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On Rainbow Vertex Antimagic Coloring of Dutch Windmill, Diamond, Octopus, and Amalgamation of Star Graphs

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AbstractA rainbow vertex antimagic coloring is one of new topics in graph theory. This topic is a natural development of the concept of antimagic labeling combined with rainbow vertex coloring. The weight of a vertex $v \in V(G)$ under f where $f : E(G) \to \{1, 2, \dots, |E(G)|\}$ is $w_f(v) = \Sigma_{e \in E(v)} f(e)$, $E(v)$ is the set of vertices adjacent to v. Vertex antimagic edge labeling is the notion given to the function f if each vertex has a unique weight. If all internal vertices on the $u - v$ path have distinct weights for each vertex u and v, the path is considered to be a rainbow path. The smallest number of colors taken over all rainbow colorings induced through rainbow vertex antimagic labelings of G is known as the rainbow vertex antimagic connection number of G, written as $rvac(G)$. In this paper, we will show the exact value of the rainbow vertex antimagic connection number of specific classes of graphs, namely Dutch Windmill $D_n^{(3)}$, diamond graph D_n, octopus graph O_n, and the amalgamation of graph operation. To have a good illustration of the obtained theorems, we will equip one of them with MATLAB GUI programming for illustrating the rainbow vertex coloring of specific graph and specific input of order n or size m.

1 Introduction

A graph is a set of vertices symbolized by $V(G)$ and a set of edges symbolized by $E(G)$. In graph theory, we have been studying about labeling and coloring [17]. One of the interesting topics in labeling is an antimagic labeling graph, while in coloring is a rainbow vertex coloring. Hartsfield and Ringel proposed the concepts of graph labeling called antimagic labeling in 1990 [18]. An antimagic labeling of a graph G with p vertices and q edges is a bijection f from the edge set to positive integers $\{1, 2, 3, ..., q\}$, so that the weight of the vertices of G are all distinct, where the vertex weight is the sum of all labels on the edge which incident with that vertex [**?**, 11].

The graph G is called rainbow-connected if for any pair of vertices u and v of G, there is a rainbow $u-v$ path [19]. If there is at least one $u-v$ path with all internal vertices having different colors, the graph is known as a rainbow vertex-connected graph [20]. The minimum number of colors is called the rainbow vertex-connection number of G, denoted as $rvc(G)$. Krivelevich and Yuster [4] proposed the concept of rainbow vertex-connection. Some result about rainbow vertex-connection number can be seen in [5, 6, 7, 8, 12, 13].

[4] Let $diam(G)$ be a diameter of connected graph of size n, it satisfies $diam(G) - 1 \leq rvc(G) \leq n - 2$. Moreover, if G has c cut vertices then $rvc(G) \leq c$.

[2] Let $\chi(G)$ be chromatic number of G, it satisfies $rvc(G) \geq \chi(G)$.

[4] For every nontrivial connected graph G, $rvc(G) \geq max\{\chi(G), diam(G)\}$.

In 2021, Marsidi et al. [3] develop a new concept namely rainbow vertex antimagic coloring. Let $G(V, E)$ be a connected graph. We define a bijection $f : E(G) \to \{1, 2, 3, \dots, |E(G)|\}$ as a labeling of a graph G. The function f is called a rainbow vertex antimagic labeling if for any two vertices a and b in $V(G)$, all internal vertices in path $a - b$ have different weight. The vertex weight denoted by $w_f(a)$ for every $a \in V(G)$, where $w_f(a) = \Sigma_{aa' \in E(G)} f(aa')$. If each edge of G is assigned with the color of the vertex weight $w_f(a)$, then G admits a rainbow vertex antimagic coloring [21]. The $rvac(G)$ is a notation of rainbow vertex antimagic connection number of graph G which means the minimum colors taken over all rainbow vertex antimagic coloring induced by rainbow vertex antimagic labeling of graph G.

Remark 1.1. [3] Let G be a connected graph, $rvac(G) \geq rvc(G)$.

Marsidi *et al* [3, 9], rainbow vertex antimagic connection number of some graph like star graph (S_n), double star graph (DS_n), and broom graph $(Br_{n,m})$. Some other researchers have also studied rainbow vertex antimagic coloring, see [10]. However, to obtain the exact value of the rainbow vertex antimagic connection numbe of graphs is not easy. If the order of graph is fixed, it will be easy to obtain it, otherwise it will be considered to be NP-problem. Thus, in this paper we will study the exach values of some certain family of graphs, namely Dutch Windmill $D_n^{(3)}$, diamond graph D_n, octopus graph O_n, and the amalgamation operation of graphs.

2 The Results on Rainbow Vertex Antimagic Coloring

In this section, we determine the rainbow vertex antimagic coloring of Dutch windmill graph D_n^3, diamond graph D_n, Octopus graph L_n, and $Amal(Tb_n, v, m)$.

Theorem 2.1. *For every natural number $n \geq 3$, $rvac(D_n^3) = 4$.*

Proof. Given a Dutch windmill graph D_n^3 with $V(D_n^3) = \{a\} \cup \{x_{ij}; 1 \leq i \leq n, 1 \leq j \leq 3\}$ and $E(D_n^3) = \{ax_{i1}, 1 \leq i \leq n\} \cup \{ax_{i3}, 1 \leq i \leq n\} \cup \{x_{ij}x_{i(j+1)}, 1 \leq i \leq n, 1 \leq j \leq 2\}$. The cardinality of the vertex set of D_n^3 is $3n + 1$, the cardinality of the edge set of D_n^3 is $4n$, and the diameter of D_n^3 is 4.

To prove $rvac(D_n^3) = 4$, we prove that $rvac(D_n^3) \geq 4$ and $rvac(D_n^3) \leq 4$. First, it will be proved that $rvac(D_n^3) \geq 4$. Based on Remark 1, we have $rvac(D_n^3) \geq rvc(D_n^3) \geq diam(D_n^3) - 1 = 4 - 1 = 3$. It gives $rvac(D_n^3) \geq 3$. The rainbow vertex coloring on D_n^3 can be illustrated in Figure 1 as follows.

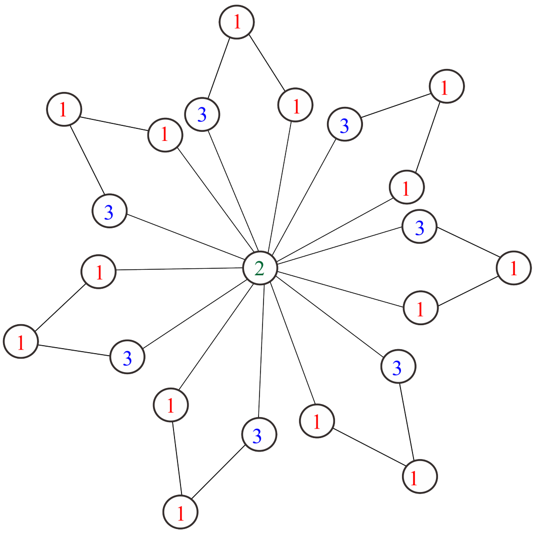


Figure 1. Illustration of RVAC on D_7^3.

Based on the Figure 1, there are two vertices which have the same color. Based on Figure 2, there are two adjacent vertices that have the same color. The vertex color is induced from the vertex weight according to the definition of rainbow vertex antimagic coloring, consequently any two adjacent vertices may not have the same weight. Therefore, any two adjacent vertices have a distinct weight and also satisfies the definition of rainbow vertex antimagic coloring. It concludes that $rvac(D_n^3) \geq 4$.

In addition, to proof $rvac(D_n^3) \leq 4$, we define the functions of edge labels as follows.

$$\begin{array}{rcll} f(x_{i1}x_{i2}) & = & i, & for 1 \leq i \leq n \\ f(x_{i2}x_{i3}) & = & 2n-i+1, & for 1 \leq i \leq n \\ f(x_{i1}a) & = & 3n-i+1, & for 1 \leq i \leq n \\ f(x_{i3}a) & = & 3n+i, & for 1 \leq i \leq n \end{array}$$

Based on the functions of edge labels, we can calculate the vertex weights as follows:

$$w(a) = 6n^2 + n; w(x_{i1}) = 3n + 1; w(x_{i2}) = 2n + 1; w(x_{i3}) = 5n + 1$$

It is clear from the vertex weight that the distinct weight is 4. We also show that every two distinct vertices of D_n^3 have rainbow vertex antimagic coloring. Assume that $v_1 - v_2 \in V(D_n^3)$, refer to the rainbow vertex $v_1 - v_2$ path is shown in Table 1.

Table 1. The rainbow vertex $v_1 - v_2$ of D_n^3

Case	v_1	v_2	rainbow vertex
1	x_{1i}	x_{3i}	x_{2i}
2	x_{2i}	x_{2j}	x_{1i}, a, x_{3j}
3	x_{1i}	x_{1j}	a
4	x_{3i}	x_{3j}	a
5	x_{1i}	x_{3j}	a

As a result, rainbow vertex antimagic coloring is used on $D3_n$. As the consequence, the value of $rvac(D_n^3)$ is 4. □

The illustration of rainbow vertex antimagic coloring on D_7^3 can be see in the **Figure 2**. We can see that the distinct weights on D_7^3 are $15, 22, 36$, and 301. The vertex color on each vertex is induced by the vertex weight. We can also see that every 2 vertices has a path with a different color on its internal vertices. Hence, it is clear that $rvac(D_7^3)$ is 4. We also create a GUI (Graphical User Interface) in Matlab to display rainbow vertex antimagic coloring on Dutch Windmill graph. To Build this GUI we use the algorithm 1. This GUI can be shown in **Figure 6**

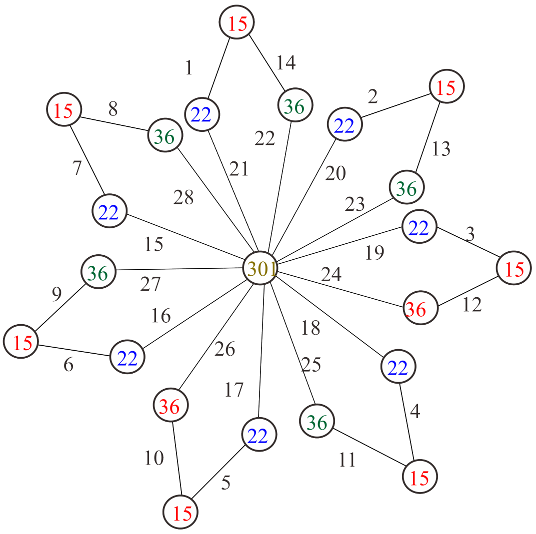


Figure 2. Illustration of RVAC on D_7^3.

Theorem 2.2. *For every even natural number* $n \geq 2$, $rvac(D_n) = 2$.

Proof. Given a diamond graph D_n with $V(D_n) = \{p\} \cup \{q\} \cup \{x_i; 1 \leq i \leq n\} \cup \{y_i; 1 \leq i \leq n\}$ and $E(D_n) = \{pq\} \cup \{px_i, 1 \leq i \leq n\} \cup \{qx_i, 1 \leq i \leq n\} \cup \{py_i, 1 \leq i \leq n\} \cup \{qy_i, 1 \leq i \leq n\}$.

The cardinality of the vertex set of D_n is $2n+2$, the cardinality of the edge set of D_n is $4n+1$, and the diameter of D_n is 2.

To prove $rvac(D_n) = 2$, we need to prove that $rvac(D_n) \geq 2$ and $rvac(D_n) \leq 2$. First, it will be proved that $rvac(D_n) \leq 2$. Based on Remark 1, we have $rvac(D_n) \geq rvc(D_n) \geq diam(D_n) - 1 = 2 - 1 = 1$. In addition, the degree of vertices p and q is $2n+1$, so that based on the definition of rainbow vertex antimagic coloring the vertex weights obtained on vertices p and q are different from other vertices. Hence, it gives $rvac(D_n) \geq 2$.

In addition, to proof $rvac(D_n) \leq 2$, we define the functions of edge labels as follows.

$$f(pq) = 4n+1$$

$$f(px_i)=\begin{cases} i, & \text{if } i \equiv 1 (mod\ 2) \\ 4n-i+1, & \text{if } i \equiv 0 (mod\ 2) \end{cases}$$

$$f(qx_i)=\begin{cases} 4n-i+1, & \text{if } i \equiv 1 (mod\ 2) \\ i, & \text{if } i \equiv 0 (mod\ 2) \end{cases}$$

$$f(py_i)=\begin{cases} 3n-i+1, & \text{if } i \equiv 1 (mod\ 2) \\ n+i, & \text{if } i \equiv 0 (mod\ 2) \end{cases}$$

$$f(qy_i)=\begin{cases} n+i, & \text{if } i \equiv 1 (mod\ 2) \\ 3n-i+1, & \text{if } i \equiv 0 (mod\ 2) \end{cases}$$

Based on the functions of edge labels, we can calculate the vertex weights as follows:

$$\begin{aligned} w(p) = w(q) &= 4n^2 + 5n + 1 \\ w(x_i) = w(y_i) &= 4n + 1 \end{aligned}$$

It is clear from the vertex weight that the distinct weight is 2. We also show that every two distinct vertices of D_n have rainbow vertex antimagic coloring. Assume that $v_1 - v_2 \in V(D_n)$, refer to the rainbow vertex $v_1 - v_2$ path is shown in Table 2.

Table 2. The rainbow vertex $v_1 - v_2$ of D_n

Case	v_1	v_2	rainbow vertex
1	x_i	x_j	p
2	x_i	y_i	p
3	x_i	y_j	p
4	p	q	x_i

As a result, rainbow vertex antimagic coloring is used on D_n. As the consequence, the value of $rvac(D_n)$ is 2. □

The illustration of rainbow vertex antimagic coloring on D_6 can be see in the **Figure 3**. We can see that the distinct weights on D_6 are 25 and 175. The vertex color on each vertex is induced by the vertex weight. We can also see that every 2 vertices has a path with a different color on its internal vertices. Hence, it is clear that $rvac(D_6)$ is 2.

Theorem 2.3. *For every natural number* $n \geq 3$, $rvac(O_n) = n + 1$.

Proof. Given an octopus graph O_n with $V(O_n) = \{a\} \cup \{x_i; 1 \leq i \leq n\} \cup \{y_i; 1 \leq i \leq n\}$ and $E(O_n) = \{ax_i; 1 \leq i \leq n\} \cup \{x_i x_{i+1}; 1 \leq i \leq n-1\} \cup \{ay_i, 1 \leq i \leq n\}$. The cardinality of the vertex set of O_n is $2n+1$, the cardinality of the edge set of O_n is $3n-1$, and the diameter of O_n is 2. The vertex weight of y_i is obtained from the label of the edge ay_i, so that the vertex weights y_i are all different. The vertex a is adjacent to vertices y_i, so that it is not possible to have the same vertex weight. Hence, it concludes that $rvac(O_n) \geq n+1$.

In addition, to proof $rvac(O_n) \leq n+1$, we define the functions of edge labels as follows.

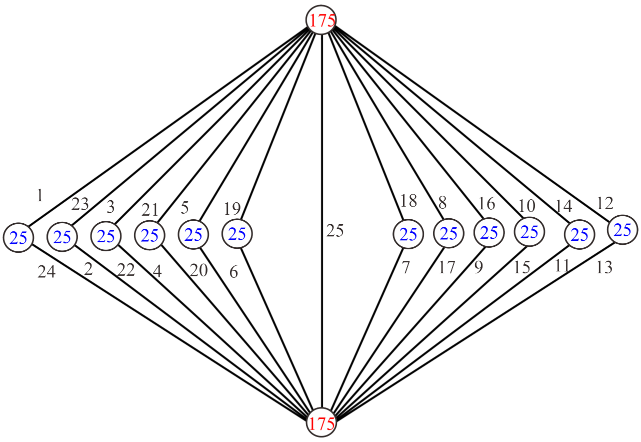


Figure 3. Illustration of RVAC on D_6.

Case 1. For $O_n, n \equiv 1(mod 2)$

$$f(x_ix_{i+1})=\begin{cases}\frac{i}{2}, & \text{if } i \equiv 0(mod\ 2)\\ \frac{n+i}{2}, & \text{if } i \equiv 1(mod\ 2)\end{cases}$$

$$f(ax_i)=\begin{cases}2n-1, & i=n\\ 2n-i-1, & \text{if } 1 \leq i \leq n-1\end{cases}$$

$$f(ay_i)=2n+i-1$$

Based on the functions of edge labels, we can calculate the vertex weights as follows:

$$w(x_i)=\frac{5n-3}{2};\ w(a)=4n^2-n;\ w(y_i)=2n+i-1$$

For $i=\frac{n-1}{2}$, it gives the vertex weight $w(y_i)=\frac{5n-3}{2}$. The next step is to see that the vertex weights induce rainbow vertex antimagic coloring on the graph O_n. The sets $w(y_i)=\{2n, 2n+1, 2n+2, ..., 3n-1\}$ and in $w(a)$ there is one vertex weight which must be distinct, thus the number of distinctt colors of $w(a) \cup w(y_i)$ is $n+1$. Using the set of vertex weights, an arithmetic sequence formula is used to calculate the number of vertex weights. The following is a solution to the arithmetic formula.

$$u_z=a+(z-1) \iff 3n-1=2n+(z-1)1 \iff 3n-1=2n+z-1 \iff 3n=2n+z \iff z=n$$

$z=n$ summed with $w(y_i)$ gives $n+1$. It illustrates how a rainbow of $n+1$ colors appears on the vertex antimagic coloring as a result of the vertex weight. Therefore $rvac(O_n) \leq n+1$.

Case 2. For $O_n, n \equiv 0(mod\ 2)$

$$f(x_ix_{i+1})=\begin{cases}\frac{i}{2}, & \text{if } i \equiv 0(mod\ 2)\\ \frac{n+i-1}{2}, & \text{if } i \equiv 1(mod\ 2)\end{cases}$$

$$f(ax_i)=\begin{cases}2n-1, & i=n\\ 2n-i-1, & \text{if } 1 \leq i \leq n-1\end{cases}$$

$$f(y_i)=2n+i-1$$

Based on the functions of edge labels, we can calculate the vertex weights as follows:

$$w(a)=4n^2-n; w(y_i)=2n+i-1; w(x_i)=\begin{cases}3n-2, & i=n\\ \frac{5n}{2}-2, & \text{if } 1 \leq i \leq n-1\end{cases}$$

For x_i with $1 \geq i \geq n-1$, it gives the vertex weight $w(x_i) = w(y_{i=\frac{n-2}{2}}) = \frac{5n}{2} - 2$ and for x_n we get the vertex weight $w(x_n) = w(y_{n-1}) = 3n-2$. The next step is to see that the vertex weights induce rainbow antimagic coloring on the graph O_n The sets $w(y_i) = \{2n, 2n+1, 2n+2, ..., 3n-1\}$ and in $w(a)$ there is one vertex weight which must be different, thus the number of distinct colors of $w(a) \cup w(y_i)$ is $n+1$. Depending on the set of vertex weights, to determine the number of vertex weights, an arithmetic sequence formula is used. The following is a solution to the arithmetic formula.

$$u_z = a+(z-1)b \iff 3n-1 = 2n+(z-1)1 \iff 3n-1 = 2n+z-1 \iff 3n = 2n+z \iff z = n$$

$z = n$ summed with $w(y_i)$ gives $n+1$. It shows the vertex weight induces a rainbow vertex antimagic coloring of $n+1$ colors. Therefore $rvac(O_n) \leq n+1$.

It is clear from the vertex weight that the distinct weight is $n+1$. We also show that every two distinct vertices of O_n have rainbow vertex antimagic coloring. Assume that $v_1 - v_2 \in V(O_n)$, refer to the rainbow vertex $v_1 - v_2$ path is shown in Table 3.

Table 3. The rainbow vertex $v_1 - v_2$ of O_n

Case	v_1	v_2	rainbow vertex
1	x_i	a	x_i, a
2	x_i	y_j	x_i, a, y_j
3	x_i	x_j	$x_i, x_k, x_j; i \leq k \leq j$
4	y_i	y_j	x_1

As a result, rainbow vertex antimagic coloring is used on O_n. As the consequence, the value of $rvac(O_n)$ is $n+1$. □

The illustration of rainbow vertex antimagic coloring on O_7 can be see in the **Figure 4**. We can see that the distinct weights on O_7 are 14, 15, 16, 17, 18, 19, 20, and 70. The vertex color on each vertex is induced by the vertex weight. We can also see that every 2 vertices has a path with a different color on its internal vertices. Hence, it is clear that $rvac(O_7)$ is $7+1=8$.

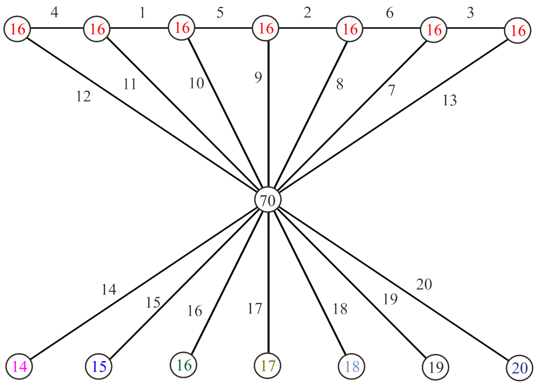


Figure 4. Illustration of RVAC on O_7.

Theorem 2.4. *For every natural number* $m, n \geq 3$, $rvac(Amal(Tb_m, v, n)) = 3$.

Proof. Given a vertex amalgamation product of star $Amal(Tb_m, v, n)$ with vertex set $V(Amal(Tb_m, v, n))$ = $\{z\} \cup \{x_i; 1 \leq i \leq n\} \cup \{y_{i,j}; 1 \leq i \leq n, 1 \leq j \leq m\}$ and edge set $E(Amal(Tb_m, v, n)) = \{zx_i; 1 \leq i \leq n\} \cup \{zy_{i,j}; 1 \leq i \leq n, 1 \leq j \leq m\} \cup \{x_i y_{i,j}; 1 \leq i \leq n, 1 \leq j \leq m\}$. Hence, we obtain $|V(Amal(Tb_m, v, n))| = nm+n+1$, $|E(Amal(Tb_m, v, n))| = 2nm+n$, and the diameter of $Amal(Tb_m, v, n)$ is 2. Since the vertex z adjacent to all other vertices, so that it is not possible to have the same vertex weight. Beside that, the vertex x_i are also adjacent to the vertices $y_{i,j}$, so that the vertex weights of x_i and $y_{i,j}$ are different. It concludes that $rvac(Amal(Tb_m, v, n) \geq 3$.

In addition, to proof $rvac(Amal(Tb_m, v, n) \leq 3$, we define the functions of edge labels as follows.

$$f(zy_{i,j})=\begin{cases} nj+i-n, & \text{if } i\equiv 1(mod\ 2)\\ nj-i+1, & \text{if } i\equiv 0(mod\ 2)\end{cases}$$

$$f(x_iy_{i,j})=\begin{cases} 2nm+n-i-nj+1, & \text{if } i\equiv 1(mod\ 2)\\ 2nm-nj+i, & \text{if } i\equiv 0(mod\ 2)\end{cases}$$

$$f(zx_i)=2nm+i$$

Based on the functions of edge labels, we can calculate the vertex weights as follows:

$$\begin{aligned} w(z) &= \tfrac{n}{2}(nm^2+4nm+m+n+1)\\ w(x_i) &= \tfrac{3nm^2+4nm+n+m+1}{2}\\ w(y_{i,j}) &= 2nm+1 \end{aligned}$$

It is clear from the vertex weight that the distinct weight is 3. We also show that every two distinct vertices of $Amal(Tb_m, v, n)$ have rainbow path oh its internal vertices. Assume that $v_1 - v_2 \in V(Amal(Tb_m, v, n))$, refer to the rainbow vertex $v_1 - v_2$ path is shown in Table 4.

Table 4. The rainbow vertex $v_1 - V_2$ of $Amal(Tb_n, v, m)$

Case	v_1	v_2	rainbow vertex
1	x_i	x_j	x_i, z, x_j
2	x_i	$y_{i,j}$	$x_i, y_{i,j}$
3	z	x_i	z, x_i
4	z	$y_{i,j}$	$z, y_{i,j}$
5	$y_{i,j}$	$y_{i,j}$	$y_{i,j}.z, y_{i,j}$

As a result, rainbow vertex antimagic coloring is used on $Amal(Tb_n, v, m)$. As the consequence, the value of $rvac(Amal(Tb_n, v, m))$ is 3. □

The illustration of rainbow vertex antimagic coloring of $Amal(Tb_3, v, 4)$ can be seen in the **Figure 5**. We can see that the distinctt weights on $Amal(Tb_3, v, 4)$ are $25, 82$, and 184. The vertex color on each vertex is induced by the vertex weight. We can also see that every two vertices has a path with a different color on its internal vertices. Hence, it is clear that $rvac(Amal(Tb_3, v, 4))$ is 3.

Furthermore, to complete the illustration of Theorem 2.4, we have developed a GUI programming in MATLAB. It helps us to draw an illustration with bigger order of graph. By means of MATLAB GUI, we will be easy to draw it for illustration, see ALgoritma 1 and Figure 6.

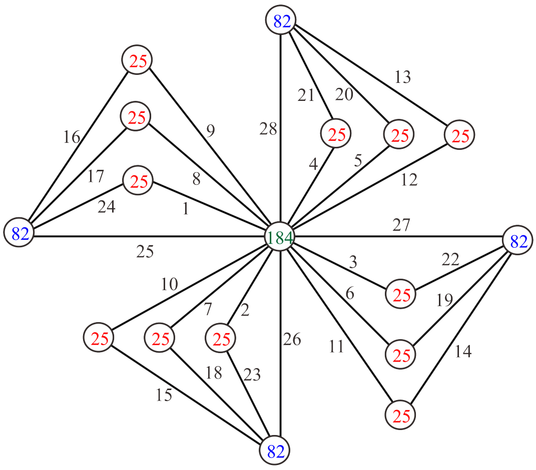
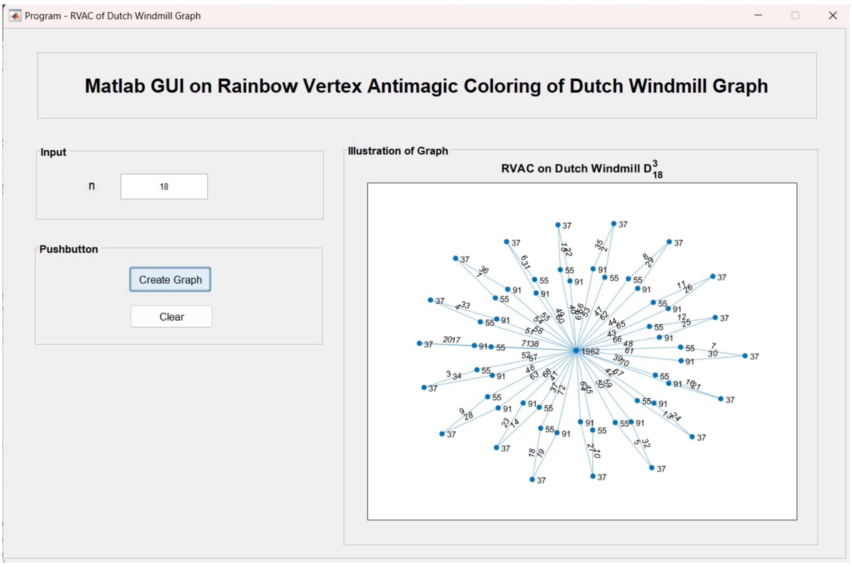


Figure 5. Illustration of RVAC on $Amal(Tb_3, v, 4)$.

Algorithm 1 Pseudocode Algorithm RVAC on Dutch Windmill Graph

```
Require: $n$ (number of expansion)
  if $n \geq 3$ then
      for $i$ from 1 to $n$ do
          Calculate edge labels in Theorem 2.1 ($f(xi1xi2), f(xi2xi3), f(xi1a), f(xi3a)$)
      end for
      Calculate vertex weights in Theorem 2.1 ($w(a), w(x1i), w(x2i), w(x3i)$)
      Initialize array $v_1$ with length $2n$, filled with zeros
      Initialize array $v_2$ with length $2n$, filled with zeros
      for $i$ from 1 to $n \times 2$ do
          if $i$ is odd then
              $v_1[i] = 2 + floor((i-1)/2) \times increment$
          else if $i$ is even then
              $v_1[i] = 2 + floor((i-2)/2) \times increment$
          end if
      end for
      for $i$ from 1 to $2n$ do
          $v_2[i] = increment$
          if $i$ is even then
              $increment$ = $increment\ t + 1$
          end if
      end for
      Create an $2n$ by $2n$ matrix $A$ filled with ones
      Initialize array $v_3$ as the first row of matrix $A$
      Concatenate arrays $v_1$ and $v_2$ to create array $V_a$
      Concatenate arrays $v_2$ and $v_3$ to create array $V_b$
      Calculate the length of array edge labels $f(xi1xi2)$
      Initialize array $b$ with length $2 \times length\ \ vec$, filled with zeros
      for $i$ from 1 to $length\ \ vec$ do
          $b[2i-1] = f(xi1xi2)[i]$
          $b[2i] = f(xi2xi3)[i]$
      end for
      for $i$ from 1 to *length vec* do
          $b[2 \times$ *length vec* $+ 2i - 1] = f(xi1a)[i]$
          $b[2 \times$ *length vec* $+ 2i] = f(xi3a)[i]$
      end for
      for $i$ from 1 to $(3n) + 1$ do
          if $i$ is 1 then
              node name$[i] = w(a)$
          else if $i > 1$ then
              if i modulo 3 is 2 then
                  node name$[i] = w(x2i)$
              else if i modulo 3 is 0 then
                  node name$[i] = w(x1i)$
              else if $i > 2$ then
                  node name$[i] = w(x3i)$
              end if
          end if
      end for
      Create an array named "node name" with $(3n) + 1$ elements
      Create a graph $G$ with nodes $Va$, edges $Vb$, edge weigths $b$, and vertex weights node name.
  end if
```



Program - RVAC of Dutch Windmill Graph

Matlab GUI on Rainbow Vertex Antimagic Coloring of Dutch Windmill Graph

Input

n 18

Figure 6. The Illustration of RVAC Dutch Windmill (D^3_{18}) using MATLAB GUI

3 Conclusion remarks

We have studied the exact values of the rainbow vertex antimagic connection number on dutch windmill graph, diamond graph, octopus graph, and amalgamation product of star with common vertex. All the results have attained the best lower bound. However, studying the existence of this study is considered to be NP-problems. Thus, we propose the following open problems: (i) Determine the $rvac$ of any graph operation such as comb product, amalgamation, or corona product of any graphs, (ii) Characterize the existence of any graph satisfying some specific properties.

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