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Structural Equation Modelling of Graph-Theoretic Classroom Seating Metrics as Predictors of Student Learning Engagement

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ABSTRACT

Classroom seating arrangement influences engagement through visibility, proximity, and interaction. This study applied a hybrid methodology combining graph theory and survey data to perform Partial Least Squares Structural Equation Modeling (PLS-SEM) in determining the best classroom structure that supports learning engagement in Philippine classrooms. traditional, window, and horseshoe layouts were compared in terms of degree and closeness centrality, high-degree frequency, and path length, while learning engagement was measured in terms of agentic, behavioral, cognitive, and emotional domains. Graph-theoretic measurements were simulated in GeoGebra in a 7×9-meter plane following the DepEd standard classroom size with a 1:36 student-teacher ratio. Statistical analysis showed that the Horseshoe layout produced the shortest path to the teacher ($M = 3.93$), the lowest number of interactions ($M=4.50$), and the lowest high-degree frequency ($f=29$) among all layouts. It also explained the strongest positive effect on learning engagement ($\beta = 1.447$, $p < .001$). Model fit indices indicated excellent validity ($SRMR = 0.041$). Findings demonstrate that engagement depends less on the number of peer links and more on physical proximity and teacher accessibility. The Horseshoe configuration optimizes these conditions by maintaining focus and balanced interaction. The study recommends that teachers adopt horseshoe seating layouts that enhance visibility and reduce off-task interaction to strengthen student engagement within existing classroom constraints, serving as a critical tool for evidence-based pedagogy.

Keywords: *classroom seating arrangement, student engagement, teacher proximity, graph theory, Partial Least Squares Structural Equation Modeling*

Introduction

Learning occurs within a spatial system. This system mediates interaction, perception, and engagement. The classroom layout is a structural condition that influences participation and cognitive activity. The row-and-column arrangement remains the standard design in most Philippine schools. This design prioritizes order but often limits visual access, attention, and interaction. Keyes (2019) argued that seating position shapes belonging and participation. Gremmen et al. (2016) found that layout also produces social hierarchies. These studies agree that spatial configuration organizes engagement itself.

The physical environment affects learning behavior and motivation. International research affirms this principle. Ahmad and Amirul (2017) showed that classroom comfort and perceptual openness increase enjoyment and productivity. Cantero (2017) described attraction factors like accessibility and visibility as necessary engagement components. Cantero et al. (2016b) found that spatial patterns regulate behavior and interaction, forming social relations. Owoseni et al. (2020) observed that physical learning environments predict academic performance in secondary schools. Across these contexts, physical space operates as a determinant of engagement.

Spatial effects are also evident in higher education. Peng et al. (2022) reported that flexible classrooms increase control and participation. Kilbourne et al. (2017) demonstrated that activity-permissive classrooms increase engagement and allow movement while sustaining attention. Zheng et al. (2024) validated that accessibility and visual proximity enhance collaboration and learning engagement. Khan et al. (2023) confirmed the value of comfort and visibility for participation in universities. Shernoff et al. (2016), as well as Guardino and Antia (2012), found that structured environments affect attention and behavior via engagement. Combined, these results indicate that learning is a function of how space facilitates communication and task orientation.

Notwithstanding consensus on space's significance, investigation into classroom seating remains scattered. Most prior works describe associations rather than model full relational systems. Hardiansyah and Rasia (2022) and Norazman et al. (2019) associated flexible seating with autonomy and motivation. Tobia et al. (2020) identified its impact on logical reflection and creativity. These studies examined individual measures. Most works did not include the relational structure of interactions. Reeve (2013) conceptualized engagement in behavioral, emotional, cognitive, and agentic terms. Little research has linked these specific dimensions with spatial arrangement. Earlier findings were often based on self-reports, and no statistical modeling of spatial mechanisms was conducted. Likewise, graph-based and structural approaches to analyzing classroom networks remain rare, and the relationships and dynamics among seating networks have gone uninvestigated.

In the Philippine context, local studies confirm the link between learning space and engagement. Galabin (2024) found a significant positive correlation between space satisfaction and engagement. Lalanan and Oco (2025) and Gaytos (n.d.) reported that the educational setting predicts learner engagement and performance. These findings validated the influence of spatial design in local classrooms. They relied mainly on descriptive statistics. None has tested how spatial topology predicts engagement across multiple dimensions.

Consequently, graph theory provides a quantitative framework for understanding these networks. Each student is treated as a node. Connections exist through proximity or visibility. Degree centrality measures the direct connections a student maintains. Closeness centrality measures how efficiently a student can reach others. Graph-level metrics such as high-degree frequency and path length describe overall structural efficiency. Integrating these measures with Structural Equation Modeling (SEM) can reveal how spatial structures predict engagement. Yet few educational studies have applied this combined framework. Gremmen et al. (2016) mapped social relations but did not model predictive effects. Quantitative integration of spatial metrics and engagement variables is absent in current research.

In the Philippines, this methodological advance is necessary. The Department of Education (DepEd Order No. 21, s. 2019) prescribes standard classroom dimensions of seven by nine meters. This includes thirty-six students. This uniformity allows controlled simulation and modeling. It highlights the importance of spatial efficiency. Classrooms cannot easily be expanded. Spatial reconfiguration within existing parameters is, thus, a feasible strategy for improving engagement. Local interventions have relied on observation and qualitative feedback. There is limited quantitative evidence that identifies the most effective arrangement.

Therefore, this study addresses this gap. It applies graph-theoretic analysis and structural equation modeling to evaluate how seating configurations predict learning engagement. The method conceptualizes the classroom as an interactive network. It explores how node and graph-level metrics are associated with behavioral, cognitive, emotional, and agentic facets of engagement. These dimensions are modeled as indicators of a latent learning engagement construct within the Structural Equation Model. This research aimed to identify structural conditions that best promote focus and minimize distraction. It shifts the focus from association to prediction. It provides an empirical model for understanding how spatial organization contributes to engagement.

The study simulated three common arrangements: traditional, window, and horseshoe. Each configuration was tested within a DepEd-standard classroom containing 36 student nodes. Degree and closeness centrality represented individual interaction potentials, while high-degree frequency and path length represented the collective structure. The analysis estimated the predictive strength on learning engagement through Partial Least Squares Structural Equation Modelling (PLS-SEM). Also, the study isolated feasible spatial factors that can be optimized within existing policy and infrastructure. The objectives of the study were as follows:

(1) To determine the average node-level metrics (degree and closeness centrality) in different seating arrangements;
(2) To determine the average graph-level metrics (high-degree frequency and path length) across the same configurations;
(3) To evaluate the predictive strength of these metrics on behavioral, agentic, cognitive, and emotional engagement using PLS-SEM; and

(4) To identify the seating arrangement that optimizes engagement while minimizing distraction.

The study contributes at two levels. Theoretically, it extends spatial learning analytics by combining graph metrics and structural modeling. It tests how structural relations explain engagement patterns. Empirically, it provides data-based insights for classroom design in Philippine secondary schools. The findings can inform seating policies that improve engagement without structural renovation. The study positions seating as a measurable design variable that shapes learning interactions. It demonstrates that classroom space, when modeled as a network, yields predictive insights into engagement and focus.

Methods

Research Design

This study employed a quantitative-predictive design using graph-theoretic modeling and Partial Least Squares Structural Equation Modeling (PLS-SEM). The design compared three classroom seating arrangements—traditional, window, and horseshoe—to determine their structural influence on student learning engagement. Quantitative-predictive research examined the explanatory power of predictors that consisted of the different classroom layouts and the graph-theoretic metrics. The analysis focused on their contribution to the variance of the main endogenous variable, in this case, learning engagement. PLS-SEM was selected over covariance-based SEM because it is a variance-based approach. This approach is optimal for prediction and theory development, particularly when integrating two distinct data sources and dealing with a formative latent variable structure, which aligns with this study's goals (Hair et al., 2017).

Graph-theoretic modeling provided a rigorous mathematical framework to analyze the relational properties of each seating configuration. This method conceptualized students as nodes and potential interactions as edges within a graphical plane. The graph metrics derived from this model served as predictor variables. SEM subsequently tested the predictive relationships between these spatial metrics and the engagement construct.

Participants

The selection of the participants of this research is divided into two sections to systematically describe the selection processes in graph nodes and survey participants.

Simulated Sample (Graph Nodes)

The study modeled a standard Philippine classroom. This followed the Department of Education's prescribed ideal class size of 36 students (DepEd Order No. 21, s. 2019). The simulated environment was a 7-meter by 9-meter coordinate plane. This replicated typical classroom dimensions and seating density. Each of the 36 student nodes was assigned a set of graph-theoretic metrics specific to its position within the three layouts.

Empirical Sample (Survey Participants)

The empirical sample included 72 senior high school students from two Science, Technology, Engineering, and Mathematics (STEM) classes. These students attended a public secondary school in Isabela. Total enumeration was used. All 36 students from each of the two classes participated, and all participants were aged 16–18 years.

Data Integration Procedure

The study employed a hybrid method to link the 36 simulated node metrics (Predictor Variables) with the 72 empirical survey responses (Outcome Variables). First, GeoGebra generated 36 unique sets of graph-theoretic scores for the 36 physical seating positions. Second, the two classrooms (Class A and Class B) adopted the seating arrangements over seven days. The students in both classes occupied positions 1 through 36 during the data collection week. Third, the learning engagement score for a specific seating position was calculated. This was done by averaging the individual survey scores of the two students who occupied that identical physical position across the two classes. This averaging process yielded 36 outcome variable scores for learning engagement. This ensured the number of empirical data points matched the number of simulated graph nodes for the PLS-SEM analysis.

Locale of the Study

The survey was conducted in a public senior high school under the Schools Division of Isabela, Region II. For the graph-theoretic metrics, the study contextualized a measurement following the standard DepEd classroom layout measuring 7 meters by 9 meters. The simulated environment replicated the typical spacing, desk orientation, and seating density observed in actual Philippine high school classrooms.

Research Instrumentation

Graph theory encoded the seating structures. In GeoGebra, students were treated as nodes. An edge (interaction line) existed only between nodes within a proximate distance of 0.5 to 1.5 meters in accordance with the principle of closeness (Bavelas, 1950, as cited in Cohen et al., 2014). This simplified model represents a proximity map for localized interaction, not a cross-room social network. This specific modeling is a methodological limitation acknowledged in the study. The following node-level and graph-level metrics served as the independent variables:

a) Degree Centrality (DC): This is the count of nearest nodes within the 0.5 to 1.5-meter range. DC was chosen because it reflects the potential for immediate peer interaction.
b) Closeness Centrality (CC): This is a normalized node-level metric (Bavelas, 1950, as cited in Cohen et al., 2014). It is encoded as the average distance, in meters, of all the nearest nodes to it.
c) Path Length (PL): This is the Euclidean distance in meters between a node's position and the fixed teacher's table position (x=3.5, 7=1 location).
d) High-Degree Frequency (HD): It refers to whether a node has more than 3 nearby nodes as measured by the degree centrality. This is a binary-coded variable. A node was coded 1 if it had more than three nearby nodes (defined by the closeness concept) and 0 otherwise.

Learning engagement was measured following Reeve's (2013) multidimensional and widely-utilized framework encompassing behavioral, agentic, cognitive, and emotional engagement. Individual scores for these four dimensions were calculated separately. For the PLS-SEM analysis, these four-dimensional scores were treated as reflective indicators of a single latent construct, Learning Engagement (LE). The study used this approach because the software requires a latent construct for structural path analysis. This strategy allows for estimating the spatial factors' overarching predictive strength on a global engagement score. Reliability and validity were assessed using Cronbach's α, Composite Reliability (rho_c), and Average Variance Extracted (AVE).

Data Collection Procedure

Data were generated and processed in three stages. First, simulation and mapping of seating configurations were conducted using GeoGebra. Each seating type was represented as a coordinate-based grid of nodes, where pairwise distances defined edge connections. Second, graph-theoretic computations and survey measurements of learning engagement were performed to derive quantitative measures of each variable, producing metric data for all 36 student nodes. Third, modelling was carried out in SmartPLS 4. The algorithm used a path weighting scheme with 5,000 bootstrap resamples to estimate the significance of structural paths. The model evaluated how graph-theoretic metrics predict overall learning engagement across three seating arrangements.

Analysis of Data

The first phase involved descriptive analysis of the graph-theoretic metrics. The mean and Standard Deviation (SD) were calculated. These statistics quantify the magnitude and variability of interaction potential and accessibility across the layouts. The second phase involved inferential analysis using PLS-SEM. Path coefficients (β), *t*-statistics, and *p*-values determined the direction and significance of relationships. The predictive strength was interpreted using the Effect Size (f^2), which quantifies the change in R^2 when a predictor is omitted. The Coefficient of Determination (R^2) measured the variance explained in the latent construct. Model fit was established using the Standardized Root Mean Square Residual (SRMR) threshold below 0.08.

Ethical Considerations

The study followed all institutional ethical standards. Participation was voluntary. Informed consent was secured from all participants and their guardians. Confidentiality and anonymity were ensured by excluding all identifiable data. The research protocol received full ethical approval from the school's Ethics Review Committee, which deemed the research to pose no ethical risk to participants. Permission to utilize the Learning Engagement material (Reeve, 2013) was secured before data collection.

Results and Discussion

Graph-Theoretic Modelling

Graph-theoretic modeling was performed using GeoGebra to quantify the structural characteristics of each seating arrangement. In the model, nodes represented individual students while edges denoted observable interaction lines. Node-level metrics measured each student's position within the interaction network, specifically the degree centrality (average number of interactions per student) and closeness centrality (average distance of students to one another). Graph-level metrics described the network as a whole with specific variables of high-degree frequency (percentage of students with more than three interactions) and path length (average shortest distance of students to the teacher). Learning engagement was measured following Reeve's (2013) multidimensional framework, encompassing behavioral, agentic, cognitive, and emotional domains.

The findings illustrate variations in the frequency and pattern of student interactions across different seating arrangements, with each configuration demonstrating unique levels of engagement and attention.

Degree Centrality (DC)

Table 1 below shows the average number of interactions per student or the degree centrality according to each seating arrangement.

Table 1. Average Degree Centrality of the Different Seating Arrangements

Seating Arrangement	Mean	SD
Traditional (Box)	6.00	1.71
Window Arrangement	4.81	1.24
Horseshoe	4.50	0.81

The traditional layout recorded the highest number of peer interactions (M = 6.00, SD = 1.71), followed by the window arrangement (M = 4.81, SD = 1.24) and the horseshoe layout with the fewest (M = 4.50, SD = 0.81). A greater frequency of interaction might suggest more peer exchanges, but it can also result in more off-task activity and a lower focus on instruction. The horseshoe's arch-like shape, on the other hand, minimized unwanted back-and-forth interactions and focused attention on the teacher.

This understanding is consistent with Gremmen et al. (2016) and Keyes (2019), who argued that close social distance would have a dispersion effect on attention, as well as on student clustering, where it may promote interactions with friends rather than the teacher. In contrast, Norazman et al. (2019) and Tobia et al. (2020) posited that flexible designs increase autonomy and creativity, but these advantages assume high self-regulation, which is questionably present in the majority of adolescents studying in secondary public schooling. The findings of Guardino and Antia (2012) that peripheral distractions are reduced as a function of spatial adjustment also support the present study's finding, suggesting fewer peer links contribute to instructionally encouraging students on tasks. Taken together, these findings suggest that low degree centrality can be beneficial when attention needs to be unidirectionally sustained rather than shared.

Closeness Centrality (CC)

Table 2 presents the average distances of students from each other (closeness centrality) in the different seating arrangements.

Table 2. Average Closeness Centrality of the Different Seating Arrangements

Seating Arrangement	Mean	SD
Traditional (Box)	1.11	0.03
Window Arrangement	1.25	0.15
Horseshoe	1.04	0.09

The horseshoe arrangement showed the shortest average distance among students (M = 1.04, SD = 0.09), followed by the traditional layout (M = 1.11, SD = 0.03) and the window configuration with the widest spacing (M = 1.25, SD = 0.15). Low closeness centrality is an indication of tighter clustering, which encourages immediate peer communication that also heightens peer distraction. The window layout, with wider spacing, reduced unnecessary proximity and created clearer visual access to the teacher. These outcomes align with Ahmad and Amirul (2017) and Peng et al. (2022), who both emphasized that spatial comfort and defined orientation sustain attention and learning engagement. Khaloufi (2016) and Correa et al. (2017) likewise noted that proximity supports emotional safety, yet excessive clustering can lead to overstimulation when structure is weak. The current results integrate these positions by indicating that optimal engagement depends not on close distance alone but on spatial balance. A moderate separation, as seen in the window layout, may be most practical in large Philippine classrooms where visual control and cognitive focus must coexist.

Graph-theoretic models using GeoGebra are presented below with 36 total nodes in a 7x9 simulated classroom area for the node-level metrics:

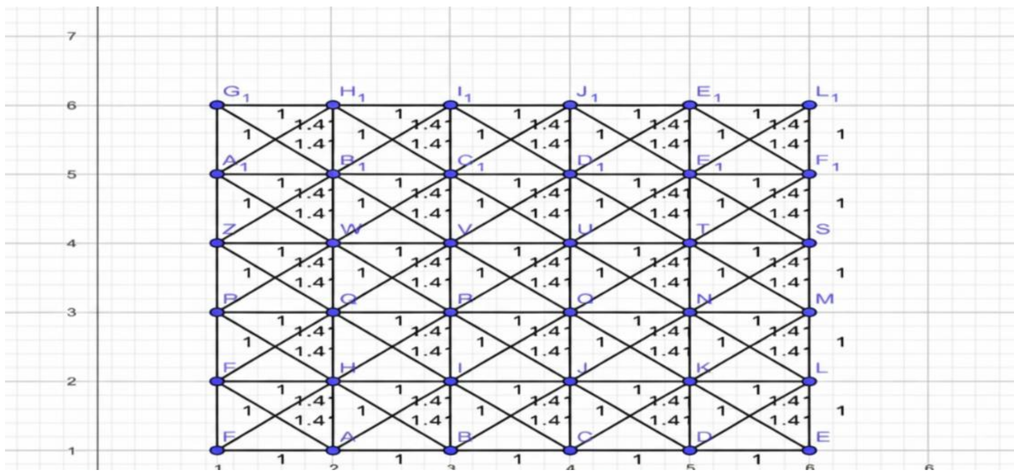

Figure 1. *DC and CC Modelling in Traditional Seating Arrangement*

The traditional seating pattern shows small interaction distances, with nodes connected 1 per seatmate and at 1.4 for diagonals (several chains of communication are possible). Although this accelerates the speed of information transfer and strengthens connections, it can easily lead to off-topic chatter and loss of focus.

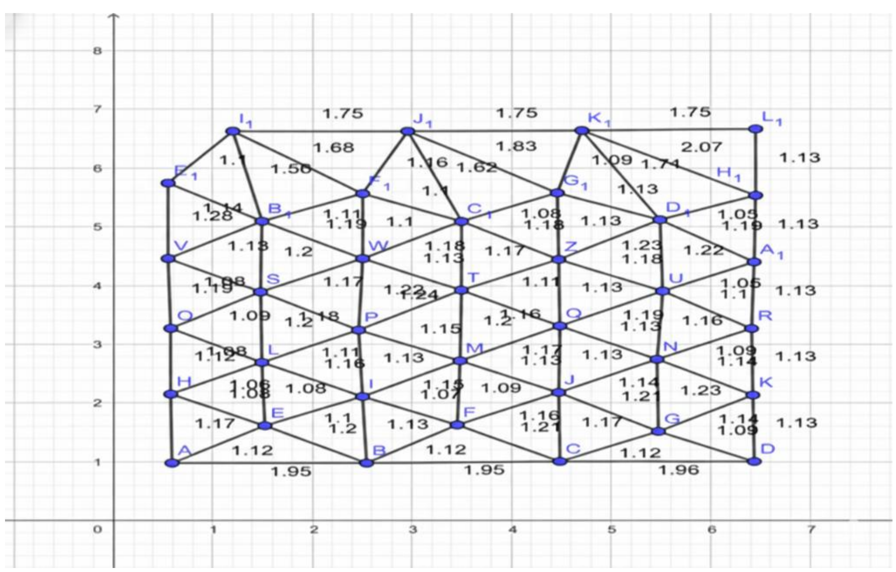

Figure 2. *DC and CC Modelling in the Window Seating Arrangement*

The window seating arrangement, as illustrated in Figure 2, shows different interaction distances throughout space, with most interactions lying between 1.1 and 1.9 units away from each other. That makes for a mildly entangled arrangement in which communication can still happen, but not as easily as the traditional setup.

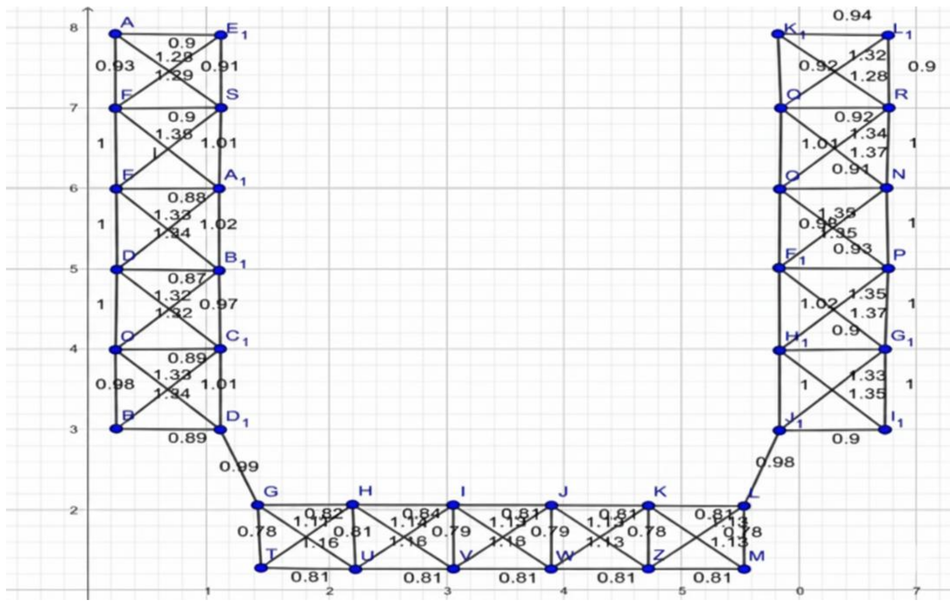

Figure 3. *DC and CC Modelling in Horseshoe Seating Arrangement*

Figure 3 shows the varying distances among learners, typically ranging from 1.00 to 1.34 more or less. Although seemingly closer, this setup has a lower number of interaction points on average as compared to the traditional setup.

High Degree Frequency (HD)

Table 3 shows the frequency of seats with more than three interaction points (high degree frequency) in the different seating arrangements.

Table 3. High Degree Frequency Count of Each Seating Arrangement

Seating Arrangement	F	%	Rank
Traditional (Box)	33	91.67%	1
Window Arrangement	30	83.33%	2
Horseshoe	29	80.56%	3

The traditional layout reflected the highest proportion of nodes with more than three connections (f = 33, 91.67%). This is followed by the window (f = 30, 83.33%) or alternate seating, and the horseshoe arrangement with the lowest count (f = 29, 80.56%). A higher count of high-frequency nodes means more seats with a greater tendency to distractions. This increases peer exchanges but also raises the potential for noise and distraction. The horseshoe configuration limited these points of convergence, helping maintain a steady line of attention toward the teacher.

This same deduction can be found from Shernoff et al. (2016), who stated that classroom structure affects engagement through its influence on attention and behavioral regulation. Owoseni et al. (2020) and Baes (2025) also observed that controlled environments enhance participation when spatial density is managed effectively. These findings differ from the flexibility-focused arguments of Norazman et al. (2019), who equated connectivity with engagement. The present analysis supports a different conclusion: engagement depends less on the number of peer interactions than on the quality of instructional accessibility. Lower high-degree frequency creates a stable communication network, reducing unnecessary exchanges and promoting sustained focus.

Path Length (PL)

Table 4 reflects the average distance of students to the teacher based on the shortest path (Path Length) in the different classroom arrangements.

Table 4. Average Path Length of Learner to Teacher Node of Each Seating Arrangement

Seating Arrangement	Mean	SD	Rank
Traditional (Box)	4.14	1.87	2
Window Arrangement	4.83	1.56	1
Horseshoe	3.93	0.88	3

The horseshoe had the lowest average teacher distance (M = 3.93, SD = 0.88), followed by traditional (M = 4.14, SD = 1.87), and then windows with the longest average teacher distance (M = 4.83, SD=1.56). A shorter path length means a more accessible teacher and a clearer range of sight for learners.

Based on these results, the horseshoe is the arrangement that kept all students in equitable proximity to teaching without crowding. Zheng et al. (2024) and Kilbourne et al. (2017) both support this, demonstrating that responsiveness to and attention toward the teacher are increased when presented spatially nearer. Khan et al. (2023) also stressed the importance of comfort and proximity for engagement. In comparison, Norazman et al. (2019) considered that flexibility was central to motivation, but their findings are based on a form of learning autonomy not typical of structured school settings.

The present result adds to the evidence that physical symmetry, not freedom of movement, underlies clarity of instruction. The horseshoe configuration, which effectively reduces variation in distance between teachers and students, optimizes teacher-pupil proximity while reconciling spatial equity with cognitive control.

Graph-theoretic models using GeoGebra are presented in Figure 4 with 36 total nodes in a 7x9 simulated classroom area for the node-level metrics.

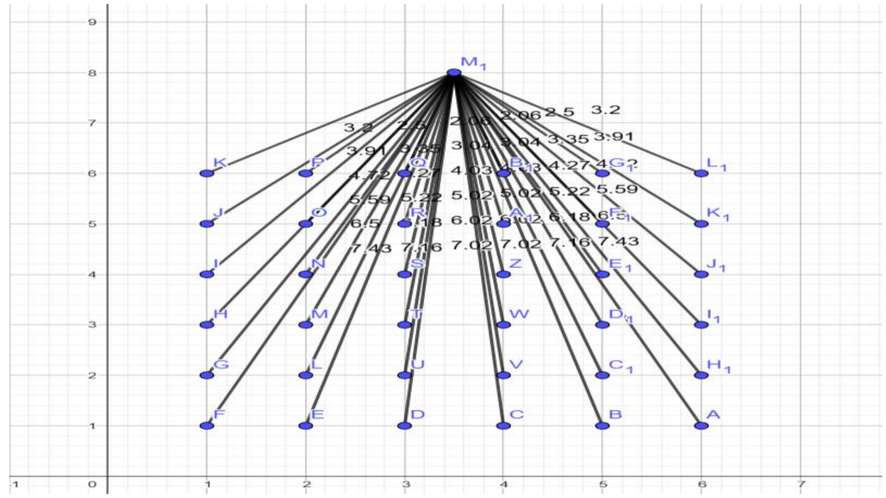

Figure 4. *Path Length Modelling of Traditional Seating Arrangement*

The network graph in Figure 4 illustrates that all students are in short paths of distance between about 1.8 and about 6 units from the teacher directly. That is, while the teacher constitutes a core system of interaction, accessibility can be different depending on where in class students sit.

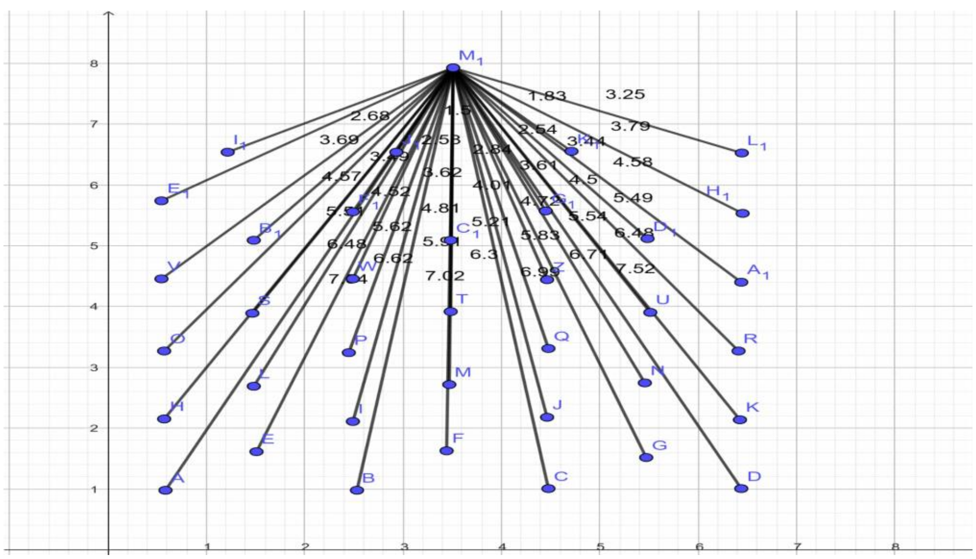

Figure 5. *Path Length Modelling of Window Seating Arrangement*

From the seating order graph of alternating windows (Figure 5), all students are able to have direct contact with the teacher, but some students are relatively far from the teacher, ranging from around 1.8 units to more than 7.5. This variation also means that students who are near the frontlines and center have better access, while those in the rear have weaker interaction, which translates to engagement and equity in opportunity for participation.

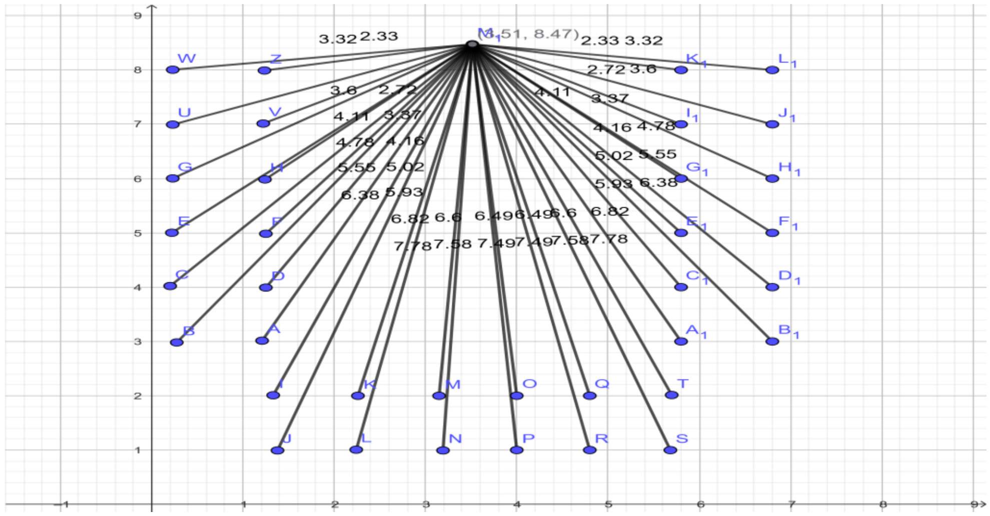

Figure 6. *Path Length Modelling of Horseshoe Seating Arrangement*

The horseshoe configuration of the nodes, as seen in Figure 6, has interaction distances that are mostly between 0.8 and 1.3 units. This arrangement pulls focus to the center of the room, helping teachers see and be seen while limiting social distraction between peers. The setup helps reduce side conversations but also limits collaboration when needed.

Structural Equation Modelling (PLS-SEM)

Structural Equation Modeling was conducted using SmartPLS 4 to estimate the relationships among seating arrangement indicators, graph-theoretic metrics, and learning engagement. The algorithm employed the path weighting scheme with 5,000 bootstrap resamples to assess the significance of structural paths. Reliability and validity indices (Cronbach's α, Composite Reliability, and AVE) were computed separately for Learning Engagement as it is the sole latent construct in the model. All other variables (e.g., centrality measures and seating types) were treated as observed single indicators; hence, internal consistency statistics were not applicable. Factor loadings were analyzed, and multicollinearity was checked using outer and inner model VIFs, all within acceptable thresholds. Model fit was evaluated using SRMR, while predictive relevance (Q^2) and explained variance (R^2) were examined to determine the adequacy of the model.

Measurement Model Evaluation

The measurement model was assessed to establish indicator reliability, internal consistency, and convergent validity. All outer loadings were examined, and most indicators met the minimum threshold of 0.70 (Hair et al., 2021). The loadings for the dimensions of learning engagement: emotional ($\lambda = 0.878$, $p < .001$), agentic ($\lambda = 0.894$, $p < .001$), behavioral ($\lambda = 0.750$, $p = .025$), and cognitive ($\lambda = 0.679$, $p < .001$)—all indicated acceptable reliability. Since there is only one latent construct (LE) and the other variables (degree centrality, closeness centrality, path length, high-degree frequency, and seating types) are observed (i.e., treated as exogenous inputs, not latent factors), cross-loadings are not required.

Table 5. Outer Loadings of Indicators for the Learning Engagement Construct

Paths	λ	STDEV	T stat	P values
AGN_ENG -> LE	0.894	0.178	5.029	0.000
BEH_ENG -> LE	0.750	0.253	2.172	0.000
COG_ENG -> LE	0.679	0.185	3.674	0.000
EMO_ENG -> LE	0.878	0.159	5.524	0.000

The reliability and convergent validity of the reflective latent construct Learning Engagement (LE) were confirmed, too. The construct demonstrated high composite reliability (rho_c = 0.924, $p < 0.001$) and strong internal consistency (Cronbach's α = 0.891, $p < 0.001$). Furthermore, the average variance extracted (AVE = 0.753, $p < 0.001$) indicated substantial convergent validity. All the results show that the LE indicators (i.e., agentic, behavioral, cognitive, emotional) reliably represent the latent construct.

Collinearity Diagnostics

All variance inflation factor (VIF) values were below 5.0, indicating no multicollinearity concerns. Collinearity diagnostics further showed that all indicators and constructs exhibited acceptable Variance Inflation Factor (VIF) values (1.00–3.53 for the outer model; 1.14–2.73 for the inner model), indicating no multicollinearity and supporting the stability of the path estimates across Degree Centrality (DC), Closeness Centrality (CC), High-Degree Frequency (HD), and Path Length (PL).

Table 6. Collinearity Diagnostics of the Measurement and Structural Model

Model Component	Range of VIF	Interpretation
Outer model (indicators)	1.00–3.53	No multicollinearity among indicators
Inner model (latent constructs)	1.14–2.73	No multicollinearity among indicators

Structural Model Evaluation

The structural model was assessed through the coefficient of determination (R^2), path coefficients, and predictive relevance as shown in Table 7.

Table 7. R-Square and Adjusted R-Square Values for Endogenous Variables

Endogenous Variable	R^2	R^2 Adjusted	95% CI (2.5%, 97.5%)	Interpretation
Closeness Centrality (CC_NLM)	0.437	0.426	[0.316, 0.539]	Strong
Degree Centrality (DC_NLM)	0.202	0.187	[0.071, 0.341]	Moderate
High Degree Frequency (HD_GLM)	0.018	-0.001	[-0.018, 0.085]	Weak
Path Length (PL_GLM)	0.065	0.047	[-0.005, 0.169]	Weak
Learning Engagement (LE)	0.271	0.228	[0.177, 0.438]	Moderate

Note. 0.26 = strong, 0.13 = moderate, and 0.02 = weak explanatory power (Cohen, 1988)

The R^2 results indicated substantial explanatory power for Closeness Centrality ($R^2 = 0.437$), moderate explanatory power for Degree Centrality ($R^2 = 0.202$) and Learning Engagement ($R^2 = 0.271$), and weak explanatory power for High Degree Frequency ($R^2 = 0.018$) and Path Length ($R^2 = 0.065$). These results demonstrate that variations in node-level measures (degree and closeness centrality) and learning engagement were better explained by the model, compared to graph-level metrics (high-degree frequency and path length), with different seatings.

The path estimates in Table 8 showed distinct path coefficients for each seating configuration with beta values for unstandardized (raw) estimates. The horseshoe arrangement produced a strong positive effect on learning engagement ($\beta = 1.447$, $t = 3.488$, $p < .001$). Students in this setup showed higher behavioral, cognitive, emotional, and agentic engagement. The configuration appeared to improve teacher visibility and balance access across positions, supporting sustained focus. However, it also had significant negative effects on closeness centrality ($\beta = -1.587$, $t = 12.698$, $p < .001$) and path length ($\beta = -0.595$, $t = 3.240$, $p = .001$). The negative paths indicate that greater engagement is linked with less clustering and shorter indirect communication routes among students. This pattern supports the view that limiting peer proximity can reduce distractions and maintain instructional attention.

Table 8. Path Coefficients Estimates

Paths	Estimate β	SD	T stat	p	Interpretation
CC_NLM -> LE	0.280	0.139	2.012	0.044	Significant
DC_NLM -> LE	-0.229	0.167	1.366	0.172	Not significant
HD_GLM -> LE	0.380	0.435	0.872	0.383	Not significant
PL_GLM -> LE	0.092	0.157	0.585	0.558	Not significant
HS_Seat -> CC_NLM	-1.587	0.125	12.698	0.000	Significant
HS_Seat -> DC_NLM	-0.212	0.171	1.241	0.215	Not significant
HS_Seat -> HD_GLM	-0.028	0.090	0.308	0.758	Not significant
HS_Seat -> LE	1.447	0.415	3.488	0.000	Significant
HS_Seat -> PL_GLM	-0.595	0.184	3.240	0.001	Significant
WIN_Seat -> CC_NLM	-1.071	0.117	9.139	0.000	Significant
WIN_Seat -> DC_NLM	0.830	0.207	4.010	0.000	Significant
WIN_Seat -> HD_GLM	0.083	0.077	1.078	0.281	Not significant
WIN_Seat -> LE	0.568	0.400	1.419	0.156	Not significant
WIN_Seat -> PL_GLM	-0.455	0.268	1.697	0.090	Not significant

The present findings align with earlier studies but extend their interpretation. Khan et al. (2023) emphasized that comfort and visibility enhance motivation, yet their analysis remained perception-based. Peng et al. (2022) confirmed that spatial structure increases participation by directing attention, which supports the current result that controlled geometry sustains focus. Shernoff et al. (2016), however, argued that engagement functions as a mediator between environment and outcomes rather than as a direct effect. The present evidence refines this view by showing that specific spatial configurations can exert a measurable influence on engagement itself. Taken together, these comparisons suggest that attention stability depends less on perceived comfort and more on how physical layout regulates connection density and teacher visibility. This finding points to the value of modeling spatial parameters as quantifiable predictors of engagement in both educational and behavioral sciences.

The window arrangement affected closeness centrality ($\beta = -1.071$, $t = 9.139$, $p < .001$) and degree centrality ($\beta = 0.830$, $t = 4.010$, $p < .001$). It allowed more peer connections but reduced compactness within the network. Its direct path to learning engagement ($\beta = 0.568$, $t = 1.419$, $p = .156$) was not significant. The design altered spatial relations but did not lead to meaningful gains in engagement. The traditional layout served as the reference category, coded as zero. Compared with it, both horseshoe and window arrangements changed interaction structures, yet only the horseshoe configuration improved engagement consistently.

The overall pattern indicates that spatial arrangements influence engagement by shaping the density and direction of student connections. Layouts that moderate clustering and support even teacher access appear to strengthen engagement across multiple dimensions. These outcomes align with Ahmad and Amirul (2017), who reported that organized spatial design improves enjoyment and concentration by reducing visual and auditory interference. Similarly, Cantero et al. (2016b) observed that structured physical environments regulate behavior by forming predictable interaction patterns. Yet, Byiringiro (2023) and Gaytos (2024) found that overly compact layouts may reduce cognitive performance when proximity allows frequent peer distraction. Baes (2025) and Lalanan, as well as Oco (2025), extended this observation to Philippine settings, showing that engagement improves when the physical learning environment enables clarity of instruction and minimizes spatial noise. The present study integrates these findings, suggesting that spatial balance, rather than density, determines the quality of engagement. In this sense, the classroom operates as a measurable system where the geometry of seating can predict behavioral focus.

Effect Sizes and Predictive Relevance

The analysis of effect size (f^2) presented in Table 9 focused on the significant paths identified in the structural model in Table 8. Closeness centrality has a small, significant effect on learning engagement ($f^2 = 0.058$).

Table 9. Effect Size (f^2) of Exogenous Variables on Endogenous Constructs

Path	f^2	SD	t-Stat	p	Interpretation
CC_NLM → LE	0.058	0.061	0.948	0.044	Small
DC_NLM → LE	0.031	0.054	0.586	0.172	Small
HD_GLM → LE	0.014	0.039	0.352	0.383	Small
PL_GLM → LE	0.010	0.058	0.176	0.558	Small
HS_Seat → CC_NLM	0.746	0.186	4.020	0.000	Large
HS_Seat → DC_NLM	0.009	0.019	0.501	0.215	Negligible
HS_Seat → HD_GLM	0.001	0.018	0.058	0.758	Negligible
HS_Seat → LE	0.244	0.150	1.623	0.000	Medium
HS_Seat → PL_GLM	0.063	0.045	1.414	0.001	Small
WIN_Seat → CC_NLM	0.340	0.107	3.186	0.000	Large
WIN_Seat → DC_NLM	0.144	0.085	1.682	0.000	Medium
WIN_Seat → HD_GLM	0.009	0.021	0.446	0.281	Negligible
WIN_Seat → LE	0.046	0.068	0.670	0.156	Small
WIN_Seat → PL_GLM	0.037	0.051	0.721	0.090	Small

This result suggests proximity to nearby peers has a limited but measurable impact on the overall engagement outcome. Regarding the seating arrangements, the horseshoe configuration demonstrated a large influence on closeness centrality (f^2= 0.746). It also showed a medium effect on overall learning engagement (f^2= 0.244). Furthermore, the horseshoe arrangement exerted a small effect on path length (f^2= 0.063). This confirms that the horseshoe layout substantially alters both student proximity and teacher accessibility. The window seating arrangement exhibited a large impact on closeness centrality (f^2= 0.340). It also has a medium effect on degree centrality (f^2= 0.144). The significant paths confirm that the seating structures effectively reconfigure the proximity and interaction potential within the classroom network.

Model Fit

The results on the model fit indicated that the hypothesized SEM fitted data well, which is verified by a SRMR=0.041 (< 0.08). The squared Euclidean distance (d_ULS = 0.093) and geodesic discrepancy (d_G = 0.037) likewise fell within recommended thresholds (< 0.10). This practically means that the proposed model adequately represented the observed relationships among seating arrangements, graph-theoretic metrics, and learning engagement.

Table 10. Model Fit Indices Using SRMR, d_ULS, and d_G

Model Fit Index	Statistics	95% CI	Criterion	Interpretation
SRMR (Saturated model)	0.041	0.054	< 0.08	Excellent fit
d_ULS (Saturated model)	0.093	0.160	< 3.0	Within threshold
d_G (Saturated model)	0.037	0.049	< 0.10	Good global fit

Model Visualization

Figure 7 presents the finalized structural equation model derived from SmartPLS.

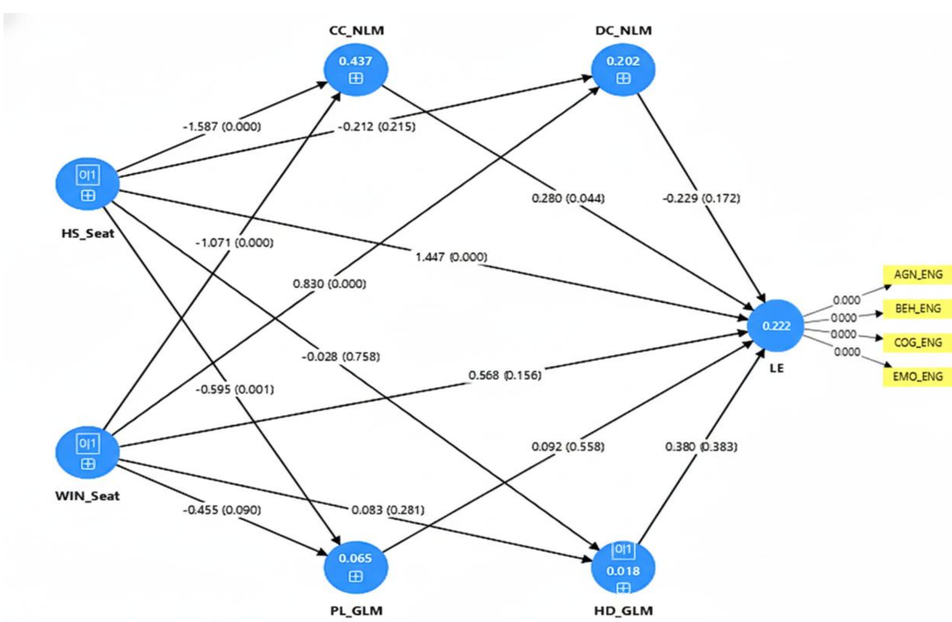

Figure 7. *The Structural Equation Model Visualization*

The diagram visually summarizes the validated relationships among seating arrangements, graph-theoretic metrics, and learning engagement, with path coefficients and p-values (in parentheses) indicating the direction, magnitude, and significance of influence.

Most Optimal Seating Arrangement Based on Results

Integrating the findings of graph-theoretic measures and PLS-SEM analysis, the horseshoe design unfolded as a pedagogically preferred layout. At the node level, relative to others, it exhibited a lower mean number of interactions per student (M = 4.50, SD = 0.81) but not mean distance (M = 1.04, SD = 0.09), suggesting a tighter and more structured arrangement by the students within nodes compared with aggregations in other schools. At the graph level, it had a lower percentage of highly connected students (80.56%) and was one step further away from the teacher on average, as measured by distance to teacher (M = 3.93, SD = 0.88). These results imply greater teacher accessibility and a structured visual field that supports attentional consistency. The PLS-SEM analysis confirmed these patterns. The horseshoe layout showed the strongest positive path to learning engagement ($\beta = 1.447$, $p < .001$) and a large effect on closeness centrality ($f^2 = 0.746$). The evidence suggests that engagement increased not through dense peer interaction but through spatial positioning that directed attention toward instruction.

This finding aligns with previous evidence that spatial organization shapes student engagement through structured visibility and access. Ahmad and Amirul (2017) noted that ordered seating improves concentration by minimizing visual distractions. Similar patterns were observed by Peng et al. (2022), who found that defined spatial geometry increases focus and behavioral regulation. Other studies, on the other hand, reported that seat placement shapes the participation and social belonging of learners (Gremmen et al., 2016; Keyes, 2019). Guardino and Antia (2012) also showed that rearranging seating reduces off-task behavior among students with attention difficulties. International research supports this directional effect, where structured layouts improve academic performance and sustained engagement (Cantero et al., 2016b; Correa et al., 2017; Owoseni et al., 2020). Philippine studies further reveal these conclusions. Baes (2025) observed that student motivation rises when classroom spaces are designed for clear visibility and limited peer interference. Lalanan and Oco (2025) reported that environmental order predicts learner participation, while Galabin (2024) and Gaytos (2024) found that satisfaction with seating arrangement correlates with engagement and achievement. Comparable outcomes were recorded by Byiringiro (2023) and Hardiansyah and Ar (2022), who linked spatial balance with reduced cognitive overload and improved task orientation. Across these studies, engagement appears most stable when spatial structure maintains proximity to the teacher while preventing excessive peer clustering, a condition best achieved in the horseshoe configuration.

Conclusion and Future Works

The study revealed that the way in which students are seated in a classroom significantly predicts student learning engagement through spatial closeness and interactions. The horseshoe arrangement predicted the most engagement through maximizing visibility, access, and peer prompt interaction. The graph-theoretic method and structural equation modeling showed that learning engagement is influenced by spatial positioning rather than the quantity of peer interactions.

These are findings that imply that the seating structure can be analyzed quantitatively in order to inform classroom design and management. The results have applied significance for teachers and administrators attempting to develop learning environments that facilitate both interaction and focused attention in formally designated public school classroom settings.

The graph-theoretic model represents an extreme simplification of a real classroom environment. The definition of an interaction line (edge) was restricted to immediate physical neighbors (0.5m to 1.5m). This approach models a proximity map for localized interaction rather than measuring a complex, cross-room social network. This methodological constraint, while necessary for the simulation and metric encoding, inherently limits the study's ability to model non-proximal interactions, such as those involving distraction or whole-class visibility, and must be considered when interpreting the predictive outcomes. The cross-sectional nature of the study should also be considered in making generalizations about its findings. This work can be extended by using classroom experimental data, considering other subject contexts, or investigating larger and non-conventional class sizes.

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Artificial Intelligence (AI) Declaration Statement

Artificial Intelligence (AI) tools were employed for the clarity and organization of a few stages in manuscript preparation. ChatGPT (OpenAI, GPT-5) was used for language and proofreading purposes, including structuring important long-form portions. Elicit and Perplexity have helped in finding, summarizing, and organizing the literature related to the study context. The application of AI tools was limited to linguistic and organizational work and did not extend to data analysis, statistical modeling, or interpretation. AI results were all manually checked, validated, and corrected by the authors to ensure accuracy and scholarly integrity in line with academic standards.