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Spatial optimization of human-activity energy harvesting potential using Space Syntax in campus buildings

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Abstract
Campus buildings are generally not designed to utilize mechanical energy generated from routine human activities such as walking and stair climbing, limiting their contribution to decentralized energy systems. This study investigates how spatial configuration can enhance the potential for human-activity-based energy harvesting in campus circulation spaces. The research develops a spatial optimization approach based on Space Syntax analysis to identify circulation zones with high potential for implementing energy harvesting. The study was conducted in the Faculty of Engineering Building at Universitas Krisnadwipayana, a multi-level campus facility characterized by intensive pedestrian movement. A quasi-experimental pre-test–post-test design compared the existing spatial layout with a redesigned configuration. Spatial analysis used connectivity and visual integration metrics calculated with DepthmapX. In addition, field observations quantified pedestrian movement intensity, including step counts and path frequency along corridor and stair circulation routes. These data were used to evaluate the spatial feasibility of implementing piezoelectric-based energy harvesting systems. The results indicate a substantial increase in the Potential Zone Ratio (PZR), from 34.6% in the existing layout to 84.72% after spatial reconfiguration. This improvement was achieved through circulation optimization, enhanced spatial continuity, and the integration of behavior-supportive architectural elements without modifying the primary structural system. These findings demonstrate that spatial configuration plays a critical role in concentrating pedestrian movement and expanding zones suitable for human-activity energy harvesting. The proposed framework provides a practical strategy for integrating spatial analysis into sustainable campus building design.

Keywords:
Energy Harvesting Zones;
Movement Analysis;
Space Syntax;
Spatial Configuration;
Sustainable Architecture;

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INTRODUCTION

Energy demand in the building sector continues to rise as human activity and space utilization increase, accounting for approximately 30-40% of global energy consumption [1][2]. Although renewable strategies such as solar energy are widely used, their performance depends heavily on weather conditions and sunlight availability [3,4,5], highlighting the need for alternative energy sources that can be directly integrated into building environments.

Educational buildings exhibit significant operational energy demand due to continuous daily activities. For example, the Faculty of Engineering Building at Universitas Krisnadwipayana consumes approximately 2,877.12 kWh per week (149,600 kWh annually) across a total floor area of 5,188 m², reflecting substantial energy use driven by intensive academic operations.

One emerging approach is harvesting energy from human activities. Walking and stair-climbing generate mechanical energy from footstep pressure, which piezoelectric systems can convert into electrical energy. Previous studies indicate that a single step can produce approximately 0.2-0.8 joules, potentially generating 2-8 watts depending on system configuration [6,7,8]. Given the continuous circulation in corridors and staircases, campus buildings present promising environments for this approach.

However, energy-harvesting effectiveness depends strongly on spatial configuration and movement distribution. Factors such as circulation layout, connectivity, and spatial networks determine pedestrian flow concentration. Space Syntax offers analytical tools, including connectivity and integration metrics, to identify high-movement zones suitable for energy harvesting implementation [9][10].

Despite growing research, energy harvesting technologies and spatial analysis are generally studied separately. Technological studies focus on device performance [11,12,13], while architectural studies emphasize movement patterns without linking them to energy potential. As a result, the integration of spatial configuration, user movement distribution, and energy harvesting remains limited. This research addresses this gap by proposing a responsive human-centered design approach, as illustrated in Figure 1.

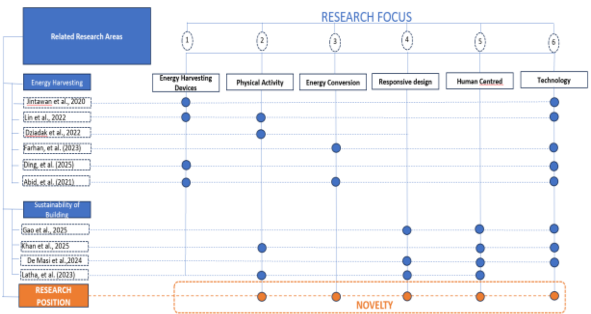

Figure 1. Mapping of Previous Studies and Research Novelty (developed by the authors based on literature synthesis)

Figure 1 illustrates the research gap: energy harvesting studies focus on device engineering, and sustainable building studies emphasize human-centered design, but their integration remains limited. Given that a single step generates approximately 0.2–0.8 joules, the high volume of movement in campus buildings represents significant yet underutilized energy potential due to unoptimized spatial configurations. Therefore, this study proposes a responsive, human-centered design approach to optimize energy-harvesting zones.

Table 1 presents a comparative overview of previous studies on energy-harvesting technologies and human-motion-based energy conversion. The comparison indicates that most existing studies focus primarily on developing and optimizing energy-harvesting devices, such as piezoelectric, electromagnetic, and vibration-based systems. Several studies also explore applications in wearable technologies or infrastructure systems; however, these studies generally emphasize technological performance rather than the spatial distribution of human activities within buildings.

As shown in the table, previous research rarely considers how spatial configuration influences pedestrian movement patterns and their implications for energy-harvesting potential. Consequently, integration between architectural spatial analysis and energy-harvesting optimization remains limited. To address this gap, the present study integrates Space Syntax–based spatial analysis with a responsive, human-centered design approach to identify zones where human activities such as walking and stair climbing can be concentrated to maximize energy-harvesting potential in campus buildings.

METHOD

This study employed a quasi-experimental design comprising two phases, namely a pre-test and a post-test, to compare the energy harvesting potential between the existing campus building layout and the proposed responsive human-centered design model. The quasi-experimental approach enables the evaluation of spatial design interventions under real operational conditions without full experimental control, making it appropriate for architectural research. Figure 2 illustrates the overall research methodology, including the pre-test, design development, and post-test stages.

Table 1. Comparative Review of Previous Studies on Human Activity-Based Energy Harvesting and Research Position of This Study (developed by the authors based on literature synthesis)

Author	Method	Focus	Key Findings	Limitation
Jintanawan et al. (2020) [11]	Simulation (MATLAB/Simulink), prototype development, experimental testing	Kinetic energy harvesting floor using electromagnetic generator	Generates up to 702 mJ per step with 520 mW average power; lead-screw mechanism improves efficiency up to 74.72%	Focuses on device engineering; does not analyze pedestrian movement patterns or building spatial configuration
Lin et al. (2023) [7]	Literature review and comparative analysis	Human motion energy harvesting devices	Identifies main mechanisms: piezoelectric, electromagnetic, friction-based systems for powering low-energy electronics	Focuses on technology review; lacks architectural and spatial analysis
Dziadak et al. (2023) [14]	Literature review and comparative analysis	Energy harvesting for wearable sensors and body area networks	Multiple energy harvesting technologies convert human motion and heat into electricity	Focuses on wearable devices; no consideration of building spatial design or pedestrian circulation
Farhan et al. (2024) [15]	Literature review and comparative analysis of vibration energy harvesting technologies	Optimization of vibration energy harvesting mechanisms including piezoelectric, electromagnetic, and electrostatic systems	Vibration energy harvesting technologies show high potential for powering low-power electronic devices through improved transduction mechanisms.	Focuses on ambient vibration sources; does not analyze human activity energy harvesting or spatial configuration in buildings
Ding et al. (2025) [16]	Literature review on piezoelectric energy harvesting technologies	Piezoelectric energy harvesting from structural vibration	Mechanical vibrations from railway systems can be converted into electrical energy using piezoelectric devices	Focuses on railway infrastructure; does not address human activity energy harvesting or spatial configuration in buildings
This Study (2026)	Quasi-experimental design using Space Syntax analysis (DepthmapX), spatial configuration evaluation, and movement-based energy estimation	Spatial optimization of human-activity energy harvesting in campus buildings	Demonstrates that spatial configuration significantly influences the distribution of walking and stair-climbing activities, increasing the Potential Zone Ratio from 34.6% to 84.72% through responsive human-centered spatial design	Limited to case study of campus buildings; further research is required for broader building typologies

The unit of analysis was circulation space within the campus building, specifically corridors and staircases, as these areas represent the primary domains of repetitive user movement. We conducted observations during regular academic weekdays (08:00–16:00) to capture typical movement patterns of students, academic staff, and administrative personnel. We selected walking and stair-climbing activities because of their repetitive nature and their potential to generate mechanical energy from footstep pressure.

We conducted spatial configuration analysis using Space Syntax through Visibility Graph Analysis (VGA) in DepthmapX version 0.8.0. We constructed the spatial model using a 1 m × 1 m grid resolution, with the analysis boundary limited to corridor and staircase areas on each floor. We computed two spatial metrics for each grid cell: Connectivity and Visual Integration (HH) using a global radius (Rn).

We identified potential energy-harvesting zones using quantitative thresholds derived from VGA outputs. We classified grid cells as high potential when both connectivity and integration exceeded the mean, medium potential when either metric exceeded the mean, and low potential when both were at or below the mean. We designated medium and high categories as potential energy-harvesting zones.

To ensure feasibility for piezoelectric module placement, we retained only continuous clusters of at least four adjacent grid cells (minimum 4 m²) as valid potential zones. The Potential Zone Ratio (PZR) was calculated as the proportion of qualified cells relative to the total circulation cells within the building. Based on the spatial analysis results, we developed responsive, human-centered design interventions to improve spatial continuity, connectivity, and movement concentration within circulation areas.

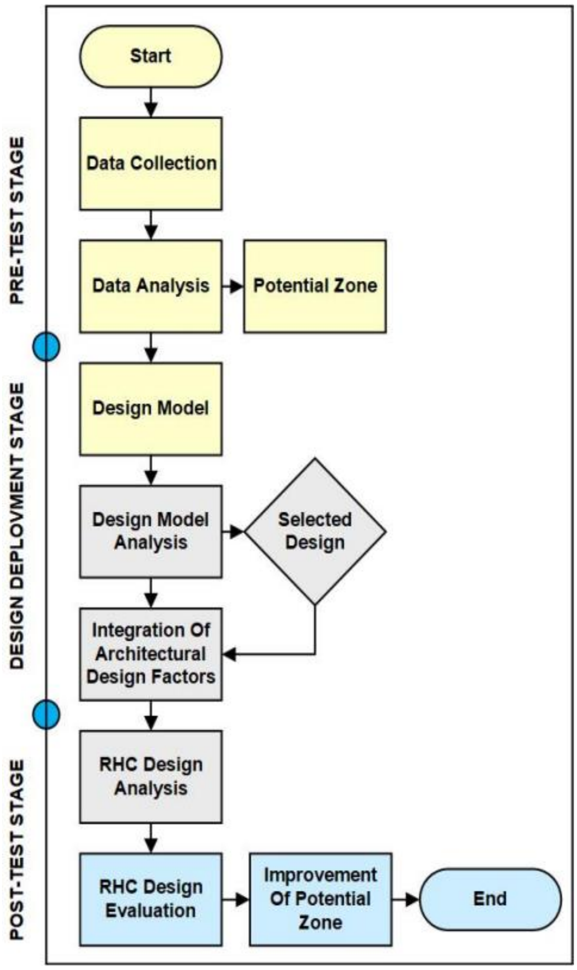

Figure 2. Research methodology comprising the pre-test, design development, and post-test stages.

The modified layouts were reanalyzed using identical VGA parameters to maintain methodological consistency.

We evaluated the intervention's effectiveness by comparing the Potential Zone Ratio (%) between the existing and redesigned layouts. Differences in proportions were tested using a two-proportion z-test (α = 0.05), and effect size was calculated using Cohen's h. Statistical calculations were performed using Microsoft Excel [17,18,19].

Theoretical Framework and Spatial Implementation

This study is grounded in Space Syntax theory, which explains how spatial configuration influences movement distribution. Spatial analysis was conducted using DepthmapX through Visibility Graph Analysis (VGA), applying connectivity and visual integration metrics.

Circulation areas were classified into high, medium, and low spatial potential using mean threshold values. High and medium zones were identified as potential energy-harvesting areas because of their higher accessibility and movement concentration. These zones guided the responsive human-centered design intervention to optimize spatial continuity and intensify movement, thereby improving conditions for piezoelectric energy harvesting.

Pre-test Phase

The pre-test phase analyzed the existing layout using VGA (connectivity and visual integration) to classify circulation areas into spatial potential categories, with medium and high zones defined as baseline energy harvesting areas. User movement observations assessed activity intensity based on walking and stair-climbing scenarios, including frequency, duration, and step count. The analysis focused on spatial performance and movement distribution as baseline indicators of energy-harvesting potential before intervention.

Design Alternative

The optimal design alternative was selected using a Multi-Criteria Decision Analysis (MCDA) based on the Weighted Sum Model. Two criteria aligned with the study objective were adopted: (1) Potential Zone Ratio – Connectivity, and (2) Potential Zone Ratio – Visual Integration. Each criterion received equal weight (0.50), and values were normalized using the min–max method before computing composite scores. Table 2 presents the evaluation results and ranking of the three design alternatives.

Alternative 3 obtained the highest composite score (1.00), outperforming the other schemes across both spatial indicators, and was therefore selected for further development in the post-test phase. Sensitivity testing of weight variations confirmed ranking stability.

To estimate theoretical energy output, we applied a simplified mechanical-to-electrical conversion model. We estimated mechanical work per step using $W = F \times d$ ground reaction force approximated as $F = m \times g$. We calculated electrical output per step $E = W \times \eta$ as, assuming a conservative piezoelectric efficiency range of 15–30% (20% baseline).

Table 2. Evaluation and Ranking of Design Alternatives Based on PZR Connectivity and Integration

Alternative	PZR–Connectivity (%)	PZR–Integration (%)	Composite Score	Rank
Alt 1	56.40	26.03	0.16	2
Alt 2	58.15	9.70	0.03	3
Alt 3	85.05	61.57	1.00	1

We derived total energy potential by multiplying energy per step by effective step counts within medium- and high-potential zones, incorporating a duty cycle factor to account for non-uniform stepping distribution. A basic sensitivity analysis confirmed proportional variation without altering comparative design performance.

Spatial modeling and scoring were conducted using AutoCAD 2022, SketchUp 2021, DepthmapX 0.8.0, and Microsoft Excel 365 to ensure reproducibility [16,20,21,22].

Post-test Phase

The post-test phase repeated the analytical procedures used in the pre-test stage to ensure methodological consistency and comparability. We reanalyzed the modified building layout, developed through the responsive human-centered design model, using identical VGA parameters in DepthmapX (grid resolution 1 m × 1 m, global radius Rn). We recalculated connectivity and visual integration metrics to assess changes in spatial configuration.

The analysis demonstrated a substantial increase in the Potential Zone Ratio (%) from 34.6% in the existing layout to 84.72% in the modified configuration. This represents an absolute difference of $\Delta p = 0.5012$. We tested the difference in proportions using a two-proportion z-test at $\alpha = 0.05$ and evaluated effect size with Cohen's h, indicating a statistically significant and substantively large improvement in spatial potential.

We repeated user movement observations under the revised layout conditions using the same walking and stair-climbing scenarios used in the pre-test phase. We recorded path frequency, step count, and activity duration to maintain procedural consistency. The comparative analysis confirmed that the revised spatial configuration increased movement concentration in medium- and high-potential zones.

By systematically comparing pre-test and post-test conditions, the study quantitatively and spatially validated the effectiveness of architectural design interventions in expanding and intensifying energy-harvesting zones.

Evaluation of Increased Zone Potential

The final phase evaluated the spatial implications of the design intervention by examining the expansion of medium- and high-potential zones following layout modification. As demonstrated in the post-test analysis, the Potential Zone Ratio increased substantially compared to the baseline configuration, indicating a structural redistribution of spatial accessibility and visibility within circulation areas.

Rather than merely increasing total circulation area, the intervention altered the spatial configuration to concentrate movement within zones with higher connectivity and integration values. This redistribution suggests greater structural alignment between user movement patterns and spatial conditions favorable for energy-harvesting implementation.

The expanded coverage of medium- and high-potential zones implies a higher likelihood of step accumulation in strategically configured areas. While this study did not focus on precise electrical output in kilowatt-hours, the spatial findings indicate that architectural configuration significantly influences the feasibility and efficiency of human activity-based energy conversion systems. These results reinforce the role of circulation design, spatial continuity, and visibility optimization as critical architectural factors in supporting decentralized energy strategies within campus buildings.

Data Analysis

Data analysis assessed the quantitative impact of the design intervention on the expansion of potential energy zones within the campus building. Spatial data were obtained from VGA-based grid cell analysis using DepthmapX, in which each 1 m × 1 m grid cell represented the basic unit of spatial observation. We used Connectivity and Visual Integration metrics to classify cells into low, medium, and high spatial potential categories.

We calculated the Potential Zone Ratio (%) as the proportion of grid cells classified as medium- and high-potential relative to the total circulation grid cells. We compared pre-test and post-test conditions using a two-proportion z-test ($\alpha = 0.05$) to assess whether the increase in potential zone area was statistically significant. We calculated effect size using Cohen's h to assess the magnitude of the spatial change.

In addition to spatial metrics, we collected user activity data, including path frequency, activity duration, and step count, under two movement scenarios: corridor walking and stair climbing. We analyzed these variables descriptively to examine the alignment between spatial reconfiguration and observed movement intensity within the identified potential zones. Although inferential testing was not applied to the activity variables, the observed patterns supported the spatial results derived from the VGA analysis.

Instrument and Material

This study utilized spatial analysis software, architectural modeling tools, and observational instruments for data collection and processing. DepthmapX 0.8.0 was used to perform Visibility Graph Analysis (VGA) with a 1 m × 1 m grid, generating connectivity and visual integration metrics to classify potential energy harvesting zones. Floor plans were prepared in AutoCAD 2022 and SketchUp 2021, and data processing and statistical analysis were conducted in Microsoft Excel 365 [23,24,25,26].

We collected user activity data through direct observation of corridor walking and stair-climbing scenarios. We recorded step counts, duration, and path frequency using smartphone-based pedometer applications to support spatial analysis, without collecting personal identification data.

RESULTS AND DISCUSSION

This study shows that implementing a responsive, human-centered architectural design significantly enhances the spatial potential for human-activity-based energy harvesting in campus buildings. DepthmapX analysis shows that the Potential Zone Ratio increased from 34.6% in the existing layout to 84.72% in the redesigned configuration.

This increase ($\Delta p = 0.5012$) was statistically validated using a two-proportion z-test ($p < 0.05$) with a large effect size (Cohen's $h = 1.09$), indicating that the design intervention substantially improved spatial conditions characterized by higher connectivity and visual integration within circulation areas.

The intervention included circulation reconfiguration, spatial guidance elements, and passive design strategies such as improved natural lighting and ventilation. These improvements enhanced spatial continuity and environmental comfort within corridor spaces, which in turn encouraged greater pedestrian concentration in strategically configured zones.

Observational results indicate higher step accumulation in medium- and high-potential zones after the intervention. Although inferential testing was not applied to movement variables, the observed patterns suggest that improved spatial configuration contributes to more concentrated walking and stair-climbing activities.

Consistent with Space Syntax theory, higher spatial connectivity and visual integration tend to attract greater pedestrian flow. Increased movement concentration consequently generates more mechanical energy from human activities, which piezoelectric systems can convert into electrical energy. Therefore, the spatial redistribution achieved in this study indicates an increased potential for cumulative energy harvesting in campus circulation spaces.

Overall, the proposed model demonstrates how architectural configuration can support decentralized energy harvesting by integrating spatial analysis, user movement behavior, and human-centered design strategies. This framework offers practical implications for sustainable campus buildings and other high-traffic environments. Future research may quantify actual electrical energy output (kWh), optimize piezoelectric module placement, and integrate the harvested energy into building-scale energy management systems.

Layout and Distribution of User Activities

The Faculty of Engineering Building at Universitas Krisnadwipayana was selected as the case study due to its multi-level configuration and intensive circulation patterns. The four-story building is organized around a double-corridor circulation separated by a central void. At the same time, three main staircases support vertical movement on the left, center, and right sides of the building. The existing ground- and second-floor layouts, together with their main circulation conditions, are presented in Figure 3.

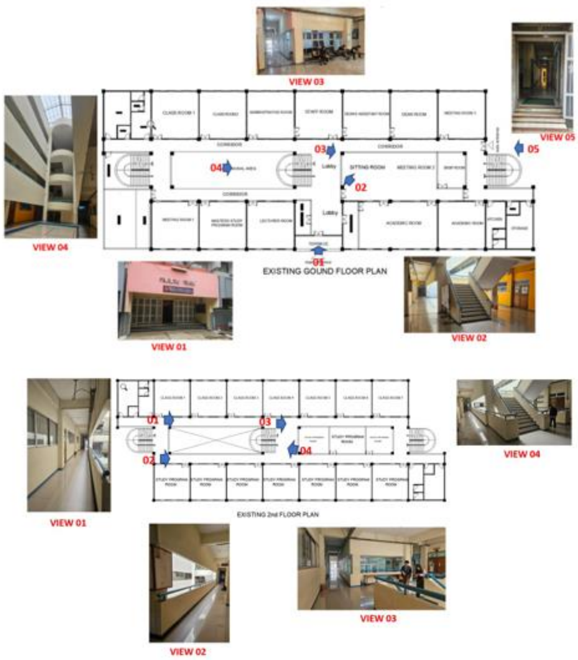

Figure 2. Ground and Second Floor Plans of the Faculty of Engineering Building, Universitas Krisnadwipayana

Source: Adapted and redrawn by the authors based on architectural plans provided by Universitas Krisnadwipayana

Spatial functions vary across floors. The ground floor accommodates classrooms and administrative offices, while the second floor contains departmental offices and classrooms arranged along the main corridors. The third and fourth floors are primarily used for instructional activities and comprise a total of 28 classrooms. The repeated floor layouts across the upper levels establish consistent circulation patterns and reinforce vertical movement through staircase use.

Pre-Test Stage

Figure 4 presents the connectivity analysis of the existing building layout, performed using Visibility Graph Analysis (VGA) in DepthmapX. The results indicate that low-connectivity areas dominate the circulation network on both analyzed floors.

On the ground floor, low-connectivity areas cover 102 m², followed by medium-connectivity areas (82 m²) and high-connectivity areas (37 m²). A similar pattern occurs on the second floor, where low-connectivity zones cover 161 m², while high- and medium-connectivity areas account for only 31 m² and 29 m², respectively.

These findings indicate that most circulation spaces in the existing configuration have low structural interconnectivity. From a spatial performance perspective, this distribution suggests limited continuity in movement corridors and a weak concentration of circulation flow, reducing the spatial conditions favorable for concentrated human activity.

From a Space Syntax perspective, lower integration values indicate reduced global accessibility within the circulation network. Consequently, the existing spatial configuration provides limited support for concentrated walking and stair-climbing activities within strategic zones.

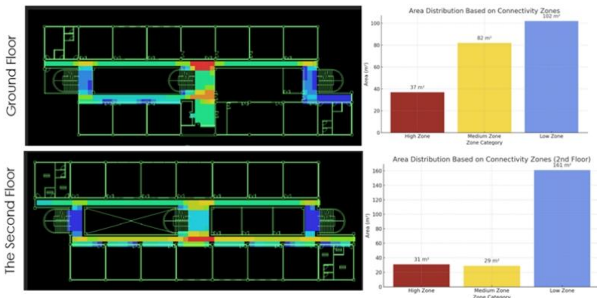

Figure 3. Connectivity analysis of the existing building layout based on Visibility Graph Analysis (VGA) using DepthmapX software
Source: Author's analysis using DepthmapX

As shown in Figure 5, lower visual integration values indicate reduced global accessibility within the circulation network, limiting concentrated walking and stair-climbing activities within strategic zones.

From a Space Syntax perspective, lower visual integration values imply weaker global accessibility within the circulation system. Consequently, the pre-intervention configuration exhibits limited spatial characteristics that support intensified walking and stair-climbing activities within clearly defined strategic zones.

Based on the pre-test spatial analysis, a responsive, human-centered design was developed to improve movement concentration within potential energy-harvesting zones. Figure 6 presents the selected design layout.

Design Intervention Stage

Room entrances align with the main corridor to improve circulation coherence. Staircases are repositioned in high connectivity zones to maximize movement intensity and energy potential. Passive design strategies (lighting and ventilation) improve comfort and efficiency. Signage and spatial cues support navigation, while color enhances user experience. All interventions are applied without altering the primary structure. Figure 7 visualizes the proposed design in three dimensions to illustrate the architectural interventions.

This visualization highlights design interventions such as piezoelectric pathways, color-coded signage, natural lighting, and aesthetic elements that enhance both user navigation and the overall spatial experience. Each strategic area is designed to optimize user movement toward zones with high energy-conversion potential, demonstrating synergy among spatial design, piezoelectric technology, and user comfort within the framework of sustainable architecture.

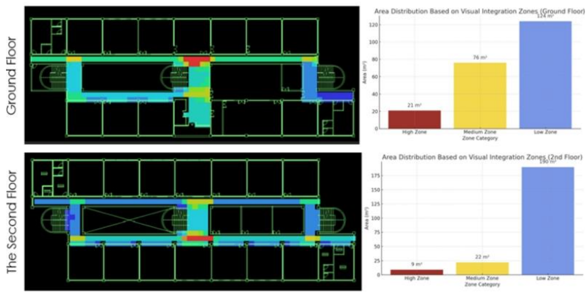

Figure 4. Existing Floor Plan Analysis – Visual Integration
Source: Author's analysis using DepthmapX

Figure 5. Selected design layout illustrating the integration of responsive human-centered design strategies and the placement of potential piezoelectric floor areas
Source: Developed by the authors

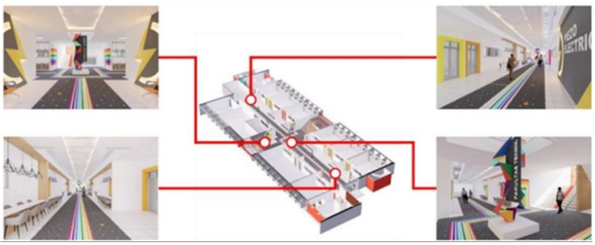

Figure 6. Visualization of the Responsive Human-Centered Design Model in the Campus Building
Source: Visualization developed by the authors using SketchUp

Post-Test Stage

Figure 8 presents the connectivity analysis of the responsive human-centered (RHC) design. The results show a clear redistribution of connectivity, with medium-connectivity zones becoming dominant (251 m² on the ground floor and 70 m² on the second floor), alongside a notable increase in high-connectivity areas (136 m²).

This shift indicates improved spatial continuity, where interconnected corridors replace previously fragmented circulation, thereby enhancing the structural capacity to support continuous pedestrian movement.

Figure 9 illustrates the Visual Integration (visibility) analysis of the RHC design. The color-coded representation shows high-integration zones in orange and low-integration zones in dark blue.

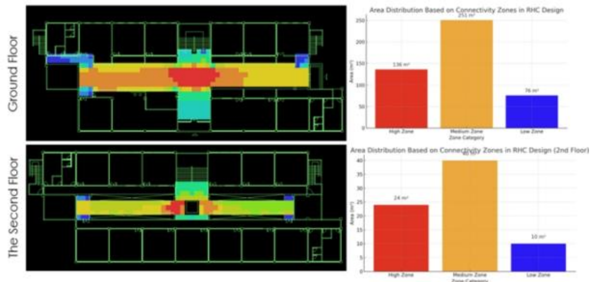

Figure 7. Spatial connectivity analysis of the responsive human-centered (RHC) design layout for the ground and second floors based on Visibility Graph Analysis (VGA)
Source: Author's analysis using DepthmapX software

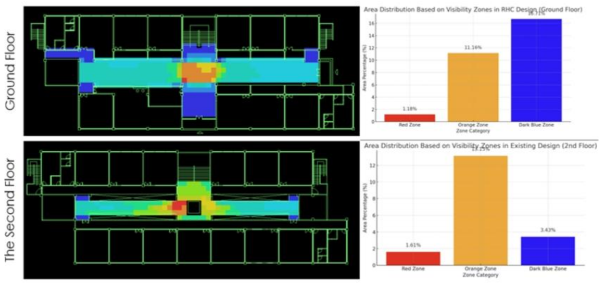

Figure 8. Spatial visual integration analysis of the responsive human-centered (RHC) design layout for the ground and second floors using Visibility Graph Analysis (VGA) in DepthmapX
Source: Author's analysis using DepthmapX

On the ground floor, high-visibility areas account for 11.16% of the total floor area, while low-visibility zones comprise 15.61%. On the second floor, high-integration zones become more spatially consolidated compared to the existing condition, indicating improved global visual accessibility across circulation areas.

This shift in visual integration distribution suggests enhanced spatial legibility and improved structural accessibility within the redesigned layout. In space syntax terms, higher integration values indicate stronger global positioning within the visibility network, which structurally supports more centralized and coherent movement patterns.

CONCLUSION

This study shows that a responsive, human-centered architectural design approach can significantly improve the spatial conditions needed for human activity-based energy harvesting in campus buildings. Using Space Syntax-based Visibility Graph Analysis, the Potential Zone Ratio increased from 34.6% in the existing layout to 84.72% in the redesigned configuration. The difference (Δp = 0.5012) was statistically significant ($p < 0.05$) with a very large effect size (Cohen's h = 1.09), indicating a substantial improvement in spatial conditions characterized by higher connectivity and visual integration.

The findings confirm that spatial configuration plays a critical role in concentrating pedestrian movement within circulation networks, thereby increasing the potential for energy harvesting from walking and stair-climbing activities. By integrating Space Syntax analysis with responsive, human-centered design strategies, this study provides a measurable architectural framework for identifying and optimizing potential energy-harvesting zones in campus buildings.

Although electrical energy output was not directly quantified in kilowatt-hours, the expansion of medium- and high-potential zones indicates a higher structural likelihood of cumulative step concentration within strategically configured spaces. The proposed framework therefore offers practical implications for sustainable campus design and other high-traffic public facilities. Future research may further quantify energy output, optimize piezoelectric module placement, and integrate human activity-based energy harvesting into building-scale energy management systems.

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