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The Effectiveness of Human-Centered Responsive Design on the Energy Output of Human Activities

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***Abstract*—** Human physical activities such as walking and climbing stairs inside campus buildings produce mechanical energy that has the potential to be converted into electrical energy. However, this potential has not been optimized in conventional architectural design approaches. This study aims to evaluate the effectiveness of human-centered responsive design in increasing the energy output of user activities. Quasi-experimental methods were used with pretest and posttest approaches to compare step frequencies and energy estimates before and after design interventions. Data is obtained through simulation of user movements in strategic zones such as corridors and stairs, with the support of DepthMapX spatial analysis with connectivity and visual integration algorithms. The energy output is calculated based on the technical parameters of the prototypes piezoelectric. The results showed that the responsive design resulted in an estimated energy output of 396.5 kWh/week from walking activities, and 283.99 kWh/week from climbing stairs, with a total contribution of 680.49 kWh/week. The Wilcoxon Marked Ranking Test showed a significant value of 0.028 ($p < 0.05$), proving a statistically significant improvement. The study confirms that the integration of user-based architectural design strategies with piezoelectric technology can increase the intensity of physical activity as well as the potential for energy harvesting. These findings contribute to the development of educational buildings that are more sustainable and adaptive to user behavior.

***Keywords*—** Energy conversion activities; Human-centered architecture; Responsive design; Sustainable campus buildings.

1. INTRODUCTION

The increasing energy demand in various sectors encourages the importance of architectural design innovations that are not only efficient, but also able to harvest energy from user activities. One potential approach is the utilization of mechanical energy from human physical activities such as walking and climbing stairs, which can be converted into electrical energy through piezoelectric technology [1-4] . Although it has been applied in urban public spaces, the application of this technology in educational buildings is still rarely researched [5-8]. In the context of campuses that have high circulation activities, the energy from user activities becomes a sustainable potential to be utilized. Therefore, architectural design needs to be directed in order to optimize the movement of users towards potential energy zones and at the same time integrate energy harvesting strategies with spatial design principles [9-11].

Human-centered responsive design models have been developed to direct user behavior towards areas of high spatial connectivity [12-14]. This approach assumes that behaviors can be shaped through strategic spatial interventions [15-17]. However, its effectiveness in increasing energy output quantitatively has not been widely studied. Most previous studies have still focused on the technical aspects of piezoelectric devices on a laboratory scale, not yet

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on their integration with user behavior and campus building space configurations. Therefore, an interdisciplinary approach that combines spatial data, user behavior, and energy simulations is needed to realize buildings that actively support renewable energy principles [18, 19].

This study aims to evaluate the effectiveness of human-centered responsive design in increasing the energy output of walking and climbing stairs in campus buildings. Through a quasi-experimental approach, this study compares pre- and post-design conditions using spatial syntax analysis and piezoelectric-based energy output calculations, as described in the next subsection.

1.1. Quasi-Experimental Method

A quasi-experimental method was used to assess the causal relationship between architectural design interventions and changes in user behavior without requiring random assignment of participants. This approach compares pre-test (existing layout) and post-test conditions (human-centered responsive design) to identify the extent to which design modifications affect the intensity of user activities as well as the energy output generated.

Unlike controlled and artificial laboratory experiments, this method is applied directly to real building environments allowing the observation of user behavior and spatial interactions in a natural context. Thus, the results not only provide empirical evidence for the effectiveness of architectural design, but also maintain ecological validity, namely the relevance of the findings to the actual operational conditions of the building.

This quasi-experimental approach requires an analysis tool that is able to map changes in user behavior towards the configuration of the space. Therefore, the theory of Space Syntax is applied through the DepthMapX software to assess the interconnectedness and potential of activity zones.

1.2. DepthMapX Space Syntax and Spatial Analysis

Space Syntax Theory provides a quantitative framework for analyzing spatial configurations and how they affect human movement, accessibility, and interaction. This theory represents the layout of architecture as interconnected nodes, allowing spatial relationships to be measured mathematically. To apply this concept, the DepthMapX software is used as a computing tool that translates architectural floor plans into visual and numerical spatial data.

In this study, two main algorithms from DepthMapX were used, namely Connectivity and Visual Integration. Connectivity Analysis identifies how each area or point is directly connected to the other, representing its level of accessibility and circulation potential. Meanwhile, Visual Integration measures how easily an area or point can be visually perceived from another space, indicating its level of superiority and spatial visibility.

The results of both analyses are visualized through color maps: red indicates high-potential zones, yellow to green represents medium zones, and blue corresponds to low zones. This color-coded output forms the basis for identifying potential areas that are most effective in directing the user's movement. The results of the spatial analysis were then associated with the estimation of the potential energy that can be converted from human activities using a piezoelectric system. This stage explains the principles and parameters of energy measurement used.

1.3. Piezoelectric-Based Energy Output

Piezoelectric-based energy output refers to the process of generating electrical energy through mechanical pressure exerted on a piezoelectric material during a human activity such as walking or climbing stairs. When the user's footstep applies force to the piezoelectric surface, the mechanical pressure in the crystal structure results in a difference in electrical potential that can be converted into usable electrical power.

In this study, the value of energy output was determined through empirical prototype testing. A single-floor module consisting of ten piezoelectric discs produces an average of 0.64 watts of power per stroke under standard running pressure. Although the system may reach a peak power of 1.2 watts temporarily, the average value is adopted to represent consistent and realistic system performance during continuous operation.

This experimentally obtained power value is then multiplied by the total number of user steps derived from spatial analysis (DepthMapX) and field observation data. The resulting Figures are expressed in kilowatt-hours [kWh], serving as a quantitative basis for comparing the total electrical energy generated between existing layouts and human-centered responsive designs (RHCs).

To ensure that the observed change in energy output was indeed significant and not the result of random variation, a statistical analysis was performed using the Wilcoxon Marked Rating Test.

1.4. Wilcoxon Signed Rating Test

The Wilcoxon Marked Ranking Test is a non-parametric statistical method used to analyze paired samples when the data does not follow a normal distribution. It compares two related conditions, in this case, energy output before and after the implementation of a responsive human-centered design to determine whether the observed differences are statistically significant.

This test was chosen because it is suitable for small sample sizes and data that are not normally distributed, conditions that are common in architectural and behavioral studies. In this study, the Wilcoxon test validated that the increase in energy output was not due to random variation, but was a statistically significant effect resulting from a design intervention.

After the entire methodological approach has been described in the previous section, the next stage of research details the application of the method to the object of study, starting from the research location to the analysis of the results of the energy comparison.

2. METHOD

This research was carried out through a series of structured stages to evaluate how responsive, human-centered architectural design can increase the energy output generated from user activities in the campus environment. The stages begin with the identification of active users and direct observation of walking activities and climbing stairs in the existing layout to obtain basic step frequency data. Furthermore, a spatial redesign was carried out using Space Syntax analysis through the *DepthMapX* software, to optimize circulation patterns and direct user movement towards the zone with the highest energy potential based on the level of connectivity and visual integration.

Using the same user data, a simulation of movement on the redesigned layout was carried out to calculate the change in step frequency and estimate energy output. The energy calculation is based on an average piezoelectric power of 0.64 W per step, which is obtained from the prototype test results. The total weekly energy (E, in kWh) for each layout is calculated using the equation:

$$E\frac{N\,x\,P}{1000\,x\,3600} \tag{1}$$

NP with is the total number of steps per week and is the average power per step (Watts).

The difference in results between the existing layout and the responsive design was analyzed using the Wilcoxon Signed-Rank Test to verify the statistical significance of the design effect on the resulting energy increase [20, 21].

2.1. Location and Object of Research

The research was conducted in the Faculty of Engineering Campus building in Jakarta as a case study. The research objects were in the form of the main circulation zone (corridor/corridor) and the main staircase that underwent design intervention in the previous study, with the transfer of the circulation path to the connectivity and high visibility zone based on the analysis of Spatial Syntax.

2.2. Stages of Research and Data Collection

The research was conducted through several structured stages, starting with the pre-testing phase, which involved the collection of physical and non-physical data. Non-physical data includes the number of users and their operational time within the building, while physical data focuses on existing layouts especially corridors and stairs and observation of user activity. From the data, several parameters were obtained, the potential spatial zones of the building layout, the effective users of the user distribution data, as well as the number of steps, frequency, and duration of the observed activities. This stage produces the energy output of the existing conditions [22, 23].

The next stage is design intervention, in which human-centered responsive designs are developed to enhance physical activity, especially walking and climbing stairs [24-26]. After this, the post-test phase measures the increase in user activity and the corresponding energy output based on the same piezoelectric parameters. The final stage involves comparing pre-test and post-test results using the Wilcoxon Signed Rank Test to determine whether the human-centered responsive design effectively optimizes the energy harvesting of user activities within the campus building.

Figure 1 shows the overall flow of the research methodology used to evaluate the effectiveness of human-centered responsive architecture design. The research stage begins with the identification of effective users, i.e. individuals who actively utilize key circulation areas such as corridors and stairs. Furthermore, user movement patterns were observed through three trajectory scenarios to obtain representative daily step frequency data.

The observation data is then normalized based on the number of effective users and the area of activity zones, to ensure a fair comparison between conditions and avoid bias due to population variations. The normalized step frequency value is converted into energy output using the average power parameter per step from the piezoelectric prototype test results. Finally, the energy output results of the existing layout and human-centred responsive design were compared to determine the extent to which the design intervention increased the energy conversion potential of user activities in campus buildings.

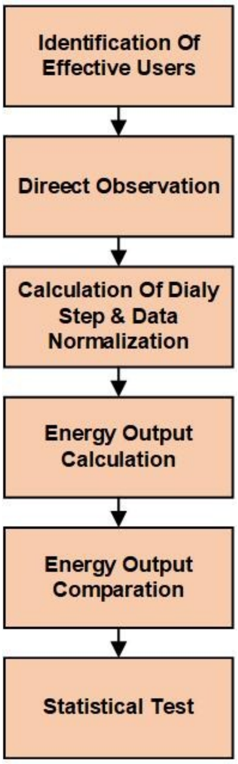

Fig. 1. Evaluation of the research flow of the effectiveness of human-centered responsive design.

The Wilcoxon Signed Rank test was applied to evaluate the statistical significance of differences in energy output before and after a design intervention. This non-parametric test is suitable for paired data that does not follow a normal distribution, which in this study corresponds to the energy output of the existing layout (pre-test) and the responsive human-centered design layout (post-test). Each pair of data represents the total weekly energy generated from walking and climbing stairs activities in both layouts. The analysis was carried out using SPSS Statistics version 26 with. A p-value of less than 0.05 indicates that the difference in energy output between the two layouts is statistically significant and can be attributed to architectural design interventions rather than random variations. This ensures the reliability of the conclusion that human-centered responsive design effectively enhances the energy harvested from user activities within campus buildings.

The performance of experimental prototypes and the resulting energy output are influenced by several factors, both physical and non-physical. To maintain consistency, the user's body mass is treated as a controlled variable (70-75 kg on average), while temperature and humidity are considered stable as all activities take place inside the building. In addition to these controlled conditions, several factors can further optimize energy harvesting based on human activities. Physical factors include spatial accessibility, circulation routes, natural lighting, user mass, and piezoelectric device configuration. Non-physical factors such as operating hours and the user's activity schedule also affect the total energy harvested, as they determine the intensity and duration of movement. Therefore, variations in energy output are mainly attributed to differences in design configurations and user movement patterns rather than environmental fluctuations.

2.3. Energy Output Calculation

The calculation of energy output in this study is based on the average power generated by the piezoelectric system when receiving pressure from walking or climbing stairs. A value of 0.64 watts per step is used as the main parameter of the calculation, which is obtained from the experimental test results of the piezoelectric prototype.

The average power value is derived from the relationship between the mechanical energy generated per step and the contact time of the foot during a running cycle. Mathematically, this relationship is expressed as:

$$P_{avg} = \frac{E}{T} = P_{peak}\ x\ \frac{tc}{T} \tag{2}$$

with a caption:

- P_{avg}= average power per step [W].
- P_{peak}= peak power at footstep [W].
- t_c= contact time of the foot with the piezoelectric surface [s].
- T= step period [s].
- E= mechanical energy produced per step [J].

Based on the results of the prototype test, the peak power () was recorded at P_{peak}1.2 W at normal footstep pressure. Referring to human biomechanical data, the average foot contact time () is t_c0.4 seconds (about 50–60% of a single step cycle), while the average step period is T0.75 seconds (the running frequency is about 1.33 Hz).

Thus, the energy generated per step can be calculated as:

$$E = P_{\text{peak}} \times t_c = 1.2 \times 0.4 = 0.48\ \text{J}$$

and its average power becomes:

$$P_{avg} = \frac{E}{T} = \frac{0.48}{0.75} = 0.64\ W \tag{3}$$

This approach ensures that the average power values used reflect realistic human running conditions as well as accurately describe the behavior of the conversion of mechanical energy to electricity in a piezoelectric system. This value is then used as a basis for calculating the total energy generated from walking and climbing stairs activities in various building design configurations, Fig. 2.

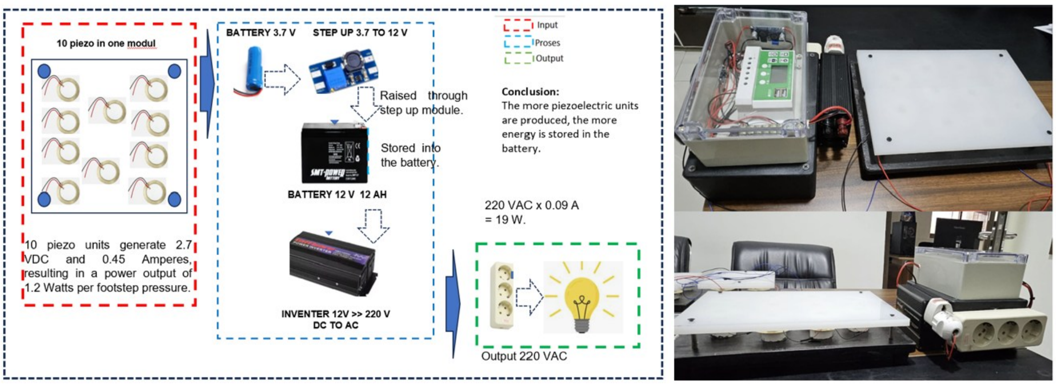

Fig. 2. Piezoelectric energy conversion scheme and prototype of energy capture module from footstep pressure.

This prototype piezoelectric system consists of a single module containing ten piezoelectric units assembled in a flat panel board. Each module produces approximately 2.7 VDC and 0.45 A when subjected to footstep pressure, resulting in a peak power of 1.2 W per stroke [27-28]. An average power value of 0.64 W per step was obtained through repeated testing and used as a reference for energy calculations in this study. The generated electrical energy is directed to the storage system through a step-up converter that raises the voltage from 3.7 V to 12 V and is then stored in a 12 V 12 Ah battery.

The stored energy is then converted to 220 VAC via a DC–AC *inverter* to power a resistive load equivalent to a 220 V, 19 W LED lamp. During the test, the system generated a stable voltage of 220 VAC with a current of 0.09 A, demonstrating the prototype's ability to supply low-power electrical needs such as corridor or stair lighting.

Although the output power of 19 W represents a single module, the system is designed to be modular and scalable, allowing the incorporation of multiple piezoelectric modules in a parallel or series configuration. This approach can increase the total voltage and current, making it potentially used for higher-power applications such as classroom lighting or IoT devices in campus environments.

This prototype serves as an empirical basis for calculating the energy output of walking and climbing stairs, while strengthening the validity of the energy conversion value used in the simulation stage. To illustrate the flow of energy conversion from human activity to electricity storage, the system is shown in the following Fig. 3.

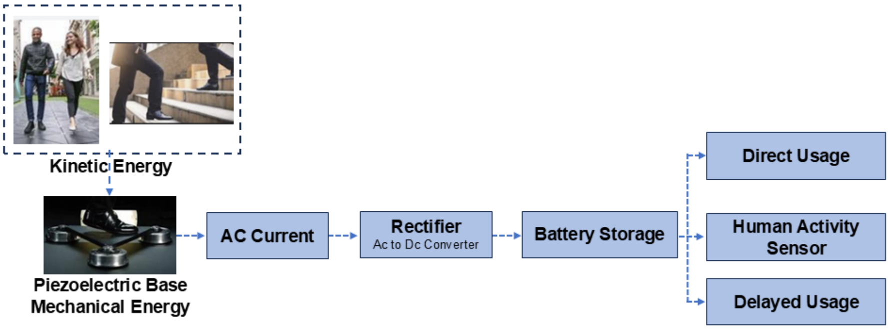

Fig. 3. Flow diagram of human kinetic energy to electrical energy Conversion through Integrated Storage and Utilization System.

Figure 3 shows the energy conversion system of walking or climbing stairs using a piezoelectric device. The mechanical energy generated from the foot pressure is converted into alternating electric current (AC) by the piezoelectric base. This current is then diverted to the rectifier circuit to be converted into direct current (DC), before finally being stored in the battery. The repair process uses a full-wave bridge rectifier consisting of four 1N4007 silicon diodes, followed by a 470 µF electrolytic capacitor as a DC filter to stabilize the voltage before entering the DC-DC step-up converter (3.7 V to 12 V). This configuration ensures stable energy conversion and minimizes power loss from the low-voltage AC output of the piezoelectric module. The stored energy can be used directly, fed to an activity sensor, or used later through an inverter. The system is designed to support energy efficiency in sustainable educational buildings. The amount of energy is calculated by multiplying the total number of steps per week by the average power per step, and then converted to kilowatt-hours [kWh] using the following equation:

$$E \frac{N\ x\ P}{1000\ x\ 3600} \tag{4}$$

where:

- E = total energy per week [kWh].
- N = total number of steps per week
- P = average power per step [W].

Calculations were carried out separately for two main types of activities, namely walking in the corridor and climbing stairs [27]. The energy outputs of the two zones are then summed to get the total weekly energy output generated after the implementation of the responsive design.

2.4. Reported Power Output Comparison

To address the variability of the reported piezoelectric energy harvesting performance under different conditions, Table 1 presents a comparison between the prototype used in this study and some previous studies. The average power per step reported in the literature ranges from less than 10 mW in the initial cantilever design to about 250 mW in recent diaphragm-based prototypes [28]. In contrast, this study prototype, consisting of ten piezoelectric elements in a 300 × 200 mm module, achieved an average power of 0.64 W (≈ 640 mW) and a peak power of 1.2 W per step. These values are within the upper range of existing studies and are consistent with the expected improvement due to the configuration of multiple sensors, optimized pressure distribution, and effective electrical connections. The comparison confirms that the parameters adopted for energy calculations are very realistic and empirically supported.

Table 1. Comparative review of the performance of different types of piezoelectric.

No.	Reference	Harvester Type	Tile Size [mm]	Reported Avg [mW]	Peak Power [mW]	Remarks
01	[29]	Piezoelectric	300 × 4300	6.04	9.5 – 12.1	Early design
02	[30]	PZN 0.5C Thick-Film Cantilever	200 × 200	12	18.8 – 24.0	Thin-film test
03	[31]	PZT Cantilever	430 × 430	1.24	1.9 – 2.5	Lab setup
04	[32]	PZT Cantilever	450 × 450	35	55 – 70	Multi-beam
05	[28]	Piezo Ceramic Diaphragm	455 × 405	249.6	| 391 – 499	MDPI (2024)
06	This study	10-sensor piezo module	300 × 200	640	1,200	Empirical prototype

The comparison shows that the values obtained (average of 0.64 W) are not assumptions or overestimates but empirically verified results that are within the upper limit of the current piezoelectric energy harvesting performance.

2.5. Effectiveness Criteria

Design effectiveness is measured through quantitative differences in energy output between pre-test and post-test conditions [33] Percentage improvement is used as an indicator of the success of architectural interventions in improving energy productivity. In addition, the analysis was carried out by comparing the concentration of activities in the strategic zones generated by each plan.

3. RESULTS AND DISCUSSION

This study produced a quantitative comparison between the existing design and the human-centred responsive design (RHC) in terms of step intensity and weekly energy output of the two main activities, namely walking in the corridor and climbing stairs. The calculation is based on the number of steps per week converted to electrical power using an average value of 0.64 watts per step, Table 2.

Table 2. Comparison of weekly energy output between existing layout and RHC design.

No	Parameter	Existing Floor Plan	RHC Floor Plan
1	Walking Activity		
	Total Steps Per Week	252,300 Steps	619,200 Steps
	Total Energy Per Week	161.47 kWh	396.5 kWh
	Energy Contribution Percentage	66,7 %	58.3%
2	Climbing Stairs Activity		
	Total Steps per week	52,065 Steps	283,362 Steps
	Total Energy Per Week	80.58 kWh	283.99 kWh
	Energy Contribution Percentage	33.3%	41.7%
3	Total Energy Per Week	242.05 kWh	680.49 kWh
4	Faculty Weekly Energy Construction	12.02%	33.79%

3.1. Walking Activities

Under the existing plan, walking activities generate 252,300 steps per week, which if converted generates 161.47 kWh/week, or accounts for 66.7% of total weekly energy. Once the RHC design was implemented, walking activity increased significantly to 619,200 steps per week, with an energy output of 396.5 kWh/week. Although the percentage contribution decreased slightly to 58.3%, in absolute terms there was an increase in energy of +145.5% in walking activities.

3.2. Climbing the stairs

Climbing stairs also experienced a sharp spike. Under existing conditions, 52,065 steps per week were recorded, producing 80.58 kWh/week or 33.3% of total energy. Meanwhile, in the RHC design, this activity increased to 283,362 steps per week, with an energy output of 283.99 kWh/week or 41.7% of the energy contribution. This shows an increase in stair energy up to +252.5% from the previous condition.

3.3. Total Energy and Design Effectiveness

Overall, the total weekly energy output increased from 242.05 kWh on the existing plan to 680.49 kWh on the RHC plan. This means that the implementation of human-centered responsive design has succeeded in increasing energy output by +181%. These significant improvements show that changes in space configuration geared towards optimizing user circulation, visibility, and connectivity not only impact mobility comfort and efficiency, but also directly contribute to the energy performance of buildings. This reinforces the urgency to integrate user-based architectural design principles in microenergy systems, especially in educational buildings that have a high volume of movement.

3.4. Faculty Weekly Energy Contribution

From the point of view of contributing to the weekly energy needs of the faculty, the existing design was only able to contribute about 12.02%, while the RHC design reached

33.79%. These improvements not only reflect the effectiveness of the design in the context of energy conversion, but also open up the potential for the integration of alternative energy systems in future educational buildings in a more scalable and sustainable way. The following is a bar diagram of the increase in activity and energy construction between the existing plan and the human-centered responsive design plan, Fig. 4.

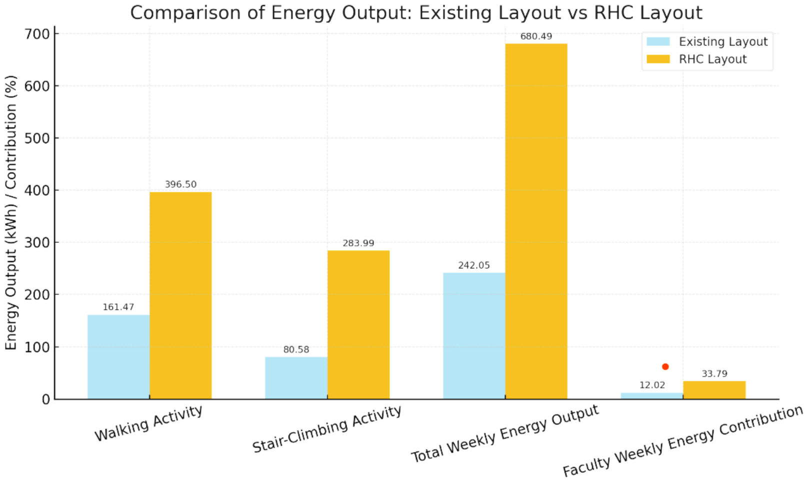

Fig. 4. Energy output comparison between existing plans and human-centered responsive design (RHC).

This comparison diagram shows a very significant increase in energy output in the Human-Centred Responsive (RHC) design compared to existing plans, both from walking and climbing stairs, which in total amount to almost three times the weekly output.

3.5. Technology Development Potential and Design Implications

The results of this study confirm that a responsive and human-centered architectural design approach plays an important role in increasing the effectiveness of energy utilization from user activities in campus buildings. A design that is able to direct the intensity of movement to strategic zones can significantly increase the potential of harvestable energy, without changing the number of users or increasing the load of activities. The energy output produced at 680.49 kWh per week is the result of spatial planning, circulation management, and the selection of zones with high spatial value. In this context, piezoelectric technology is used as a quantification instrument, not as the main focus. This means that the success of these systems depends on how the design facilitates and directs physical activity efficiently.

In the future, this approach can be further developed by integrating user behavior-based design concepts into the campus sustainable energy ecosystem. Systems such as campus microgrids can combine results from various renewable energy sources, including from human activities, to support energy distribution efficiency. Technology support such as IoT sensors, real-time monitoring systems, and battery storage will complement the design function in creating an adaptive, self-contained, and future-oriented building.

3.6. Limitations and Recommendations

This study used a quantitative approach to analyze the energy output generated from walking and climbing stairs, based on the number of user steps and the average power of 0.64 W per step obtained from the testing of the piezoelectric prototype. This value represents the average power derived from the peak of 1.2 W per step and is influenced by the technical factors of the device as well as the user's body mass (70–75 kg) as a controlled variable. While temperature and humidity were considered to have minimal effect, a value of 0.64 W/stroke was applied consistently to pre- and post-design conditions to maintain the validity of the results comparison.

The main focus of this research is not on improving the technical efficiency of piezoelectric systems, but on the role of responsive architectural design in optimizing the circulation pattern and distribution of user activities in campus buildings. However, this study has several limitations, including the assumption of homogeneity of user movements, the use of average parameters that do not cover all population variations, and the absence of direct system implementation tests in the field.

For further development, it is recommended to carry out field validation through the installation of actual systems, long-term monitoring of the dynamics of user movements, and the application of similar methods to other campus building typologies. In addition, an economic feasibility analysis between design and energy conversion technology needs to be carried out so that this activity-based design approach can be applied as an alternative energy-based sustainable architecture strategy.

3.7. Design Effectiveness Hypothesis Test

To assess the effectiveness of the application of human-centered responsive architecture design in increasing the energy output of user activities in campus buildings, a hypothesis test was conducted using the Wilcoxon Signed-Rank Test method, which was chosen because it was suitable for analyzing data paired with non-parametric distributions Table 3.

The hypotheses tested are as follows:

H_0: There is no significant increase in energy output between the existing plan and the human-centered responsive plan.

H_1: There is a significant increase in energy output between existing plans and human-centered responsive plans.

Table 3. Wilcoxon hypothesis test results/ hypothesis test summary.

Null Hypothesis	Test	Sig.	Decision
The median differences between Total Existing Week Power kWh and Total RHC Week Power kWh equals 0.	Related-Samples Wilcoxon Signed Rank Test	0.028	Reject the null hypothesis.

The test results showed a significance value (Sig.) of 0.028, which is smaller than the significance level $\alpha = 0.05$. Based on these results, H_0 was rejected and H_1 was accepted, so it can be concluded that there was a statistically significant increase in weekly energy output after the implementation of human-centered responsive design. These findings corroborate previous quantitative results that user-based design not only changes movement patterns but also has a real impact on improving energy conversion from human activities. Statistically, RHC designs have proven to be more effective in directing movement to strategic zones and increasing the potential for energy harvesting in campus buildings.

4. CONCLUSION

This study evaluates the effectiveness of human-centered responsive architectural design in increasing the energy output of walking and climbing stairs in campus buildings. A quasi-experimental approach was carried out by comparing the energy output between the existing plan and the design resulting from the architectural intervention, using the estimate of the actual number of steps and the power calculation from the piezoelectric prototype. The results showed a significant increase in total energy output, from 242.05 kWh to 680.49 kWh per week, which was mainly due to the redistribution of movement to strategic zones as a result of design optimization. Statistical validation using the Wilcoxon Signed Rank Test gave a significant value of 0.028 ($p < 0.05$), confirming that the increase in energy was not accidental, but the result of a design change. Thus, it can be concluded that architectural design that is responsive to user behavior patterns has a real contribution to improving the effectiveness of human activity-based energy conversion systems. This research emphasizes the importance of integrating human-centered design strategies in supporting the vision of sustainable campus architecture, where design is not only a forum for activities, but also an energy-producing instrument.

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