Efficiency and Feasibility Analysis of a Renewable Energy Generation System based on Piezoelectric Principle

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Abstract

This research analyzes the possibility of generating renewable energy from the kinetic energy generated by people walking on tiles equipped with piezoelectric sensors. The main objective is to determine the efficiency of this system and its ability to reduce conventional electrical energy consumption. The study is based on a review of existing literature and the construction of a piezoelectric tile prototype. Tests and measurements are performed to evaluate the power generation and improvements in the prototype design are proposed. The results show that the system is feasible and that the power generation is adequate to cover the electrical energy demand in a specific environment. It is concluded that the implementation of this system can be cost-effective and beneficial to reduce conventional energy consumption.

Keywords
Renewable energy, Clean energy, Piezoelectric, Piezoelectric effect and Tiles

1. Introduction
Today, thanks to human capacity, the development of various societies with great achievements in various fields has allowed the survival and comfort of the population. However, this only sometimes considered the impact of industries and everyday tasks on Earth. Given this, the question arises about the efforts and possible improvements that help to reduce the environmental impact they generate. One of the fields with the most significant effect on environmental deterioration is the energy generation industry since it uses non-renewable resources. In consequence, the dissemination and innovation of clean solutions is sought. However, it is necessary to consider some factors, especially if these will be implemented in cities, such as the factors: economic, existence of the resource, efficiency for the utilization, and social and environmental factors (Barragán-Escandón et al., 2019). If developed and utilized efficiently, renewable energy sources will go a long way toward providing energy security, ecological employment, and sustainable growth and development (Maji, 2015).

Following a review of the relevant literature, a technology capable of generating energy was identified, allowing a society to meet its requirements. Energy harvesting (EH) is a technique for collecting and generating energy from diverse sources, such as mechanical stresses and vibrations. Due to the pervasiveness of motion and vibration, mechanical energy harvesting technology has attracted considerable interest (Ali et al., 2021). The energy research works on a tile prototype that has installed piezoelectric sensors that make possible energy transformation when people step on it. Also, a system capable of reducing or eliminating negative environmental impacts is recommended. In 2018, Martínez and Alcántara (2019) demonstrated a 3.8% increment on using clean energies.

In addition, even though the Multidimensional Energy Poverty Indicator (MEPI) has progressively decreased, Coello et al. (2018) declare there are still approximately 7.3 million Peruvians who still do not have access to electricity. Gouveia et al. (2019) demonstrate that energy poverty vulnerability assessment at such a disaggregated regional scale could bridge the divide between conventional country-wide analyses and local-scale initiatives aimed at vulnerable households. Therefore, it would be essential to develop the term prosumer, which refers to a person who engages in eco-friendly behaviors not only in economically advantageous situations but also daily throughout their entire lives. Promoting prosumers can be extremely advantageous for society as a whole; it will contribute to an increase in pro-environmental behavior. This will reduce energy consumption not only in private residences but also in hotels and businesses. Due to this, it should be a top priority for local governments to encourage environmentally conscious behavior and increase the number of prosumers producing sustainable energy and heat (Ali et al., 2022). However, one should utilize low-tech, which entails implementing and utilizing innovative solutions that are simple to develop within the constraints of available resources. Consequently, the fundamental criterion for a solution to be low-tech is not its monetary cost, but rather a combination of satisfying the fundamental requirements of the local community, utilizing local resources, being readily replicable, and being environmentally sustainable (Bozena et al., 2022).

As a result of this problem, the following research question was raised: How could implementing a new renewable energy system based on the piezoelectric principle reduce the consumption of conventional electrical energy? In the same way, the defined hypothesis is: After applying energy-collecting tiles, which follow the piezoelectric principle, it would be possible to reduce the consumption of conventional electrical energy. The main purpose of the investigation to be carried out is to determine the efficiency of the built system. On the other hand, the specific objectives set are to determine the cost-benefit of the energy-collecting tiles and reduce the cost per consumption thanks to their use.

1.1 Objectives

The main purpose of the investigation to be carried out is to determine the efficiency of the built system. On the other hand, the specific objectives set are to determine the cost-benefit of energy harvesting tiles, the design limitations that this energy source would have, and the productivity of the proposed mechanism.

2. Literature Review

The piezoelectric effect converts mechanical energy in the form of vibration in the environment into electrical energy, namely alternating current (AC) (Edla et al., 2022). The model under study follows the principle of this effect, which occurs in certain crystals when subjected to mechanical stress, acquire an electrical polarization and a potential difference and electrical charge appear on their surface (Vega, 2021).

It should be noted that the tiles to be installed do not require the person to make an additional effort to walk on them. A tile has several disks installed inside. When activated by pressure on it, they generate quasi-static charges because they produce positive and negative voltage spikes, which are adequate with a rectifying diode (Flores, 2020). Once the mechanical energy has been transformed into electricity by the piezoelectric disc, it is conducted through the cable circuit to a battery, where it is stored and/or connected to the lighting or equipment that will be powered by it.

An average of up to 3.6 W can be obtained by efficiently distributed piezoelectric, with a peak of 12 W, and the average energy collected is 1.8 J per step (Liu et al., 2018). This system will influence the monthly cost of electricity consumption since it will decrease; however, the investment must be considered. According to Benavente (2020), the cost-benefit obtained in his simulation is 5.56 PEN for each 1 PEN invested. Likewise, for a good understanding and development of this research, it is essential to define the following concept: renewable energies, according to Martínez and Alcantara, (2019):

The so-called alternative or inexhaustible energies take advantage of the kinetic energy present in nature. For example, such as solar energy is used by solar panels (photovoltaic); the action of the wind uses wind power; geothermal energy is used of underground energy and bioenergy based on sustainable agriculture such as dry wood.

On the other hand, the primary material to be used to develop this model is piezoelectric discs. These elements transform a physical magnitude into an electrical signal by direct effect. It should be noted that the phenomenon that uses this material, piezoelectric, works mainly by mechanical vibrations.

When the sensor undergoes stress, the level of electrical charge will depend on the electromechanical material's strength, characteristics, structure, and performance (Cao et al., 2018).

After reviewing the literature of the last five years, exceptional application cases could be collected. One of them is the implementation of these piezoelectric discs in a voltage double boost converter (VDBC) circuit where the built prototype converted a 1.25 Vac and 100 Hz input AC voltage to 1.11 Vdc with an output power of 12.321 µW (Deguchi et al., 2023). Another application in which the use of the kinetic energy of the human body is achieved can occur when a person rests on a bed. According to what was developed by López and Prudencia (2020), 2.4 A, 12 V was obtained, with a power of 28.3 W after collecting the energy generated throughout a night, in which the volunteer had to sleep on discs installed on a box spring. Among the notes in the development of the prototype, the use of a full wave rectifying diode that takes advantage of the polarity produced in the disk, for the generation of electrical energy, is highlighted. As well as the determination if the installation should be given series or in parallel, considering its action of sum of voltages and sum of amps, respectively. Also, it is important to highlight the factor of the size of the discs, to determine the best efficiency, even though they have the same thickness. As well as confirm that, at smaller effective areas with a greater thickness, a higher energy register will be obtained. As Manayay (2020) did, who worked with effective areas of 17 mm and 23 mm, both with a thickness of 0.33 mm, the results obtained were 23.15 V and 12.66 V, being the ideal for working with the second voltage.

On the other hand, other papers were found with a development like the present study, and they are beneficial because they allow taking into account some limitations found in their models or additional systems, which increase their use. For example, when following a cantilever beam-type structure, it is advisable to apply a rapid unloading of force to cause deformation in the structure, to free it from environmental vibrations, and improve efficiency (Wang et al., 2021). Likewise, some research refers to using self-sustaining wireless sensors in the system, which allow the control or measurement of certain variables in specific environments (Aranda et al., 2021). To complement the previously described proposal, Ahn et al., (2018) detail a piezoelectric tile system that produces 42 V and 52 μA. This model feeds a wireless transmitter sensor and a switch module, which receives electrical energy. In this way, when the system is activated by receiving a footstep, the sensor allows the lighting installed in the structure to activate.

Edla et al. (2023) presents a bent branched bean harvester (BBBH) prototype where the highest average power of 786 μW was obtained at 4 Hz during the shaker test and 813 μW during the human motion test (running). A last case of similar application is evidenced by Jintanawan et al. (2020) in the developed prototype, a tile energy generation mechanism is followed through a generator, which converts the mechanical energy put into it to electrical energy. The result was a generation of 2 Watts per step, collected for storage in batteries and other devices.
It is also worth mentioning that the 6-mm displacement also falls within the range recommended by the Americans with Disabilities Act (Liu et al., 2018).

2.1 Piezoelectric Effect

Edla et al. (2023) note that numerous studies have been conducted to investigate micro-energy harvesting alternatives to conventional batteries. Mechanical motion has emerged as a primary energy source in recent years and has been extensively investigated for micro-energy harvesting. Electrostatic, electromagnetic, triboelectric, and piezoelectric transduction are prominent mechanical energy-based mechanisms for energy transfer.
Cao et al. (2018) state that piezoelectric energy harvesting technology employs electromechanical coupling of piezoelectric materials, thereby directly converting mechanical energy to electrical energy. These are electrically charged when subjected to stress, with the amount of electrical charge determined by the force, characteristics, electromechanical coupling performance of piezoelectric material, and structure.
Liu et al. (2018) state that human walking exerts a 500–1000 N dynamic force on the ground. As the piezoelectric effect dictates, electrical energy will be produced in proportion to the quantity of force applied above the constructed prototype.

2.2 Piezoelectric Materials

High energy density and a high transduction coefficient (Ahn et al., 2018) are required to enhance the application of piezoelectric materials in energy harvesting. Core components of piezoelectric energy harvesting are piezoelectric materials; advances in materials research determine the energy collection efficiency. (Cao et al., 2018) The energy density of the material parameters of piezoelectric voltage (g) and the piezoelectric strain coefficient (d) multiplied by (d * g). Typical piezoelectric materials include zinc oxide nanorods (ZnO), barium titanate (BaTiO3), and lead zirconate titanate (PZT). Among these candidates, ZnO nanorods have demonstrated exceptional efficacy owing to their distinctive properties (Ali et al., 2022). In this sense, the selected piezoelectric material is a sensor ceramic containing zinc as its primary component.

2.3 Energy harvesting

Off-grid power supply for sensors used in smart infrastructure, structural health monitoring, and environmental sensing could rely heavily on energy harvested from the surrounding environment. Researchers have been concentrating on harvesting energy from the interaction between a person's foot and the ground for quite some time. The MIT Media Lab's energy-harvesting footwear demonstrated this capability (Liu et al., 2018).

In addition, numerous studies have been conducted on piezoelectric energy harvesters for powering battery-free wireless sensor nodes. It is crucial to note that Piezoelectric harvester circuits should be designed with the reduction of circuit components in mind in order to save chip area and money (Chen et al., 2021). Given their compact size, low cost, and high efficiency in harvesting ambient mechanical energy (Ahn et al., 2018), the goal is to develop a tile capable of harvesting the kinetic energy of human footfall.

3. Methods

As previously developed, this research is based on the following proposed model, visible in Figure 1. The construction process of the prototype was led by the understanding of the piezoelectric effect and its core component, as well as the energy harvesting theory.

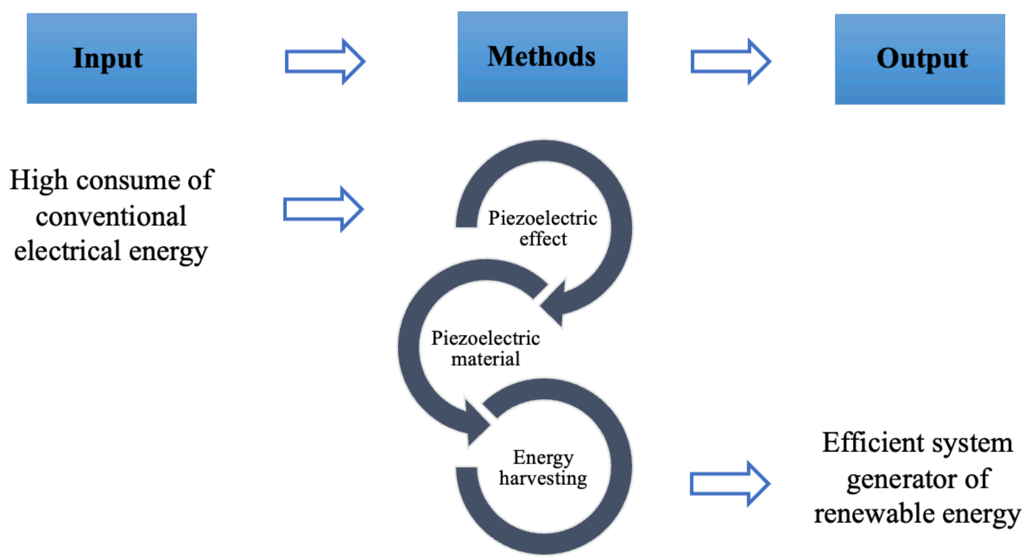

Figure 1. Proposed model

To verify the efficiency of the proposal, its construction was carried out. Materials implemented are listed below (Table 1):

Table 1. List of materials, prices and quantities

Material	Amount	Unit cost (PEN)	Total Cost (PEN)
35 mm piezoelectric disks	24	2.50	60.00
Full-wave rectifier diode KBP 206	1	2.80	2.80
15 mm thick OSP wood	0.33	120.00	39.60
Solder paste	1	13.73	13.73
Hot silicone	10	1.00	10.00
Tin	2	1.27	2.54
10 meters of red	10	0.34	3.40
10 meters of black wire	10	0.34	3.40
Insulating tape	1	6.90	6.90
Fat	1	4.00	4.00
Springs	12	0.50	6.00
Guides	12	0.50	6.00

Screws 1/2x40mm	24	0.15	3.60
Led spotlights	3	0.17	0.51

Likewise, the instruments are the following:

- Voltmeter: It will determine the power in the circuit.
- Scale: It will allow measuring the body mass of the participants.
- Measuring tape: Used to determine the height of the proposed participants.
- Soldering iron: It will be used to join the wires with the piezoelectric disks.
- Drill: Holes will be drilled for the passage of the wires and for screwing the wood of the lower and upper bases.
- Silicone gun: It will be used to melt the silicone bars.

Subsequently, the construction of the prototype began; previously, the collected sources were reviewed to determine the size of the piezoelectric tile to be used, in this case, 40 cm x 40 cm.

First, the required measurements were marked on the wood to determine the number of piezoelectric tiles, springs, and guides to use and their location. Simultaneously, cardboard circles were cut out to be placed under the piezoelectric in the wood so that they would support the pressure of the weight on them. However, when different tests were carried out, it became evident that the cardboard was worn out due to weight and use. Therefore, an attempt was made to try a material with more excellent resistance, so tests were made with polyurethane foam. However, since the material had a higher density, it did not allow the sensor to work properly. Thus, it was concluded that the best method for good performance and care of the sensors would be to make holes the size of the ceramic on the surface of the wood (Figure 2).

Figure 2. Piezoelectric disc placement process

Similarly, the 12 springs to be placed in the wood required recesses in the surface, with a depth of about 1 cm (Figure 3) Surface. This so the final height of the compression allows a good reading on the sensors. Likewise, for the wood to descend in a balanced manner, 12 guides were used, located in the upper wood of the tile, and fit into their respective holes in the lower one; these were greased for smooth sliding. The wires that allow the circuit to be connected also needed holes to pass through, which were made with a drill. These holes go all the way through the bottom wood. It was done this way to have more order in the circuit and to avoid pressure on them.

Figure 3. Design of springs and guides and of the wiring system

On the other hand, screws were placed in the upper wood so that when the head descended, it would have direct contact with the piezoelectric ceramic. Also, pieces of wood were screwed to the sides of the base. Next, we soldered the wires of 2 colors: red to the ceramic and black to the metallic part; in each sensor. This was done to distinguish the current, where two positive and negative outputs were obtained at the end.

In the beginning, the connection was in parallel and by groups of 11 and 13 sensors; however, after testing, it became evident that the current did not add up, and the results between groups varied. The result was negative because, having a parallel connection, the value to be obtained will be that of the first contact, which is not always the highest. Afterward, it was decided to test the series connection; however, the result was also negative since, not having strong intensity, they did not add up correctly. Consequently, it was decided to assemble the connection in a group of 4 sensors and four groups of 5 sensors, in which the connection is in series and parallel. The parallel groups are:

- Group 1: 1-5
- Group 2: 6-10
- Group 3: 11-15
- Group 4: 16-20
- Group 5: 21-24

The series connections are groups 1 and 2, groups 2 and 3, groups 3 and 4, and groups 4 and 5. After making the aforementioned connection, it was connected to a full-wave rectifier, which allows us to obtain a direct current; parallel to this, a set of cables was connected, which would allow us to measure the alternating current of the piezoelectric. After the rectifier, three green LED lights were connected, which light up every time the tile is stepped on, and a set of cables, which allow us to measure the direct current voltage emitted by the prototype (Figure 4).

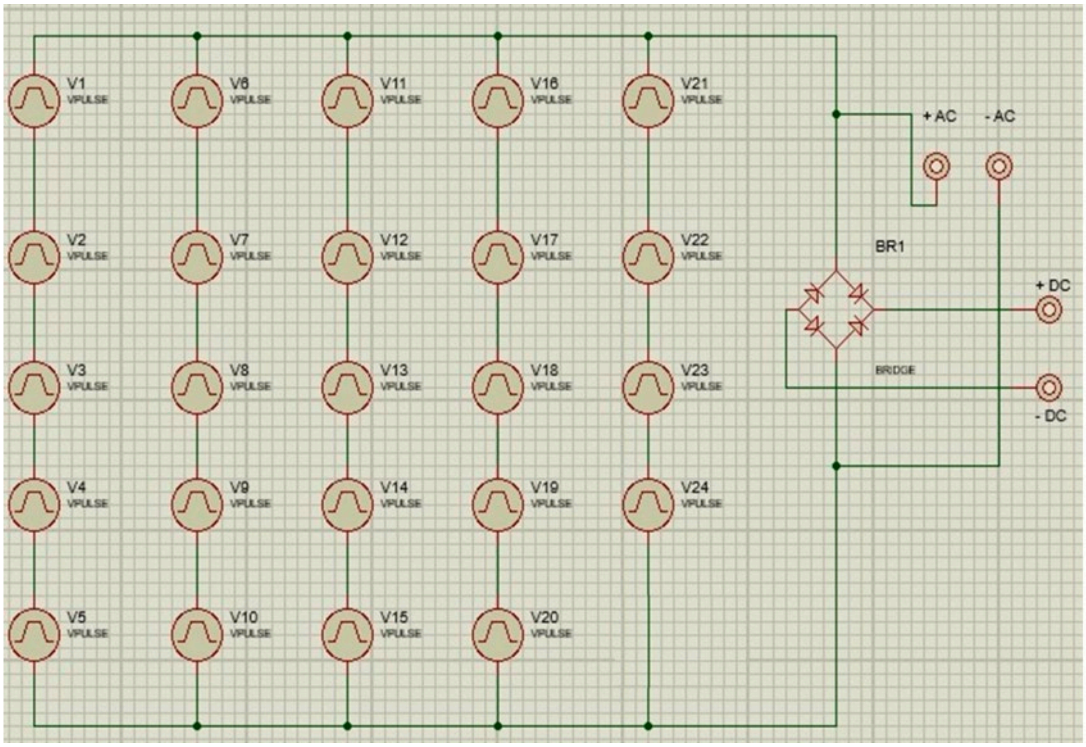

Figure 4. Piezoelectric circuit design

Additional wood was placed under the lower base to protect the cables when the connections were completed.

4. Data Collection

The population selected for this research are men and women older than three years who live in Lima, preferably in the district of Santiago de Surco or neighboring districts.
The formula to obtain the number of people necessary; considering that we have a population of 150 people per hour who enter the Multicenter Benavides on a day with a higher frequency of public was.

$$\frac{N \cdot Z^2 \cdot p \cdot q}{e^2 \cdot (N-1) \cdot Z^2 \cdot p \cdot q}$$

Z = 1.96
q = 0.15
p = 0.85
N = 105
e = 0.05

The sample obtained was 81 people, 32 men and 49 women.

5. Results and Discussion

5.1 Numerical Results

After having calculated the necessary sample, having collected first-hand information, for compilation are obtained through research (Torres et al., 2020), directly to the object of study, through established methods, and having built the prototype. The measurement of 81 footprints was carried out. At the end of these measurements, a model was built, with the purpose of simulating a month of use in the "Multicenter Benavides". For this, 3 routes were proposed that people could take, the first consists of 70 tiles, the second of 50 tiles and the third of 30 tiles. Each had a pass rate of 20%, 30%, and 50%. Since, according to what was observed in the locality, there was a greater probability that people go to buy something punctual; therefore, take a short tour (Figure 5).

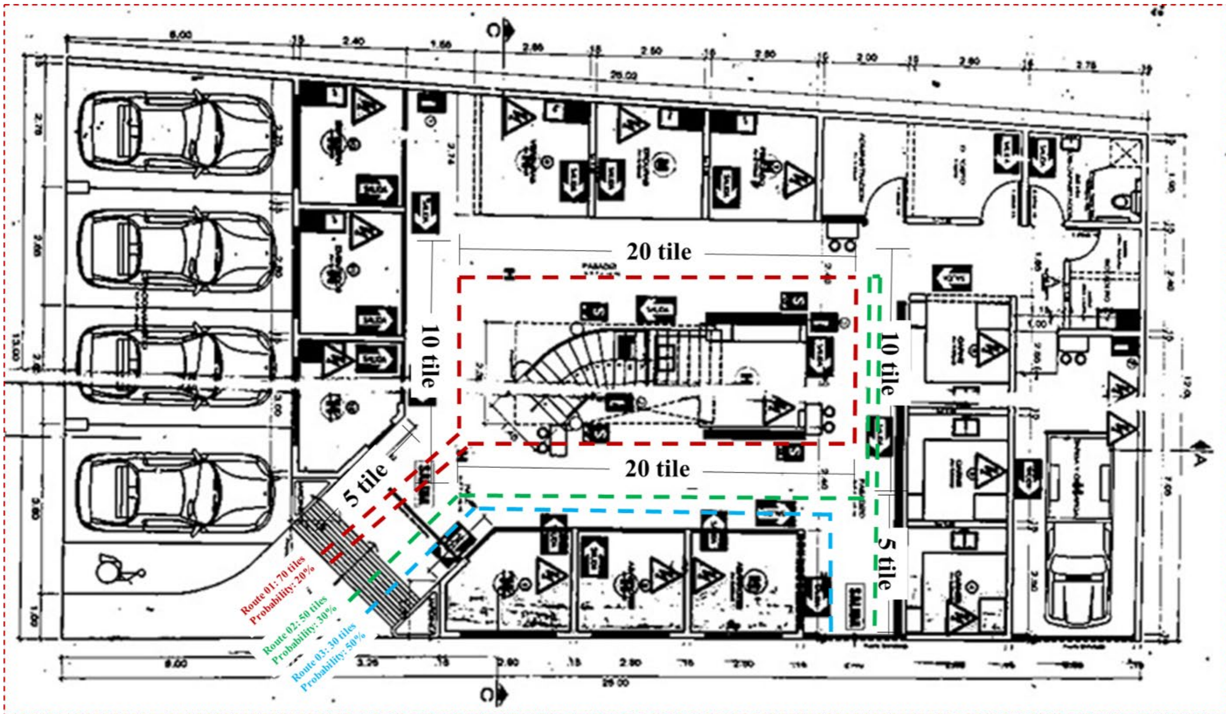

Figure 5. Simulation layout

Considering that the marketplace isn't busy the same every day and hour. It was determined to establish 'rush hours' for the simulation. For that, the following variables were taken into consideration:

- Number of entities that arrive: 140
- Number of tours: 3
- Total number of tiles: 150
- Interval between arrivals (seconds): 15
- Weight of individuals entering: Between 45 to 99 kilograms.
- Volts per Kg ratio: 0.03

To calculate the volts per kg, the following formulas were used.

$$\frac{\Sigma\, Volts\ generated}{\Sigma Weights\ of\ all\ the\ people} = \frac{152.28}{5308.3} = 0.03$$

In this case, the proportion will be multiplied by the weight of the person and the number of tiles. For example, if the person has a weight of 60 kg and walks 10 tiles, this person will generate 18V.

$$60 \cdot 10 \cdot 0.03 = 18$$

Furthermore, weight is the force exerted on a support point of a body, in this case the built tile. As confirmed by the following formula.

$$P = m \cdot g$$

- P = Force (N)
- m = Weight (kg)
- g = Gravity (9,8 m/s2)

For example, a person who weighs 60 kg generates greater force than someone who weighs 45 kg (Table 2).

Table 2. Example force formula

60 kg	**45 kg**
P = 9.8 * 60	P = 9.8 * 45
P = 588 N	P = 441 N

After doing the corresponding analysis, the simulation was carried out in the arena, which is programmed for the passage of 140 people in 1 hour, these have random weights between 11 kg and 100 kg. As can be seen Figure 6, the first route contains 35 tiles, the second has 25 tiles and the last 7. This is because the program has a limit of operations to have; Therefore, in the first rounds the tiles use a ratio of 0.06 (double the calculated one), while in the last one they use a ratio of 0.13. Likewise, each route has a counter whose purpose is to count the people who passed through that route, the sum of their weights and the sum of the voltages of each step of the people. Finally, there is a fourth counter whose purpose is to find the 3 indicators of the previous counters, but for the entire circuit.

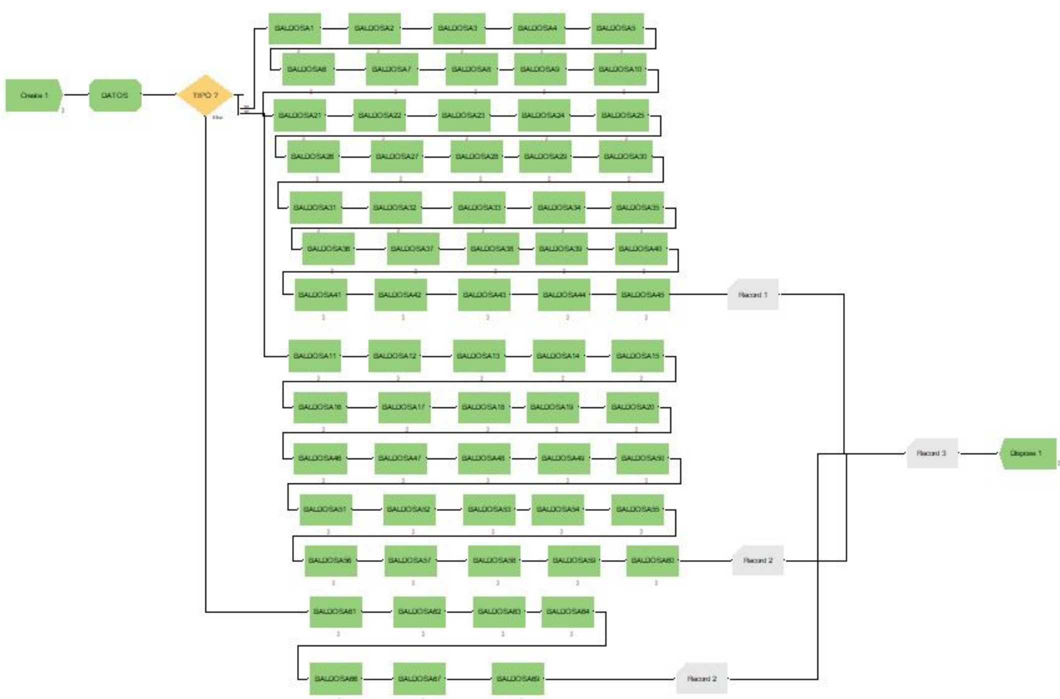

Figure 6. Simulation layout

After performing a simulation for 1 hour with 140 people, it was obtained that for the first run 3544.8 V, for the second run 4401 V and for the last run, which consisted of fewer tiles, 35440.8 V were collected, the data obtained is (Figure 7):

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                              Summary for Replication 1 of 1

Project: Unnamed Project                                      Run execution date :12/18/2022
Analyst: HP                                                   Model revision date:12/18/2022

Replication ended at time      : 3600.0 Seconds
Base Time Units: Seconds

                                       TALLY VARIABLES

Identifier                           Average   Half Width  Minimum    Maximum   Observations
____________________________________________________________________________________________

PERSONA.VATime                       60.321     (Insuf)    37.500     105.00        140
PERSONA.NVATime                      .00000     (Insuf)    .00000     .00000        140
PERSONA.WaitTime                     .00000     (Insuf)    .00000     .00000        140
PERSONA.TranTime                     .00000     (Insuf)    .00000     .00000        140
PERSONA.OtherTime                    .00000     (Insuf)    .00000     .00000        140
PERSONA.TotalTime                    60.321     (Insuf)    37.500     105.00        140

                                  DISCRETE-CHANGE VARIABLES

Identifier                           Average   Half Width  Minimum    Maximum   Final Value
____________________________________________________________________________________________

PERSONA.WIP                          2.3458     (Insuf)    .00000     140.00     .00000

                                          COUNTERS

Identifier                             Count   Limit
_______________________________________________________

peso total                              9879  Infinite
Counter tipo 3                            74  Infinite
Counter tipo 2                            42  Infinite
Counter tipo 1                            24  Infinite
Counter total                            140  Infinite
Counter peso1                           1688  Infinite
Counter peso2                           2934  Infinite
Counter peso3                           5257  Infinite

                                          OUTPUTS

Identifier                           Value
_______________________________________________________

IND VOLT TIPO1                       3544.8
IND VOLT TIPO2                       4401.0
IND VOLT TIPO 3                      4731.3
PERSONA.NumberIn                     140.00
PERSONA.NumberOut                    140.00
System.NumberOut                     140.00
```

Figure 7. Arena results

The power of the continuous current circuit is then calculated, supported by the following formula:

$$P = V \cdot I$$

P = Power (W)
V = Volts (V)
I = Intensity (A)

Table 3. Results

Descrption	Value
Sum of Volts (V)	12677

Footfalls in total (#)	6000
Average volts per step (V)	2.1
Total system weight (kg)	9879
Number of people	120
Current intensity (A)	0.4
Sum of watts(W)	5071

In this simulation it will be saved 40 PEN in one hour, because the KW.h in Peru costs 0.784 PEN.

$$\frac{0.784\ PEN}{KW.h} \cdot 5.071\ KW = 40\ \frac{PEN}{h}$$

As previously mentioned, the obtained numbers are the result of a 'rush hour' of occurrence in "Multicentro Benavides". In a real practice, configurated conditions would have to be equal or higher to obtain the same benefit or a better one.

5.2 Graphical Results

One of the ways to verify that the piezoelectric tile was in operation is to turn on the green LED lights that can be seen at the bottom. Likewise, a voltmeter which allowed measuring the electricity that was generated every time a person stepped on the tile. As you can see in the image below (Figure 8).

Figure 8. Piezoelectric tile working

5.3 Proposed Improvements

A proposal for improvement in tile design has been identified in reference to the material that protects the system, wood. By nature, wood is not a waterproof material and is not easy to maintain. Therefore, it is recommended to use a material that provides the necessary protection to achieve a full life cycle and avoid additional costs for reactive maintenance. As demonstrated by Pavegen (2023), the power generation system is fully covered and protected by a material that can withstand the most extreme weather conditions found anywhere in the world.

5.4 Validation

Next, the analysis of the results obtained based on the proposed objectives will be developed. As principal, it was proposed to determine the efficiency of the tile; for this, it will be measured in volts per person. As observed in Table 3, choosing route 1, made up of 70 tiles, generates 147.67 volts per person. While for the second tour, 104.79 volts per person was obtained, considering 30 tiles. Finally, in the third tour, 63.94 volts per person was obtained. Thus, concluding, an efficiency of 316.4 volts per person.

10 peak hours and 74 standard hours a week are considered, as well as an input of 140 and 30 people per hour, respectively. Considering a conversion of 4.3 weeks per month, 394131.12, 489328.33, and 526052.97 volts were obtained for the first, second and third tours, respectively. If an intensity of 0.4 A is maintained in all the routes, a total of 563.8 KW per month would be generated. This allows us to verify the viability of the tile since the "Multicenter Benavides" consumes an average of 450 KW per month.

Likewise, it seeks to identify the benefit-cost of the tile, which has a cost of 10,000 PEN for the implementation of 50 tiles, which have a useful life of 10 years. For the "Multicenter Benavides," 200 rafts of 40 cm x 40 cm would be needed, thus having an investment of 40,000 PEN and a cost-benefit of 1.30. A simple energy metering rate 1E is used, which has a cost of charge for active energy of 0.784 PEN/KW.h, with this obtains that the "Multicenter Benavides" has an energy charge of 434.34 PEN per month; that is, 5212.03 PEN per year.
Likewise, it seeks to identify the benefit-cost of the tile, which has a cost of 10,000 PEN for the implementation of 50 tiles, which have a useful life of 10 years. For the "Multicenter Benavides," 200 rafts of 40 cm x 40 cm would be needed, thus having an investment of 40,000 PEN and a cost-benefit of 1.30.

6. Conclusion

To conclude, it is determined that the application of the prototype under study is feasible because the test and confirmation of positive results in the analysis of the objectives are achieved.
Regarding the main objective, after comparing the results of the three runs. It is concluded that the first case has an efficiency of 316.4 volts per person, which allows covering in its totality the demand of KW for the "Multicenter Benavides".
Similarly, it can be concluded, based on the results of the specific objectives, the feasibility of the implementation, since the cost of conventional energy consumption is wholly eliminated since the capacity of kW generation per month is greater than what is consumed monthly in the market.
Finally, a cost-benefit of 1.3 is obtained. This means that for each tile invested for ten years, there will be a return of 1.3.

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