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Exploring Graph Isomorphism of *Pucuk Rebung* Ornaments

Juriaty Ilma Zailani[1], Masnira Ramli[1*], Wan Nurul Husna Wan Nordin[1]

[1]*Department of Mathematical Sciences, Faculty of Computer and Mathematical Sciences, Universiti Teknologi MARA, Kelantan Branch, Machang Campus, Bukit Ilmu, 18500 Machang, Kelantan, Malaysia*

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ABSTRACT

Pucuk Rebung ornaments are widely recognized in Malaysia, particularly in traditional textiles such as *songket, batik sarong*, and *limar* cloth. The *Pucuk Rebung* pattern has many variations across Southeast Asia, particularly in Malaysia, Indonesia, and Thailand. In this study, *Pucuk Rebung* patterns from Malaysia are highlighted for four different pattern variations through graph isomorphism. A major challenge in studying traditional motifs is the lack of a systematic approach to quantify and compare their structural similarities. Traditional analyses rely heavily on visual interpretation, making it difficult to determine the uniqueness of each pattern mathematically. To address this issue, this study employs a graph-theoretical approach by transforming *Pucuk Rebung* patterns into zero-one matrices through image processing. Then, the corresponding graphs based on the zero-one matrices are created and analyzed for their structural similarities using graph isomorphism. The findings suggest that no *Pucuk Rebung* patterns are isomorphic, which confirms the originality of each *Pucuk Rebung* pattern. Through the study, it emphasizes the efficacy of graph theory in mathematically distinguishing traditional motifs, thereby facilitating a deeper understanding of their structural characteristics within the context of mathematical theory.

1. INTRODUCTION

Pucuk Rebung is a Southeast Asian cultural and artistic design motif that symbolises bamboo shoots. According to Legino and Ruslan (2016), *Pucuk Rebung* is a geometric pattern inspired by the *rebung* (shoot). *Pucuk Rebung* patterns were classified into several types, including *Pucuk Rebung Bertunas*, *Pucuk Rebung Sekuntum*, *Pucuk Rebung Kaluk Paku*, and *Pucuk Rebung Sirih Tunggal* (Marzal, 2015). Figure 1 depicts the *Pucuk Rebung* patterns with different designs but the same geometric shape,a triangle that resembles a bamboo shoot.

[1*] Corresponding author. *E-mail address*: masnira@uitm.edu.my
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Fig. 1. Patterns of *Pucuk Rebung* (Hadi, 2022)

Pucuk Rebung is well known for its cultural importance, featuring detailed geometric designs and aesthetic value. Despite that, there was still a clear lack of research on the mathematical ideas behind these patterns. It was found that most previous studies on this *Pucuk Rebung* pattern had only focused on their history, art, and design. Prior to this, Legino and Ruslan in 2016 conducted a study on the geometric identification of *Pucuk Rebung* patterns, examining their shapes and structures. Meanwhile, another study by Abd Rahim et al. (2020) focused on the traditional Malay artwork including geometrical identification of traditional *Pucuk Rebung*, examining the cultural and mathematical ideas through symmetrical analysis. Other than that, there is a study that connected the patterns through ethnomathematical study with geometry concept, such as an earlier work by Ronse (1985), which highlighted the isomorphism for digital images. However, it is not related to the zero-one matrices, specifically to the *Pucuk Rebung* pattern.

This study revealed the involvement of the mathematical concept of graph theory. Therefore, this study examined the similarities between the four patterns of *Pucuk Rebung* using the principles of graph theory. It showed how the variety of *Pucuk Rebung* patterns could be classified. This aligned with the concept of isomorphism in graph theory, which determined whether two graphs were fundamentally the same, despite appearing different. The main purpose of identifying the isomorphism graphs was to verify whether the *Pucuk Rebung* patterns were equivalent in structure, rather than relying on the appearance of the graphs that were different visually.

In addition, the uniqueness of each *Pucuk Rebung* pattern was recognized through the concept of isomorphism. To complete this study, images of *Pucuk Rebung* patterns are transformed into zero-one matrices. MATLAB is used to transform the images of *Pucuk Rebung* patterns started with preprocessing the images which involving four stages which were scaling, grayscale, thresholding, and binarization. Then, graph of *Pucuk Rebung* is constructed based on the zero-one matrices representing *Pucuk Rebung* pattern. To check whether two graphs were isomorphic or not, three conditions need to be fulfilled. For any two isomorphic graphs, the number of vertices, edges, and degree sequence of the two graphs should be identical. Once the results were identical between those two graphs, it proceeded to check if there existed a one-to-one and onto function between the two graphs of *Pucuk Rebung* patterns. After determining that two graphs are isomorphic, checking their adjacency properties is crucial to verify that the mapping between vertices preserves edges correctly and maintains structural consistency. Graph isomorphism requires a bijection between vertices such that adjacency relationships remain unchanged. This means that for every edge (u, v) in the first graph, there must be a corresponding edge $\big(f(u), f(v)\big)$ in the second graph, where f is the isomorphism function. Ensuring this adjacency preservation prevents incorrect mappings and two graphs are identical in structure.

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2. LITERATURE REVIEW

2.1 *Pucuk Rebung* Motif and Diversity of Crafts

Bamboo shoots, also known as *Pucuk Rebung*, refers to the shoots of the bamboo plant. Inspired by the structure of bamboo shoots, the *Pucuk Rebung* motif is explored as a symbolic of Malay culture and is widely used in crafts. *Pucuk Rebung* is an original Malay motif that have been used for a long time and are still applied as a traditional Malay motif (Legino & Ruslan, 2016). The *Pucuk Rebung* motif holds significant cultural and artistic value in Malay heritage due to its geometric intricacy and aesthetic appeal. It is widely found in various forms of Malaysian art, particularly in textiles such as *songket*, *batik sarong*, and *limar* cloth (Legino & Ruslan, 2016). A prominent batik motif that is continuously used until today is known as *Pucuk Rebung* which was inspired by the tapered triangular feature of *rebung* or bamboo shoot (Samsuddin et al., 2020). Among the commonly used variations in *songket* production, *Pucuk Rebung Lawi Ayam* is particularly notable (Md Nawawi et al., 2015). Other than that, the motif also appears on traditional Malay headdress, the *tanjak* or also known as *tengkolok*. *Tengkolok* is one of the headdresses for Malay men which have been made infamous by the royal families. It is also the formal attire to a *Sultan*, King or *Yang di-Pertuan Besar* in *Tanah Melayu* states with a monarchy reign (Manan et al., 2020).

Beyond textiles, the motif is also prevalent in architectural designs, such as the Tjong A Fie house in Medan, Indonesia, which features numerous Malay Deli ornaments, including the *Pucuk Rebung* pattern (Rudiansyah, 2019). In 2020, Ghassany and Santoso (2020) reported that the pattern of *Pucuk Rebung* was introduced to Sumatera by Malay settlers, it is widely used in crafts, especially in Pekanbaru, Riau Archipelago. The usage of *Pucuk Rebung* pattern as design also grown rapidly on Sumatra Island, particularly in the Riau district (Pratiwi, 2021). This motif has become a significant cultural phenomenon for the local community because the *Pucuk Rebung* pattern is applied on various woven *songket* fabrics, such as *tanjak*, *sarongs* and scarves. Despite its historical and artistic significance, further exploration is needed to understand the mathematical properties and structural characteristics of *Pucuk Rebung* patterns.

2.2 Graph Isomorphism and its Applications

Graph theory is one of the mathematical branches that examines the relationships between objects that can be represented as graphs, which are made up of vertices (nodes) and edges (connections). Graph theory belongs to the well-known area in mathematics called ‘discrete mathematics’ (Deepa & Anitha, 2022). Leonard Euler's 1735 work on the "Seven Bridges of Königsberg" problem served as the foundation for graph theory's originality. Graphs can be categorized using a variety of characteristics, such as simple, directed, undirected, and mixed graph. Graphs are interconnected, and two graphs are considered isomorphic if their relation is equivalent. This ensures that the structure maintains a one-to-one correspondence between the vertices and edges. Bondy and Murty (1976) define isomorphism as the identical structural properties of two graphs, even though they differ in the labelling of the edges and vertices. This necessitates a straightforward mapping of the vertices in the graphs G and H, ensuring that the linked vertices in G correspond to those in H. Create a pair of mappings that preserve adjacency relationships to ascertain that two graphs are isomorphic.

In addition, Dana-Picard (2009) states that any two graphs are isomorphic if they can represent visually in the same way. Since the graphical view are similar, hence the matrices related to the graph are also equal. The definition of graph isomorphism based on Bondy and Murty (1976) is defined as Definition 1.

Definition 1. Two graphs G and H are said isomorphic (written $G \cong H$) if there exist bijections $\theta: V(G) \rightarrow V(H)$ and $\theta: E(G) \rightarrow E(H)$ such that $\emptyset(e) = uv$ if and only if $\emptyset\big(\theta(e)\big) = \theta(u)\theta(v)$. This pair of mappings (θ, ϕ) is called an isomorphism between G and H, $G \cong H$.

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Graph also can be represented as a matrix where it provides its own characteristics such as adjacency matrix and incidence matrix. A graph can be represented through multiple types of matrices, such as the incidence matrix, adjacency matrix, cut-set matrix, circuit matrix, and path matrix (Islam et al., 2022). Entries of 0 and 1 are very common in defining the matrices for the graph. In the context of graph isomorphism, if the two graphs are isomorphic, zero-one matrices can be modified via row and column exchanges. This adjustment is only acceptable if the zero-one matrices of both graphs have the same set of eigenvalues (Ren & Li, 2024). This condition can be applied to simple graph and undirected graph in finding the isomorphism between the graphs since based on the definition.

According to Grohe and Schweitzer (2020), deciding two graphs are structurally identical or isomorphic, is a classical algorithmic problem that has been studied since the early days of computing. The graph isomorphism gained prominence in the theory community in the 1970s, when it emerged as one of the few natural problems. In year 2020, overview of recent advances on the graph isomorphism problem is studied where the main focus is on the Babai's quasi-polynomial (Grohe & Neuen, 2020). Graph theory is very significant in various fields, including modelling, network analysis, and operations research, primarily within the field of mathematics. Cavallaro et al. (2021) demonstrated the application of graph theory by providing the understanding of the patterns or strategies used by criminal to build networks among their affiliates. In network analysis, graph isomorphism algorithms are applied and one of the focuses is on structural equivalence to simplify solver space, aiding applications like protein design, chemical pathways, and community detection (Feng et al., 2024). In another study, speech emotion recognition is studied which applies graph isomorphism network on Long Short-Term Memory outputs for global emotion modelling in the non-Euclidean space (Liu & Wang, 2021). Overall, the current studies demonstrate that graph theory, particularly group isomorphism, plays an important part in its relationships with various fields.

3. METHODOLOGY

This study highlights four types of *Pucuk Rebung* pattern which are *Pucuk Rebung Bertunas*, *Pucuk Rebung Sekuntum*, *Pucuk Rebung Kaluk Paku,* and *Pucuk Rebung Sirih Tunggal*. All the patterns are represented by 5×5 zero-one matrices and graphs.

3.1 Image Processing and Zero-one matrix Transformation

Each *Pucuk Rebung* pattern image is transformed into zero-one matrices of specified order 5×5 through an image processing technique to standardise and extract structural features. In this paper, the MATLAB software is used to assist the transformation of *Pucuk Rebung* image to the zero-one matrices. Step 1 up to step 4 which starts from scaling, followed by grayscale, thresholding, and binarization are done using commands from MATLAB software. The following steps encompass:

(i) Step 1: Scaling

Adjusting the image size to ensure that each pattern is uniform. The RGB values are identified.

(ii) Step 2: Grayscale

Transforming the image into a grey image, and the grayscale values are determined through the RGB values.

(iii) Step 3: Thresholding

Enhancing the contrast of the image by setting a fixed intensity value for pixel differentiation. Threshold value, T , is determined to define the binary value for the image.

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(iv) Step 4: Binarization

The image is transformed into a black and white image. Threshold value from step 3 is used to determine the value of each pixel (entries of matrix). Black pixels are represented as 1, and white pixels as 0.

Through the zero-one matrices that represent *Pucuk Rebung*, a graph is created where each row and column represent vertices, and the entry of the matrix is encoded as the existence of the connections between the vertices through edges. The entry of the matrix with value 1 at $a_{i,j}$ indicates the existence of the edge between vertex i and vertex j, while 0 indicates the absence of the edges.

3.2 Graph Construction and Isomorphism Analysis

The zero-one matrices obtained are transformed into graphs, where the entries of the matrix are represented as vertices and edges. The structural property of the graph is analysed including the degree distribution. To identify the isomorphism between graphs, determining if there is a bijective function (one-to-one and onto) To figure out the similarity of two graphs, it can be recognized by the number of edges, vertices and degrees. For instance, graph isomorphism can be determined by comparing the degrees of vertices, as studied by Dana-Picard (2009). However, they are not isomorphic because the degrees are not consistently matched between them. There are options in identifying isomorphism between graphs:

(i) Vertex Count- There must be an equal number of vertices in both graphs. They cannot be isomorphic if the number of vertices in G, represented by the symbol $|V(G)|$, is not equal to the number of vertices in H, represented by the symbol $|V(H)|$.

(ii) Degree Sequence - Two graphs must be isomorphic if their degree sequences, which are lists of vertex degrees arranged in descending order, are identical. The graphs are not isomorphic if these sequences are different.

(iii) Vertex Mapping – To find a bijective function f: $V(G) \rightarrow V(H)$ such that $(u, v) \in E(G)$if and only if $\left(f(u), f(v)\right) \in E(H)$. Finding the suitable permutation of the vertex set involves going through all of them in this phase. For a pair of vertices in $u, v, V(G)$, if u is adjacent to v in G, then $f(u)$ must be adjacent to $f(v)$ in H.

4. RESULTS AND DISCUSSION

The transformation for four types of *Pucuk Rebung* patterns into a zero-one matrix of order 5×5 is considered. Through the four stages of image processing and the utilisation of MATLAB software, the actual image of *Pucuk Rebung* patterns is transformed to a binary format to establish zero-one matrices of order 5×5. Figure 2 shows the command used in MATLAB software to transform each image of the *Pucuk Rebung* pattern. The MATLAB software is used to assist image transformation into matrices. The image of the *Pucuk Rebung* pattern was uploaded from the specified file path and displayed to show the original image as well as the actual size. In the following step, the resize function was used to convert the image of *Pucuk Rebung* to 5×5 pixels. The process yields different results for RGB values, grayscale values, binary images, and threshold values. It influenced the entries of zero-one matrices in each pattern.

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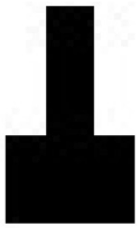
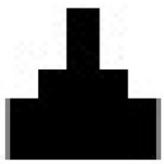
```
m0 = 'C:\Users\User\Documents\MATLAB\';
m1 = 'PRBertunas';
m2 = '.';
m3 = 'jpg';
z = [m0 m1 m2 m3];                          % Construct the full file path
a = imread(z);                              % Read image from file path
figure, imshow(a), title('Original Image'); % Display original image
disp('SIZE OF ORI IMAGE');
disp(size(a));                              % Display RGB value
rez1=imresize(a,[5,5]);                     % Resize to 5x5 pixels
disp('SIZE OF RESIZED IMAGE 5x5');
disp(size(rez1));                           % Show dimension(resized image)
figure, imshow(rez1), title('scaling image 5x5');
size(imgray);                 % Retrieve dimensions of grayscale image
level=graythresh(imgray)      % Obtain optimal threshold using Otsu's method
BI=imbinarize(imgray,level); %Convert into binary image
thr=level*255
figure, imshow(BI), title('binary image of 5x5');
display(rez1)
display(imgray)
disp(BI)                      % Display binary image
```

Fig. 2. MATLAB command for transforming the image of *Pucuk Rebung* pattern onto zero-one matrix

The RGB and greyscale values of the image are defined to determine the threshold value based on the image processing described above. Table 1 shows the results of converting the *Pucuk Rebung* pattern into a zero-one matrix. Observation revealed that the binary images of each pattern are not similar, with different threshold values, resulting in distinct matrices.

Table 1. *Pucuk Rebung* patterns with their binary image and zero-one matrices

Pucuk Rebung Pattern	Binary Image and threshold value	Zero-one matrix
 *Pucuk Rebung Bertunas* (*A*)	 $T = 196.50$	$A = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \end{bmatrix}$
 *Pucuk Rebung Sekuntum* (*B*)	 $T = 198.00$	$B = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

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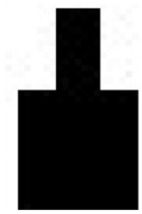
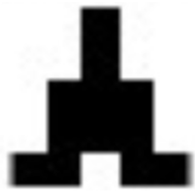
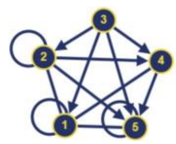
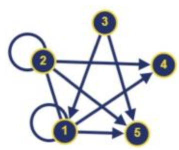
 *Pucuk Rebung Kaluk Paku* (C)	 $T = 178.50$	$C = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \end{bmatrix}$
 *Pucuk Rebung Sirih Tunggal* (D)	 $T = 201.00$	$D = \begin{bmatrix} 1 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 & 1 \end{bmatrix}$

Each pattern possesses distinct structures that affect their representations in zero-one matrices and graphs. The threshold values influence the binarization of the image, determining the value assigned to each pixel. Patterns A and C exhibit analogous binary images and zero-one matrices, as their structures appear similar, albeit differing in size. Nevertheless, upon comparing the zero-one matrices, the entry values are not equivalent. The distinct zero-one matrices imply that none of the patterns are isomorphic, implying that each pattern is distinct in its graph representation. Table 2 displays the graph representation for *Pucuk Rebung* patterns created with zero-one matrices. The columns and rows of zero-one matrices are defined as vertices, while the entries are defined as the edges that connect each vertex. The number of vertices, edges, and degrees is also included in the graph properties list.

Table 2. Graph of *Pucuk Rebung* patterns

Type of *Pucuk Rebung*	Graph	Graph properties
Pucuk Rebung Bertunas (A)		Number of vertices = 5 Number of edges = 16 In-Degree sequences = (0,3,3,5,5) Out-Degree sequences = (2,2,4,4,4)
Pucuk Rebung Sekuntum (B)		Number of vertices = 5 Number of edges = 10 In-Degree sequences = (0,2,2,3,3) Out-Degree sequences = (0,0,2,4,4)

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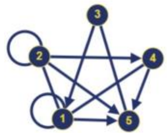
Pucuk Rebung Kaluk Paku (*C*)		Number of vertices = 5 Number of edges = 14 In-Degree sequences = (0,2,2,5,5) Out-Degree sequences = (2,2,2,4,4)
Pucuk Rebung Sirih Tunggal (*D*)		Number of vertices = 5 Number of edges = 13 In-Degree sequences = (1,2,2,4,4) Out-Degree sequences = (1,2,2,4,4)

Next, to identify the isomorphism between the patterns, three properties of graph isomorphism must be satisfied: two graphs are said to be isomorphic if the number of vertices and edges is the same. Other than that, the number of degrees must also be equal for each vertex. In this case, in and out degree must be considered since the graph created from the zero-one matrix of each pattern is a directed pseudograph, since multiple edges and self-loops exist. Then, the two graphs must fulfill the bijection operation where it must be one-to-one and onto.

Six comparisons are made between pattern A and B, A and C, and D, B and C, B and D, and C and D, based on four *Pucuk Rebung*-based patterns. Every graph in Table 2 has five vertices, as they were generated from a zero-one matrix of order 5×5. However, the number of edges in each graph varies, with graphs $A, B, C,$ and D having 16, 10, 14, and 13 edges, respectively. As a result, the first property of graph isomorphism is not met. It is also supported by the number of degrees for each vertex in each pattern. Table 2 shows that the degree sequences for each pattern are unique, with no single sequence being equal. The comparisons between four *Pucuk Rebung* patterns are not isomorphic which are $A \ncong B$, $A \ncong C$, $A \ncong D$, $B \ncong C$, $B \ncong D$, and $C \ncong D$.

This demonstrated that every *Pucuk Rebung* pattern is distinct, with no structural similarities between them. The graph isomorphism supports the common observation that society, particularly arts and culture experts, believes that each pattern is distinct, with no similarities between the patterns, confirming the patterns' uniqueness.

5. CONCLUSION

Each *Pucuk Rebung* pattern was transformed into a zero-one matrix, enabling a structured mathematical representation. The patterns were then analyzed as graphs, allowing for a detailed examination of their structural properties. Finally, the similarity between the patterns was analyzed using graph isomorphism properties. Based on the results, no isomorphism was found between any pair of *Pucuk Rebung* patterns, which shows that each pattern is structurally distinct and unique.

Visual observations indicate that the patterns were distinctive in their shape and design. This study provided mathematical proof by demonstrating that each pattern of *Pucuk Rebung* is not isomorphic. Although patterns A and C appear analogous in the binary image, a detailed examination of the zero-one matrix, along with the graph, edge counts, and degree sequences, uncovered substantial discrepancies. These findings corroborated the concept of visual observation, emphasizing the significance of mathematics, particularly graph theory, in connecting cultural knowledge within a mathematical framework.

In future studies, various pixel sizes should be examined in lieu of the existing 5×5 pixels to ascertain whether enhanced resolution increases accuracy and to substantiate the current findings. Analysing various pixel dimensions would elucidate whether different order of matrices produce superior outcomes. By

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diversifying this research, scholars can enhance their comprehension of cultural patterns via mathematics and further connect tradition with contemporary analytical methods.

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7. CONFLICT OF INTEREST STATEMENT

The authors declare there is no conflict of interest in the subject matter or materials discussed in this manuscript.

8. AUTHORS' CONTRIBUTIONS

Juriaty Ilma Zailani conducted a study centred on data analysis and thesis writing. Masnira Ramli formulated the primary research concept, established the theoretical framework, and supervised the research advancement. Wan Nurul Husna Wan Nordin is reviewing and formatting the manuscript. Writing, reviewing, and editing are conducted concurrently.

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