{cases} 3, & \text{for } n = 3 \\ 4, & \text{for } n \ge 4. \end{cases} \tag{3}$$

Proof. We consider two cases. Cases 1. (C_n, m) for n=3. We show that $\chi_L(C_3, m) \le 3$, for $m \ge 2$. Define the 3-locating coloring of (C_3, m) as Equation (4).

$$\begin{aligned} &c(v_{1,1}) = 1, \\ &c(v_{i,2}) = 2, \quad \text{for } 2 \le i \le m, \\ &c(v_{i,1}) = 3, \quad \text{for } 2 \le i \le m. \end{aligned} \tag{4}$$

So, $c_\Pi(v_{i,j}) \in C_{3,m}$ for $n \ge 2$ are Equation (5):

$$\begin{aligned} &c_\Pi(v_{1,1}) = (0, 1, 1), \\ &c_\Pi(v_{i,2}) = (2i-1, 0, 1), \quad \text{for } 2 \le i \le m, \\ &c_\Pi(v_{i,1}) = (i-1, 1, 0), \quad \text{for } 2 \le i \le m. \end{aligned} \tag{5}$$

Because every vertex on the graph has a different color code, then as a result, $\chi_L(C_{3,m}) \le 3$. Next, we determined the lower bound of $\chi_L(C_{3,m})$. In the research of Chartrand et al. (2002), it was shown that $\chi_L(C_{3,m}) \le 3$. Therefore, $\chi_L(C_{3,m}) = 3$. Case 2: $(C_{n,m})$ with $n \ge 4$.

Let $(C_{n,m})$ with 4-locating coloring for $n \ge 4$. First, we will show that $\chi_L(C_{n,m}) \le 4$ for $n \ge 4$, then $c(v_{i,j})$ can be seen from Equation (6).

$$\begin{aligned} &c(v_{1,1}) = 1, \\ &c(v_{i,1}) = c\left(v_{i,\lceil \frac{n}{2} \rceil + 1}\right) = 4 \quad \text{for } 2 \le i \le m, \\ &c(v_{i,j}) = \begin{cases} 2, & \text{if } j \text{ even, } 2 \le j \le \left\lfloor \frac{n}{2} \right\rfloor, \\ 3, & \text{if } j \text{ odd, } 2 \le j \le \left\lfloor \frac{n}{2} \right\rfloor, \end{cases} \\ &c(v_{i,k}) = \begin{cases} 2, & \text{if } j \text{ odd, } \left\lceil \frac{n}{2} \right\rceil + 2 \le j \le n, \\ 3, & \text{if } j \text{ even, } \left\lceil \frac{n}{2} \right\rceil + 2 \le j \le n. \end{cases} \end{aligned} \tag{6}$$

So, the color code of vertex in $C_{n,m}$ for $n \ge 4$, can be observed in Table 1.

Table 1 shows that each vertex has a distinct color code. Hence, $\chi_L(C_{n,m}) \le 4$ for $n \ge 4$ and $m \ge 2$. Next, we need to show that $\chi_L(C_{n,m}) \ge 4$ for $n \ge 4$ and $m \ge 2$. By Theorem 3.1, we determine that $\chi_L(C_{n,m}) = 3$.

We assign three colors for every vertex in $C_{n,m}$, where vertices $v_{(i,1)}$ have the same color. Then, $c_\Pi(v_{(i,4)}) = c_\Pi(v_{(i+1,n/2)})$ = $(1, 2, 0)$ for i odd and n even, and $c_\Pi(v_{(i,2)}) = c_\Pi(v_{(i+1,2)}) =$ $(1, 0, 1)$ for i even and n odd. If vertices $v_{(i,1)}$ are given different colors when n is even, then the color code of $c_\Pi(v_{(i,2)})$ is the same as $c_\Pi(v_{(i,n)})$. However, if vertices $v_{(i,1)}$ are given different colors when n is odd, then the color code of $c_\Pi(v_{(2,1)})$ is the same as $c_\Pi(v_{(3,n)})$. Therefore, $\chi_L(C_{n,m}) \ge 4$.

So, $\chi_L(C_{4,2}) = 4$ for $n \ge 4$ and $m \ge 2$. Based on case (1) and (2), Equation (3) is proven.

Theorem 3.2 Let (C_{n_i}, m) be a cyclic chain graph for $n_i = i + 2$, $m \ge 2$, and $1 \le i \le m$. The vertex and edge sets of (C_{n_i}, m) are stated in Equations (1) and (2) as shown in Figure 2. Then, $\chi_L(C_{n_i}, m) = 4$.

Proof. We discovered the highest limit for determining the locating chromatic number of $(C_{(n_i)}, m)$, where $n_i = i + 2$, $1 \le i \le m$, and $m \ge 2$.

The coloring of vertices is the same as the locating-4 coloring in Theorem 3.1. Table 2 shows that each vertex has a

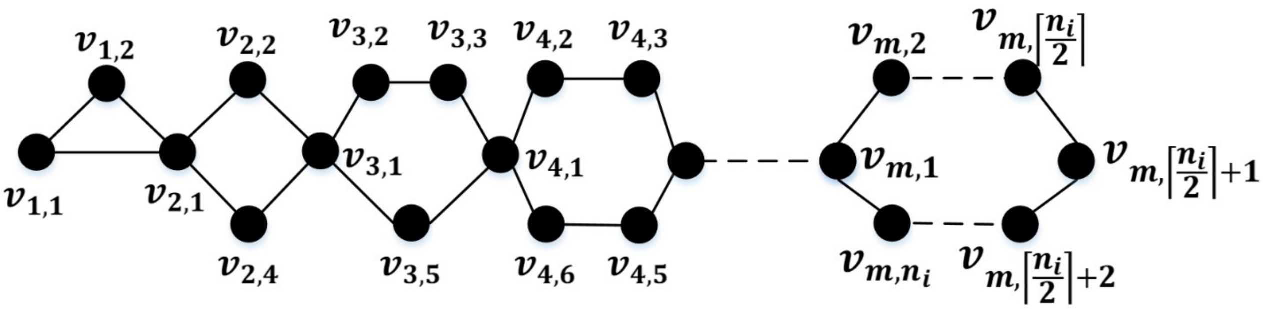

Figure 2. The Graph $C_{i+2,m}$ is Defined for $m \geq 2$ and $1 \leq i \leq m$

distinct color code. Hence, $\chi_L(C_{(n_i)}, m) \leq 4$ for $n_i = i + 2$, $1 \leq i \leq m$, and $m \geq 2$.

Next, we consider a locating-3 coloring where the vertices $v_{i,1}$ are assigned the same color. In this case, we have $c_\Pi(v_{1,2}) = c_\Pi(v_{2,2}) = (1, 0, 2)$. However, if the vertices $v_{i,1}$ are assigned different colors, then $c_\Pi(v_{1,1}) = c_\Pi(v_{2,2}) = c_\Pi(v_{2,4}) = (0, 1, 1)$. Therefore, we conclude that $\chi_L(C_{n,m}) \geq 4$.

4. CONCLUSIONS

In this research, we calculate the identifying locating chromatic number of the cyclic chain graph $C_{n_i,m}$. In Case (1), where $n_1 = n_2 = \cdots = n_m = n$, we have $\chi_L(C_{n_i,m}) = 3$ for $n = 3$, and $\chi_L(C_{n_i,m}) = 4$ for $n_i = n \geq 4$. In Case (2), where $n_i = i + 2$ for $1 \leq i \leq m$, we obtain $\chi_L(C_{n_i,m}) = 4$.

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