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Article

Evaluation of Reinforced Adobe Techniques for Sustainable Reconstruction in Andean Seismic Zones

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Abstract: This research presents a methodological process for selecting the most appropriate construction technique for the reconstruction of housing after a seismic disaster in a rural and heritage context. This process, which is applicable to a large part of the Andean region, incorporates sustainability criteria to guarantee the economic, social and environmental balance of the intervention. The methodology was developed on a case study: the Colca Valley in Arequipa, Peru. In 2016 an earthquake affected this zone, where traditional unreinforced earthen buildings suffered serious damage. The objective of this research focuses on comparing six traditional building techniques strongly related to self-building: four techniques for adobe housing—reinforced with cane (CRA), wire mesh (WMRA), geogrid (GRA) and halyard ropes (HRRA)—and two techniques for masonry buildings—confined (CM) and reinforced (RM). For this purpose the authors used the Integrated Value Model for Sustainable Assessment (MIVES), a Multiple Criteria Decision Analysis (MCDA) model used to compare alternatives by assigning a "sustainability index" to each evaluated construction technique. This research study includes two types of variables: quantitative, such as economy ($/m^2) and environmental impact (kgCO_2/m^2), among others, and qualitative, such as perception of safety, respect for the urban image and popular knowledge. The research results show that reinforced adobe techniques are a viable and competitive option, highlighting the cane reinforced adobe technique (CRA), with a value of 0.714 in relation to industrialized materials such as masonry. This technique has the same safety characteristics, but at almost half the price, with the additional advantage of using traditional materials and construction methods, having less environmental impact and showing better thermal performance in cold climates.

Keywords: evaluation; MCDA (Multiple Criteria Decision Analysis); MIVES (The Spanish Integrated Value Model for Sustainable Assessment); reconstruction; index; sustainability

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1. Introduction

From 1970 to 2020, earthquakes in developing countries caused 1,015,000 deaths, affected 178,000,000 inhabitants and produced damages of 226 billion dollars [1]. This latent problem requires the use of mechanisms that allow proper selection of construction techniques that guarantee resilient housing, with an integrated approach for effective implementation. There are successful experiences of reconstruction and damage assessment in rural populations with heritage value located in seismic areas such as Peru, Italy [2], Nepal [3], Indonesia [4] and Chile [5].

Since 2000, MCDA methods have gained importance in comparative evaluations of the construction sector, where the nature of the variables is increasingly complex and requires more rigorous decision-making methods in addition to adequate weighting criteria. These type of holistic evaluations have been driven by the need to approach the building process with a more comprehensive method; most of them are based on a life cycle assessment (LCA) using tools such as Eco-Quantum (The Netherlands), ATHENA (Canada), EcoEffect

(Sweden), LCA House (Finland) and ENVEST (United Kingdom), among others, which are promoted by developed countries, use industrialized materials and are applied in urban contexts [6]. Recent studies have tried to incorporate these evaluation methodologies in developing countries to guarantee greater scientific rigor in the decision-making processes in situations of special importance, such as post-disaster reconstruction. The challenge is greater due to the difficult access to information and limited diffusion of these processes in the academic and professional fields. Table 1 shows research projects in developing countries that have used some MCDA methods for the selection of building techniques based on various variables.

Table 1. MCDA in the construction sector in developing countries.

Year	Country	Author	Research	Criteria				Ref.
				Economy	Environment	Social	Others	
2020	Ethiopia	Daget, Y.	Industrialized housing systems			X	X	[7]
2019	Peru	Tarque, N	Selecting reinforcement for masonry walls	X			X	[8]
2019	Egypt	Haroun, H.	Reuse of heritage buildings	X	X	X	X	[9]
2016	Malaysia	Khoshnava, S.	Classification of sustainable materials	X	X	X		[10]
2016	Iran	Hosseini A.	Technologies for post-disaster temporary housing	X	X			[11]
2013	Brazil	De Azevedo, R.	Construction of apartment buildings	X		X	X	[12]
2007	South Africa	Ugwu, O.	Sustainability in the construction industry	X	X	X	X	[13]

According to the National Institute of Statistics and Informatics (INEI) 2017 housing census, in Peru, 31% of the population (9,765,000 inhabitants) still live in different types of earthen housing, mostly adobe and mud wall (tapial) [14]. In Peru, 230,000 adobe housing units were built from 1993 to 2017, almost 9500 houses per year [14], most of them without technical advice. Masonry construction, as the most economical industrialized technique in use, represented t55.8% of houses in the country in 2017 [14]. The confined masonry type is most widely used in urban contexts, due to the fact that the population is closer to the production centers and to the availability of qualified labor. Though there is a growing expansion of masonry building systems in rural contexts, these do not necessarily have the same possibilities and conditions as urban contexts. However, masonry remains the construction material to which many humble people aspire, even among the 2.9% of the total population (928,000 inhabitants) that still live in extreme poverty (daily income less than $2) [15].

Certainly in Peru there is an interesting scientific literature on earth building construction, mainly focused on the use and characterization of adobe, although also highly focused on two specific aspects: an architectural point of view, considering historical premises and/or urban determinants, and an engineering point of view, which very strictly addresses structural and/or construction issues. This situation generates proposals with a reduced range of action that leave aside decisive variables in the reconstruction processes, such as the economy, community participation and access to materials, essential requirements for contexts of special heritage value such as the Colca Valley. The use of methodologies that systemically facilitate decision making in the construction sector in Peru represent isolated cases [16], although their implementation is necessary in the public housing programs, as stated by one of the objectives of the current national housing and urban planning policy in Peru [17].

In this sense, this research project focuses on reconstruction scenarios in rural populated centers susceptible to being affected by seismic events. The objective is to develop an agile tool that allows systematizing the selection of the most suitable building system for the reconstruction of housing in the Colca Valley, a mechanism that could be extrapolated to a large part of the Peruvian Andean rural area. The main contribution is that the tool unifies variables of the qualitative and quantitative type in a single index that facilitates decision making, in addition to making a contribution to the scarce existing research projects regarding the selection of building techniques in rural contexts in the Andean region.

This article is structured as follows. Section 1 presents the introduction. Section 2 defines the methodology to build the evaluation framework for Section 3, which analyzes the case study and presents the selection of the alternatives for reconstruction. Section 4 describes the proposed evaluation model, and Section 5 illustrates the application and the analysis of the case study results.

2. Methodology

Given the complexity of the research, which encompasses quantitative and qualitative variables, the Integrated Value Model for a Sustainable Evaluation (MIVES) was chosen. This methodology, in comparison with others, allows systematizing of the information in relatively simple steps and supported by important tools such as value functions and the weighting of variables by groups of experts; this allows for objective evaluations and decision making using a more comprehensive approach. Furthermore, its tree-structured model and its simple implementation make MIVES especially suitable for communicating results to non-experts.

MIVES is a decision support methodology that allows for obtaining a single index and comparative studies, transferring the different characteristics of the objects to a series of homogeneous and quantifiable parameters that facilitate the selection [18]. The process is based on disaggregating the different evaluation parameters, defining a model that is capable of being weighted for each of the alternatives in a dimensionless magnitude that will be called the "Sustainability Index".

The use of this method has been successful in the selection of various construction alternatives, such as types of concrete columns [19], reinforcing fibers [20], wooden structures [21], selection of building systems for schools [22], sports spaces [23] and underground pipe systems [24]. It has also been used for the evaluation of post-disaster housing solutions such as the location of temporary housing [25] and the sustainability of self-help housing [26]. Figure 1 shows the process diagram.

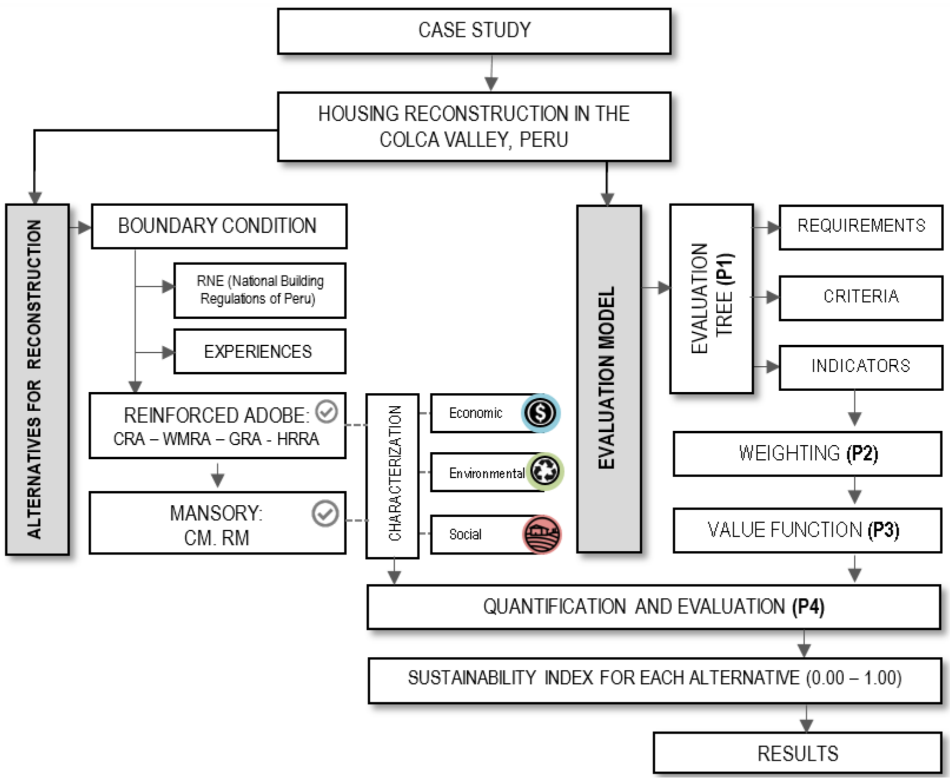

Figure 1. Sequence of application of the evaluation model (own source).

The process is divided into two stages. The first is to define the alternatives for reconstruction for subsequent evaluation using the "boundary conditions" as a selection tool; these are the minimum technical requirements that the alternatives must meet. The definition of the boundary conditions is followed by their economic, environmental and social characterization.

The second stage consists of applying the evaluation model, which includes the following: development of the tree of requirements (P1), establishing the requirements, criteria and indicators; weighting and assignment of relative weights (P2), involving experts who establish the level of importance of the variables; assignment of function value (P3), allowing the comparison between indicators with different units of measurement and incorporating statistical parameters; quantification and evaluation of the indicators (P4), which, with the help of the value function, allows for the establishment of a dimensionless variable with a range from 0.00 to 1.00 for each constructive alternative, which we call the "Sustainability index".

3. Case Study

The case study of this research is the possible reconstruction scenarios based on the selection of the most suitable building system for the Ichupampa district in the Colca Valley in southern Peru. This area was affected by an earthquake of magnitude 5.2 on the Richter scale (Figure 2), which caused the collapse of 390 houses and left another 1224 uninhabitable and caused four fatalities and 68 injuries throughout the Colca Valley [27].

Figure 2. Consequences of the earthquake in the Colca Valley in 2016. Source: Google maps and ©ENCUENTRO.

In Peru, national and regional bodies lack methodological tools that guarantee an objective and integrated selection of building systems for housing projects. The selection, in most cases, is based on economic profitability criteria, opting for industrialized materials and systems such as confined or reinforced masonry, which in the popular imagination are also considered "safer" and "more modern". The local building tradition and the socio-cultural and environmental aspects that should be implicit in this type of project are usually ignored.

The scenario configures an uncertain future for these populated centers; if an appropriate system is not chosen, it would seriously endanger the equity value of houses. In this sense, it is appropriate to illustrate the experiences of Sibayo (Figure 3) and Cabanaconde (Figure 4), also located in the Colca Valley, which in past years took opposite paths regarding the preservation of their traditional building techniques.

Figure 3. SCENARIO A—SIBAYO: with the use of traditional building techniques and technical assistance, safe homes were constructed, becoming a prominent tourist attraction in the Colca Valley.

Figure 4. SCENARIO B—CABANACONDE: the use of industrialized techniques without technical assistance does not guarantee the structural safety of the houses, in addition to irreversibly damaging the urban image. ©Matyas Rehak.

3.1. Alternatives for Reconstruction

According to the scenarios set out in Figures 3 and 4, two classes of building techniques were considered: improved traditional techniques and industrialized techniques. The former appeals to the concept of "Appropriate Technology" [28], allowing for the revaluing of traditional techniques by incorporating technological advances at the scale and need of the most disadvantaged populations, achieving a considerable improvement over traditional adobe with a reduced investment. These techniques have already demonstrated their experimental efficacy, which allowed their incorporation into the technical standard E-080 of the National Building Regulations of Peru RNE [29], a pioneer in Latin America. These Regulations recognize reinforced adobe as a safe and viable material, provided that certain technical criteria are respected [30]. On the other hand, we have the industrialized techniques (brick and concrete), which are increasingly used in rural areas due to the desire of the new generations to have "safer" and "more modern" housing, alluding to the idea of progress that is coming from nearby cities. These techniques are included in the National Building Regulations, in standard E-070 of the RNE.

3.2. Boundary Conditions

Each constructive alternative must meet certain minimum technical requirements (boundary conditions) in order to be included in the study. These requirements allow us to significantly limit the scope of alternatives to evaluate. These conditions are as follows: (1) it must have been approved by the National Building Regulations (RNE), thus validating the structural characteristics and seismic capacity of the selected technique; and (2) it must demonstrate use in large-scale reconstruction processes to show the feasibility of its implementation. Table 2 identifies the main parameters of the building techniques that exist in the local environment to which the selection criteria is applied. The alternatives in adobe that met the required conditions were those reinforced with cane (CRA), wire mesh (WMRA), geogrid (GRA) and halyard ropes (HRRA), which were validated by the Technical Standard E-080. In addition, those using confined masonry (CM) and reinforced masonry (RM) techniques were validated by the Technical Standard E-070 [31]. These techniques are described below.

- Cane reinforced adobe (CRA) is a building system that uses open cane as horizontal reinforcement and whole cane as vertical reinforcement in courses of mud mortar. The vertical canes must be anchored to the foundation and the base beam [30].
- Wire mesh reinforced adobe (WMRA) is based on the placement of electro-welded mesh on the surface of the walls, simulating confinement beams and columns in adobe walls, to provide greater rigidity and avoid the separation of these by seismic action [32].
- Geogrid reinforced adobe (GRA) uses a polypropylene mesh that is responsible for confining the adobe blocks that are joined together by pieces of rope that go through the wall and are placed in the mortar joints [30].

- Halyard rope reinforced adobe (HRRA) is a system of synthetic ropes that wrap the walls vertically and horizontally, forming a mesh that confines the walls of the house and prevents them from collapsing [30].

Table 2. The techniques chosen for evaluation with MIVES are shaded.

Material	Technique		Acronyms	Year Introduced	Boundary Conditions		Refs.
					RNE Code	Experience	
Earthen Construction	Simple Adobe		SA	750 AC	-	Yes	
	Adobe reinforced with:	Canes	CRA	1978	E-080	Yes	[33,34]
		Wire mesh	WMRA	1997	E-080	Yes	[33]
		Geogrid	GRA	2007	E-080	Yes	[33,34]
		Halyard ropes	HRRA	2015	E-080	Yes	[33]
		Tire-straps	TSRA	2011	-	-	[35]
		Steel profiles	SPRA	2005	-	-	[36]
		Reinforced concrete	RARC	2011	-	-	[37]
	Prefabricated Quincha		PQ	1984	-	Yes	[34,38]
Masonry	Confined masonry		CM	1982	E-070	Yes	[39]
	Reinforced masonry		RM	1986	E-070	Yes	[40]

- Confined masonry (CM) uses reinforced concrete columns and beams around its perimeter; the concrete is poured after the setting of walls, which are generally made of fired clay bricks [31].
- Reinforced Masonry (RM) uses steel rods distributed vertically and horizontally and integrated by concrete of fluid consistency, which the different components acting together to resist the efforts. In Figure 5 the different techniques described are shown schematically [31].

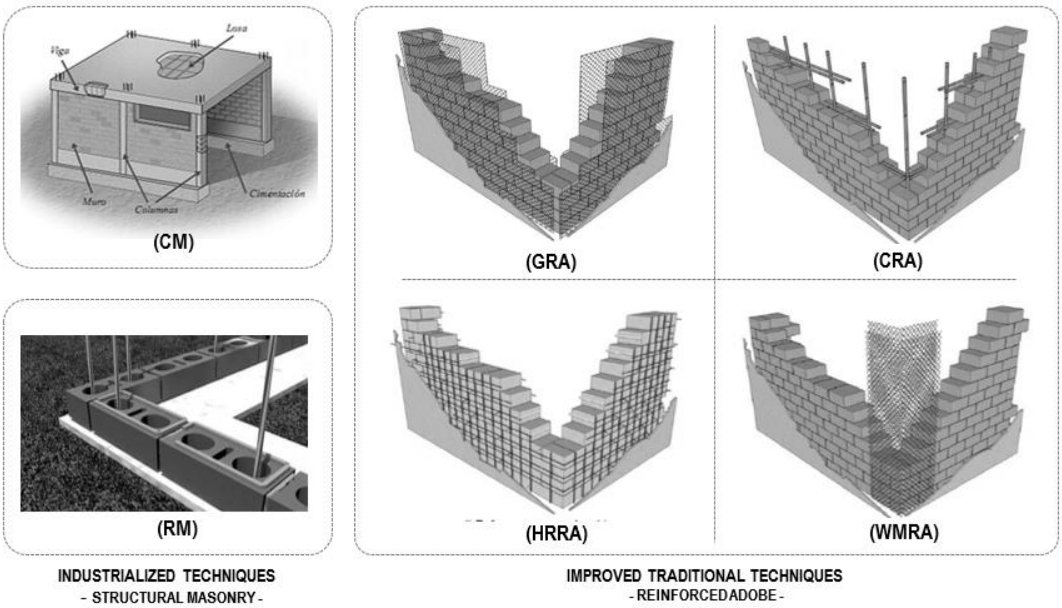

Figure 5. Construction techniques to be evaluated.

3.3. Characterization of Techniques

Figure 6 presents the detailed characteristics of each of the selected building techniques, based on economic, environmental and social indicators. These data will be used for developing the requirements tree that allows comparison and evaluation of the selected building techniques.

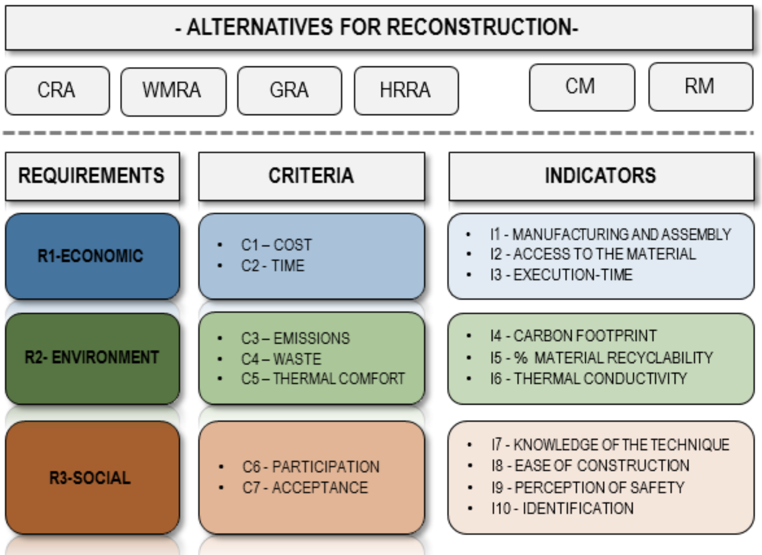

Figure 6. Characteristics of techniques based on indicators.

3.3.1. Economic Indicators—R1

- Manufacturing and assembly—€/m^2 (I1): we analyzed popular housing modules already executed in Peru, formulated by institutions with experience in reconstruction issues such as PUCP (Pontifical Catholic University of Peru), COPASA (Cooperation for the Sustainable Development Process of Arequipa), GIZ (German Agency for Technical Cooperation), SDC (The Swiss Agency for Development and Cooperation-SDC), JICA (Japan International Cooperation Agency) and PNVR (National Rural Housing Program), among others. In order to have more comparable data, we took as a criterion the cost per m^2 of useful area, since adobe walls have a thickness of 0.40 m and masonry thickness is 0.15 m. The cost includes basic finishes such as wall plastering and wood carpentry, which as a whole are not significant in proportion to the structural elements. The cost options in the reinforced adobe houses range from €197.5/m^2, if using halyard ropes, to € 225.4/m^2, if using wire mesh reinforcement. We observed similar values in the case of cane reinforcement, with a value of € 212.5/m^2, and the geogrid reinforcement, with a value of € 215.3/m^2; however, if cane reinforcement were more accessible, the value would drop considerably. In the case of confined masonry, the value is € 370.5/m^2, practically double the value of reinforced adobe. Reinforced masonry has a value of € 307.9/m^2; its cost is lower than that of confined masonry, because it does not require reinforced concrete elements such as columns and confinement beams (Table 3).
- Access to the material (I2): for each construction technique we calculated the distance in km from the town of Ichupampa, the one most affected by the 2016 earthquake, to the closest material distribution point. The geogrid, the wire mesh and the concrete blocks for reinforced masonry are the most difficult materials to obtain because they must be brought from the city of Arequipa (200 km distance). The canes are brought from the lower valleys (50 km) and the halyard ropes are sold in most hardware stores in the populated centers of the Colca Valley. Brick and concrete can be purchased in Chivay, capital of the province (15 km), but they have costs above the national average for being brought from the city of Arequipa (Table 3).
- Execution time (I3): the time required in man-hours (MH) to execute 10 m^2 of wall was established as the unit cost analysis for each construction technique. Of the reinforced adobe techniques, the WMRA requires 10.9 MH because it needs a concrete complement in the corners; the HRRA requires 9.2 MH because it needs more manual work in the placement of the ropes and knots; the CRA requires 8.7 MH and the GRA requires 8.4 MH, which are comparatively shorter times because the placement of the

canes and geogrid is faster and more practical. The confined masonry technique, CM, requires 22.6 MH due to the placement of formworks for the confinement of columns and beams; the reinforced masonry technique, RM, needs 15.1 MH, less time than in the CM, because it does not require confinement elements in the reinforced concrete (beams and columns) (Table 3).

Table 3. Evaluation of economic indicators.

Technique		Manufacturing and Assembly				Access to the Material		Execution Time	
		Authors	**Useful Area (m^2)**	**€/m^2 ***		**Supplier**	**km**	**Man Hours, MH (10 m^2 of Wall)**	
Adobe Reinforced with:	Wire mesh—WMRA	CARITAS	33.0	225.4 €	[34]	Arequipa	200	10.9 **	[41]
	Canes—CRA	CARITAS, JICA	34.0	212.5 €	[34,41]	Pedregal	50	8.7	[41]
	Geogrid—GRA	GIZ-COSUDE, CARE [1]-PUCP	34.1	215.3 €	[34]	Arequipa	200	8.4	[42]
	Halyard Ropes—HRRA	GIZ-COSUDE, CARE-PUCP	34.0	197.5 €	[34]	Ichupampa	5	9.2 **	[41]
Confined masonry—CM		MVCS [2]	34.0	370.5 €	[43,44]	Chivay	15	22.6	[45]
Reinforced masonry—RM		MVCS	25.0	307.9 €	[43]	Arequipa	200	15.1	[46]

* Prices to 2020. ** Own calculation, from reference bibliography. [1] CARE is a humanitarian organization fighting global poverty. [2] Ministry of Housing, Construction and Sanitation.

3.3.2. Environmental Indicators—R2

- Carbon footprint (I4): the unit of measure kg CO_2/m^2, equivalent to kg of CO_2 for the construction of 1 m^2 of wall, was used for each of the six techniques. Confined masonry has a value of 301 kg CO_2/m^2 because it requires industrialized materials such as fired clay brick and concrete (cement plus aggregate), both with a high CO_2 emission, especially from clinker, the main component of cement. Reinforced masonry reaches a value of 455 kg CO_2/m^2 by using steel rods that require a high CO_2 value for production. Adobe reinforced with canes consists of natural materials; thus, the CO_2 emitted during its production is considered as null, with only the emission from the adobe production considered (74 kg CO_2/m^2). Wire mesh (electro-welded) is manufactured from low-alloy steel and presents a considerably high energy consumption in its production process (96 kg CO_2/m^2). The biaxial geogrid is made with high molecular weight and high tenacity polypropylene that provides high passive load resistance (79 kg CO_2/m^2). Finally, the halyard rope has nylon as its main component, which is a synthetic polymer that belongs to the group of polyamides; being a petroleum derivative, it has an impact on the environment (82 kg CO_2/m^2) (Table 4).
- Thermal conductivity (I5): the Colca Valley is over 3000 m high, requiring construction materials to withstand the intense cold in this area, especially between June and August, with temperatures reaching −4 °C [47]. The economic conditions of this area prevent the use of heating or additional insulating materials, so the adoption of a suitable enclosure material is in many cases the only protection against the effects of the weather. The unit of measure of thermal conductivity, W/mK, is used for the main materials of each construction technique [48]. In this regard, the four reinforced adobe techniques reached a similar value of 0.46 W/mK, which is basically attributed to the adobe units because the contribution of the reinforcement elements is considered thermally negligible. Confined masonry has a value of 1.04 W/mK, and reinforced masonry has a value of 0.91 W/mK (Table 4).
- Recyclability of material (I6): once the life cycle of a building is completed, it is important to establish the proportion (%) of material that can be recycled or reincorporated into a production cycle. The higher the recycling percentage is, the lower the impact on the environment, due, among other factors, to the lower amount of energy required to produce new construction materials from extraction and processing of raw materials. In the case of adobe, according to the study carried out by E. Vargas (2020) [49], 80% recycling capacity is reached due to the physical properties of the earth of being easily reintroduced into the production cycles and, in this sense, generating low residue levels. In the case of confined masonry, the percentage is 23%, because

brick requires more complex processes for recycling. Reinforced masonry reaches 44%; simple grinding can produce light aggregate (Table 4).

Table 4. Assessment of environmental indicators.

	Technique	Waste: % of Material Recyclability		Thermal Comfort: Thermal Conductivity (W/mK)		Emissions: Carbon Footprint	Emissions: kg CO_2/m^2 of Wall		Emissions: Partial
Adobe Reinforced With:	Wire mesh—WMRA *	80%	[49]	0.46	[50,51]	Low alloy steel ** Adobe wall	22 74	[52] [53]	96
Adobe Reinforced With:	Canes—CRA *	80%	[49]	0.46	[50,51]	Reeds ** Adobe wall	0 74	[52] [53]	74
Adobe Reinforced With:	Geogrid—GRA *	80%	[49]	0.46	[50,51]	Polypropylene ** Adobe wall	5 74	[52] [53]	79
Adobe Reinforced With:	Halyard ropes—HRRA *	80%	[49]	0.46	[50,51]	Nylon ** Adobe wall	8 74	[52] [53]	82
Confined masonry—CM		23%	[49]	1.04	[53]	Solid brick	301	[53]	301
Reinforced masonry—RM		44%	[49]	0.91	[53]	Precast concrete + 2% steel	455 455	[52] [52]	455

* The value of adobe without reinforcement is considered because the contribution of the reinforcement elements is thermally negligible.
** Own calculation, based on the physical properties of the material and its CO_2 emission per kg of reinforcement material.

3.3.3. Social Indicators—R3

Given the qualitative nature of these indicators, fieldwork was carried out through surveys with multiple-choice questions (Figure 7) and workshops in Ichupampa (Figure 8), the district that was most affected by the 2016 Colca Valley earthquake. According to the INEI (National Institute of Statistics and Informatics of Peru), the population of this district in 2019 was 572 inhabitants [54]. A sample (n) of 82 surveys for this population had a 95% confidence level, whose development is explained in Equation (1) [55]; the results are described in indicators I7, I9 and I10.

$$n = \frac{N \times Z_a^2 \times p \times q}{d^2 \times (N-1) + Z_a^2 \times p \times q} \quad (1)$$

n = Sample size (number of surveys)
N = Population size
Z = Confidence level
p = Probability of success, or expected proportion
q = Probability of failure
d = Precision (maximum permissible error in terms of proportion)

- Knowledge of the technique (I7): 100% of those surveyed stated that they knew the confined masonry technique because it is one of the most widely used and widespread techniques, while in terms of reinforced masonry only 26% of those surveyed knew about it. Of the adobe reinforcement techniques, the best known was the wire mesh technique with 33% of respondents knowing of it (several housing modules were built after the 2001 earthquake), followed by reinforcement with canes with 29% and geogrid with 24%. The halyard ropes technique had only 6% recognition, as it is the most recent to be introduced and still has very little diffusion. Additionally, 80% of the population stated that they had participated in the construction of at least one adobe house, but they stated that this tradition is being lost because the new generation has greater resources and gives preference to masonry construction (Table 5).
- Ease of construction (I8): this factor measures the level of complexity in the construction process of each reinforcement technique and the feasibility of it being replicated by the inhabitants, in self-building processes, with minimal training and the use of simple tools. For measuring between the cost of unskilled labor and the cost of total labor, we used a ratio; data were obtained from the housing modules already analyzed in Table 5. Under this analysis, the reinforcement with halyard ropes requires 50.46%,

reinforcement with canes 49.30%, reinforcement with wire mesh 42.41%, and with geogrid 41.42%. In confined masonry this value reaches 31.25%, and for reinforced masonry 15.30%. The more complex the technique, the higher the ratio of specialized labor, which logically also implies a higher economic cost (Table 5).

- Perception of safety (I9): a chromatic scale was used with a ranking range from 1 to 10 (with 1 being very bad and 10 very good) for measuring this variable and for a better understanding of the method by the surveyed population. The confined masonry reached, according to the perception of safety that the respondents showed, a value of 8.40, and the reinforced masonry reached value of 7.50. In the case of reinforced adobe, the technique with wire mesh reached a value of 6.50; cane, 6.30; geogrid, 6.90; halyard ropes, 5.90. This shows greater confidence in masonry techniques compared to reinforced adobe constructions, which is explained by the growing fear generated by the collapse of adobe housing after the 2016 earthquake. However, it must be remembered that these houses did not have the proper structural reinforcement (Table 5).
- Identification (I10): this indicator measures the level of identification of the population with each construction technique and how they believe it contributes wealth and heritage value to their district. A total of 90% of those surveyed consider that their town has an important heritage value, and 88% attribute it to the traditional buildings (housing and churches). Under these criteria, on a ranking scale from 1 to 10 (1 being very bad and 10 very good), confined masonry reaches a value of 3.3, reinforced masonry reaches a value of 3.0, and adobe constructions in general reach a value of 8.0. The adult population shows greater attachment to traditional buildings, while young people feel identify more with industrialized techniques such as masonry (Table 5).

(**a**) (**b**) (**c**)

Figure 7. Development of surveys using a chromatique chart for the rating from 1 to 10 of the indicators of knowledge of the technique (**a**), perception of safety (**b**) and identification (**c**).

(**a**) (**b**)

Figure 8. Participatory workshop held in the Colca Valley (**a**,**b**).

Table 5. Results of social indicators.

Technique		Participation				Acceptance			
		Knowledge of the Technique		Ease of Construction (% of Unqualified Labor Force)		Perception of Safety (1 to 10)		Identification (1 to 10)	
Adobe reinforced with:	Wire mesh—WMRA	33%	*	42.41%	[34]	6.50	*	8.00	*
	Canes—CRA	29%	*	49.30%	[34,41]	6.30	*	8.00	*
	Geogrid—GRA	24%	*	41.42%	[34]	6.90	*	8.00	*
	Ropes—HRRA	6%	*	50.46%	[34]	5.90	*	8.00	*
Confined masonry—CM		100%	*	31.25%	[44,56]	8.40	*	3.30	*
Reinforced masonry—RM		26%	*	15.30%	[56]	7.50	*	3.00	*

* Results of surveys.

4. Evaluation Model

A structured process is proposed that, supported by the MIVES methodology, allows us to obtain a "Sustainability Index", with a ranking range from 0.00 to 1.00 for each of the building techniques.

For this purpose, the weighted sum of each of the value functions assigned to each indicator was made, thus obtaining a final dimensionless value that allows merging qualitative and quantitative variables, as well as facilitating the comparison of results.

The stages of this model are detailed in the following sections.

4.1. Development of the Tree of Requirements (P1)

A branched diagram was used to integrates the main and most discriminative aspects to be studied and to group the requirements, criteria and indicators of the evaluation model responding to the following: economic criteria, such as cost and construction times; environmental criteria, such as emissions, percentage of waste and thermal comfort; and social criteria, such as community participation and acceptance by the population. In Figure 9, the final structure and the components of the requirements tree is presented.

4.2. Weighting and Assignment of Relative Weights (P2)

This section involves experts in recognized fields, who through interviews and surveys established the criteria and indicators to be developed as well as the respective weighting, using the direct percentage allocation method established in MIVES, which ranges from 0% to 100% according to the level of importance of the variables.

This part of the process is very important because it ensures greater objectivity in the evaluation and decision making. Table 6 shows the list of experts consulted, who were classified based on three areas of expertise: (1) construction systems, with a focus on applied research related to reinforced adobe or structural masonry; (2) rural housing, with experience in the execution and implementation of low-cost housing projects; (3) heritage, with participation of specialists in the conservation and promotion of buildings that fit into the surrounding natural and cultural landscape.

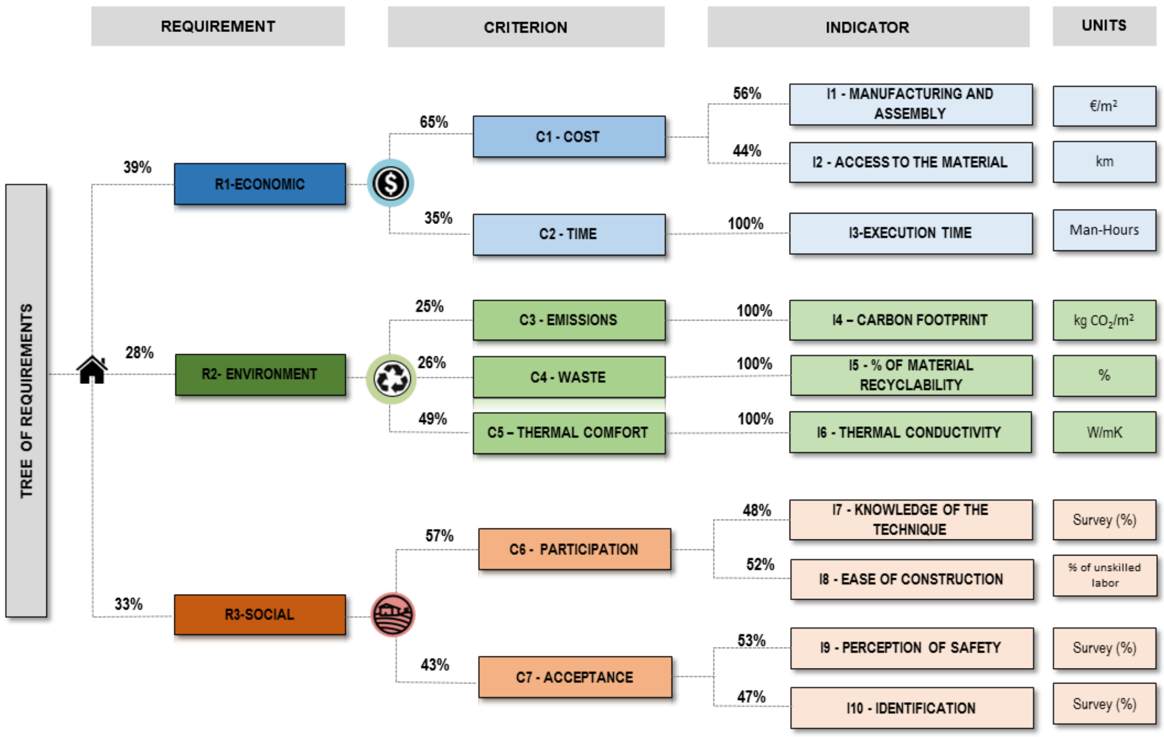

Figure 9. Tree of requirements with the weights given by groupings.

Table 6. List of specialists consulted for the structure and weighting of the requirements tree.

Field	Expert	Speciality	Years of Experience
Building systems	BS1	Post-disaster earthquake-resistant housing: adobe and masonry	30
	BS2	Structural safety of reinforced and unreinforced masonry	15
	BS3	Earthquake-resistance for social and sustainable housing	30
	BS4	Unconventional building materials	25
Rural housing	RH1	Participatory technology transfer for the Andean region.	25
	RH2	Design and construction with participatory methods.	20
	RH3	Technology transfers for low-cost housing	18
	RH4	Construction with earth and other natural materials	20
Heritage	H1	Consultant in the development of heritage building regulations	30
	H2	Consultant for the UNESCO Heritage Committee	20

As a result, the requirements tree is obtained with the necessary weightings at the level of requirements, criteria and indicators, as shown in Figure 9. At the requirements level, the economic factor is the most important, with 39%; this is likely due to the high poverty rates and vulnerability in the Andean region and is broken down into costs (65%) and associated times (35%). This is followed by the environmental aspect, which reaches a value of 28%, driven by the need for thermal comfort (49%) to face the low temperatures that the region supports in the winter months. The level of emissions reaches a value of 25% and the generated waste, 26%. Finally, the social aspect, with 33%, is divided into community participation (57%) and acceptance (43%).

4.3. Assignment of Function Value (P3)

The value function can range from a quantification of a variable or attribute to a dimensionless variable range, between 0.00, which reflects the minimum satisfaction (S_{min}), and 1.00, which reflects the maximum satisfaction (S_{max}). The main objective of the methodology is to be able to compare the evaluations of the indicators with different units of measure [57].

For example, it is about being able to compare variables of the same type: time, cost, temperature, indicators quantified by attributes, etc. In this way, a weighted sum of the different valuations of each of the indicators can be made. The value function used is defined by five parameters, which, by varying them, allow obtaining all kinds of shapes: S, concave, convex, or linear; see Table 7 and Figure 10. The parameters that define the type of function are K_i, C_i, X_{max}, X_{min}, and P_i (Equation (2)). The value of B is calculated starting from the five previous values (Equation (3)) [58].

$$V_{ind} = B.\left[1 - e^{-K_i \times \left(\frac{X - X_{min}}{C_i}\right)^{P_i}}\right] \tag{2}$$

$$B = \left[1 - e^{-K_i \times \left(\frac{X_{max} - X_{min}}{C_i}\right)^{P_i}}\right]^{-1} \tag{3}$$

where [58]:

X_{min} is a value in the abscissas, whose ranking is equal to zero (in the case of increasing value functions).

X_{max} is the abscissa of the indicator that generates a value equal to 1 (in the case of increasing value functions).

X is the abscissa of the evaluated indicator (variable for each alternative),

P_i is the shape factor that defines whether the curve is concave, convex, straight or S-shaped. Concave curves are obtained for values of $P_i < 1$, convex or "S-shaped" if $P_i > 1$ and linear curves for $P_i = 1$. In addition, it roughly determines the slope of the curve at the point of coordinate inflection (C_i, K_i),

C_i approaches the abscissa of the inflection point,

K_i approaches the ordinate of the inflection point, and

B is a factor that allows the function to remain in the value range from 0 to 1. This factor is defined by Equation (2).

Table 7. Showing the different types of value functions.

	Increasing Function		
Function	***C***	***K***	***P***
Lineal	$C \approx X_{min}$	≈0	≈1
Convex	$X_{min} + \frac{X_{max} - X_{min}}{2} < C < X_{min}$	<0.5	>1
Concave	$X_{min} < C < X_{min} + \frac{X_{max} - X_{min}}{2}$	>0.5	<1
S-shaped	$X_{min} + \frac{X_{max} - X_{min}}{5} < C < X_{min} + (X_{max} - X_{\text{min}}) * \frac{4}{5}$	0.2/0.8	>1

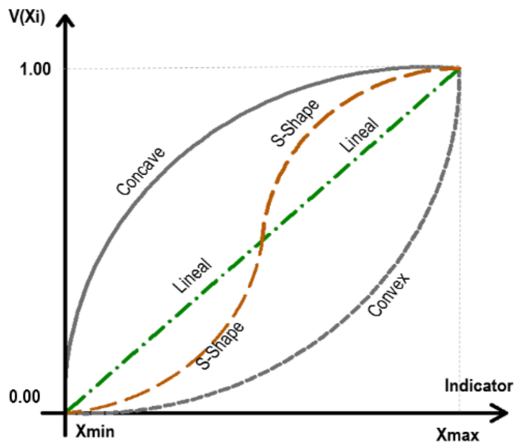

Figure 10. Evaluation parameters for the different types of value functions.

Below, Equations (2) and (3) are developed, taking as an example indicator I1—manufacture and assembly, whose value is a function of decreasing curve S.

$$Value = B.\left[1 - e^{-0.5\times\left(\frac{X-500}{250}\right)^3}\right] \qquad B = \left[1 - e^{-0.5\times\left(\frac{500-o}{250}\right)^3}\right]^{-1}$$

where X is the answer to the evaluated indicator (manufacturing and assembly cost per m^2); K_i = 0.5 approaches the ordinate of the inflection point; X_{max} = € 500/m^2 is the maximum value of the abscissa in the range of the alternatives of the evaluated indicator; C_i = € 250/m^2 is the inflection point in the abscissa; P_i = 1 is the shape factor of a straight curve; B is the value that maintains the function in the range from 0 to 1. This factor B is defined in Equation (2), where: K_i = 0.5; X_{max} = € 500/m^2; X_{min} = € 0/m^2 is the minimum value of the abscissa in the range of the alternatives of the evaluated indicator; C_i = € 500/m^2; P_i = 3. Figure 11 shows the development of this value function.

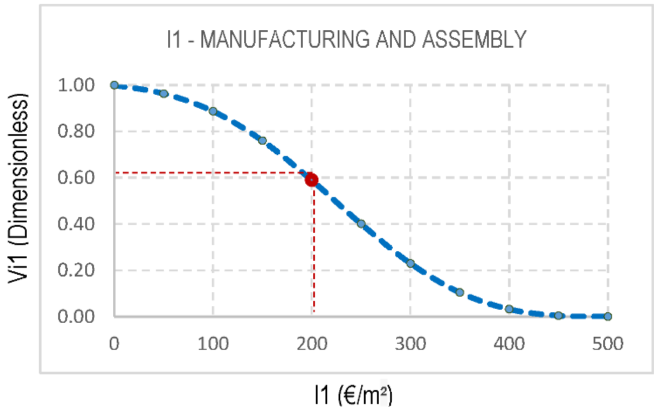

Figure 11. Value function of Indicator I1—manufacturing and assembly.

For example, in the case of HRRA, if you have an indicator of € 197.46/m^2, which, evaluated in Figure 11, gives a Vi1 of 0.60, then this value will be weighted average with the other indicators to obtain the "Sustainability Index" for the HRRA, as explained in Section 4.4.

Table 8 shows the value functions for each of the indicators. It should be mentioned that the type of function selected is adapted to the particular characteristics of each variable. The following were proposed: four S functions, because the variation in satisfaction (value in the ordinate) is appreciated more clearly in the central values; five linear functions, to consider values from 0% to 100%, which generate a change in equal proportion without influencing the position of the abscissa; one convex function, since satisfaction increases or decreases much more when the increase or decrease of the indicator variable is closer to the X_{max} values. In Appendix A the characteristics of each value function are graphically detailed.

4.4. Quantification and Evaluation (P4)

The calculation of the "Sustainability Index" is a process that requires the following steps [59]:

- Value of the indicators is obtained from the value function and the quantification of the indicator for each alternative. The quantification of the alternative is the abscissa of the point of the value function, whose ordinate is the value of the indicator for the alternative studied. It is shown in the example in Figure 12.
- Value of the criteria is obtained from the value of the indicators belonging to the same criterion multiplied by their respective weights (Equation (4)).
- Value of the requirements is the sum of the values of the criteria belonging to that same requirement multiplied by their weights (Equation (5)).

– Value Index is determined by adding the value of the requirements multiplied by their weights (Equation (6)).

Table 8. Parameters of the value functions for each indicator.

	Indicator	Units	Function	X_{min}	X_{max}	C	K	P
I1	Manufacturing and assembly	Euro/m^2	S-Decr	500	0	250	0.5	3
I2	Access to the material	km	S-Decr	300	0	150	0.5	3
I3	Execution time	Man-Hours	S-Decr	40	0	20	0.5	3
I4	Carbon footprint	kg CO_2/m^2	S-Decr	600	0	300	0.5	3
I5	% of material recyclability	%	Linear	0	100	90	0.01	1
I6	Thermal conductivity	W/mK	Convex	1.2	0	1.08	0.5	0.5
I7	Knowledge of the technique	Survey (%)	Linear	0	100	10	0.01	1
I8	Ease of construction	% of unskilled labor	Linear	0	100	10	0.01	1
I9	Perception of safety	Survey (%)	Linear	0	10	1	0.01	1
I10	Identification	Survey (%)	Linear	0	10	1	0.01	1

$$V_{Criterion} = \sum_{i=1}^{n} V_{Indicator} \times W_i \tag{4}$$

$$V_{Requirement} = \sum_{i=1}^{n} V_{Criterion} \times W_i \tag{5}$$

$$Indicator\ value_{Alternative} = \sum_{i=1}^{n} Requirement \times W_i \tag{6}$$

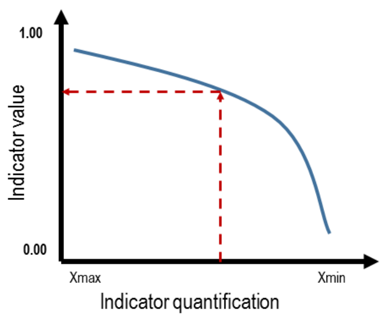

Figure 12. The value function as a tool for quantifying indicators.

Next, as an example, the calculation of the Sustainability index for the HRRA is developed:

$$ECONOMIC - R1 = 0.39\langle 0.65 * [0.56 * V1 + 0.44 * V2] + 0.35 * [1.00 * V3]\rangle = 0.315$$
$$ENVIRONMENT - R2 = 0.28\langle 0.25 * [1.00 * V4] + 0.26 * [1.00 * V5] + 0.49 * [1.00 * V6]\rangle = 0.238$$
$$\underline{SOCIAL - R3 = 0.33\langle 0.57 * [0.48 * V7 + 0.52 * V8] + 0.43 * [0.53 * V9 + 0.47 * V10]\rangle = 0.156}$$
$$\text{Sustainability Index for the HRRA} = 0.709$$

5. Analysis of Results

With the help of the MIVES software, the evaluation is carried out, and the different requirements, criteria and indicators are unified in a single index. Table 9 summarizes the results of the "Sustainability Index" for each construction technique. As explained in the previous section, the rankings for each indicator, criteria and requirements are broken down. Below, in Table 9, the ranking for each constructive alternative is detailed.

Table 9. Rating indicators for obtaining Sustainability Index.

Global Ranking of Techniques												
Requirement		**Economic**			**Environment**			**Social**				**Index**
Criterion		**Cost**		**Time**	**Emissions**	**Waste**	**Thermal Comfort**	**Participation**		**Acceptance**		
Indicator		**Manufacturing and Assembly**	**Access to the Material**	**Execution-Time**	**Carbon Footprint**	**% Material Recyclability**	**Thermal Conductivity**	**Knowledge of the Technique**	**Ease of Construction**	**Perception of Safety**	**Identification**	
Adobe reinforced with:	Canes—CRA	0.076	0.101	0.119	0.067	0.058	0.114	0.026	0.051	0.048	0.054	0.714
	Halyard ropes—HRRA	0.086	0.112	0.117	0.066	0.058	0.114	0.006	0.051	0.045	0.054	0.709
	Geogrid—GRA	0.076	0.015	0.120	0.066	0.058	0.114	0.023	0.041	0.053	0.054	0.620
	Wire mesh—WMRA	0.068	0.015	0.109	0.064	0.058	0.114	0.032	0.043	0.050	0.054	0.607
Confined Masonry—CM		0.010	0.112	0.040	0.028	0.017	0.059	0.090	0.032	0.064	0.023	0.475
Reinforced Masonry—RM		0.030	0.015	0.086	0.004	0.032	0.077	0.024	0.015	0.057	0.021	0.361

The techniques that achieved the highest "Sustainability Index" were those of reinforced adobe, due to its lower cost, low environmental impact and constructive ease, led by the reinforcement with canes (CRA) with a value of 0.714, followed closely by reinforcement with halyard ropes (HRRA) with an index of 0.709. In third place was the reinforcement with geogrid (GRA), which reached a value of 0.620, followed closely by the reinforcement with wire mesh (WMRA), with an index of 0.607. Masonry techniques obtained a lower ranking due to their higher construction costs, higher CO_2 emissions in their production and low thermal performance against cold. However, the local population widely accepted them because they see in them as a "safer" and "more modern" alternative. The confined masonry CM achieved an index of 0.475, and the reinforced masonry had a value of 0.361. Figure 13 shows the sustainability index based on the 3 requirements: economic, environmental and social; the contribution of each one in the final score is appreciated comparatively.

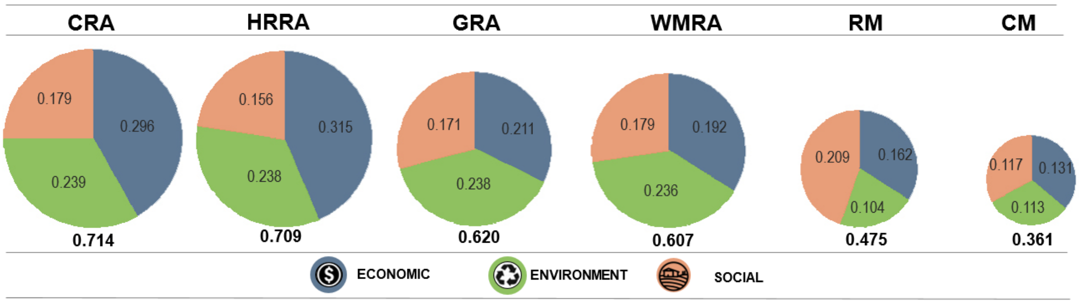

Figure 13. Results of the three requirements: economic, environmental and social. Software MIVES.

For the economic requirement, the ranking associated with reinforced adobe construction costs is considerably lower than RM and CM. Reinforced adobe techniques have the advantage of using local materials and reinforcements are easily accessible, except for GRA. The RM and CM use industrialized materials that have to be purchased in the city of Arequipa (200 km). Finally, the reinforced adobe techniques are faster to execute because they do not require formwork or setting periods as in the case of RM and CM.

Regarding the environment requirement, reinforced adobe techniques have a lower carbon footprint due to the use of local materials, better thermal performance against cold and a great recycling capacity. CM and RM, due to their industrial nature, require higher energy consumption, which translates into higher emissions, little recycling capacity and a thermal behavior less appropriate for cold climates. At the level of reinforcement techniques, the more industrialized the material, the lower its availability and the greater its impact on the environment.

For the social requirement, the population recognizes the value of adobe as a symbol of identity. In addition, the reinforced adobe techniques allow a greater participation of unskilled labor. Industrialized techniques, RM and CM, obtained better ranking in perception of safety; in the knowledge of the technique, RM is the best known by the population due to its wide dissemination in recent years.

Figure 14 shows the main attributes and weaknesses of each construction technique, based on 10 indicators. The CRA and HRRA stand out for their thermal conductivity and execution time, but their weakest point is their lack of diffusion among the population. The GRA and WMRA have their ranking decreased due to the distance in access to the material. CA shows a high level of diffusion among the population but has high construction costs. RM is a technique of rapid execution, but it requires skilled labor as well as being the most polluting technique.

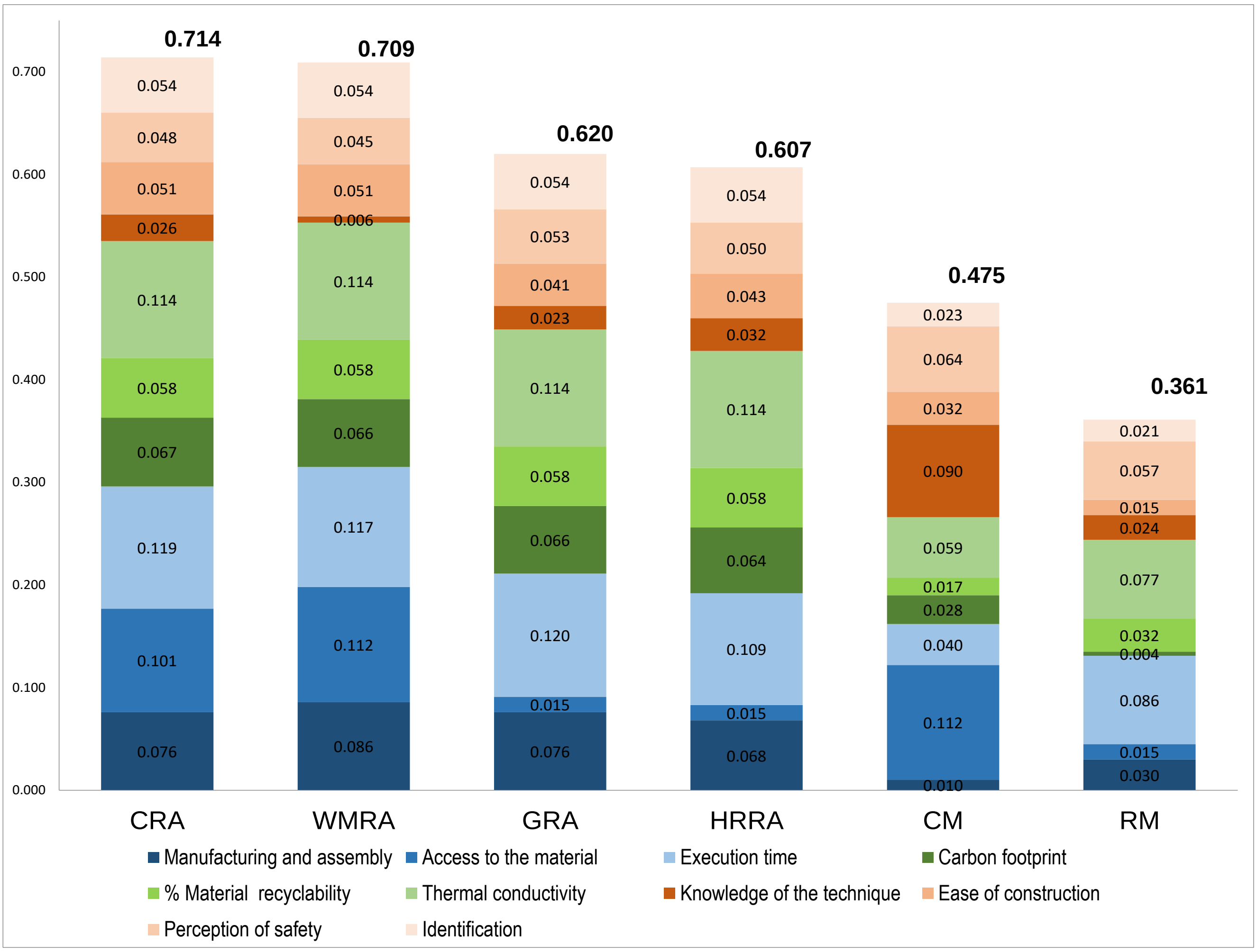

Figure 14. Evaluation of the indicators and calculation of the sustainability index.

This article presents an evaluation of construction techniques under a sustainability approach; the structural aspect was not addressed because it was implicit in the techniques already approved by the National Building Regulations of Peru. This strategy allowed concentrating efforts on the analysis of economic, environmental and social variables, which have been little studied in systemic evaluation processes like this one. However, future lines of research could explore the structural aspect in greater depth by conducting experimental and quantitative studies.

6. Conclusions

- The MIVES methodology demonstrated its effectiveness in the development of multi-criteria decision processes for the case study. The new decision-making tool could be applied in other contexts of the Andean rural area, adapting the requirements tree structure and updating the weighting of the criteria involved.
- From the evaluation carried out, the reinforced adobe technique achieved the highest score due to its affordable cost, low environmental impact and ease of construction. The leader in this category was reinforcement with canes (CRA), with a value of 0.714, followed closely by reinforcement with halyard ropes (HRRA), with an index of 0.709. In third place was reinforcement with geogrid (GRA), which reached a value of 0.620, followed closely by reinforcement with wire mesh (WMRA), with an index of 0.607. Masonry techniques have a lower value for having higher construction costs, higher CO_2 emissions in their production and low thermal performance against the cold; however, they are widely accepted by the local population, who see in them as a safer

and more modern alternative. The confined masonry (CM) achieves an index of 0.475, followed by the reinforced masonry, with a value of 0.361.

- These research results show that reinforced adobe techniques are a viable and competitive option with respect to masonry because they meet the same safety characteristics but at almost half the price, with the additional advantages of using traditional materials and construction methods, producing less environmental impact, using a reduced amount of embodied energy, producing fewer emissions associated with transportation, and having better thermal performance in cold climates.
- Industrialized techniques such as confined and reinforced masonry would be a viable option in towns close to distribution centers, preferably less than 50 km away, which ensures that the equity value of their environment is not endangered and where qualified labor is available.

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

Appendix A

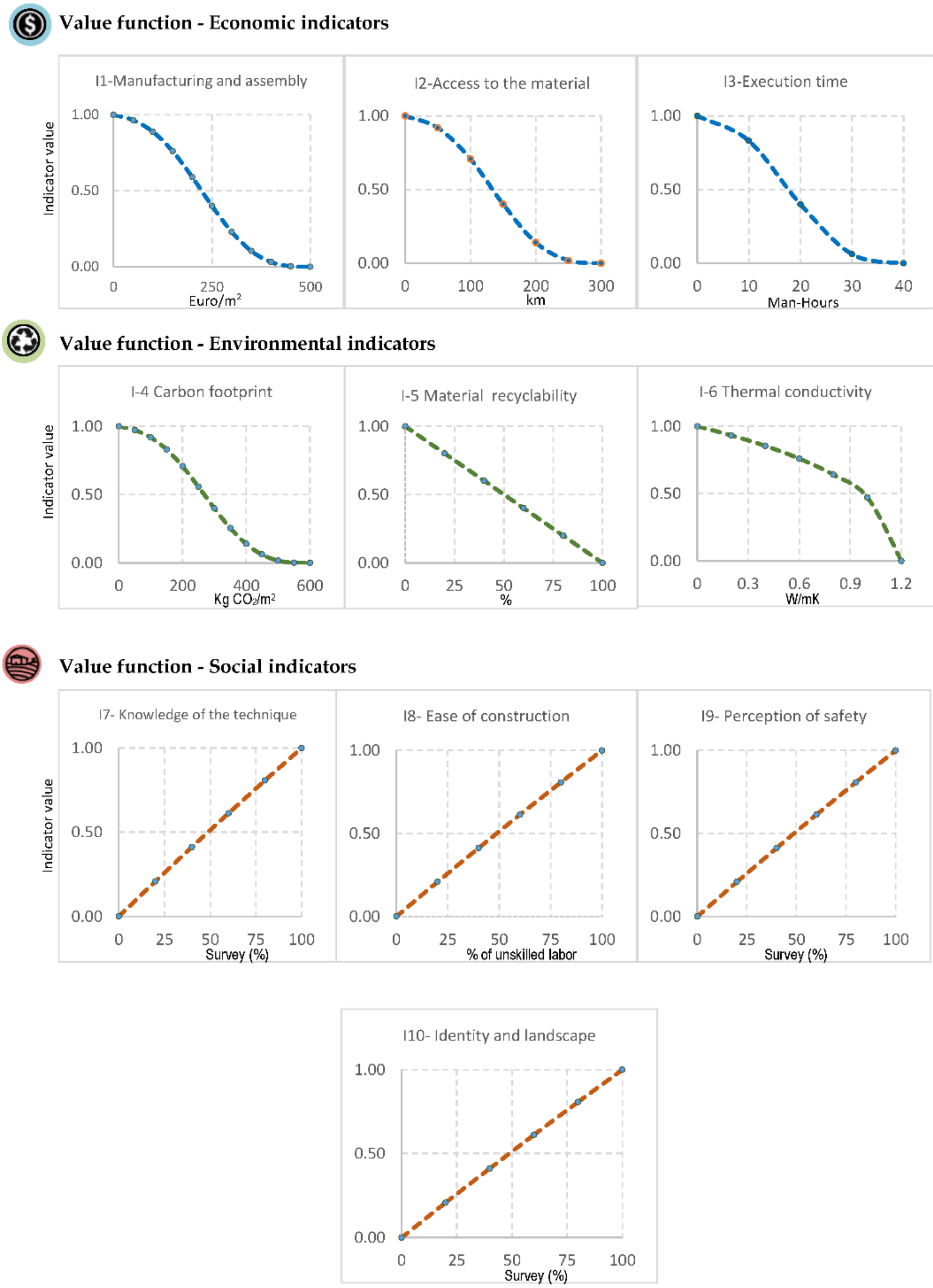

Figure A1. Diagrams for the value functions used in the case study for each indicator.

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