sustainability

Article

The Sedentary Process and the Evolution of Energy Consumption in Eight Native American Dwellings: Analyzing Sustainability in Traditional Architecture

María Jesús Montero Burgos [1,*], Hipólito Sanchiz Álvarez de Toledo [1], Roberto Alonso González Lezcano [2] and Antonio Galán de Mera [3]

1 Facultad de Humanidades y Ciencias de la Comunicación, Campus de Moncloa, Universidad San Pablo-CEU, CEU Universities, 28040 Madrid, Spain; hsan@ceu.es
2 Escuela Politécnica Superior, Montepríncipe Campus de Boadilla del Monte, Universidad San Pablo-CEU, CEU Universities, 28040 Madrid, Spain; rgonzalezcano@ceu.es
3 Facultad de Farmacia, Montepríncipe Campus de Boadilla del Monte, Universidad San Pablo-CEU, CEU Universities, 28040 Madrid, Spain; agalmer@ceu.es
* Correspondence: mar.montero@ceindo.ceu.es

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Abstract: According to the research developed by André Leroi-Gourhan in 1964, entitled "Gesture and speech", the evolution of human beings during Prehistory was linked to the search for work efficiency. As time passed, man designed increasingly complex tools whose production implied a decreasing amount of energy. The aim of the present research was to determine if this evolution, which occurred in parallel to the sedentary process, also affected architecture, specifically if it can be detected on traditional dwellings, particularly in those built by the Native American Indians during the pre-Columbian period. Due to their great diversity, since both nomad and sedentary models can be found among them, and to the available information about their morphology and technical characteristics, these models offer a unique opportunity to study the consequences of this process for architecture. In order to achieve it, an alternative parameter that can be determined for any type of building was designed. It allows us to establish the amount of energy an envelope is equal to. The results obtained suggest that the efficiency of the dwellings decreased as this process went forward, but this pattern changed in its last step, when agriculture appeared and permanent settlements started to be built. Besides, statistical graphs were used in order to show graphically the relationship between it, the climate, the morphology of the dwellings and their technical characteristics.

Keywords: vernacular architecture; sustainability; energy efficiency; history; statistics; society

1. Introduction

Native American architecture offers a unique opportunity to reconstruct the dwellings used and designed by the prehistoric communities. When the European explorers arrived in America at the end of the 15th century, they found a world that was already impossible to reconstruct in Europe [1]. By means of the information contained in their chronicles, the dwellings built by the communities that inhabited those lands can be reconstructed. They also show that their lifestyles ranged between nomadism and sedentarism, comprising a great variety of systems as a result of the combination of both of them. However, sedentarism is considered the final step of this process which continues until today and which was consolidated with the construction of the first settlements.

Studying the evolution of culture during Prehistory, the anthropologist and historian Leroi-Gourhan [2,3] published research in 1964 which contained a graph about the evolution of flint tools. That graph showed that, as millennia went by, the amount of flint used to obtain each point decreased as the resulting sharp increased. This way, he demonstrated that the evolution of human beings was determined by the efficiency improvement at work. In parallel to this transformation, the sedentary process had gone forward and each community had chosen a different system to live in, as the North America of the 15th century shows [4].

This way, it is viable to understand that the sedentary process went forward according to the pattern found by Leroi-Gourhan. Proceeding on this basis, the aim of the present research consists in determining if that pattern can also be found in the evolution of the dwellings which were designed during the sedentary process that took place throughout Prehistory in North America. In other words, if the evolution from the nomad dwellings to the sedentary models pursued an improvement on energy efficiency.

In order to achieve it, eight of the most relevant dwellings built by the North American natives were analyzed. The dwellings which were chosen are the tipis, used by tribes such as the Crow or the Sioux [4–18]; the wigwams built by the Ojibwa or the Chippewa [4,19–25]; the Navaho hogans [4,22,26–31]; the Caddoan grass houses [1,4,32–35]; the earthlodges built by the Mandan, the Hidatsa and the Arikara [4,22,36–38]; the plank houses used by the Haida [4,39–46]; the Iroquois longhouses [4,20,21,47–54]; and the pueblos, specifically one of the adobe houses built in Acoma [55–60]. Each one corresponds to a different step of the sedentary process (Figure 1).

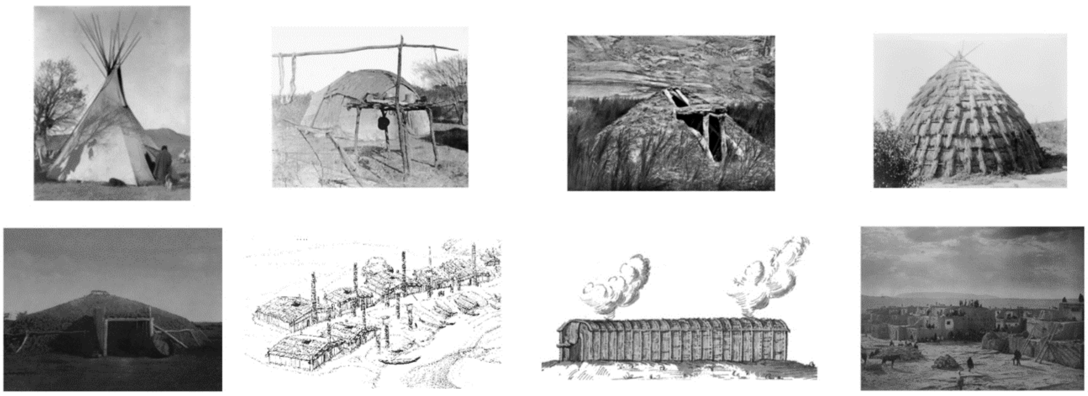

Figure 1. The dwellings that were analyzed. First row, from left to right: tipi [61], wigwam [62], hogan [31] and grass house [61]. Second row, from left to right: earthlodge [63], plank house [45], longhouse [47] and pueblos [63].

The most affordable way to determine the efficiency level of the chosen dwellings would were by means of the shape factor. Defined as the ratio between the envelope surface area and the volume of air contained under it [64], it is one of the most popular parameters used to estimate the relation between the design of a building and its energy losses due to outward exposure. Despite its undeniable utility, it simplifies the morphology of the building and does not take into account some of its characteristics, such as its orientation, the existence of any excavated surface area or its indoor compartmentalization.

In order to solve these lacks, the present research proposes to determine the capacity of an envelope to transform the outdoor conditions into the indoor ones, proposing to interpret these buildings as if they were machines. This way, it consists in analyzing the capacity of an envelope to transform the outdoor temperature and the outdoor humidity into the indoor temperature and the indoor humidity, just by means of its presence. This means that an envelope works as an air-conditioning machine and contributes an amount of energy.

Besides, a statistical method was used in order to understand the relation of this parameter with the morphological and the technical aspects of the dwellings, as well as with their corresponding weather data.

2. Materials and Methods

2.1. Methodology

2.1.1. Equivalent Energy

The calculation method is based on psychrometry. The particles contained in the air, both indoors and outdoors, move on their own at different speeds, which implies that they contain different amounts of energy. Therefore, those air masses contain an amount of energy produced by the movement of those particles. For example, as can be seen on a psychrometric chart, if the temperature rises at a constant level of humidity, the temperature of those particles rises too, as the energy contained in them does. In the same way, if temperature decreases, the amount of energy, known as enthalpy, also decreases. In addition, for constant temperature, if humidity rises, enthalpy also rises.

The state function that allows tracking the marks left by the energy variations at a constant pressure is the enthalpy [65]. It is only possible to determine its variations after a thermodynamic process; this is the reason why it is expressed as the variation of the amount of energy that is expelled to the environment or absorbed by a system during one of those processes. Therefore, its value is expressed in terms of exchanged energy [66].

This way, by means of psychrometry and characterizing these air masses by their temperature (t) and their humidity level (φ), it is possible to determine the amount of energy contained in them. Knowing the amount of energy contained in the outdoor air mass (h_e) and the amount of energy contained in the indoor air mass (h_i), the amount of energy that was contributed by the building just with its presence can be determined (Δh).

In other research proposals, the indexes which assess the energy efficiency of a construction are usually determined by the indoor and the outdoor temperature, but they do not depend on the humidity levels [67].

Contrary to the shape factor, by this method, it is possible to calculate the amount of energy that can be isolated by a building, taking into account multiple factors such as its morphology, the composition of its envelope, its orientation, the presence or absence of openings or its indoor compartmentalization. The proposed value does not consist in valuing the sustainability grade of a building, the aim of other researches [68], but on establishing the capacity of an envelope to modify the outdoor conditions provided by nature. The higher the difference between indoor conditions and outdoor conditions is, the higher this parameter is.

Virtual Modeling

Just as the outdoor enthalpy was obtained, the enthalpy value for the interior of each model was determined by calculating the indoor temperature and the indoor humidity level for each one of the corresponding ten locations.

Virtual reconstruction of each model by means of DesignBuilder v6.1.2.005 (DesignBuilder Software Ltd, Stroud, UK) (Figure 2) was carried out with the aim of obtaining its indoor conditions (temperature and humidity level) in each location. Occupancy has not been taken into account, so 0 persons per square meter is the value determined for the eight dwellings.

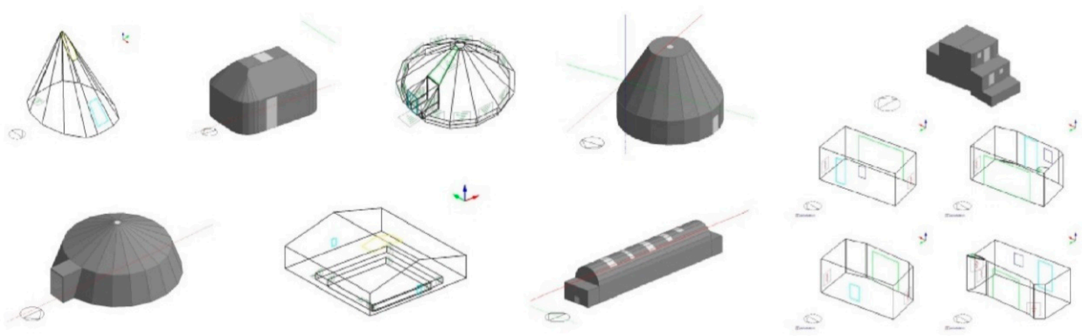

Figure 2. Virtual models developed by means of DesignBuilder v.6.0. Left group, first row, from left to right: tipi, wigwam, hogan and grass house. Left group, second row, from left to right: earthlodge, plank house and longhouse. Right group, upper part: pueblo.

Morphology and Dimensions

The modeling work of the dwellings takes as basis a previous researching work, based on the documents referenced in the Introduction.

In Table 1 the main morphological information is presented.

Table 1. Dimensions of the analyzed dwellings.

	Living Surface Area (m^2)	Volume (m^3)	Envelope Surface Area (m^2)	Openings Area (m^2)
Wigwam	17.6	45.2	65.96	3.16
Hogan	21.38	26.3	41.43	1.3
Tipi	38.54	95.68	98.15	3.16
Earthlodge	69.41	165.09	143.56	2.77
Grass house	42.3	164.78	151.05	42.3
Longhouse	338.13	2209.93	1058.58	338.13
Pueblo	49.59	105.76	136.47	49.59
Plank house	192.93	813.81	491.41	192.93

Technical Description

The materials used to build the chosen models are detailed in the section called Appendix A (Table A2). Those values were calculated according to the information gathered throughout the chronicles referenced in the Introduction.

Calculation: Outdoor and Indoor Environment

Each model was located in ten archaeological sites and one weather station was allocated to each of these sites. In each case, the nearest station was chosen, a decision that implies that some of the stations are assigned several times.

By means of using several locations for each dwelling, the results are representative. These locations are detailed in the section of Appendix A (Figure A1 and Table A1).

The climate data used in this section were obtained from https://energyplus.net/ (U.S. Department of Energy 2019) [69].

Once the outdoor conditions are known, the indoor ones can be calculated. This means that the humidity level and the temperature were determined for both environments. This way, both enthalpies can be obtained.

The enthalpy that corresponds to the pair temperature–humidity of energy in each ambient for each single hour of a year was calculated. This implies that each dwelling in each site is linked to 8760 enthalpy values and 8760 outdoor enthalpy values. These data can be seen in the Appendix A (Table A4).

Result

The difference between both enthalpies is the energy per mass unit that each envelope is able to isolate. This result receives the name of "equivalent energy" and is represented by Δh from now on. An example of the calculation process can be seen in Figure 3 and Table 2.

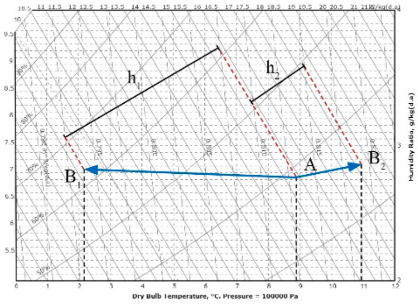

Figure 3. Psychrometric chart detail. The enthalpy values for a wigwam and for a pueblo dwelling on January 2 are marked [70].

Table 2. Environmental Conditions Corresponding to January 2 at 14:00h in the Pueblo of Taos.

	Temperature (°C)	Relative Humidity φ (%)	h (KJ/kg of dry air)	Δh (KJ/kg)
A—Outdoor conditions	8.85	39	15.9	
B1—Inside the pueblo dwelling	2.27	63.02	9.49	|15.9 − 9.49| = 6.41 KJ/kg of dry air
B2—Inside the wigwam	10.89	35.63	18.28	|15.9 − 18.28| = 2.38 KJ/kg of dry air

h: enthalpy; Δh: equivalent energy.

2.1.2. Statistical Links between the Results

Once we obtained this value, its links with the morphological aspects and the climatic circumstances of the dwellings, as well as the technical characteristics of their building materials, were analyzed, in order to better understand its functioning. By means of statistical graphs, it was possible to link morphological characteristics, that is to say qualitative data to quantitative data, such as the thermal transmittance or the wind speed. Therefore, in order to ascertain which factors influence the value of Δh, the statistics software PAST v3.25 [71–73] was used.

By means of it, a canonical correspondence analysis was carried out, that is to say a correspondence analysis based on a site/species matrix, in which values for one or more environmental variables are assigned to each site/specie.

The ordination axes of the resulting graph show the values of the combinations of those variables. This type of analysis is a direct gradient analysis, in which the gradient in environmental variables is known and the situation of the species (their presence or their absence) is the response to that gradient.

Hence, the data corresponding to each model located in each site occupy a line in a spreadsheet. The environmental variables, such as rainfall or indoor temperature, are inserted in its columns (Table 3). Last, also in columns, the information corresponding to each model about the presence or absence of the predefined species in each site, or about the presence or absence of the architectonic characteristics in each model and site, as occurs in the present research, is introduced.

Thus, both weather and environmental variables correspond to numerical data, while the morphological characteristics are the equivalent to the values of the species (Table 3). This means that the presence of one of these characteristics implies that number one is the value written in the corresponding cell, while its absence means that number zero is written in it.

The dwellings that were analyzed are represented according to the symbols shown in Table 3. The resulting table can be consulted in the Appendix A (Table A5).

The climate classification that was used is the Köppen scale, established in 1884 by Wladimir Köppen [74] and updated in 1936 [75,76]. The information about wind speed was gathered by means of https://es.windfinder.com [77], a database which presents the values obtained by more than 21,000 weather stations since 1999.

Table 3. Scatter graphs legend.

Dwellings (10 Sites per Dwelling)				**Species**					
W	"Wigwam"	GH	"Grass house"	Morphology		Envelope Materials		Structural Materials	
H	"Hogan"	LH	"Longhouse"	K	Entrance gallery	S	Hides	Q	Earth
T	Tipi	P	Pueblo	L	Several levels	T	Grass	R	Wood
E	"Earthlodge"	PH	"Plank house"	M	Domed shape	U	Turf		
				N	Vault shape	V	Bark		
				O	Conical shape	W	Mats		
				P	Expandable space	X	Earth		
						Y	Wood		
Variables									
Climate				Morphology		Technical Aspects			
1	Wind speed (km/h)			9	Shape factor	10	Equivalent energy (KJ/kg)		
2	Annual rainfall (mm)					11	Equivalent energy (KJ/kg m^2)		
3	Average outdoor temperature (°C)					12	Effusivity (s$^{1/2}$ W/m^2 °C)		
4	Average indoor temperature (°C)					13	Diffusivity (m^2/seg 10^{-6}.)		
5	ΔTemperature*					14	Thermal transmittance (W/m^2 °K)		
6	Average outdoor humidity (%)								
7	Average indoor humidity (%)								
8	ΔHumidity **								

* ΔTemperature = average outdoor temperature − average indoor temperature (°C); ** ΔHumidity = average outdoor humidity − average indoor humidity (%).

In conclusion, this method allows us to link three concepts: locations, species and variables. The locations are represented by black dots in the graphs. Each one is attached to a letter that indicates the dwelling, plus a number that indicates the archaeological site (Appendix A, Table A1); in total, there are ten black points per dwelling, since each dwelling was located in ten archaeological sites. The species are identified by orange dots joined to their corresponding letter (Table 3). Finally, the variables correspond to the green lines. These vectors mark the zone of the graph where the locations and the species that correspond to the higher values of that specific variable are gathered.

There are three rules that must be followed to read these graphs. First, the links between location, species and variables can be concluded by observing the distance between them. The further a location or a specie is from the vector of a variable, the smaller the influence of that variable is on that location or specie. Second, the closer a location or a specie is to the coordinate origin, the more significant is its presence in the group. Third, the length of a vector depends on the amount of information about its variable that is present in the graph. The longer a vector is, the more information about that variable is contained in the graph.

2.2. Theoretical Fundamentals

The enthalpy values were calculated by means of Equation (4), result of the substitution of Equation (2) and Equation (3) in Equation (1).

$$h = (c_{pa} \cdot t) + [W \cdot (Lo + (c_{pw} \cdot t))] \quad (1)$$

$$W = 0.622 \cdot (p_w/(p - p_w)) \quad (2)$$

$$\varphi = p_w/p_{ws} \quad (3)$$

$$h = \left(1.004 \cdot t\left(^{\circ}\mathrm{C}\right)\right) + \left[\left(0.622 \cdot \left[\frac{0.7 \cdot e^{14.2928 - \frac{5291}{t\ (^{\circ}\mathrm{K})}}}{1 - \left(\varphi \cdot e^{14.2928 - \frac{5291}{t\ (^{\circ}\mathrm{K})}}\right)}\right]\right) \cdot \left(2500.6 + t\left(^{\circ}\mathrm{C}\right)\right)\right] \tag{4}$$

$$\Delta \mathrm{h}\ (\mathrm{KJ/kg})_{1\ldots 8760} = |\mathrm{h}_{e,1\ldots 8760} - \mathrm{h}_{i,1\ldots 8760}| \tag{5}$$

$$\Delta \mathrm{h}\ (\mathrm{KJ/kg}) = \underline{X} \Delta \mathrm{h}\ (\mathrm{KJ/kg})_{1\text{-}8760} \tag{6}$$

where c_{pa} is specific heat of dry air (1.004 KJ/kg °K); c_{pw} is specific heat of water vapor (1.86 KJ/kg °K); t is temperature; φ is relative humidity (%); p_w is partial pressure of water vapor in the air; p_{ws} is saturation vapor pressure; p is atmospheric pressure (1 bar); h is enthalpy (KJ/kg); h_e is outdoor air enthalpy (KJ/kg); h_i is indoor air enthalpy (KJ/kg); L_0 is latent heat of vaporization of water at 0 °C (2500.6 KJ/kg); and W is absolute humidity (kg of water/kg of dry air).

Following, the difference between both values is calculated in order to determine the energy that each envelope is equal to in each hour of the year. Last, the absolute values of these results were averaged. This average is the equivalent energy, the energy that can be isolated by each envelope (Equations (5) and (6)).

Taking this as a starting point, four approaches were designed. They allow us to analyze the possible links between the equivalent energy and the shape factor, the morphology, the location and the building materials. Both the information that was used for these calculations and the results are detailed in Appendix A (Table A4).

2.3. Approaches

The following comparisons and approaches were carried out in order to achieve the aforementioned goals.

Equivalent energy—Shape factor. All the dwellings, original building materials, original locations and original morphology: The resulting values for equivalent energy were compared with the corresponding shape factors in order to check if there is any relation between them. The dwellings were situated in their original locations, and their original building materials were assigned. This way, the features that do not influence on the shape factor, but do influence on the equivalent energy, affect the results and the difference between these two values can be observed. Besides, the factors that influence these conclusions were analyzed.

Equivalent energy—Morphology. All the dwellings, same building materials, same locations, without openings: In order to establish a relation between the results of equivalent energy and the morphology of the dwellings, the models were reduced to their volumes. This means that their openings were removed, the same material was assigned to all of them and they were situated in the same ten locations (where the pueblos of New Mexico were built, that is to say, the locations the most sedentary dwelling was built). This way, all the dwellings contain the same information as the shape factor takes into account; that is to say, the surface of their envelope and the volume that is contained under it. The only characteristic which could not be eliminated was the orientation of the dwellings, not present in the shape factor and impossible to be removed from the DesignBuilder calculations. The building materials that were used in this approach are the ones that correspond to the template entitled "Timber frame-superinsulated", which appears on the database of DesignBuilder v6.1.2.005 and whose details are featured in Appendix A (Table A3).

Equivalent energy—Location. All the dwellings, both original and same locations, original building materials and original morphology: Two groups of calculations were developed for this approach in order to determine how location influence the equivalent energy. First, the equivalent energy corresponding to the original placements, their original materials and their original openings, was calculated. Second, those dwellings were moved to the locations where the New Mexican pueblos were built, and the corresponding equivalent energy was calculated as well. Therefore, the only feature that changes from one case to the other one is the location. This way, by moving the dwellings from their original locations to the ones of New Mexico, it can be determined if the values of equivalent energy for each dwelling are influenced by its location and its climatic conditions.

Equivalent energy—Building materials. Just one dwelling, original materials and same locations: By means of this approach, it was possible to determine the links between the original building materials and the equivalent energy. In order to achieve it, the morphological and environmental factors were eliminated. Thus, it is possible to establish the relation between the temperature, the humidity level, the technical characteristics of the building materials and the equivalent energy that correspond to each of them. This way, the consequences that each material has on the indoor ambient and on the equivalent energy can be determined.

Specifically, the calculations presented in this section imply to take one single dwelling and assigning it the main building materials of the other dwellings which were analyzed. Thereby, the chosen dwelling was the wigwam, and the composition of all the envelopes was assigned to it one by one: the cattail mats (its original material), the hogan envelope, the tipi hides, the multilayer envelope that covered the earthlodge, the bundles of grass typical of a grass house, the bark sheets that wrapped the longhouses, the adobe that composed the walls of the pueblos and, finally, the cedar planks that protected the interior of Haida houses. Eight versions of the same dwelling that were situated in the ten locations corresponding to the pueblos of New Mexico.

All the building materials described before were characterized by means of their diffusivity, their effusivity, their thermal transmittance and their thermal lag [78].

3. Results

3.1. Equivalent Energy—Shape Factor

In this section, the original status of the dwellings is analyzed. This way, they were assigned their original materials, were placed in their original locations and their morphology was kept.

The traditional dwellings which are built in temperate climates are those that would correspond to the highest shape factor values, whereas those from cool climates tend to be associated with lower values [64]. The orthogonal dwellings, whose presence is regular throughout the Mediterranean coasts, could be an example of the first case, whereas the snow domes built in the Arctic would represent the second group. As long as the climate is warmer and it is less necessary to modify the environmental conditions, people can extend the surface of dwellings envelopes, prioritizing other factors, such as the optimization of the available space to build on.

As can be seen (Figure 4), the highest values of the shape factor, those corresponding to the hogan and the wigwam, do not have any relation with climate, since the first one was built in a temperate desert, New Mexico, whereas the second one was typical of a zone whose humidity levels were higher and whose temperatures were lower, the vicinity of the Great Lakes.

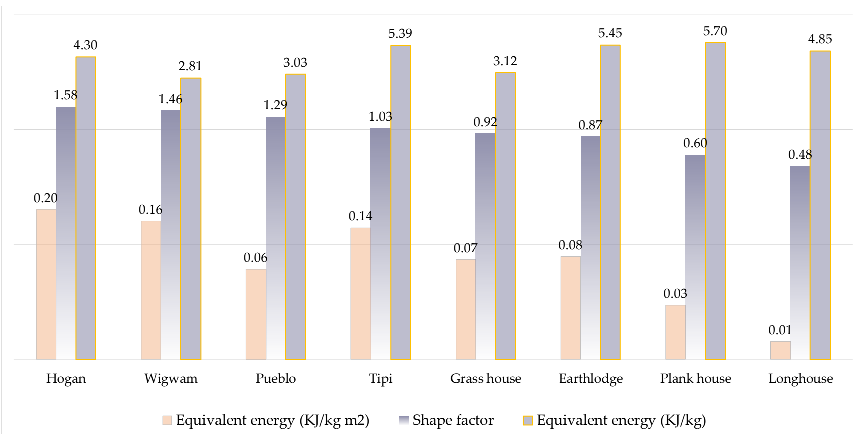

Figure 4. Equivalent energy for original locations and original materials vs. shape factor.

The results concerning the longhouse, built in the same region as the wigwam, point to the same direction. However, the first one was used by an almost sedentary community, the Iroquois community, and the second one served to a seminomadic way of life, the one developed by the Chippewa. This means that their morphologies and building systems were influenced also by their practical functioning.

By comparing the shape factor values with the equivalent energy ones, it can be seen that the order of the dwellings does not concur, unless they are calculated with respect to the living area. Taking into account the architectonic characteristics obviated by the shape factor, as the equivalent energy does, such as the building materials, the climate, the orientation or the presence or absence of openings, a more precise assessment of the way the building adapts to the environment can be obtained.

In conclusion, the designs that reach a higher difference between the indoor and outdoor conditions, those whose equivalent energy has the highest values, are those who correspond to the highest shape factor.

As explained before, the equivalent energy measures the capacity of an envelope to transform the outdoor conditions into the indoor ones. The bigger this increment or decrement is, the higher the equivalent energy is. In conclusion, the designs that reach a larger difference between the indoor and outdoor conditions, those whose equivalent energy has the biggest values, are those who correspond to the highest shape factor as a rule.

3.2. Equivalent Energy—Morphology

In order to carry out the analysis proposed in this section, the same building materials were assigned to all the dwellings, they were situated in the same locations and their openings were removed.

As can be observed in Figure 5, the highest values of equivalent energy correspond to the conical or hemispherical dwellings, such as the hogan, the wigwam and the tipi. The order of the dwellings does not change, except in the case of the pueblos, whose equivalent energy is similar to the ones of the hemispherical designs. This circumstance is possible because the pueblo design manages to reduce the surface of its envelope by overlapping its constituent volumes.

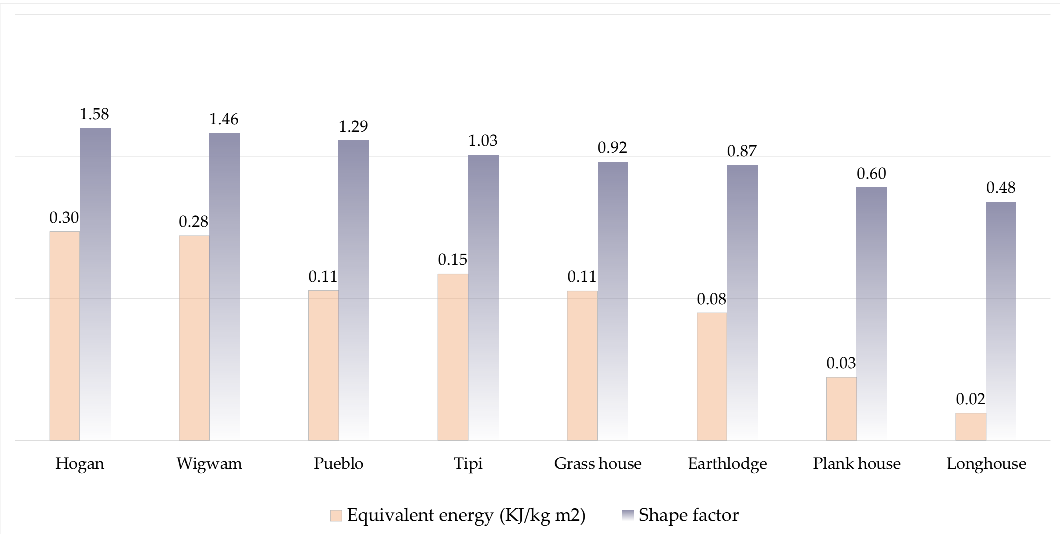

Figure 5. Timber frame-superinsulated template as the envelope of all the dwellings, situated in the New Mexican locations and without openings (KJ/kg m^2 of living surface).

This effect can be explained in the following way [64]. A cube composed by a 36-units^3 volume, has a 65-units^2 envelope, but if that same volume, those 36 units^3 are arranged horizontally, they create a 96-units^2 envelope. In the first case, the shape factor is 1.8, whereas, in the second one, it is 2.6 [64]. The opposite happens about the plank houses and longhouses, whose shape tends to be horizontal.

Even though all the models were homogenized, there is another characteristic that the shape factor cannot take into account, besides the orientation. It is the indoor compartmentalization of the buildings. As indicated before, the pueblos were composed by several volumes, whose overlapping reduces the outdoor exposure of their dwellings influencing the amount of energy isolated by these constructions, but do not influence their shape factor.

As can be seen, the rest of models appear in the same order for both values. The proportions between them are the only differences. The highest and the lowest values are more distant, whereas the ones located in the middle form a different group. This way, it can be said that the equivalent energy value qualifies the information provided by the shape factor.

Figure 6 shows the results that correspond to the original locations of the dwellings. Besides, they have also been coated with their original materials. It shows that some designing decisions, such as the entrance galleries (K), the vaulted spaces (N) or the distribution in several levels (L), are normally not related to the envelopes which achieve a high Δh (11).

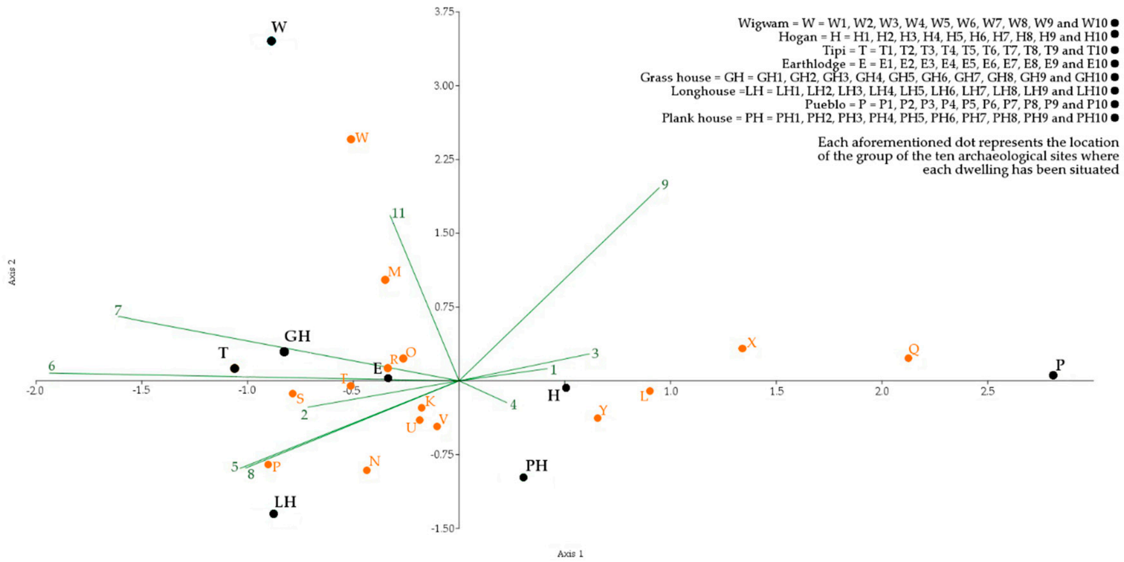

Figure 6. Scatter graph. Links between the environmental characteristics and the equivalent energy.

3.3. *Equivalent Energy—Location*

For this section, the dwellings were placed in both their original locations and in the same ones, their original building materials (Table 4) were assigned and their original morphology was respected.

When analyzing the dwellings in their original locations, it can be seen that the resulting order changes slightly with respect to when they were placed in the locations of New Mexico (Figure 7). The circular dwellings keep occupying the highest places. The hogan achieves the largest difference, and three dwellings increase their equivalent energy with respect to their original locations. The longhouse, the grass house and the wigwam isolate more energy in New Mexico than in their original locations. The grass house obtains the biggest difference.

However, all these differences are not significant, and even the value corresponding to some models, such as the plank house, is nearly the same. This means that the capacity of an envelope to modify the outdoor conditions, the pair temperature–humidity, does not depend on the location of the dwelling. An envelope provides a higher or a lower difference, and it is this capacity, higher or lower, that is used to adapt a building to its environment.

Table 4. Thermal lag of the building materials.

Dwelling	Envelope Layer	Thermal Lag	Dwelling	Envelope Layer	Thermal Lag
Wigwam			Earthlodge		
Wall/roof		0.3231	wall/roof		16.0424
	Cattail	0.0722		Wood	5.5892
	Air	0.0172		Wood (branches)	5.5892
	Cattail	0.0722		Grass + grass from turf	2.5518
	Cattail	0.0722		Earth from turf	2.3122
	Air	0.0172	Longhouse		
	Cattail	0.0722	wall/roof		0.5314
Tipi				Tree bark	0.5314
Wall/roof		0.1051	Pueblo		
	Hide	0.1051	wall		18.8570
Hogan				Earth	18.8570
Wall/roof		16.9469	roof		15.8050
	Wood	5.5892		Wood (branches)	5.0303
	Tree bark	0.5314		Grass	1.5311
	Earth	10.8262		Earth	9.2436
Grass House			Plank house		
Wall/roof		16.6290	wall		3.9125
	Grass	16.6290		Wooden planks	3.9125
			roof		0.5314
				Tree bark	0.5314
Dwelling	Thermal lag (h)		Dwelling	Thermal lag (h)	
Tipi	0.105		Earth lodge	16.04	
Wigwam	0.32		Plank house	3.91	
Hogan	16.94		Longhouse	0.53	
Grass house	16.63		Pueblo	18.85	

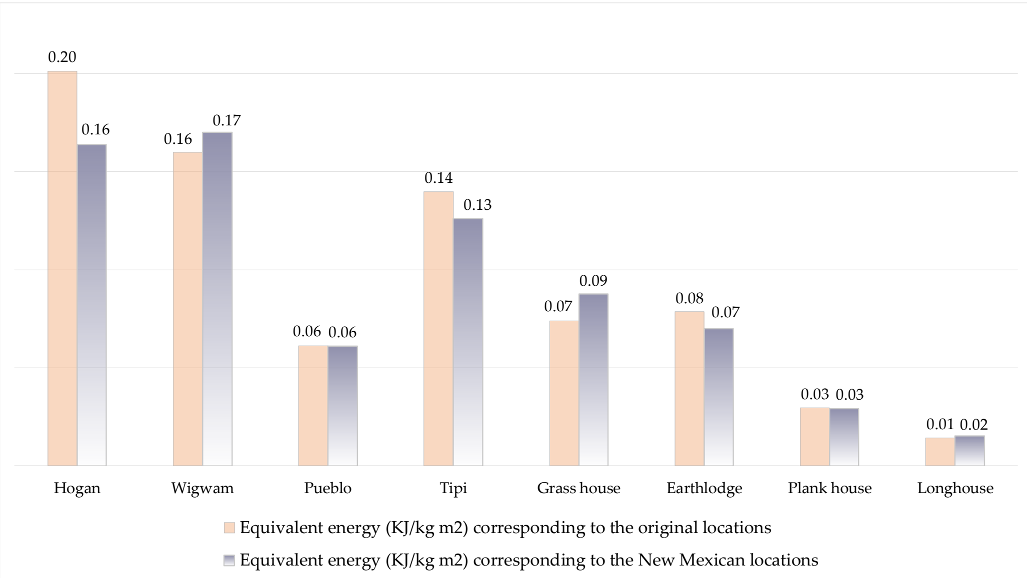

Figure 7. Equivalent energy for original building materials (KJ/kg m^2 of living surface).

Taking as an example the highest values, the hogan was built in a temperate region located in the southwest of the United States (Bsk, Bwk and Dfb zones, according to the Köppen classification), whereas the wigwam was typical of the Great Lakes region, where temperatures are cooler and the humidity level is higher (Dfa, Dfb, Cfa and Cfb). The longhouse was built in this second region too, and this is the dwelling with the lowest Δh value. The results for hogan and pueblos (Bsk, Dfb and Cfb), both built in the same region, New Mexico, point to the same direction.

By observing the scatter graph shown in Figure 6, it can be seen that the highest values of the shape factor (9) are associated with high values of average outdoor temperature (3), whereas the highest values of equivalent energy (11) are linked to the highest levels of indoor humidity (7). It can be seen that Δϕ (8) and Δt (5) determine the value of Δh (11) equally, but they are not related to the shape factor (9).

If the data are analyzed without taking into account the living surface of the dwellings, and just the energy isolated by these specific envelopes is observed (KJ/kg) (Figure 4), it can be seen that the earthlodge achieves to duplicate the result of the wigwam. In this case, the plank house obtains the highest value of Δh.

However, if this information is analyzed from the point of view of the sedentary process, it can be seen that the dwellings that were used by the sedentary groups were also those which are equivalent to a smaller amount of energy. These three dwellings, the longhouse, the plank house and the pueblo adobe house, are equivalent to a smaller amount of energy per living square meter. All of them are orthogonal in plan, the model that is usually adopted by the sedentary communities.

Among them, the Native Americans who developed the agriculture and sedentarism the most, those groups which inhabited the zone of New Mexico and built the adobe dwellings, chose the model that was equivalent to the greatest amount of energy. However, if they wanted the model that was equivalent to the highest level of energy among the most popular designs, they should have chosen the wigwam (0.17 KJ/kg m^2), taking into account the living surface, and the plank house (5.64 KJ/kg), if comparing exactly the models presented in this research.

3.4. *Equivalent Energy—Building materials*

In order to develop this section, just one dwelling, the "wigwam", was considered. The original materials, which are summarized in Table 4, were assigned to it, and it was placed in the locations of New Mexico, where the pueblos were built.

This approach has made it possible to see that the elm bark sheets (from *Ulmus americana* L. or from *Ulmus rubra* Muhl.) which covered the Iroquois longhouses were the material that implied the highest amount of energy (Figures 8 and 9). The most abundant building material the natives who inhabited the forests of the Great Lakes region had at their disposal was wood. These forests, located both in Dfb and Cfa zones, according to Köppen scale, were full of coniferous trees, such as *Tsuga canadensis* (L.) Carrière or *Picea rubens* Sarg., and deciduous trees, such as *Quercus rubra* L or *Betula alleghaniensis* Britton. Besides, this region is characterized by a high ambient humidity, against which the bark tree provides a quality solution thanks to its waterproofing capacity.

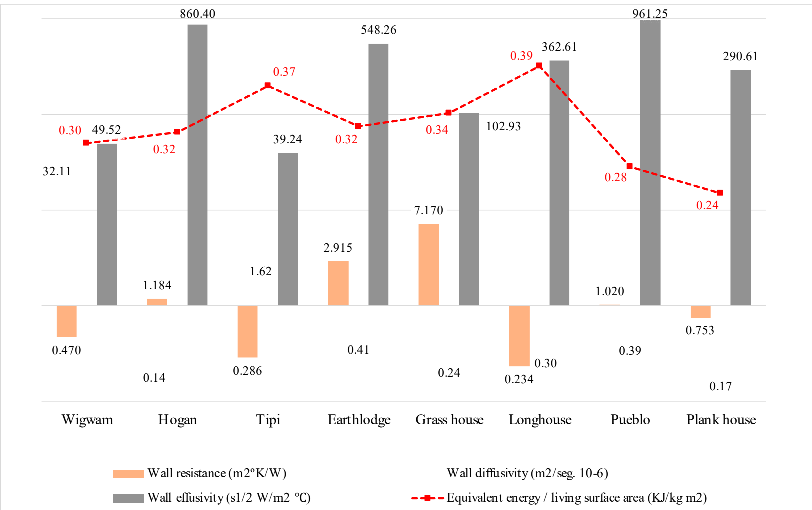

Figure 8. Thermal characteristics of the original building materials. They were assigned to the same dwelling, whose openings were removed.

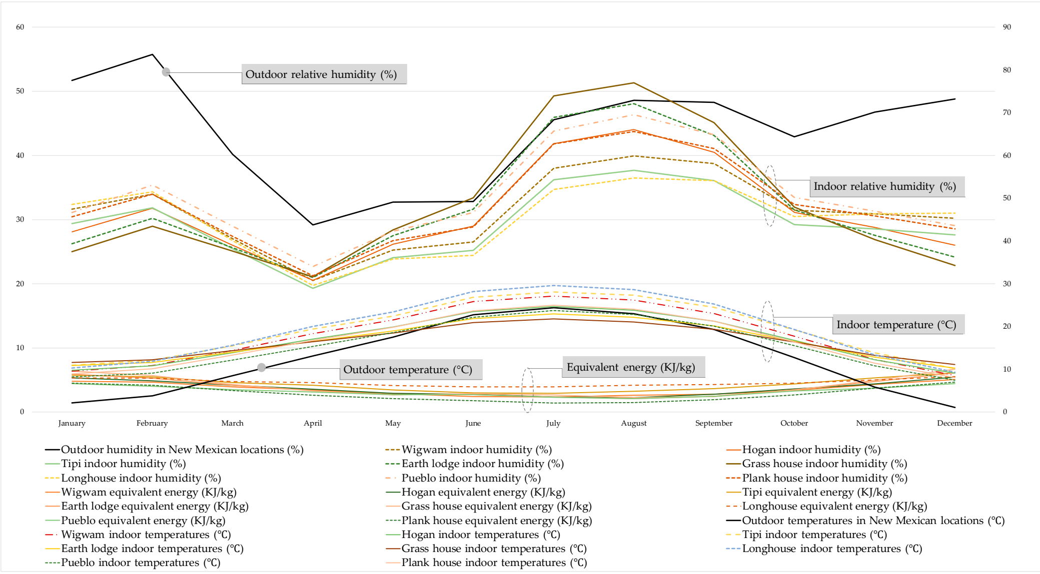

Figure 9. Indoor conditions in a dwelling whose openings were removed. All the analyzed building materials were assigned to it, and it was placed in the New Mexican locations.

Due to have the lowest thermal resistance of all of the materials that were analyzed, the bark sheets provide the most stable difference between the outdoor and the indoor conditions throughout the whole year. Unlike the other building materials, whose thermal resistance or effusivity is higher, this material neither stores heat nor offers a great resistance to its passage. Because of these reasons, it achieves a practically constant difference between the indoor and outdoor conditions throughout the year.

By observing Figures 5 and 8, it can be concluded that the amount of energy the wigwam envelope is equal to that of a timber frame superinsulated template (Figure 5) and is lower than the values obtained for the traditional materials in the same dwelling (Figure 8). The only exception is the case of wooden planks. This means that, contrary to the results obtained in previous researches about traditional architecture [79], traditional materials would have achieved better results than the present ones, if taking into account the energy they are equal to.

As can be seen in Figure 10, the transmittance (14) is the thermal characteristic more closely related to the equivalent energy (10 and 11). The second characteristic most related to it is the diffusivity (13). However, it is practically opposite to the effusivity (12). This means that the highest values of Δh (10 and 11) correspond to the highest values of transmittance (14).

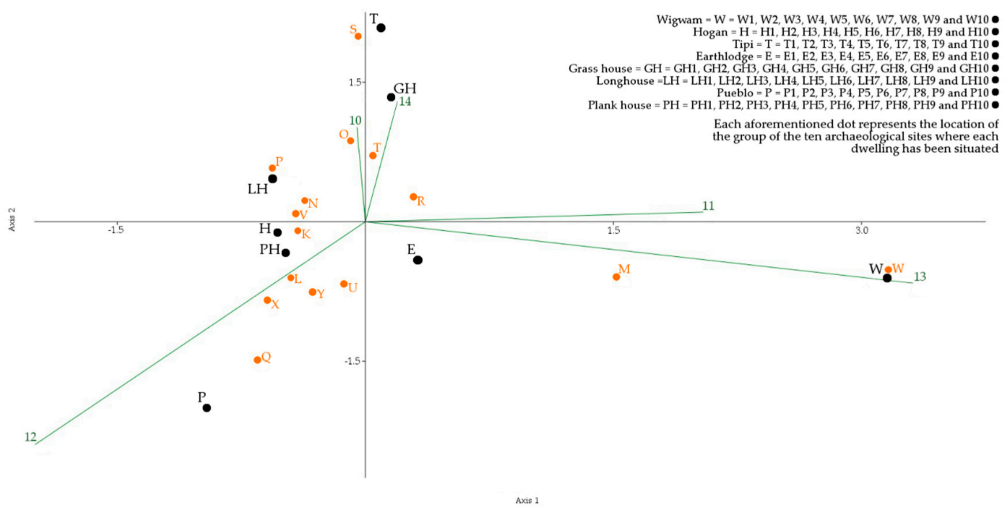

Figure 10. Scatter graph. Links between the building materials and the equivalent energy.

Moreover, in this graph, it can be seen that the tree-bark envelope (V), the one used for coating the longhouses and the roofs of the plank houses, is influenced by both the effusivity (12) and the thermal transmittance (14). However, the grass house (GH) and the tipi (T), which have the next highest values of Δh (10), are related exclusively to the transmittance (14). Its location in the graph indicates definitively that this is the factor that influences Δh the most (10 and 11).

The envelopes composed of several layers, or with a high presence of earth, offer a higher resistance to the heat transfer. The consequence of this circumstance is that indoor temperatures are lower in summer, as are their differences with respect to the outdoor temperatures. Since these differences are lower, the amount of energy these envelopes are equivalent to is usually lower during the summer too.

However, the building material that is equivalent to the lowest amount of energy is the one that covers the plank house walls, the cedar planks. Again, it is a dwelling built in a region with high humidity levels due to its proximity to the coast. This territory corresponds to a region classified as Cfb by the Köppen scale, and there are four most abundant tree species in this rainy climate, located in the northwest of the United States: *Pseudotsuga menziesii* (Mirb.) Franco, T*suga heterophylla* (Raf.) Sarg., *Thuja plicata* Donn ex D. Don and *Fraxinus latifolia* Benth. Specifically, it was *Thuja plicata* Donn ex D. Don, or Canadian Western red cedar, the wood used for building, since it is coated with a special type of oil that makes it resistant to water, preventing it from rotting [80].

The wood planks correspond to one of the lowest values of heating speed (diffusivity), similar to the one of the bark sheets which comprise the envelope of the longhouse. Their capacity to store heat is very similar. The biggest difference between them concerns their thermal resistance, since the value corresponding to the plank house almost triples the one of the longhouse. Their heating speed is also reflected in the thermal lag that characterizes both materials (Table 4). The dissimilarity among them provokes that the size of the difference between the indoor and the outdoor temperatures depends on the period of the year.As can be seen in Figure 11, the tree bark keeps the indoor temperature higher than the outdoor temperature during the summer, whereas the temperature achieved by the wooden planks is almost the same as it. The thermal resistance of the wooden planks, higher than the one of the tree bark, ensures that the indoor temperature takes longer to change. This means that the indoor ambient is less vulnerable to the weather changes inside a plank house and that its thermal lag reaches a higher value.

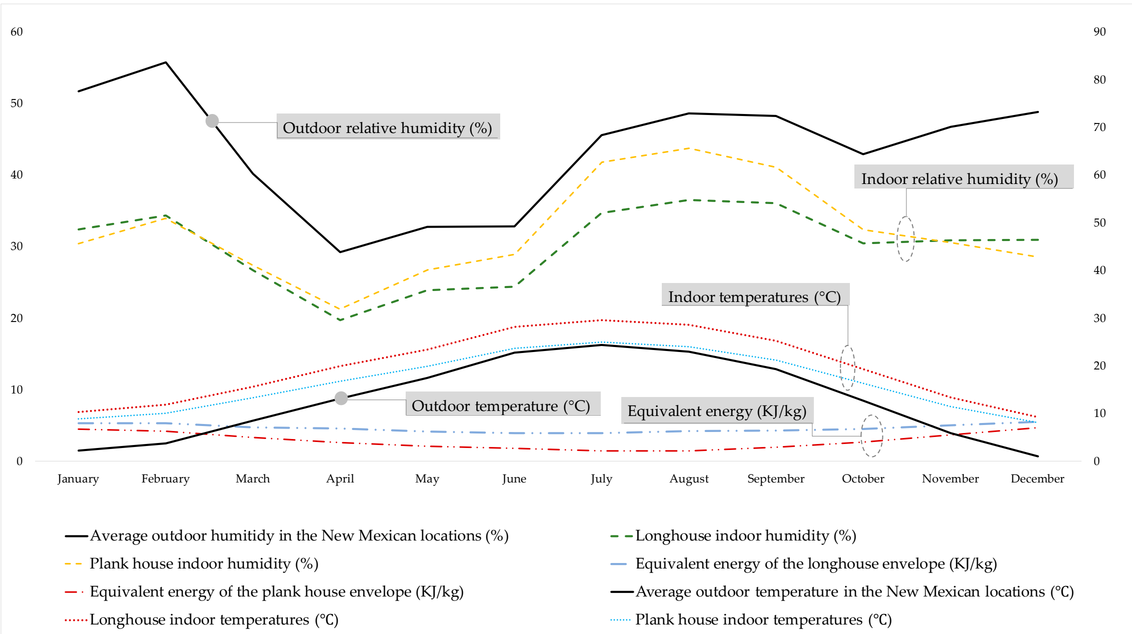

Figure 11. Comparison between the outdoor and the indoor conditions generated in the same dwelling by the envelope of a longhouse and by the envelope of a plank house.

However, the higher speed the thermal wave passes through the bark strip at ensures that the difference of temperature between the outdoors and the indoors is almost constant throughout all the year. At the same time, the humidity level changes, since it decreases when the temperatures rises and rises when the temperatures decrease.

4. Discussion of Results

As can be seen in Figure 7, the circular dwellings correspond to the highest value of equivalent energy per living square meter. This relation takes place both if the dwellings are situated in their original locations and if they are situated in the New Mexican locations, where the sedentary process had been most developed during the pre-Columbian North America. However, the models which isolate a lower amount of energy are the orthogonal ones. Besides, the former, the circular models, are related to nomad communities, whereas the latter ones were mainly designed by sedentary groups.

Contrary to the results of the research developed by Leroi-Gourhan [2], the energy the dwellings are equivalent to decreases as long as the sedentary process goes forward. The value of Δh decreased progressively, and the energy required to achieve the same indoor conditions increased as long as that process was developed. It seems that the priority in the design of these dwellings was not air-conditioning saving, neither in shape of hearths for heating nor in shape of natural ventilation.

As explained in the Introduction, the dwellings which were selected correspond to models that are built in regions where nomad lifestyle coexisted with sedentary lifestyle. This way, if these models are classified according to their provenances, it can be seen that the nomad dwelling is always equivalent to more energy than its sedentary counterpart (Table 5).

Table 5. Equivalent energy of the analyzed dwellings according to their sedentary grade.

	Nomad or Seminomad Dwelling	Equivalent Energy (KJ/kg m^2)	Sedentary Dwelling	Equivalent Energy (KJ/kg m^2)
Northeast of the United States	Wigwam	0.16	Longhouse	0.014
South of the United States	Tipi*	0.14	Pueblo	0.061
Southwest of the United States	Hogan	0.2		
Southwest of Canada	Tipi*	0.14	Grass house	0.074
North of the United States	Tipi*	0.14	Plank house	0.03
Southwest of the United States	Tipi*	0.14	Earthlodge	0.079

*Taking into account the obtained results when modifying the location of the analyzed dwellings, it can be assumed that the amount of energy a tipi is equal to is the same wherever it is placed.

This tendency was inverted in the last step of the process, the one represented by the pueblos. The longhouses represent those communities which were about to achieve the same sedentary level as the pueblos, thanks to the development of agriculture, but they are also the dwellings equivalent to the lowest amount of energy. Figure 5 shows this situation. The longhouses are the models that isolate the least amount of energy. This way and according to the evolution of the sedentary process, if the nomad dwellings are the models that isolate the highest amount of energy, the Native Americans from the pueblos, the most sedentary group, should have designed the dwelling that was equivalent to the lowest amount of energy, but that was not the case. They succeeding in designing a dwelling that isolates more energy than the longhouse and the plank house, placing it at the same level as the nomadic models. As described before, its equivalent energy was so high thanks in part to its morphology, that is to say the overlapping of volumes, the indoor compartmentalization and the reduction of the outer surface by attaching several dwellings. Regarding the building materials they were built with, the determining factor is the high value of the effusivity of earth (961.24 $s^{1/2}$ W/m^2°C). The thermal lag also stands out (18.85 h) and indicates that the changes in the outdoor ambient were not practically perceptible inside them.

These adobe dwellings were not built just in New Mexico, but they were also used in the Middle East. Several of them can be found in sites such as Çatal Hüyük or Ain Ghazal [81], linked to other agricultural and sedentary societies.

The results presented in this research may indicate that the priority when designing these dwellings changed throughout the sedentary process. According to them, the energy required to achieve the same ambient conditions inside the dwellings rose progressively until the adobe orthogonal dwellings were built for the first time. However, they did not achieve the same values as the nomadic and seminomadic dwellings, of which all of them were circular, did. The circumstances human beings lived in changed throughout this process and maybe at its end it was necessary to add the floor optimization to the resources' optimization, which had been the main objective until the rise of agriculture and fishing. This way, the pueblos design let the Native Americans have a solution for two problems in a balanced way. Its orthogonal floor plan let them dedicate as much surface as possible to agriculture, and it also isolated more energy than the other orthogonal models they could know about.

According to the results that were obtained, it can also be concluded that the dwelling designed by the Native Americans from New Mexico did not provide the most comfortable indoor environment (Figure 12). However, these adobe dwellings provided a higher level of humidity, a lack to be compensated in the desert of New Mexico.

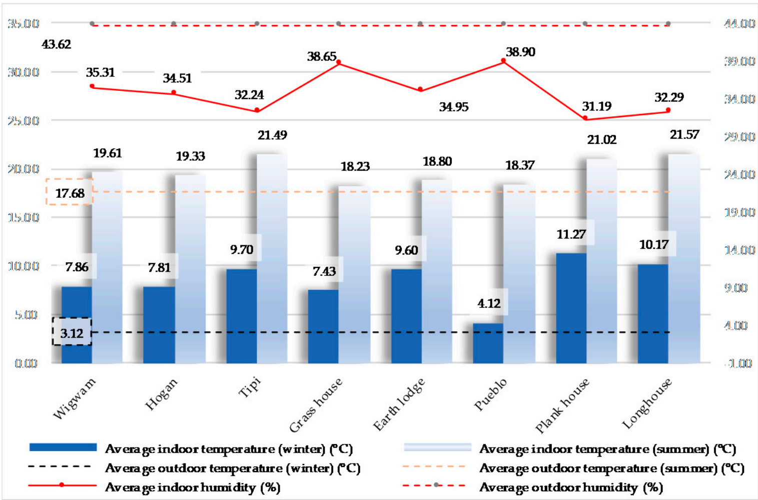

Figure 12. Environmental conditions of the analyzed dwellings. The original materials were assigned to them, and they were placed in the New Mexican locations.

4.1. The Equivalent Energy

The shape factor offers an affordable method to estimate the design quality of a building. However, it does not take into account some of the characteristics that influence the energy consumption. The equivalent energy solves these deficiencies since it depends on the outdoor and the indoor environmental conditions, with the latter being the result of the morphology of the building.

According to the obtained results, the location does not influence the amount of energy the dwellings are equivalent to in a meaningful way. The envelopes are equal to a specific amount of energy and isolate a specific amount of energy. This way, the modification of the outdoor conditions they achieve remains stable.

Taking as a basis the building materials which were analyzed, it can be concluded that those with the lower thermal resistance provide the envelopes with the highest values of equivalent energy. A high diffusivity provokes that weather changes modify the indoor conditions very fast, and thereby, the capacity of the envelope to alter the outdoor conditions remains practically stable throughout all the year. Therefore, this capability is not influenced by the placement of the building, specifically in New Mexico, where the present research is focused in and where the summer is more pronounced.

Not at all it is intended to assess that the indoor conditions achieved by low diffusivity materials reach the comfort level. The aim of this research is to determine the capacity of an envelope to modify the outdoor conditions; it is not to determine if the indoor conditions that it achieves are the most comfortable ones. However, it can be very useful for complementing other values, such as the concept of Zero Energy Buildings [82], since the higher the equivalent energy of a building is, the lower its energy consumption is.

4.2. Statistical Links between the Results

By means of the scatter graphs, it was possible to analyze the links between the technical data of the dwellings (quantitative data) and their morphological characteristics (qualitative information). These graphs show that the thermal transmittance (14) is the value that influences most in the equivalent energy (10 and 11), as the shape factor (9) and the indoor humidity (7) also do.

They have to read in terms of probability. This means that, for example, as can be seen in Figure 6, the sum of the wind speeds (1) of the plank house locations (192.61 km/h), the adobe house locations (150.01 km/h), the hogan locations (126.78 km/h) and the wigwam locations (155.57 km/h), which is equal to 624.97, is higher than the corresponding sum of the rest of the dwellings (548.19). The aforementioned dwellings are situated in the direction of the wind speed vector (1), and that is the zone of the graph where the highest sum of wind speeds is concentrated. This way, the position of the dwellings and the species on the graphs must be understood according to this system. This method is very useful for analyzing vernacular architecture in general, since it allows for the discovery of the logic of its morphological features and its links with its environmental circumstances. This would be the case of the research work developed by Varela Boydo and Moya [83]. It would allow us to identify which characteristics of the traditional windcatchers respond to cultural features and which ones are related to their adaptation to the proper circumstances of each geographical and climatic zone. The same could be determined about the Malay traditional houses analyzed by Ghaffarianhoseini, Berardi, Dahlan and Ghaffarianhoseini [84]. This method allows us to transform the morphological features of the Malay houses, such as the characteristics of their roofs, into numerical data. This way, it would be possible to establish the relation of this distinguishing element with the climate and the environmental information of each specific region.

5. Discussion

If Prehistory is understood as the pursuit of the stability provided by settling, it can be seen that the equivalent energy decreased as man approaches his objective. However, the last model, the adobe stepped dwellings, revitalized that value. It is necessary to take into account that, as long as the sedentary lifestyle went forward, the global temperatures rose progressively too, until reaching a value that made settling and agriculture viable. The greatest problem faced by the dwellings in the temperate climates, where man could live on agriculture, was that the temperatures were significantly higher in summer than in the past. That was probably the main problem to be solved, since winter could be solved, if necessary, by means of hearths. As Danny H. W. Li [85] asserted, when the temperatures began to rise, as happened 18,000 years ago, when agriculture was established, the greatest problem to be faced was the summer, and the dwellings must adapt to it. Consequently, the energy demand rises in the arid regions during these periods.

This way, of the three aforementioned sedentary dwellings, the one that isolates more energy, the model from New Mexico, is the one located in the zone that reached the highest temperatures. Facing the consequent increment of energy demand that took place during the summer, the sedentary human being designed the sedentary dwelling that isolated the highest amount of energy with respect to the known models that let him clear the largest amount of terrain for agriculture, that is to say, the orthogonal models. It would also be important to point out that the color of the envelopes would have influenced these results. As was demonstrated, the use of light colors in hot areas, such as the ones used in the pueblos, and dark colors in cold regions, such as the envelope of the earthlodge, reduce the energy consumption of the dwellings [86]. The main solution proposed in the aforementioned research [85] for this problem consists of increasing the adaptability of the dwellings built in these regions. This idea could be reinforced by analyzing the tipis, built in one of the hottest areas of North America, the Great Plains. The versatility of this shelter is one of its strengths, thanks both to its mobile envelope and to its morphology. Its smoke hole allows people to control the indoor ventilation and the indoor temperature at the same time, both at will, by means of two poles. No less important was the airtightness achieved by the envelope seams. This factor [87,88] was determinant to provide a comfortable indoor ambient. In the same way, it can be easily turned around in order to avoid strong winds [18] during a storm, since its structure is not symmetrical. This efficient design is contained in the old legend which explains the origin of tipis, since, according to it, the shape of the cottonwood leaves inspired its triangular shape. Both of them, the tipis and the leaves, use the Venturi effect to withstand wind and, in the case of tipis, improve indoor ventilation. Something similar happens in Acoma dwellings, whose shape, according to a legend, is based on the shape of the surrounding mountains. The airflow system that was used to dry the harvests on the houses' roofs works in the same way that the airflows move in the slopes of the mountains. During the day, the airflow rises from the valley, since the peak of the mountain is cooler and hot air is lighter than cool air, whereas during the night, the cycle is reversed and the air that rests in the peak turns cooler and descends to the valleys. This is the physical principle that Ralph Knowles, professor and member of the American Solar Energy Society, had already intuited and described in 1974. Thus, the mountains are not only a metaphorical reference to the design of these dwellings, but they also influence on their operation and distribution. These ideas go in the same direction as the results of the research carried out by Zahraa Saiyed and Paul D. Irwinb [89]. As they conclude, Native American legends reflect a knowledge about the environment which goes further than symbolism. These stories indicate that Native American Indians deeply knew how their surrounding environment worked, and that fact let them use the resources at their disposal in a respectful and efficient way. Moreover, as can be seen in the research developed by César J. Pérez and Carl A. Smith [90], the indigenous techniques, the so-called Indigenous Knowledge Systems (IKS), which often underlay these old stories, can be very useful for the environment protection at present.

The nomad lifestyle is more closely linked to nature than the sedentary lifestyle is. This can be seen by analyzing the Navaho culture, as the research presented by Len Necefer concludes [91]. This fact also affects their dwellings, the hogans. One of their most remarkable features is that their smoke hole cannot be closed. Unlike the tipis, whose smoke hole controls the exit of air and smoke, the hogan's can never be closed, as Thibony explains [29]: "Visitors ask what happens when it rains or snow", said a Navajo working at the visitor center. "They want to know if they cover the smoke hole. '*You let things happen*' I tell them. '*You let the rain come in. The dome represents the sky, and the floor is the earth. The earth shouldn't be covered up. It reminds you of who you are and where you came from. The hogan places you where you belong. You take your identity from it*'". Features like this allow understanding how a culture works and the stance their members take in relation to current challenges, such as the energy consumption or the environmental resources management.

6. Conclusions

The results show that there was a decreasing progression on the energy a dwelling is equal to throughout the sedentary process. This evolution was broken in its last step by the settled agricultural communities, the pueblos, since their adobe dwellings are equal to a similar amount of energy of those used by the nomad and seminomadic groups.

This value is linked to the morphology of the analyzed building and to its building materials, but it is not related to the zone where it is set up.

Two theoretical ideas were developed to obtain this conclusion. First, the equivalent energy was the value designed to indicate the capacity of a building to transform the outdoor conditions into the indoor ones. It means that the building itself is understood as if it was a machine and its power is quantifiable. Second, a statistical method was brought from botany and archaeology to architecture. The canonical correspondence method allows us to establish links between quantitative data and qualitative information. This way, it transforms the morphological characteristics of a building into numerical information, in such a way that both quantitative and qualitative data can be related graphically.

From these bases, the present research will go on. On the one hand, the equivalent energy will be calculated and analyzed for current buildings. On the other hand, the canonical correspondence analysis will be used to determine the relation between more examples of vernacular architecture and their corresponding environments. This is the architectural field where it can be more useful, since the design of this type of dwelling derives directly from the limitations imposed by nature.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

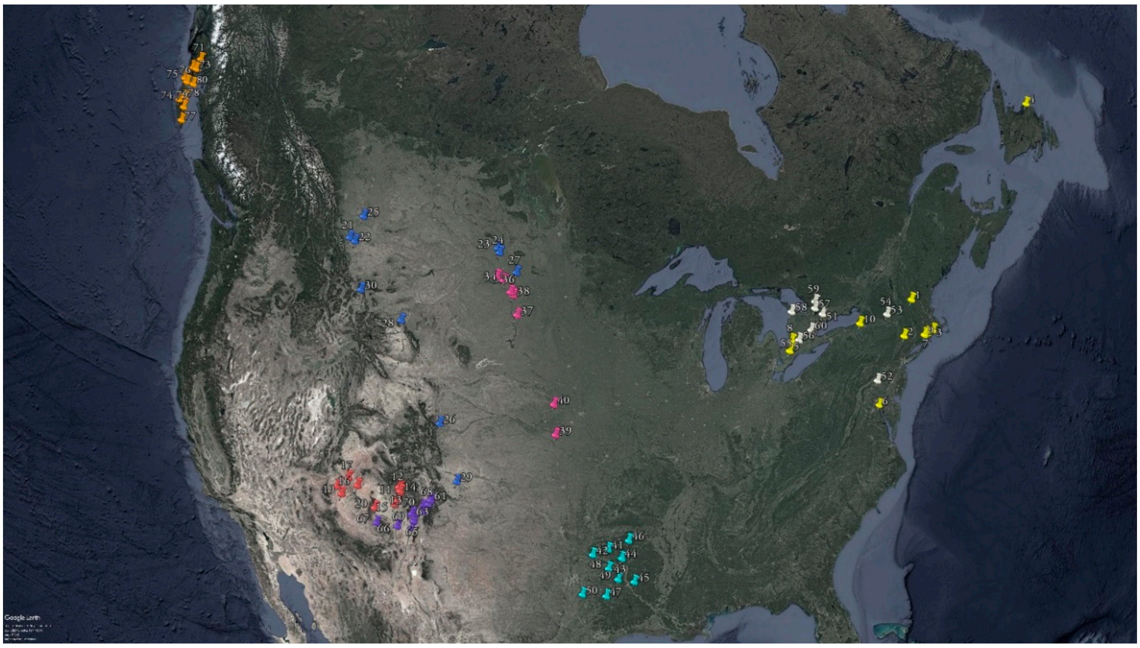

Figure A1. Location of the archaeological sites. Source: Own elaboration over Google Earth Pro 2017© cartography.

Table A1. Archaeological sites.

	Archaeological Site	Climatic Zone [74]	Nearest Weather Station
		Wigwam	
1	Skitchewaug site	Dfb	Springfield-Hartnes.State.AP.726115_TMY3
2	Site 230-3-1, Wappinger Creek	Cfa	Poughkeepsie-Dutchess.County.AP.725036_TMY3
3	Salt Pond Archaeological Site	Cfa	Groton-New.London.AP.725046_TMY3
4	Boyd's Cove	Dfb	Gander.718030_CWEC
5	Bellamy	Dfb	London.716230_CWEC
6	Pig Point	Cfa	Andrews.AFB.745940_TMY3
7	Pequot Fort	Cfa	Groton-New.London.AP.725046_TMY3
8	Figura Site	Dfb	St.Clair.County.Intl.AP.725384_TMY3
9	Localización documentada por Ezra Stiles	Cfa	Groton-New.London.AP.725046_TMY3
10	Kipp Island	Dfb	Syracuse-Hancock.Intl.AP.725190_TMY3
		Hogan	
11	Navajo Reservoir District-LA 3021	Dfb	Durango-La.Plata.County.AP.724625_TMY3
12	Navajo Reservoir District-LA 3460	BSk	Farmington-Four.Corners.Rgnl.AP.723658_TMY3
13	Bist-star BS-511 (43-2)	BSk	Farmington-Four.Corners.Rgnl.AP.723658_TMY4
14	Gobernador Canyon LA1869	BSk	Farmington-Four.Corners.Rgnl.AP.723658_TMY5
15	Chaco Canyon CM-4	BSk	Gallup-Sen.Clarke.Field.723627_TMY3
16	Kayenta	BSk	Gallup-Sen.Clarke.Field.723627_TMY3
17	Rainbow Lodge	BSk	Blanding.Muni.AP.724723_TMY3
18	Cedar Ridge	BSk	Winslow.Muni.AP.723740_TMY
19	Tuba City	BWk	Page.Muni.AWOS.723710_TMY3
20	Window Rock	BSk	Gallup-Sen.Clarke.Field.723627_TMY3
		Tipi	
21	Greasewood Creek 486	Dfb	Kalispell.727790_TMY2
22	Spring Lake 584	BSk	Cut.Bank.Muni.AP.727796_TMY
23	Souris River 32RV416	Dfb	Estevan.718620_CWEC
24	Souris River 32RV419	Dfb	Minot.727676_TMY2
25	The Cranford Site	BSk	Lethbridge.712430_CWEC
26	Indian Mountain site 5BL876	BSk	Fort.Collins.AWOS.724769_TMY3
27	Sheyenne River 32SH205	Dfb	Bismarck.Muni.AP.727640_TMY3
28	Demijohn Flats 24CB736	BSk	Cody.Muni.AWOS.726700_TMY3
29	Pinon Canyon Maneuver Site-Training Area 7	BSk	La.Junta.Muni.AP.724635_TMY3
30	Pilgrim Site 24BW675	BSk	Butte-Bert.Mooney.AP.726785_TMY3
		Earthlodge	
31	Hidatsa Village	Dfb	Bismarck.Muni.AP.727640_TMY3
32	Awatixa Village	Dfb	Bismarck.Muni.AP.727640_TMY3
33	Awatixa Xi'e Village	Dfb	Bismarck.Muni.AP.727640_TMY3
34	Rooptahee	Dfb	Bismarck.Muni.AP.727640_TMY3
35	Like-a-fishhook 32ML2	Dwb	Dickinson.Muni.AP.727645_TMY3
36	On-a-Slant Village 32MO26	Dfb	Bismarck.Muni.AP.727640_TMY3
37	Arikara Battle 1823 T20N S25 R30E	Dfa	Mobridge.Muni.AP.726685_TMY3
38	Huff site 32M011	Dfb	Bismarck.Muni.AP.727640_TMY3
39	Kansas Monument site 14RP1	Cfa	Concordia-Blosser.Muni.AP.724580_TMY3
40	Fullerton 25NC7	Dfa	Columbus.Muni.AP.725565_TMY3
		Grass house	
41	Clement site 38Mc8	Cfa	Cox.Field.722587_TMY3
42	Sanders site	Cfa	Sherman-Perrin.AFB.722541_TMY
43	Hill Farm site 41BW169 (Hatchel)	Cfa	Texarkana-Webb.Field.723418_TMY3
44	Roseborough Lake site	Cfa	Texarkana-Webb.Field.723418_TMY3
45	McLelland site 16B0236	Cfa	Shreveport.722480_TMY2
46	Caddo Indian Burial Ground Norman 3MN386	Cfa	Hot.Springs.Mem.AP.723415_TMY3
47	George C. Davis site 41CE19	Cfa	Nacogdoches.AWOS.722499_TMY3
48	Walker Creek project Pilgrim's Pride site 41CP304	Cfa	Greenville.Muni.AP.722588_TMY3
49	Pine Tree Mound 41HS15	Cfa	Longview-Gregg.County.AP.722470_TMY3
50	Vinson site 41LT1	Cfa	Waco.Rgnl.AP.722560_TMY

Table A1. *Cont.*

	Archaeological Site	Climatic Zone [74]	Nearest Weather Station
		Longhouse	
51	Mantle site (AlGt-334)	Dfb	Mount.Forest.716310_CWEC
52	Strickler site (36La3)	Cfa	Wilmington.724089_TMY2
53	Klock site	Dfb	Utica-Oneida.County.AP.725197_TMY3
54	Garoga site	Dfb	Utica-Oneida.County.AP.725197_TMY3
55	Norton site (AfHh-86)	Dfb	London.716230_CWEC
56	Lawson site (AgHh-1)	Dfb	London.716230_CWEC
57	Wiacek site (BcGw-26)	Dfb	Muskoka.716300_CWEC
58	Nodwell site (bChI-3)	Dfb	St.Clair.County.Intl.AP.725384_TMY3
59	Baumann site (BdGv-14)	Dfb	Muskoka.716300_CWEC
60	Myers Road site (AiHb-13)	Dfb	London.716230_CWEC
		Pueblo	
61	Taos	Dfb	Taos.Muni.AP.723663_TMY3
62	Isleta	BSk	Albuquerque.Intl.AP.723650_TMY3
63	Tesuque	Cfb	Santa.Fe.County.Muni.AP.723656_TMY3
64	Zia	BSk	Albuquerque.Intl.AP.723650_TMY3
65	Sandia	BSk	Albuquerque.Intl.AP.723650_TMY3
66	Acoma	BSk	Albuquerque.Intl.AP.723650_TMY3
67	Zuni	BSk	Deming.Muni.AP.722725_TMY3
68	Picuris	Cfb	Santa.Fe.County.Muni.AP.723656_TMY3
69	Jemez	BSk	Albuquerque.Intl.AP.723650_TMY3
70	San Juan	BSk	Albuquerque.Intl.AP.723650_TMY3
		Plank house	
71	Old Kasaan	Cfb	Ketchikan.Intl.AP.703950_TMY3
72	Howkan	Cfb	Hydaburg.Seaplane.Base.703884_TMY3
73	Klinkwan	Cfb	Hydaburg.Seaplane.Base.703884_TMY3
74	Kaisun	Cfb	Sandspit.711010_CWEC
75	Kiusta	Cfb	Sandspit.711010_CWEC
76	Kung	Cfb	Sandspit.711010_CWEC
77	Ninstints	Cfb	Sandspit.711010_CWEC
78	Skidegate	Cfb	Sandspit.711010_CWEC
79	Tanu	Cfb	Sandspit.711010_CWEC
80	Hiellan	Cfb	Prince.Rupert.718980_CWEC

Table A2. Building materials.

Dwelling	Layer	Thickness (m)	Specific Heat (J/kgK)	Density (kg/m^3)	Thermal Transmittance U (W/m^2 °K)
Wigwam*					
wall/roof					2.13/2.27
	Cattail	0.001	1630.00	300	
	Air	0.005	1012.00	1	
	Cattail	0.001	1630.00	300	
	Cattail	0.001	1630.00	300	
	Air	0.005	1012.00	1	
	Cattail	0.001	1630.00	300	
Tipi**					
wall/roof					3.50/3.91
	Hide	0.0058	1400	22	
Hogan					
wall/roof					0.84/0.87
	Wood	0.1	1380.00	510.00	
	Tree bark	0.0127	1364.00	482.00	
	Earth	0.15	880.00	1460.00	
Grass house					
wall/roof					0.14/0.14
	Grass	0.35	1630.00	130.00	

Table A2. *Cont.*

Dwelling	Layer	Thickness (m)	Specific Heat (J/kgK)	Density (kg/m^3)	Thermal Transmittance U (W/m^2 °K)
Earthlodge					
wall/roof					0.34/0.35
	Wood	0.1	1380.00	510.00	
	Wood (branches)	0.1	1380.00	510.00	
	Grass + grass from turf	0.05	1630.00	150.00	
	Earth from turf	0.1	880.00	1460.00	
Longhouse***					
wall/roof					4.28/4.91
	Tree bark	0.0127	1364.00	482.00	
Pueblo					
wall					0.98
	Earth	0.51	1100.00	1400.00	
roof					0.52
	Wood (branches)	0.09	1380.00	510.00	
	Grass	0.03	1630.00	150.00	
	Earth	0.25	1100.00	1400.00	
Plank house					
wall					1.33
	Wooden planks	0.07	1380	510	
roof					4.91
	Tree bark	0.0127	1364.00	482.00	

* [92]; **In order to obtain the data about tipi hides, we used the information about other nomad tents whose envelopes were also made from animal skins. First, we used the information about goat skins presented in the research carried out by Shady Attia [93]. Second, we also took the information about yurt envelopes generated by Peter Manfield [94]. *** [95].

Table A3. Details of the building materials which compose the template called "Timber frame-superinsulated" from DesignBuilder v6.1.2.005.

	Thermal Transmittance (W/m^2 °K)		Thermal Transmittance (W/m^2 °K)
Outdoor walls	0.375	Sub-surfaces	
Bellow grade walls	0.375	Walls	0.156
Flat roof	5.983	Floors	
Pitched roof	2.93	Ground floor	0.866
Semi-exposed		Internal floor	0.866
Ceilings	0.228		
Floors	0.259		

The aforementioned template contains more building materials, but only the information about those which were assigned in the present research is contained in the previous table.

Table A4. Equivalent energy for each location and for each model in the corresponding approaches.

	Original Building Materials, Original Locations, with Openings	Original Building Materials, New Mexican Locations (Locations of Pueblos), with Openings	Original Building Materials from each Model Assigned to a Wigwam in New Mexican Locations (Locations of Pueblos), without Openings	Same Materials (Timber Frame-Superinsulated), New Mexican Locations (Locations of Pueblos), without Openings
Wigwam	0.160	0.170	0.304	0.275
1	0.202	0.232	0.371	0.318
2	0.166	0.162	0.295	0.266
3	0.137	0.180	0.318	0.287
4	0.169	0.162	0.295	0.266
5	0.177	0.162	0.295	0.266
6	0.133	0.162	0.295	0.266
7	0.137	0.136	0.258	0.269
8	0.173	0.180	0.318	0.287
9	0.137	0.162	0.295	0.266
10	0.166	0.162	0.295	0.266

Table A4. *Cont.*

	Original Building Materials, Original Locations, with Openings	Original Building Materials, New Mexican Locations (Locations of Pueblos), with Openings	Original Building Materials from each Model Assigned to a Wigwam in New Mexican Locations (Locations of Pueblos), without Openings	Same Materials (Timber Frame-Superinsulated), New Mexican Locations (Locations of Pueblos), without Openings
Hogan	0.201	0.164	0.316	0.296
1	0.214	0.213	0.410	0.323
2	0.183	0.153	0.290	0.291
3	0.183	0.177	0.345	0.307
4	0.183	0.153	0.290	0.291
5	0.203	0.153	0.290	0.291
6	0.203	0.153	0.290	0.291
7	0.176	0.153	0.318	0.272
8	0.321	0.177	0.345	0.307
9	0.146	0.153	0.290	0.291
10	0.203	0.153	0.290	0.291
Tipi	0.140	0.126	0.371	0.149
1	0.145	0.160	0.456	0.157
2	0.159	0.123	0.364	0.149
3	0.132	0.129	0.372	0.149
4	0.121	0.123	0.364	0.149
5	0.129	0.123	0.364	0.149
6	0.148	0.123	0.364	0.149
7	0.128	0.106	0.323	0.141
8	0.142	0.129	0.372	0.149
9	0.118	0.123	0.364	0.149
10	0.175	0.123	0.364	0.149
Earthlodge	0.079	0.070	0.323	0.079
1	0.082	0.088	0.422	0.090
2	0.082	0.059	0.298	0.075
3	0.082	0.097	0.354	0.083
4	0.082	0.059	0.298	0.075
5	0.080	0.059	0.298	0.075
6	0.082	0.059	0.298	0.075
7	0.080	0.062	0.314	0.080
8	0.082	0.097	0.354	0.083
9	0.060	0.059	0.298	0.075
10	0.075	0.059	0.298	0.075
Grass house	0.074	0.088	0.339	0.113
1	0.057	0.098	0.441	0.139
2	0.055	0.068	0.314	0.104
3	0.061	0.147	0.368	0.121
4	0.061	0.068	0.314	0.104
5	0.057	0.068	0.314	0.104
6	0.066	0.068	0.314	0.104
7	0.066	0.072	0.326	0.121
8	0.067	0.147	0.368	0.121
9	0.074	0.068	0.314	0.104
10	0.173	0.068	0.314	0.104
Longhouse	0.014	0.015	0.394	0.016
1	0.015	0.018	0.450	0.017
2	0.012	0.015	0.389	0.015
3	0.014	0.015	0.396	0.016
4	0.014	0.015	0.389	0.015
5	0.014	0.015	0.389	0.015
6	0.014	0.015	0.389	0.015
7	0.017	0.013	0.362	0.015
8	0.014	0.015	0.396	0.016
9	0.017	0.015	0.389	0.015
10	0.014	0.015	0.389	0.015
Pueblo	0.061	0.061	0.276	0.113
1	0.077	0.077	0.353	0.112
2	0.056	0.056	0.253	0.115
3	0.062	0.062	0.298	0.108
4	0.056	0.056	0.253	0.115
5	0.056	0.056	0.253	0.115
6	0.056	0.056	0.253	0.115
7	0.075	0.075	0.292	0.118
8	0.062	0.062	0.298	0.108
9	0.056	0.056	0.253	0.115
10	0.056	0.056	0.253	0.115

Table A4. *Cont.*

	Original Building Materials, Original Locations, with Openings	Original Building Materials, New Mexican Locations (Locations of Pueblos), with Openings	Original Building Materials from each Model Assigned to a Wigwam in New Mexican Locations (Locations of Pueblos), without Openings	Same Materials (Timber Frame-Superinsulated), New Mexican Locations (Locations of Pueblos), without Openings
Plank house	0.030	0.029	0.244	0.028
1	0.033	0.037	0.327	0.031
2	0.035	0.028	0.225	0.027
3	0.035	0.031	0.270	0.029
4	0.027	0.028	0.225	0.027
5	0.027	0.028	0.225	0.027
6	0.027	0.028	0.225	0.027
7	0.027	0.023	0.229	0.026
8	0.027	0.031	0.270	0.029
9	0.027	0.028	0.225	0.027
10	0.030	0.028	0.225	0.027

Table A5. Data used in PAST v3.25.

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y		K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
W1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH1**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W2	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH2**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W3	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH3**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W4	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH4**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W5	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH5**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W6	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH6**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W7	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH7**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W8	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH8**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W9	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH9**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
W10	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	**GH10**	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0
H1	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH1**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H2	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH2**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H3	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH3**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H4	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH4**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H5	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH5**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H6	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH6**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H7	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH7**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H8	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH8**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H9	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH9**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
H10	1	1	0	0	1	0	0	1	0	0	0	1	0	1	0	**LH10**	1	0	0	1	0	1	0	1	0	0	0	1	0	0	0
T1	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P1**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T2	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P2**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T3	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P3**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T4	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P4**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T5	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P5**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T6	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P6**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T7	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P7**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T8	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P8**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1

Table A5. *Cont.*

	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y		K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
T9	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P9**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
T10	0	0	0	0	1	0	0	1	1	1	0	0	0	0	0	**P10**	0	1	0	0	0	0	1	0	0	0	0	0	0	1	1
E1	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH1**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E2	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH2**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E3	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH3**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E4	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH4**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E5	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH5**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E6	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH6**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E7	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH7**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E8	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH8**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E9	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH9**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1
E10	1	0	1	0	0	0	0	1	0	1	1	0	0	0	1	**PH10**	0	1	0	1	0	0	0	1	0	0	0	1	0	0	1

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