Jurnal Elemen, 12(2), 591-615, April 2026
https:/doi.org/10.29408/jel.v12i2.34059

Jurnal Elemen
e- ISSN: 2442 - 4226

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From cultural movement to structural equivalence: Modeling graph isomorphism through *serampang dua belas* dance

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Abstract

This study addresses a limitation in ethnomathematics research, which often does not go beyond identifying visual patterns, by examining how ethnomathematical modeling of traditional dance can illuminate graph isomorphism. Focusing on the *Serampang Dua Belas* dance of North Sumatra, the study employs a qualitative ethnographic approach, with data collected through performance observations, video documentation, interviews with cultural experts in Serdang Bedagai Regency, and a review of choreographic literature. Movement sequences were analyzed through data reduction, categorization of transition patterns, and reconstruction of spatial–temporal relations, then modeled as directed graphs using GeoGebra. Dancers' positions were represented as vertices and transitions as directed edges, enabling formal analysis through adjacency matrices and bijective mappings to verify isomorphism. The findings reveal that although the variations differ visually, several segments exhibit structural equivalence across linear, cyclic, and loop-containing graphs. This study advances ethnomathematics toward formal structural verification grounded in graph theory and highlights its potential to support relational understanding in discrete mathematics learning.

Keywords: directed graph modeling; embodied learning; ethnomathematics; graph isomorphism; structural equivalence

How to cite: Ramadhani, R., Bina, N. S., Narpila, S. D., Mazaly, M. R., & Rusmini, R. (2026). From cultural movement to structural equivalence: Modeling graph isomorphism through *serampang dua belas* dance. *Jurnal Elemen, 12*(2), 591-615. https://doi.org/10.29408/jel.v12i2.34059

Received: 1 February 2026 | Revised: 12 April 2026
Accepted: 29 April 2026 | Published: 10 May 2026

Introduction

Cultural heritage represents a nation's identity, encompassing values, philosophies, and systems of knowledge transmitted across generations. Among its diverse cultural expressions, traditional dance occupies a distinctive position, as it functions not only as an aesthetic form but also as a structured symbolic system rich in meaning. In the Indonesian context, characterized by extensive ethnic and cultural diversity, thousands of traditional dances embody conceptual potential that has not yet been fully explored through a mathematical lens. The perspective of ethnomathematics provides a framework for understanding that cultural practices contain structures and modes of reasoning that can be formalized in mathematical language (Kurniawan & Hidayati, 2020). Through this approach, mathematics is viewed as a socio-cultural construction embedded in human activity, rather than merely an abstract symbolic system detached from context (Khasanah et al., 2025).

A substantial body of ethnomathematics research has identified and analyzed mathematical ideas, methods, and techniques developed within various sociocultural groups. Mathematical elements such as geometry, arithmetic, patterns, and transformations are frequently integrated into traditional arts, including shadow puppetry (Risdiyanti & Prahmana, 2021), batik motifs (Faiziyah et al., 2021; Irawan et al., 2019), architecture (Supiyati et al., 2019), and dance choreography (Endilina et al., 2025; Khairullah et al., 2025; Ma'rifah et al., 2019; Radiusman et al., 2021). Ethnomathematical approaches through traditional dance have been shown to be effective in explaining abstract mathematical concepts and introducing cultural elements to students (Gazanofa & Wahidin, 2023). However, most existing studies remain limited to the identification of visual patterns and geometric transformations in a largely descriptive manner. Analyses rarely advance toward the formalization of abstract relational structures that could support the learning of advanced mathematical concepts. Moreover, ethnomathematical approaches often conclude at the stage of contextualization without providing rigorous mathematical methods to verify the structures identified (Bernales & Powell, 2018; Orey & Rosa, 2021). This gap underscores the need for approaches that not only identify mathematical elements in cultural practices but also formally model them to support knowledge development and instructional innovation.

These limitations become particularly significant in the context of graph theory instruction, especially regarding the concept of graph isomorphism. Numerous studies indicate that students frequently experience difficulty in understanding structural equivalence between graphs that appear visually different. They tend to focus on spatial layout or surface features rather than on the preservation of adjacency relations, which constitutes the core definition of isomorphism. The process of establishing bijective mappings between vertices is often treated as a purely technical procedure, without deep comprehension of its structural meaning. As a result, students struggle to generalize, construct formal proofs, and systematically identify structural equivalence. This condition suggests that graph theory instruction must more effectively cultivate students' relational and structural reasoning before progressing to symbolic formalization.

One cultural heritage with the potential to address this need is the *Serampang Dua Belas* dance, a traditional Malay Deli dance from North Sumatra. This dance consists of twelve sequential movement variations performed at a lively tempo with systematic partner interactions (Sari & Rosramadhana, 2018). Each variation presents specific positional configurations and movement transitions that form a network of spatial and temporal relationships. Previous studies have identified elements of symmetry and recurring floor patterns in Malay dance (Lorente, 2024; Thomas & Peebles, 2016), yet such analyses have largely remained at the level of visual description. To date, no study has systematically modeled the relational structure among movements using formal mathematical representations or examined structural equivalence across its variations.

To address this gap, the present study employs graph theory as an analytical framework to represent and examine the structure of dance movements. In this approach, dancers' positions are represented as vertices and movement transitions as directed edges, enabling each variation to be modeled as a graph that systematically captures relational structures. Each dance variation involves specific configurations of positions and movement trajectories that form networks of spatial and temporal relationships, which can be represented as directed graphs (Mannone & Turchet, 2019). This representation allows for analysis of topological properties such as connectivity, paths, and relational structure that may not be apparent through visual observation alone. Furthermore, the concept of graph isomorphism is used to determine whether choreographically distinct movement variations possess equivalent relational structures. Graph isomorphism is defined as a bijective mapping between the vertices of two graphs that preserves adjacency relations (Budinski et al., 2022). In educational contexts, understanding this concept is essential for fostering students' abstraction and structural reasoning abilities (Hausberger, 2017; Hicks, 2024).

Modeling dance movements as directed graphs also aligns with the perspective of embodied cognition, which emphasizes that physical experience can support abstract mathematical thinking (Chatain et al., 2024; Valentini & Guarnacci, 2021). Interactions and transitions in dance provide concrete relational experiences that can be transformed into formal representations. Thus, cultural context serves not merely as illustrative material but as a source of mathematical structure that can be formalized and verified. The integration of mathematics with creative activities such as dance has been shown to enhance student engagement and learning outcomes (Stern & Bachman, 2021). This approach facilitates a gradual transition from concrete experience to deeper structural abstraction.

Based on the methodological gaps in the ethnomathematics literature and the pedagogical needs in graph theory instruction, this study aims to model the variations of the *Serampang Dua Belas* dance as directed graphs and to verify the existence of structural isomorphism among its movement variations. The study also explores the implications of this modeling for supporting the development of students' structural reasoning. Theoretically, this research extends ethnomathematics from the identification of visual patterns toward rigorous structural analysis. Methodologically, it offers a graph-based analytical model situated within a cultural context. Pedagogically, it contributes to the development of more contextualized and meaningful approaches to graph theory instruction.

Methods

This study employs an ethnographic approach grounded in an ethnomathematical perspective to examine isomorphic graph representations within the movement patterns of each variation of the *Serampang Dua Belas* dance. This approach views cultural practices as sources of mathematical knowledge construction; therefore, the analysis integrates exploration of cultural context with formal mathematical modeling. The methodological framework is informed by the contextual inquiry model developed by Alangui (2020), which positions cultural practice as the starting point for analyzing mathematical structures.

The study began with the formulation of three core ethnographic questions: (1) What positional configurations and movement transitions characterize each variation of the *Serampang Dua Belas* dance? (2) What symbolic and social meanings are embedded in those movement patterns? (3) Do structurally distinct variations share equivalent relational structures that satisfy the formal definition of graph isomorphism? To obtain contextual data, in-depth interviews were conducted with three cultural experts in Serdang Bedagai Regency: a senior *Serampang Dua Belas* practitioner and choreographer with over 25 years of experience, a cultural preservation officer from the regional arts council, and an ethnomusicologist specializing in Malay Deli performing arts. These interviews aimed to elicit insights into the social values, symbolism, and meaning structures embedded in each variation of the *Serampang Dua Belas* dance. In addition to interviews, data collection included non-participant observation of recorded performances, visual documentation in the form of photographs and movement recordings, and systematic notation of the sequence and transitions within each movement variation. The collected data were then reduced and categorized using a three-stage coding procedure: (1) open coding to identify discrete positional states and movement transitions; (2) axial coding to group transitions by spatial direction, symmetry, and recurrence; and (3) selective coding to reconstruct the relational network of positions constituting each variation. Two members of the research team independently coded a shared subset of field notes. Initial inter-rater agreement on the identification of positional states and transition sequences reached 80%, indicating satisfactory level of consistency in applying the coding criteria. All remaining discrepancies were resolved through discussion and re-examination of the video documentation until full consensus was reached.

Subsequently, the analysis focused on the structural aspects of the movement patterns. Observations were directed toward identifying spatial configurations, positional relationships among dancers, and transition patterns within each variation. Each movement segment was reconstructed into a graph representation by mapping dancers' positions as vertices and movement transitions as directed edges. Graph modeling was conducted using GeoGebra (version 6) following a four-step procedure: (1) each discrete dancer position identified through coding was assigned a labeled point in the GeoGebra geometry environment (e.g., v_{1M}, v_{2M}); (2) directed edges were drawn using the vector tool to represent each observed movement transition; (3) the resulting graph was exported and cross-checked against the coded field notes to verify that all transitions were correctly represented; and (4) adjacency matrices were constructed manually from the graph and verified against GeoGebra's relational output. Data analysis proceeded with the construction of adjacency matrices, examination of one-to-one correspondences between graphs, and verification of adjacency preservation as an indicator of isomorphism. Source triangulation was carried out by comparing graph modeling results derived from three independent data sources: video frame-by-frame analysis, expert interview accounts of transition sequences, and systematic field notation. All three sources yielded consistent identification of positional states and transition sequences across the analyzed variations, with no structural discrepancies detected, thereby confirming the credibility and internal consistency of the graph models constructed.

In this study, graph modeling functions not only as a tool for structural analysis but also as a conceptual foundation for supporting the development of structural reasoning in graph theory instruction. By formalizing cultural movement relationships into directed graph representations and systematically verifying isomorphism, the model provides an initial framework for bridging concrete experience with relational abstraction in mathematics learning contexts.

Results

This section presents the research findings revealing the presence of mathematical structures in the form of isomorphic graphs within the movement patterns of each variation of the *Serampang Dua Belas* dance, as analyzed through the graph modeling procedures described in the methodology. Based on the reconstruction of dancers' positions as vertices and movement transitions as edges, relational equivalence was identified among several variations that appear visually distinct yet share equivalent connectivity structures. These findings indicate that choreographic variation does not necessarily imply structural difference; rather, it may embody latent relational equivalence.

Isomorphism analysis was conducted by examining one-to-one correspondences between vertices and verifying the preservation of adjacency relations in the compared graphs. The results demonstrate that spatial transformations in the movement patterns do not alter the underlying relational structure. Thus, this cultural practice embodies principles of structural equivalence consistent with the formal definition of graph isomorphism in discrete mathematics. This verification affirms that the concept of isomorphism is not confined to abstract symbolic representation but is also manifested in dynamic movement systems embedded within cultural traditions.

The primary contribution of this study lies in shifting perspectives regarding conceptual sources for learning graph theory. Rather than beginning with formal mathematical representations and proceeding toward contextual applications, this study demonstrates that cultural structures can serve as the starting point for conceptual construction. In educational contexts, modeling movement patterns as graphs offers a theoretically grounded framework through which students may develop an understanding of structural equivalence through observational and representational experiences. This process has the potential to strengthen structural reasoning, generalization skills, and relational understanding as central components of graph isomorphism, though these pedagogical outcomes require empirical investigation through future classroom implementation studies.

Accordingly, these findings not only extend ethnomathematics into the domain of graph theory but also propose an alternative epistemological framework for introducing the concept of isomorphism. Integrating cultural practice as a medium for analyzing mathematical structure creates opportunities for more reflective, contextualized, and meaningful learning without compromising formal conceptual precision. The following sections describe the characteristics of graph structures within selected dance variations and outline the stages of isomorphism identification. The selection of Variations 1, 3, and 9 for in-depth analysis was guided by a criterion of structural typicality rather than exhaustive coverage: each selected variation represents a qualitatively distinct graph type that does not recur in the remaining variations. Variation 1 exemplifies the pure directed path; acyclic, with no loops and maximum linearity. Variation 3 exemplifies a minimal cyclic graph with a self-loop embedded in a dense two-vertex structure. Variation 9 exemplifies a loop-augmented directed path; predominantly linear but with a single point of self-recurrence at an intermediate vertex. Together, these three structural archetypes account for the full range of graph-theoretic properties; linearity, cyclicity, and self-recurrence; observed across all twelve variations. The remaining nine variations were also modeled and found to instantiate one of these three structural types; they are therefore not analyzed separately, as doing so would not yield additional graph-theoretic insight.

Variation 1: Opening movement

Variation 1 of the *Serampang Dua Belas* dance represents the initial encounter between a young man and a young woman. This segment portrays the emotional dynamics of a first meeting, including the young woman’s hesitation and the young man’s curiosity. These interpretive dimensions provide contextual meaning for understanding each positional change and movement pattern performed. As illustrated in Figure 1, the sequence begins with two dancers standing side by side, the male dancer on the left and the female dancer on the right. This initial configuration serves as the reference point for subsequent transitions. The dancers then move backward simultaneously, followed by lateral movements in opposite directions. This sequence produces orderly spatial reconfigurations that can be identified as discrete positions.

When each position is represented as a vertex and each transition as a directed edge, the movement pattern in Variation 1 forms a directed graph consisting of seven vertices and six edges. The resulting connectivity structure constitutes a directed path, in which the first vertex functions as the source and the final vertex as the sink, while each intermediate vertex has one incoming edge and one outgoing edge. This structure indicates that the movement sequence is progressive and does not form a cycle.

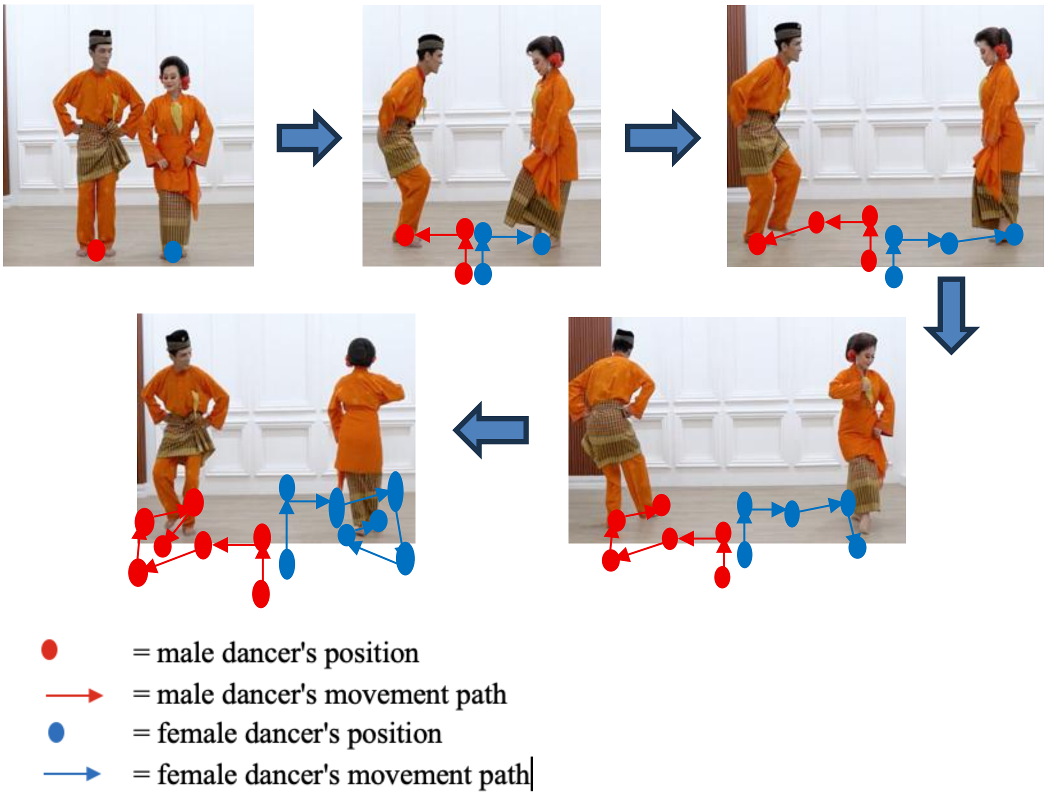

Figure 1. Movement pattern in Variation 1

Figure 1 illustrates the sequential positional configurations of the male (left-red) and female (right-blue) dancers across seven discrete positions. Each frame corresponds to one vertex in the directed graph model, progressing from the initial side-by-side stance through backward and lateral displacements to the final position, with no return to any prior position.

The movement pattern in Variation 1 forms a directed graph, in which $v_{1M}$and v_{1F}represent the initial positions of the male and female dancers, respectively, while v_{7M} and v_{7F} denote their final positions in the movement sequence of Variation 1. Formally, this structure can be expressed as follows:

$$G_M = (V_M, E_M), G_F = (V_F, E_F) \tag{1}$$

where:

The graph representing the male dancer's movement pattern is defined as

$G_M = (V_M, E_M)$, with

$V_M = \{v_{1M}, v_{2M}, v_{3M}, v_{4M}, v_{5M}, v_{6M}, v_{7M}\}$, and

$$E_M = \{e_{1M}, e_{2M}, e_{3M}, e_{4M}, e_{5M}, e_{6M}\} \tag{2}$$

The graph representing the female dancer's movement pattern is defined as

$G_F = (V_F, E_F)$, with

$V_F = \{v_{1F}, v_{2F}, v_{3F}, v_{4F}, v_{5F}, v_{6F}, v_{7F}\}$, and

$$E_F = \{e_{1F}, e_{2F}, e_{3F}, e_{4F}, e_{5F}, e_{6F}\} \tag{3}$$

The graph representations of these movement patterns are presented in Figure 2.

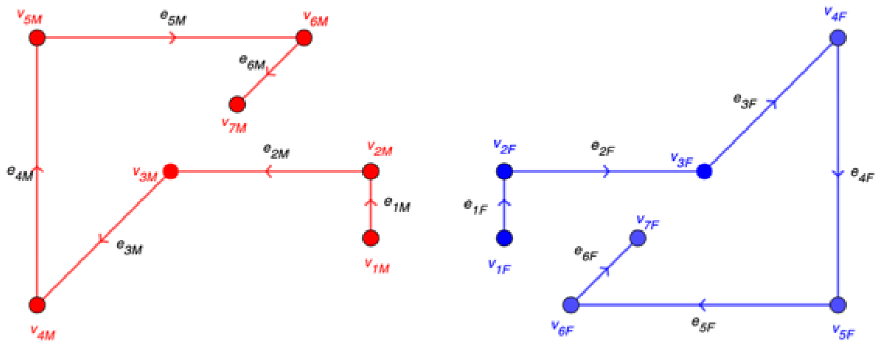

Figure 2. Graph representation of the movement pattern in Variation 1

Figure 2 shows a directed path graph with seven vertices (v_{1M}/v_{1F} through v_{7M}/v_{7F}) six directed edges. The first vertex serves as the source (in-degree 0) and the last as the sink (out-degree 0), reflecting the progressive, acyclic nature of the opening movement sequence.

Based on Figure 2, the resulting connectivity structure forms a directed path graph. The first vertex has an in-degree of 0 (source), and the final vertex has an out-degree of 0 (sink), while each intermediate vertex has exactly one incoming edge and one outgoing edge. This structure indicates that the movement sequence is progressive and does not form a cycle.

The adjacency matrix representations of both graphs exhibit an upper-triangular pattern with entries equal to 1 along the superdiagonal, confirming a linear path structure without repetition.

	v_{1M}	v_{2M}	v_{3M}	v_{4M}	v_{5M}	v_{6M}	v_{7M}
v_{1M}	0	1	0	0	0	0	0
v_{2M}	0	0	1	0	0	0	0
v_{3M}	0	0	0	1	0	0	0
v_{4M}	0	0	0	0	1	0	0
v_{5M}	0	0	0	0	0	1	0
v_{6M}	0	0	0	0	0	0	1
v_{7M}	0	0	0	0	0	0	0

	v_{1F}	v_{2F}	v_{3F}	v_{4F}	v_{5F}	v_{6F}	v_{7F}
v_{1F}	0	1	0	0	0	0	0
v_{2F}	0	0	1	0	0	0	0
v_{3F}	0	0	0	1	0	0	0
v_{4F}	0	0	0	0	1	0	0
v_{5F}	0	0	0	0	0	1	0
v_{6F}	0	0	0	0	0	0	1
v_{7F}	0	0	0	0	0	0	0

Figure 3. Adjacency Matrix of the Movement Graph in Variation 1.

Figure 3 shows the upper-triangular pattern with 1s along the superdiagonal confirms a linear path structure with no repeated or cyclic transitions. Both the male and female dancer graphs produce identical matrices, establishing the basis for isomorphism.

This structural similarity (see Fig. 3) indicates that the two graphs share identical connectivity patterns. It is important to clarify that G_M and G_F were constructed independently from one another: the vertex set and edge set of each graph were derived separately from the observed movement sequences of the male and female dancer respectively, without presupposing any equivalence between them. The identification of isomorphism is therefore a substantive empirical finding; the result of independent modeling and subsequent verification; rather than a tautological consequence of how the graphs were defined. To establish this equivalence formally, a bijective mapping function $f: V_M \to V_F$ is defined by the rule $f(v_{iM}) = v_{iF}$ for each $i = 1,2,\ldots,7$. This mapping preserves adjacency relations between corresponding vertices and therefore satisfies the formal definition of directed graph isomorphism. Consequently, it follows that $G_M \cong G_F$.

The progressive and acyclic nature of this directed path graph aligns with the narrative meaning of Variation 1, which portrays the initial encounter between a young man and a young woman. The movement sequence unfolds gradually from the initial position to the final position without repetition, so the resulting mathematical structure reflects the dynamics of its underlying meaning. The structural equivalence between the two dancers' graphs demonstrates that differences in visual expression do not alter the foundational relational pattern.

Variation 3: Turning movement

The movement pattern in Variation 3 exhibits characteristics distinct from Variations 1 and 2. Based on the sequence of movements, both dancers rotate and step in accordance with the musical rhythm in a more dynamic manner. These circular movements generate spatial configurations that are no longer linear but instead tend to recur and intersect, forming interrelated patterns. Narratively, Variation 3 represents a phase in which feelings of affection between the young man and woman intensify. The rotational dynamics reflect emotional turbulence, including unexpressed longing and inner restlessness. Although these emotions have not yet been explicitly conveyed, there is a discernible progression toward deeper relational engagement. This evolution of meaning corresponds to the increasingly complex movement pattern, which is no longer progressive in the manner observed in Variation 1.

This shift in emotional dynamics is reflected in the spatial configuration, which includes circular transitions and returns to previously occupied positions. As illustrated in Figure 4, several movement trajectories form recurring patterns. When each position is represented as a vertex and each transition as a directed edge, the resulting structure indicates the presence of a cycle within the graph. Accordingly, the movement sequence in Variation 3 does not form a linear path but rather a directed graph containing one or more cycles.

The presence of cycles demonstrates that the movement pattern in Variation 3 possesses a higher level of structural complexity than the acyclic structure identified in Variation 1. Structurally, the resulting graph represents recurring relational dynamics, consistent with the ongoing emotional development that has not yet reached resolution. This structure provides a foundation for further analysis of connectivity characteristics, vertex degree distribution, and the potential structural equivalence of this variation with others.

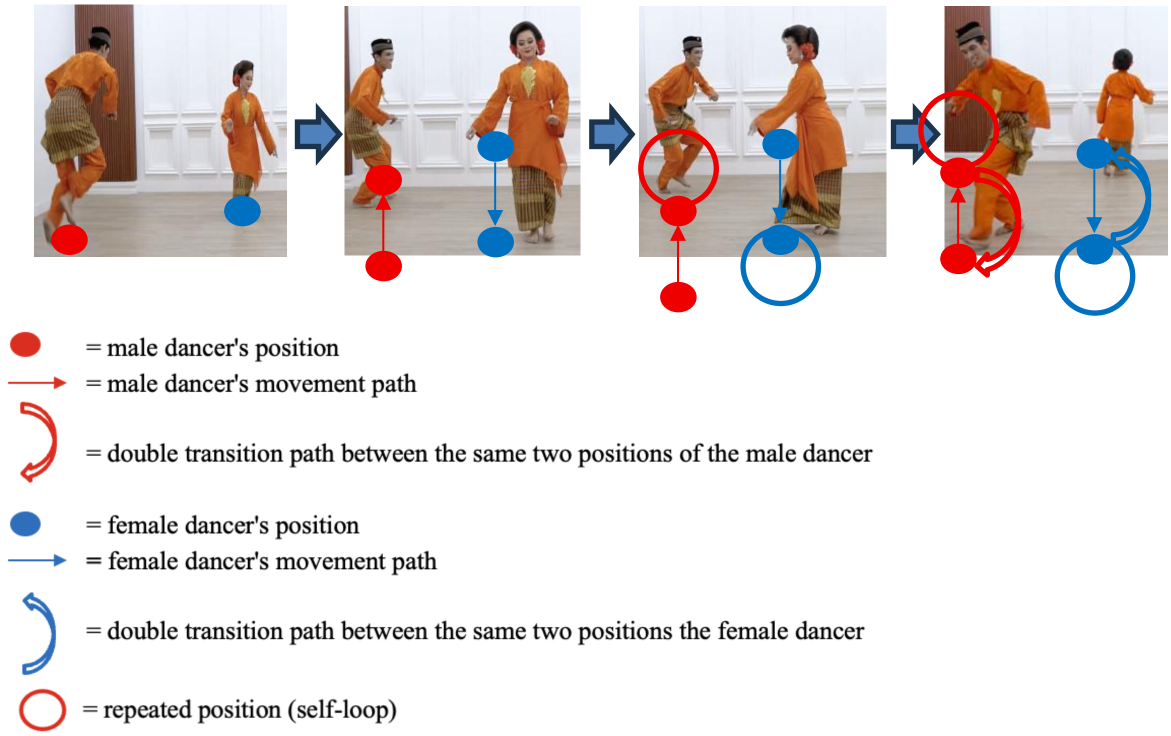

Figure 4. Movement pattern in Variation 3

Figure 4 shows the circular and rotational configurations performed by both dancers. The frames capture the two functionally distinct positional states: an initial standing position (v_1) and a rotational position (v_2). Transitions between and within these states; including the self-return at v_2, form the edges of the directed graph model for this variation.

The movement transitions performed by both dancers in Variation 3 also form a directed graph, with v_{1M} and v_{1F} as the initial positions. The structure allows a return to certain vertices through loops. The graph represented in the movement pattern of Variation 3 is presented in Figure 5 below.

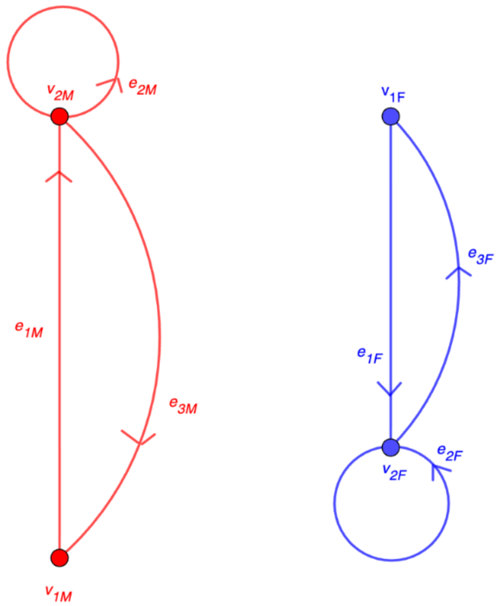

Figure 5. Graph representation of the movement pattern in Variation 3

Figure 5 shows a two-vertex directed graph (v_1, v_2) with a reciprocal edge between the two positions and a self-loop at v_2. The loop represents the repeated rotation at the second position, reflecting the cyclic, unresolved emotional dynamic of this variation.

As shown in Figure 5, the movement transitions in Variation 3 are represented as a directed graph, in which each dancer's position is modeled as a vertex and each movement transition as a directed edge. In contrast to Variation 1, which forms a linear and acyclic path, the structure in Variation 3 exhibits returns to previously occupied positions as well as repetition at a specific point, thereby forming a loop edge. The two-vertex model employed here reflects the choreographic reality of this variation: systematic analysis of the movement sequence through video documentation and expert interviews revealed that Variation 3 involves only two functionally distinct positional states; an initial standing position and a rotational position; with all transitions occurring between these two states or recurring at the rotational position. Intermediate body orientations during the turning motion were not treated as distinct vertices because they do not constitute stable positional endpoints recognized by the choreographic conventions of this dance; they are continuous motion rather than discrete states. This granularity criterion; defining a vertex as a stable, functionally distinct position rather than any momentary body orientation was applied consistently across all analyzed variations and was validated against expert accounts of how positions are conceptualized in the dance tradition.

It is necessary to address directly the question of whether isomorphism between two graphs on two vertices constitutes a trivial finding. In graph theory, graph size; measured by the number of vertices; does not determine the substantive significance of an isomorphism result. What matters is whether the structural equivalence was foreknown or whether it was an empirical discovery. In the present case, the two-vertex structure of Variation 3 is not a modeling simplification but a faithful representation of the choreographic reality: the dance admits exactly two stable functional positions, and the transitions among them; including self-recurrence; constitute the complete relational vocabulary of this variation. Moreover, the analytical interest of this variation lies precisely in its edge structure rather than its vertex count: the simultaneous presence of a bidirectional edge and a self-loop on a single vertex produces a non-simple directed graph whose degree sequence (in-degree and out-degree of 1 at v_1; in-degree and out-degree of 2 at v_2, including the loop contribution) is non-trivial and non-uniform. Demonstrating that this specific edge configuration arises independently and identically from two separately observed movement sequences; one for each dancer; is a substantive finding, not a definitional one.

Based on this modeling, two directed graphs are constructed: the graph representing the male dancer's movement pattern, G_M, and the graph representing the female dancer's movement pattern, G_F. Formally, these graphs are defined as follows:

$$G_M = (V_M, E_M), G_F = (V_F, E_F) \tag{4}$$

where:

$$V_M = \{v_{1M}, v_{2M}\}, E_M = \{(v_{1M}, v_{2M}), (v_{2M}, v_{1M}), (v_{2M}, v_{2M})\}$$
$$V_F = \{v_{1F}, v_{2F}\}, E_F = \{(v_{1F}, v_{2F}), (v_{2F}, v_{1F}), (v_{2F}, v_{2F})\} \tag{5}$$

This structure produces identical adjacency matrices for both graphs:

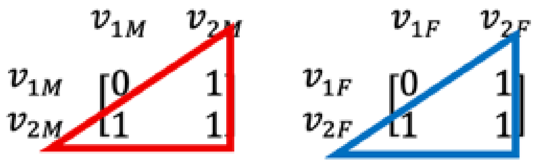

Figure 6. Adjacency matrix of the movement graph in Variation 3.

Figure 6 shows the entry of 1 in the diagonal position of the second row and column indicates the loop at vertex v_2. Both male and female dancer graphs produce identical 2×2 matrices, confirming structural equivalence.

The entry in the second row and second column of the adjacency matrix (see Fig. 6) is equal to 1, indicating the presence of a loop at vertex v_2. Therefore, both graphs are classified as non-simple directed graphs, as they contain a loop, although they do not include multiple edges.

In terms of vertex degrees, considering that a loop contributes one to the in-degree and one to the out-degree of the same vertex, the following results are obtained:

For v_1: in-degree = 1 and out-degree = 1.

For v_2: in-degree = 2 and out-degree = 2 (including the contribution of the loop).

This degree distribution indicates that the second vertex plays a more dominant relational role, serving as a point of movement recurrence. The structural equivalence between G_M and G_F can be established through a bijective mapping function $f: V_M \to V_F$ defined by $f(v_{1M}) = v_{1F}$ and $f(v_{2M}) = v_{2F}$. This mapping preserves all adjacency relations, including the presence of the loop. Accordingly, based on the formal definition of directed graph isomorphism that permits loops, it follows that:

$$G_M \cong G_F \quad (6)$$

The presence of a loop in this graph structure represents a movement pattern that repeats and returns to a particular position, symbolically reflecting the emotional dynamics in Variation 3 that have not yet reached resolution. Thus, the resulting mathematical structure not only demonstrates relational equivalence between the two dancers but also mirrors the development of meaning within the narrative progression of the dance.

Variation 9: Leaping movement

Variation 9 is characterized by upward leaping movements performed rhythmically by both dancers in accordance with the musical tempo. This vertical motion marks a shift in dynamic quality compared to earlier variations, which were dominated by horizontal or circular transitions. The repeated jumps create a structured ascending–descending pattern within the performance space. Narratively, these leaping movements represent the heightened anticipation experienced by a couple awaiting their parents' blessing. The increased intensity of motion and the pronounced vertical direction reflect emotional tension alongside growing hope. Thus, the change in movement quality not only enriches the choreographic variation but also signifies the climax of emotional dynamics within the narrative progression of the dance.

This emotional transformation is reflected in the spatial configuration formed during the movement sequence. As shown in Figure 7, the pattern in Variation 9 exhibits repeated transitions between an initial position and a leaping position. When each position is represented as a vertex and each transition as a directed edge, the resulting structure forms a directed graph that demonstrates reciprocal relationships between positions. The upward movement followed by a return to the previous position indicates the presence of pairs of oppositely directed edges and, in certain instances, may result in repetition at the same vertex.

This relational structure reveals that the movement pattern in Variation 9 differs fundamentally from Variation 1, which is progressive and linear, and from Variation 3, which contains a loop at a fixed vertex. The ascending–descending pattern in Variation 9 reflects reciprocal and intensified relations, symbolically representing the emotional turbulence experienced during the phase of anticipation. This configuration provides the basis for the formal graph analysis presented in the following section.

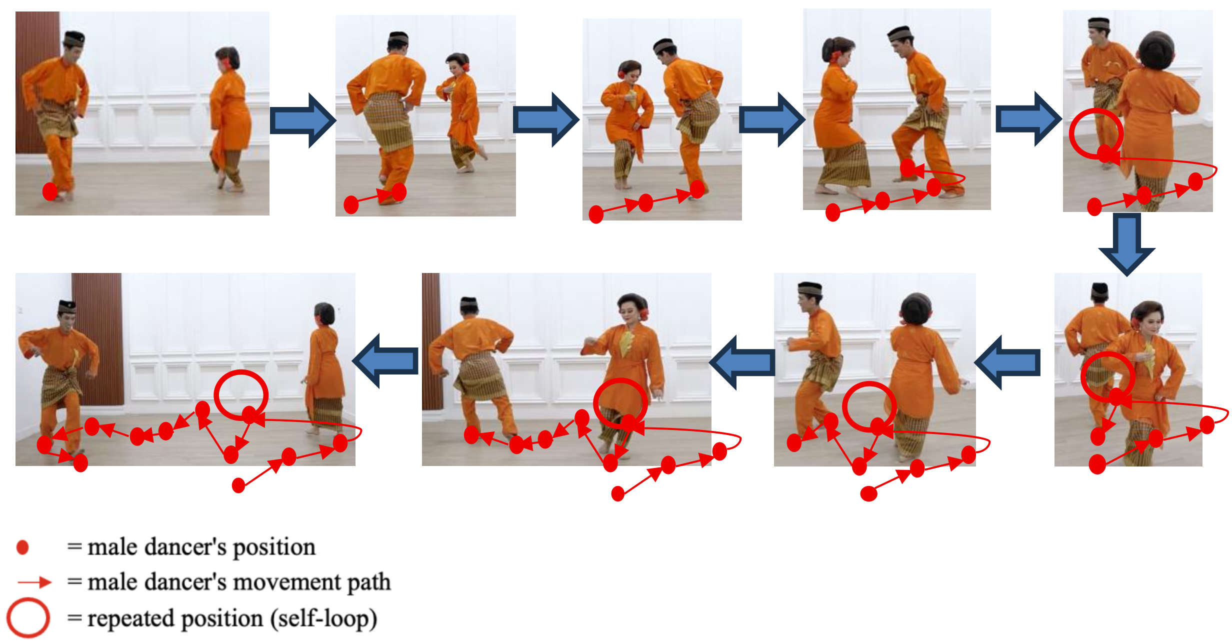

Figure 7. Movement pattern in Variation 9

Figure 7 shows the ascending and descending leaping sequences performed rhythmically by both dancers. Each frame corresponds to a discrete positional state (v_1 through v_{12}). Note the repeated leaping position at v_{10}, which generates the self-loop in the graph model and reflects the peak of emotional intensity before the sequence progresses toward its conclusion.

For clarity of presentation, Figure 7 displays the movement pattern of the male dancer only. Given that the study establishes structural isomorphism between the male and female dancer graphs; meaning both share identical adjacency structures; the male dancer's pattern serves as a representative illustration of the relational structure common to both dancers. The female dancer's movement pattern follows the same sequence of positional states and transitions, differing only in spatial orientation.

The movement transitions performed by both dancers in Variation 9 also form a directed graph, with v_{1M} and v_{1F} representing the initial positions and v_{12M} and v_{12F} representing the final positions of the dancers. The graph corresponding to the movement pattern in Variation 9 is presented in Figure 8 below.

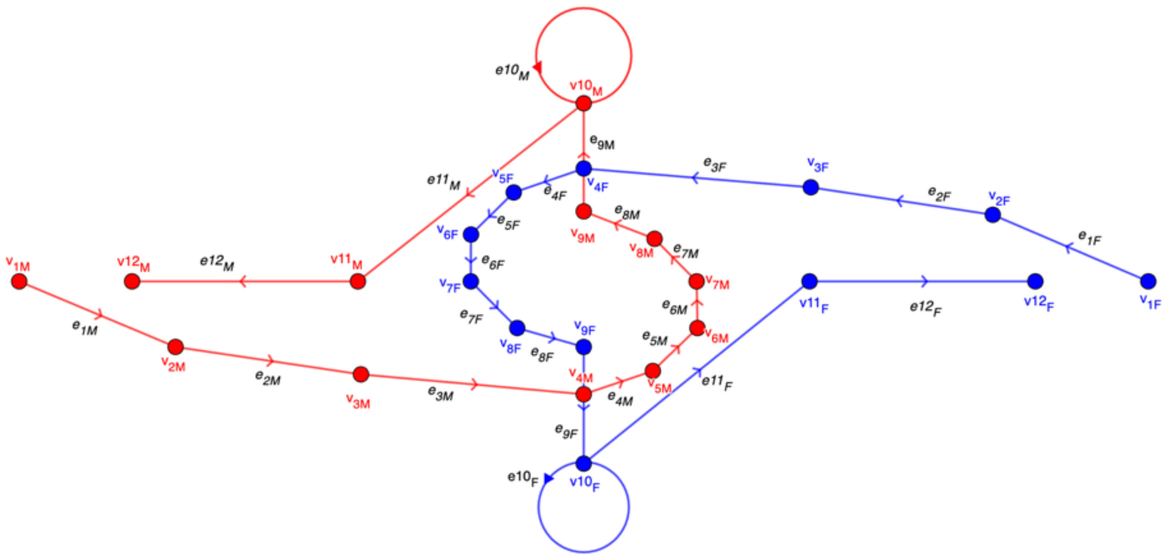

Figure 8. Graph Representation of the Movement Pattern in Variation 9

Figure 8 shows a directed graph with 12 vertices and 12 edges arranged in a predominantly linear path. Note the self-loop at vertex v_{10}, which represents the intensified leaping movement repeated at that position before the sequence continues to v_{11} and v_{12}.

As shown in Figure 8, the movement transitions in Variation 9 form a directed graph, in which v_{1M} and v_{1F} represent the initial positions, while v_{12M} and v_{12F} denote the final positions of the two dancers. Each position is modeled as a vertex, and each movement transition as a directed edge.

Formally, the graphs representing the movement patterns of the male and female dancers are defined as follows:

$$G_M = (V_M, E_M), G_F = (V_F, E_F) \quad (7)$$

where:

$$V_M = \{v_{1M}, v_{2M}, \dots, v_{12M}\}, V_F = \{v_{1F}, v_{2F}, \dots, v_{12F}\} \quad (8)$$

Each graph consists of 12 vertices and 12 directed edges arranged progressively from the initial position to the final position. The adjacency matrix representation displays an almost linear pattern, with entries equal to 1 along the superdiagonal, indicating sequential transitions from v_i to v_{i+1}. However, at vertex v_{10}, the diagonal entry is equal to 1, indicating the presence of a loop at that vertex.

$$
\begin{array}{c|cccccccccccc}
 & v_{1M} & v_{2M} & v_{3M} & v_{4M} & v_{5M} & v_{6M} & v_{7M} & v_{8M} & v_{9M} & v_{10M} & v_{11M} & v_{12M} \\
\hline
v_{1M} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{2M} & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{3M} & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{4M} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{5M} & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{6M} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
v_{7M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
v_{8M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
v_{9M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
v_{10M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
v_{11M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
v_{12M} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
$$

$$
\begin{array}{c|cccccccccccc}
 & v_{1F} & v_{2F} & v_{3F} & v_{4F} & v_{5F} & v_{6F} & v_{7F} & v_{8F} & v_{9F} & v_{10F} & v_{11F} & v_{12F} \\
\hline
v_{1F} & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{2F} & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{3F} & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{4F} & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{5F} & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
v_{6F} & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
v_{7F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
v_{8F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
v_{9F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
v_{10F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\
v_{11F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\
v_{12F} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{array}
$$

Figure 9. Adjacency Matrix of the Movement Graph in Variation 9.

Figure 9 shows the superdiagonal pattern of 1s confirms the predominantly linear progression from v_1 to v_{12}. The diagonal entry of 1 at row 10, column 10 marks the loop at vertex v_{10}. Both male and female dancer graphs yield identical matrices, establishing isomorphism.

The presence of this loop indicates that the graph in Variation 9 (see Fig. 9) is not a simple directed graph but rather a non-simple directed graph, as it contains a loop, although it does not include multiple edges.

In terms of vertex degrees:

- v_1 has out-degree = 1 and in-degree = 0 (source);
- v_{12} has in-degree = 1 and out-degree = 0 (sink);
- vertices v_2 through v_9, as well as v_{11}, each have one incoming edge and one outgoing edge;
- vertex v_{10} has in-degree = 2 and out-degree = 2, due to one incoming edge, one outgoing edge, and one loop (which contributes one to the in-degree and one to the out-degree).

This structure indicates that Variation 9 essentially forms a progressive directed path with a single point of repetition at vertex 10. The loop represents the intensification of the leaping movement performed at that position before progressing to the subsequent stage. The identical adjacency and incidence matrices of G_M and G_F demonstrate that the two graphs share the same relational structure. With the bijective mapping defined by $f(v_{iM}) = v_{iF}$ for each $i = 1,2,\dots,12$, all adjacency relations, including the loop at vertex 10, are preserved. Therefore, based on the formal definition of directed graph isomorphism that permits loops, it follows that

$$G_M \cong G_F \tag{9}$$

Structurally, the graph of Variation 9 exhibits a combination of a progressive linear pattern and a single point of repetition, corresponding to the emotional dynamics of anticipation reaching its peak before resolution.

Comparative analysis of adjacency matrices across variations

A cross-variation comparison of the three adjacency matrices (Figures 3, 6, and 9) reveals structural insights that extend beyond the individual analyses presented above. The three matrices represent fundamentally distinct graphs types, each capturing a different relational pattern embedded in the dance. The adjacency matrix of Variation 1 is a strictly upper-triangular matrix with non-zero entries confined exclusively to the superdiagonal, reflecting a graph with no cycles, no loops, and maximum linearity; every vertex connects to exactly the next vertex and nothing else. In contrast, the adjacency matrix of Variation 3 is a dense 2×2 matrix in which all entries are equal to 1, including the diagonal, indicating that a small number of vertices sustain a highly concentrated relational structure with both reciprocal transitions and self-recurrence. The adjacency matrix of Variation 9 shares the superdiagonal pattern of Variation 1, indicating predominantly linear progression, but differs from it in one critical entry: the diagonal value of 1 at position (10, 10), which marks a single point of self-recurrence embedded within an otherwise acyclic path.

The comparative reading reveals a progression in structural complexity across the three variations. Variation 1 represents the simplest graph type; a directed path with no self-interaction. Variation 9 introduces a single departure from linearity through one loop at an intermediate vertex, while otherwise maintaining the same path architecture as Variation 1. Variation 3 represents the most concentrated relational structure, where two vertices sustain three distinct edge types simultaneously (forward, backward, and self-loop). Crucially, despite these structural differences across variations, the male and female dancer matrices remain identical within each variation, consistently demonstrates that structural equivalence between the two dancers is not property specific to any one graph type but is a stable feature of the choreographic system as a whole.

Beyond structural description, this comparative analysis yields three graph-theoretic observations with broader implications. First, the three variations instantiate three distinct isomorphism classes of directed graphs with loops: the directed path P_n, the complete digraph on two vertices with a self-loop (K_2), and the loop-augmented directed path $P_n + loop$. The fact that the dance embeds all three classes within a single choreographic system suggests that the *Serampang Dua Belas* is not merely a culturally meaningful artifact but a structurally rich one; capable of generating diverse relational configurations within a coherent compositional framework. Second, the stability of intra-variation isomorphism across all three structural types confirms that the choreographic symmetry between the male and female dancer is a system-level property, not a local coincidence: it holds regardless of whether the underlying graph is simple or non-simple, acyclic or cyclic, minimal or extended. Third, from a pedagogical standpoint, these three structural types offer a natural progression of instructional cases; from the simplest isomorphism (two identical paths) to progressively more complex cases involving non-simple graphs and embedded self-recurrence; which could be sequenced to scaffold students' understanding of structural equivalence without relying on purely abstract examples.

Discussion

Structural analysis of the movement variations in the *serampang dua belas* dance

The structural analysis of the movement variations in the *Serampang Dua Belas* dance reveals that choreographic differences that appear visually diverse are, in fact, constructed upon consistent relational equivalence. This finding demonstrates the presence of underlying mathematical principles; particularly the concept of graph isomorphism, and challenges the assumption that visual variation necessarily reflects structural disparity. Through formalization using graph theory, this study verifies that beneath aesthetic variation lies an equivalent relational structure. Accordingly, this research not only extends ethnomathematical inquiry toward formal verification but also opens space for pedagogical reflection in discrete mathematics instruction.

These findings carry theoretical significance when examined in relation to the development of structural reasoning in graph theory learning. The verification of bijective mappings that preserve adjacency relations confirms that graph equivalence is determined by relational preservation rather than by visual configuration alone. This perspective aligns with frameworks of structural reasoning that emphasize the ability to identify relational invariants underlying representational variation. Thus, the present analysis not only establishes graph equivalence mathematically but also provides a conceptual model that could, in future classroom implementation, enable students to move from recognizing visual patterns to understanding the abstract structures that underpin them. Representing dance movements as directed graphs offers a concrete embodied context that may facilitate this transition prior to more advanced symbolic formalization, though empirical validation in instructional settings is needed to confirm these potential benefits.

Graph isomorphism in the movement patterns of the *serampang dua belas* dance

In this study, dancers' positions are represented as vertices and movement trajectories as edges, forming directed graph models that allow formal analysis of relationships among movements. This approach is consistent with the application of graph theory in modeling interactions and motion within dynamic systems (Budinski et al., 2022). Graph isomorphism, defined as a bijective mapping between the vertices of two graphs that preserves adjacency relations, serves as a crucial tool for establishing structural equivalence. Isomorphism indicates that two graphs share the same structure regardless of differences in visual representation or symbolism, differing only in surface features (Veith et al., 2025).

The present approach is specifically designed to address documented student difficulties in graph theory instruction. González et al. (2021) identified that learners frequently remain at lower levels of graph-theoretic reasoning, attending to visual or spatial layout rather than to the relational properties that formally define a graph's structure. Similarly, Veith et al. (2025) found that inconsistent responses on isomorphic concept items often reflect underlying misconceptions about structural equivalence. The dance-based modeling proposed here directly targets both difficulties: by presenting two graphs (male and female dancer) that are visually distinct yet formally identical in their adjacency structure, students are confronted with a concrete case that foregrounds relational preservation over surface appearance, thereby supporting the shift from perceptual to structural reasoning that the literature identifies as critical for understanding isomorphism.

Testing across selected movement variations of the *Serampang Dua Belas* dance demonstrates that spatial transformations in movement patterns do not alter their underlying relational structures. This confirms that the cultural practice embodies principles of structural equivalence consistent with the formal definition of graph isomorphism in discrete mathematics. In Variation 1, the graphs constructed from the male and female dancers' movements exhibit a progressive and acyclic directed path structure, reflecting the narrative of an initial encounter. Adjacency and matrix analyses demonstrate one-to-one correspondence between vertices and preservation of relations, formally establishing that $G_M \cong G_F$.

Similarly, in Variation 3, although rotational movements produce cycles within the directed graph; symbolizing unresolved emotional dynamics; the graphs of both dancers remain isomorphic. This indicates that the resulting mathematical structure reflects deep relational equivalence beneath visual variation. Even in Variation 9, where a loop edge is present, the adjacency and incidence matrices of both graphs remain identical, as they share equivalent degree distributions and relational patterns. This confirms that isomorphism applies even to graphs of greater structural complexity. Collectively, these findings demonstrate that the aesthetics of traditional dance can be systematically decomposed into consistent and well-structured mathematical patterns.

Contribution to ethnomathematics

This analysis of the *Serampang Dua Belas* dance contributes significantly to the field of ethnomathematics by demonstrating how cultural structures can serve as foundational sources for constructing mathematical concepts. The approach enables understanding of structural equivalence through observational and representational experience, enriching ethnomathematical scholarship and offering an alternative epistemological framework for introducing isomorphism.

Ethnomathematics explores the relationship between mathematics and the cultural contexts in which it develops (Dominikus et al., 2024; Orey & Rosa, 2021). By contextualizing abstract concepts within local knowledge systems; such as traditional Indonesian dances that incorporate geometric, arithmetic, and transformational ideas; this approach supports meaningful learning (Gazanofa & Wahidin, 2023). Demonstrating mathematics embedded in cultural activity helps students recognize mathematics as a cultural construction rather than solely as universal abstract knowledge (Özcan & Bahadır, 2023). As a culturally responsive lens, ethnomathematics promotes meaningful learning by situating abstract ideas within lived experience (Harding, 2022; Nasrum et al., 2025) Studies such as Demaine et al. (2007) on sand drawing and Kholid & Husodo (2025) on batik Sidomukti Solo further confirm that traditional practices often embody sophisticated graph-theoretical structures.

Implications for mathematics education

Strengthening structural and conceptual reasoning

This study does not include classroom implementation data; its contribution in the domain of mathematics education is therefore epistemological rather than empirical. Specifically, the study proposes that the formal structures identified in the *Serampang Dua Belas* dance; spanning simple directed paths, non-simple graphs with self-loops, and loop-augmented linear paths; constitute a set of culturally grounded mathematical objects that are candidates for instructional use in graph theory, particularly for the concept of isomorphism. The theoretical basis for this proposal rests on three premises: (1) the identified graph structures are formally precise and mathematically non-trivial, as demonstrated in the preceding analysis; (2) the structures span a range of graph-theoretic complexity that aligns with documented learning progressions from concrete to abstract reasoning (González et al., 2021; Tiwari et al., 2021), and research on isomorphism-based combinatorial strategies further suggests that such structural reasoning can be cultivated and transferred across mathematical domains through contextually meaningful instruction (Zenkl & Vondrová, 2023); and (3) the cultural embeddedness of these structures is consistent with ethnomathematical frameworks that argue for the pedagogical value of situating abstract concepts in culturally meaningful contexts (Harding, 2022). Whether these theoretical premises translate into measurable improvements in students' structural reasoning remains an open empirical question; one that this study explicitly defers to future research involving controlled classroom implementation with pre- and post-measures of graph-theoretic understanding.

Contextual learning and cultural relevance

Integrating local cultural contexts, such as traditional dance, makes abstract concepts more accessible and relevant to students (Endilina et al., 2025; Khairullah et al., 2025). As a culturally responsive curriculum strategy, ethnomathematics connects mathematical learning to students' lived experiences and cultural backgrounds (Rosa & Orey, 2020; Tran & Castro Schepers, 2023). In the present study, the three graph structures identified across the variations of the *Serampang Dua Belas* dance; the directed path, the loop-containing cyclic graph, and the loop-augmented linear path; provide culturally situated instantiations of graph-theoretic concepts that students may encounter first through observation of familiar movement before engaging with abstract formalization. This approach enhances motivation and engagement while helping students recognize mathematics as integral to their cultural traditions, supporting cognitive, social, and emotional development (Bito & Fredy, 2020; Dominikus et al., 2024).

Cultural integration has also been shown to foster critical thinking and interdisciplinary appreciation, as ethnomathematics encourages inquiry from multiple perspectives (Nicol, 2018; Shahidayanti et al., 2024). By utilizing cultural resources such as the *Serampang Dua Belas* dance, teachers can create opportunities for students to connect their multidimensional identities with mathematical learning, thereby strengthening both mathematical proficiency and identity. When students reflect on diverse cultural connections, their intrinsic motivation and confidence increase, shifting motivation from external rewards toward genuine enthusiasm and satisfaction derived from problem-solving (Fouze & Amit, 2019, 2021).

Embodied learning approach

Integrating motor activity such as dance into mathematics instruction supports embodied cognition theory, which recognizes that sensorimotor experience plays a crucial role in constructing and understanding abstract concepts (Abrahamson et al., 2020; Levin & Walkoe, 2022). When students physically engage in practicing dance movement patterns and subsequently model them as graphs, they experience isomorphism both cognitively and kinesthetically (Vieyra et al., 2024). The structural progression identified in this study; from the acyclic path of Variation 1, through the self-recurring loop of Variation 3, to the hybrid structure of Variation 9; offers a concrete embodied sequence through which students may gradually internalize increasingly complex relational configurations, moving from linear to cyclic to loop-augmented structures in a manner grounded in physical experience rather than purely symbolic instruction.

Hands-on and body-based activities can elicit and display mathematical understanding, making concepts more tangible and memorable (Boonstra et al., 2023). Transforming abstract representations into embodied experiences enables active use of sensorimotor resources in mathematical comprehension (Khatin-Zadeh et al., 2022). Research indicates that students aged 7–8 who integrated mathematics learning with creative dance achieved significantly higher learning outcomes than control groups (Leandro et al., 2018). Dance thus facilitates transitions across sensory modalities that are essential for embodied learning, bridging cultural experience and mathematical understanding. Moreover, children's pre-instructional mathematical experiences derived from play and everyday embodied activity represent valuable yet underutilized resources for developing algebraic and other mathematical concepts (Levin & Walkoe, 2022).

The use of ethnomathematics through dance analysis promotes a paradigm shift in mathematics instruction from a purely formal-abstract approach to a culturally contextualized one. Beginning with familiar cultural structures allows complex mathematical concepts to be constructed inductively. This not only enables students to view mathematics as integral to their cultural heritage but also encourages critical thinking and interdisciplinary appreciation. Curriculum implementation grounded in ethnomathematical methodology can examine its impact on mathematics teaching and learning, supporting teachers in emphasizing connections between mathematics and other disciplines while considering students' cultural backgrounds in designing mathematical activities (Orey & Rosa, 2021; Owusu-Darko et al., 2023).

Overall, this study demonstrates that the movement structure of the *Serampang Dua Belas* dance embodies not only aesthetic and cultural value but also principles of relational equivalence that can be mathematically analyzed through graph isomorphism. This formalization strengthens the role of ethnomathematics as a bridge between cultural practice and mathematical theory while offering a pedagogical approach that integrates cultural context, structural reasoning, and embodied experience in mathematics education.

Conclusion

This study demonstrates that the movement patterns of the *Serampang Dua Belas* dance embody principles of relational equivalence that can be formalized through the concept of graph isomorphism. Representing dancers' positions as vertices and movement transitions as directed edges reveals that, although the variations differ visually and narratively, the resulting adjacency structures remain equivalent. Findings from Variation 1 with its acyclic path structure, Variation 3 with its cyclic configuration, and Variation 9 containing a loop indicate that isomorphism persists across varying levels of graph complexity as long as adjacency relations among vertices are preserved. These results extend ethnomathematical scholarship by providing formal verification of mathematical structures embedded in cultural practice, while also highlighting their theoretical pedagogical potential to strengthen structural reasoning, deepen understanding of relational preservation, and integrate contextual and embodied learning into graph theory instruction. These pedagogical implications remain conceptual and await empirical validation through future classroom implementation studies.

Nevertheless, this study has several limitations. The analysis focuses on structural modeling of selected movement variations without direct implementation in classroom practice; consequently, the pedagogical implications remain conceptual rather than empirically validated. Additionally, the study does not incorporate quantitative measures to assess improvements in students' understanding or reasoning. The research is also situated within the specific cultural context of Malay Deli tradition, which may limit the generalizability of the findings. Future research is therefore recommended to evaluate the effectiveness of this approach through experimental designs or longitudinal studies across diverse educational levels and cultural settings. Further exploration of digital technology integration; such as interactive graph visualization or software-based movement simulations; may expand accessibility and deepen students' conceptual understanding of graph isomorphism within a contextualized and sustainable learning framework.

Acknowledgment

We sincerely thank the reviewers for their insightful and constructive feedback, which has significantly improved the quality of this manuscript.

Declarations

Conflicts of Interest	:	The authors declare no conflict of interest.
Generative AI Statement	:	Generative AI tools, such as Grammarly and ChatGPT, were employed solely for language editing and minor phrasing enhancements. All conceptualization, analysis, and scholarly content were independently developed and verified by the authors.

Funding Statement : This work received no specific grant from any public, commercial, or not-for-profit funding agency.

Author Contributions : **Rahmi Ramadhani:** Conceptualization, writing - original draft, editing, reviewing, formal analysis, visualization, methodology, validation, investigation, and data curation; **Nuraini Sri Bina:** Writing - review & editing, formal analysis, and methodology; **Suci Dahlya Narpila:** Writing - review , formal analysis, validation, and data curation; **Muhammad Rizky Mazaly:** Writing - review, formal analysis, data curation, and visualization; **Rusmini Rusmini:** Writing - review , formal analysis, data curation, and validation.

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