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ON THE SUSTAINABILITY OF NOISE MITIGATION MEASURES

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ABSTRACT

In recent years, the issue of sustainability has assumed great importance in every field, including noise mitigation measures, and interested stakeholders have found themselves struggling with still evolving and uncertain techniques to evaluate the related social, economic, and environmental aspects. Indeed, the sustainability assessment can be accomplished with many different methods and countless indicators.
To clarify the problem and identify suitable methodologies to assess the sustainability of noise mitigation solutions for roads, the Italian PIARC committee TC 3.4.2 has undertaken an in-depth study on the most ascertained techniques, from Life Cycle Sustainability Assessment to the more recent Envision protocol.
This study has involved a broad and focused effort to define the meaning of sustainability, from the perspective of infrastructure managers, users, and the general population. Criteria and indicators to describe the performance of noise mitigation solutions have been identified and a general procedure for assessing the sustainability of noise mitigation measures has been defined.
The selected method and indicators have then been applied to a case study, located in a suburban environment, to test their applicability and reliability.
In this paper, the main outcomes of this study are reported.

Keywords: *noise, mitigation, sustainability.*

1. INTRODUCTION

Road traffic is the primary source of noise pollution in Europe, with noise levels projected to rise in urban and rural areas over the next decade due to urban growth and increased demand for mobility. Despite the EU recommends avoiding long-term exposure to noise levels greater than 55 decibels – dB(A) – it is estimated that in most European countries, more than 50 % of inhabitants within urban areas are exposed to road noise levels of 55 dB(A) or higher during the day-evening-night period. To counteract this trend, EU Member States are already taking a variety of actions to reduce and manage noise levels, according to the rules fixed by the Environmental Noise Directive 2002/49/EC, but further efforts are needed to clarify the effectiveness and sustainability of noise mitigation measures.
In recent years, the issue of sustainability has assumed great importance in every field, including noise issues, and interested stakeholders have found themselves struggling with still evolving and uncertain techniques to evaluate the related social, economic and environmental aspects. Indeed, the sustainability assessment can be accomplished with many different methods and countless indicators.
To clarify the problem and identify suitable methodologies to assess the sustainability of noise mitigation solutions for roads, the Italian PIARC committee TC 3.4.2 has undertaken an in-depth study on

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the most ascertained techniques, from Life Cycle Sustainability Assessment to the more recent Envision protocol.

2. THE PIARC TC 3.4.2

The TC 3.4.2 is a technical committee of PIARC, the World Road Association, focused on the environmental Sustainability of Road Infrastructures and Transport.
The Italian Technical Committee (TC) brings together authorities, road administrators, university professors, scholars, and sector operators of special prestige. The TC mirrors the Goals/Objectives and Scope of the International Committee. Among these, the identification of factors and criteria that may affect the choice of a solution to protect against road noise, by the principles of sustainable development.
The Italian Committee represents PIARC at the national level, helps to intensify involvement in the Association's activities, and contributes to the widespread dissemination of results and recommendations.
As such, the Italian Committee has delivered a report on the current state of the art on noise mitigation measures based on the field and scientific research activities, case studies, and literature review. It includes design, construction, and maintenance improvements and criteria to choose the best solutions to protect against noise, considering the principles of sustainable development.

3. NOISE MITIGATION MEASURES

Noise mitigation solutions and measures are traditionally distinguished into three types: at the source, along the propagation path, and on the receiver.

3.1 Noise mitigation measures at the source

Reducing noise emissions at the source is well known to be the most efficient mitigation strategy. Several solutions can be adopted at the source by different actors and in different contexts. They include measures on the vehicle, city planning, traffic management, and low-noise pavements.
From this perspective, reducing noise in the vehicle entails mainly the reduction of noise generated by the propulsion system (engine noise) and tires (rolling noise). As for propulsion and rolling noise, their contribution is strongly dependent on speed and vehicle type. At lower speeds, less than 40 km/h, the engine noise prevails over rolling noise in light vehicles. The latter becomes predominant at higher speeds. Therefore, different mitigation strategies must be adopted according to traffic flow conditions. When the problem is mainly due to the propulsion system, noise mitigation can be pursued by providing: 1) a gradual reduction of noise emission levels of ICEVs (about 3-4 dB at low speed); 2) incentives to shift towards the widespread adoption of EVs (the use of electric vehicles below 30 km/h is 4-5 dB less noisy than the ICEVs); 3) encouraging road users to adopt milder driving behaviours (Ecodriving - more responsible driving behaviours are estimated to reduce the overall noise level by 5 dB).
When rolling noise becomes more prominent than propulsion noise it is possible to act on two elements: tires (low-noise tires) and road pavement characteristics (the wearing course texture, the acoustic absorption property, and the elasticity of the pavement) [1].
Whilst these mitigation measures compete mainly with automotive manufacturing and infrastructures, planning measures represent the fundamental tool for the Administrations to contain environmental noise. They consist mainly of:

- measures on mobility, which include selective accessibility actions (reduction of overall traffic volumes, restrictions on the composition of the vehicle fleet), establishment of limited traffic and/or controlled speed zones, Intelligent Traffic Systems (ITS), adoption and incentive to use car sharing and carpooling, taxes and tolls;
- measures on the urban layout, which include the targeted planning roads layout and the adoption of acoustic zones.

Measures on mobility are less expensive and reversible and can provide reductions up to about 3 dB. Measures on the urban layout are more expensive and almost not reversible, but they can lead to achieving greater performance, especially if adopted during the design phase.

3.2 Noise mitigation measures on the propagation path

When high perceived reductions along the propagation path are needed, acoustic barriers are the most effective solution. Their extrinsic performance mainly depends on site topography, ground surface type, local meteorology, geometric dimensions, and airborne sound insulation of the barrier. However, they can be customized, i.e., adopting specific reflective or absorbent materials on one or both sides of the barrier, or improved by applying "added devices" acting as single or multiple diffractors of the sound field on the upper edge of the barrier.

Recent European standards permit to qualify the intrinsic characteristics of airborne sound insulation and sound absorption on site, i.e., on installed noise barriers. They are currently applied in many European countries [2][3]. Although many researchers have measured [4] the effect of several single or multiple diffractors on the upper edge [5][6], current installations only adopt simple shapes, i.e. horizontal panels placed in a "T" shape above the barrier or cylindrical or almost cylindrical elements.

3.3 Noise mitigation measures on the receivers

Several characteristics of the facade shape and the surface treatment may influence the propagation of road traffic noise on the environment and the impact on receivers, such as the vertical dimension, the material used (sound-absorbing or sound-reflecting with specular or diffuse reflections) or the presence of openings, protruding elements (balconies, terraces, loggias, ledges, lintels, sunscreens, solar collectors on the roof, etc.) and vegetation.
Noise reaching the façades interacts with the building boundary elements (i.e., walls, windows) and is partially radiated inside the buildings. Poor insulation of the weak elements of the façades may prejudge the insulation performance of the façade as a whole.
Noise mitigation measures on the receiver envisage a limited number of actions, mainly aimed at enhancing the soundproofing of the façades. These typically include the replacement of windows with more soundproofing materials and, rarely, the juxtaposition of soundproofing panels to the outer walls to enhance their acoustic properties.

4. METHODS TO ASSESS THE SUSTAINABILITY OF NOISE MITIGATION MEASURES

Noise mitigation measures are designed to reduce noise pollution and its impact on the environment and human health. The sustainability of these measures is an important issue in their design and implementation. Noise mitigation measures can be sustainable if they are designed to be effective over the long term from an environmental, economic, and social perspective.
Standardized life cycle analyses have been developed over time, in the attempt to implement sustainability analysis in different fields of application. The most interesting and applied methods are the following:

- the ISO-based standards, which refer to the life cycle assessment through a detailed analysis of the environmental impacts (LCA), the estimate of costs (LCC or LCCA), and social impacts assessment (SLCA), eventually converging into the life cycle sustainability assessment (LCSA).
- The Envision Protocol (sustainable performance and resiliency of physical infrastructure), where the emphasis is given to civil engineering, infrastructures, and resilience. Here, public, and private infrastructures are addressed, including Energy, Water, Waste, Transportation, Landscape, and Communication.

4.1 The Life Cycle Sustainability Assessment

The Life Cycle Sustainability Assessment (LCSA) refers to the assessment of environmental, social, and economic impacts and benefits of products throughout their life cycle. This type of assessment allows for the provision of a complete picture of a product's positive and negative impacts, supporting companies and players in identifying the weak points in the value chain and the actions to be taken to make their product more sustainable. Likewise, the results of this evaluation constitute a useful aid in the decision-making process when it comes to investing or choosing the products themselves.
Therefore, the sustainability assessment of a product must consider all life cycle phases, starting from the extraction of the product’s raw materials to its manufacturing and use, up to its disposal. In this way, it is possible to identify the weight of each phase in the various dimensions of sustainability (environmental, social, and economic) and possibly make corrections to the process, if unbalanced environmental, social, or economic loads are highlighted.
To date, the techniques used to evaluate the three dimensions of sustainability are based on the approach outlined by ISO 14040 and ISO 14044. Specifically, the environmental dimension is analysed with the Life Cycle Assessment (LCA) technique, while the economic aspect is assessed using the Life Cycle Costing analysis (LCC). Finally, the social dimension is treated with the Social Life Cycle Assessment (S-LCA) [7].
The concept of Life Cycle Sustainability Assessment (LCSA) was introduced by Walter in 2008. Klopffer suggested combining the results of LCA, LCC and S-LCA to obtain an integrated and all-encompassing vision of product sustainability:

$$LCSA = LCA + LCC + SLCA$$

The Life Cycle Sustainability Assessment follows the general approach defined by ISO 14040, which is

composed of four phases: (i) definition of the scope and objectives, (ii) analysis of the inventory, (iii) assessment of the impacts, and (iv) interpretation of the results.
Since the LCSA must combine the three assessments (LCA, LCC, and S-LCA), whose scope and objectives are defined, it is necessary to identify a common ground of evaluation, i.e., define the scope and objectives valid for the three evaluations.
The LCSA assessment must also include all the functional units identified in the three sub-processes, some of which may be shared, as shown in Figure 1.

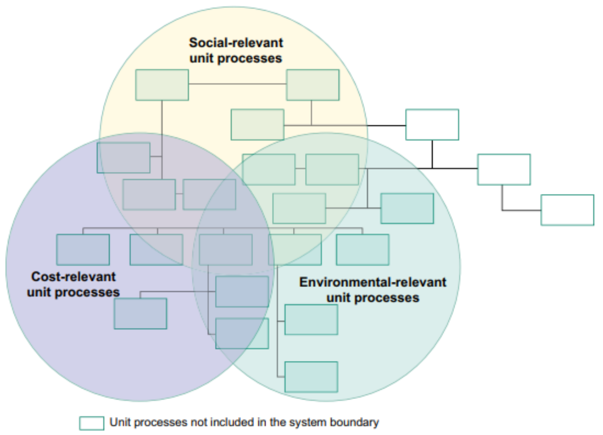

Figure 1 – Identification of the LCSA scope [7].

This also includes the identification of the impacts individually detected within the three assessments.
In the inventory phase, it is necessary to consider all the information related to the three evaluations (LCA, LCC, and S-LCA) for each of the process units that make up the system.
In the impact evaluation phase, the impacts listed in the previous inventory phase are classified and assigned to impact categories. Since the impact categories differ in the three assessments, it is advisable to keep this step separate from the three components, as illustrated in figure 2.
The last phase of the evaluation entails the interpretation of the results in a combined way, considering the simultaneous presence of benefits and critical aspects referring to the three dimensions of sustainability: economic, environmental, and social.
This type of analysis allows to highlight those parts of the process that can be improved from the sustainability perspective. Likewise, when used to compare products that show the same functions, it supports the identification of the most sustainable solutions.

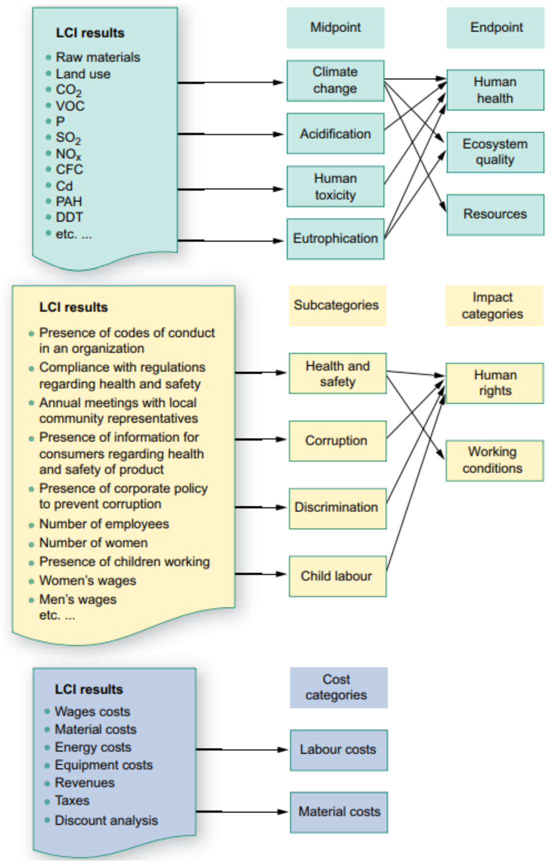

Figure 2 - Example of classification and assignment of impact categories in the LCSA [7]. Light green refers to environmental aspects, yellow to social aspects and grey to costs.

The integration and subsequent interpretation of the results achieved with the above-mentioned analyses (LCA, LCC, and S-LCA) can be carried out by applying one of the multi-criteria decision-making methods (MCDM) currently available. Depending on the multi-criteria method selected for the analysis, the data referring to each sustainability criterion are normalized, weighted, and aggregated to calculate a global numerical index representative of the product/service analysed.
The normalization process has the purpose of converting the results achieved with different indicators and measurement units into dimensionless units on a scale from 0 to 1.

Once normalized, the results relating to the various criteria are typically weighted using coefficients reflecting their importance according to the objectives of the evaluation and benchmarks.
Finally, these normalized and weighted attributes are aggregated to provide a sustainability index that evaluates and classifies the proposed alternatives.
Multi-criteria methods present critical issues related to the subjectivity of the parameters used. First, the weighting coefficients, which are assigned by the decision-makers themselves, the MCDM method and the presence or absence of dominant alternatives with respect to others for one or more attributes.
The results of these evaluations can also be affected by errors coming from the use of non-independent indicators, i.e., indicators in some way linked to other indicators, or by the uncertainty of data themselves.

4.2 The ENVISION protocol

ENVISION is a protocol that allows the assessment and measurement of the sustainability of infrastructure projects, through the entire range of social, economic, and environmental indicators. Envision is designed as a holistic sustainability rating system applicable to all types and sizes of public and private infrastructures. ENVISION's purpose is to promote more sustainable projects and to support stakeholders in the development and implementation of resilient and sustainable long-term solutions.
The ENVISION protocol [8] consists of a flexible system of performance criteria and objectives aimed at identifying sustainable approaches during the various phases of a project's life cycle. It consists of 64 sustainability and resilience indicators, called "credits", organized around five fundamental pillars: quality of life, leadership, resource allocation, nature, climate and resilience. In turn, these include aspects such as human well-being, mobility, community development, collaboration, planning, economics, materials, energy, water, location, conservation, ecology, emissions, and resilience, which, taken together, contribute to assessing the degree of sustainability of projects (Figure 3).

Fig. 3 - Infrastructures subject to evaluation of the ENVISION protocol [8].

Each of the 64 credits defines multiple levels of achievement that represent the spectrum of possible performance goals, from slight improvement beyond conventional practice to conservation and restoration of communities and environments. By evaluating the achievement of each of the 64 credits, the project teams can establish to what extent the project is sustainable with respect to the multiple aspects of the evaluation and identify the parameters responsible for the sustainability performance. Each of these credits is assigned a score that reflects the performance of the action implemented. The sum of all the scores provides the final evaluation.
The score refers to the achievement of the following performance in terms of sustainability:

- Improved: improvement with respect to regulatory/conventional requirements.
- Enhanced: higher performance than regulatory requirements.
- Superior: high-level performance.
- Conserving: zero impact performance.
- Restorative: Services that restore natural or social systems. This performance is awarded the highest score.

The evaluation criteria are indicated with letters ranging from A to E and include both qualitative and quantitative requirements.

For performance evaluation, it is necessary to establish a baseline against which to determine the improvements resulting from the application of a solution or several alternative solutions.

The ENVISION protocol can be applied in the different phases of the life cycle of a project, from planning to the decommissioning of the infrastructure at the end of its life. The earlier it is applied, the more effective and efficient the pursuit of sustainability objectives.

Projects that offer greater durability and flexibility to extend infrastructures' lifetime receive further recognition. Prolonging the durability of the built infrastructure reduces the need for replacement structures. Furthermore, more credit is given to those projects which incorporate the principles of deconstruction and allow for the reuse and recycling of materials and equipment.

5. CASE STUDY

The case study considered for the application of the sustainability analysis refers to a suburban area, located in the city of Rome, crossed by the motorway A90. Despite the predominantly industrial character of the area, several residential buildings are present, including two sensitive receivers: a nursery school and a primary school. Given the proximity of many receivers to the road source, along the A90 motorway noise barriers have been erected. Nonetheless, sound pressure levels were found still above the noise limits. Therefore, to further abate noise, two restorative solutions have been designed and the Envision protocol has been applied to identify the most sustainable solution.

5.1 Noise impact assessment

The noise impact assessment of the area was carried out using a calculation model opportunely calibrated with acoustic data collected on site at a series of representative receivers. Between January and May 2021, several measurements were carried out to ascertain the actual noise levels and to proceed with the calibration of the calculation model. Table 1 shows the measurement results. As indicated by Directive 2002/49/EC on Environmental Noise, the noise map was calculated at a reference height of 4 m and at 1 m from the facades. On average, the simulation results show values exceeding the noise limits from 1 to 4 dB(A). Higher noise levels were detected on residential buildings facing the motorway, with values exceeding noise limits by 11 dB(A) to up 16 dB(A).

Table 1. Measuring results.

Receiver	Address	Point height (m)	LAeq dB(A)
PR1	18, Orazio Raimondo Street	4	52,0
PR2	Primary school “Federico Fellini”	4	54,0
PR3	Nursery “Uno, Due Tre … Stella”	4	55,0
PR4	Ubaldo Comandini Street	4	67,0
PR5	Emilio Brusa Street	4	73,5
PR6	Salvatore Barzilai Street	4	75,0
PR7	Giacomo Delitala Street	4	73,0

5.2 Identification and design of noise mitigation measures

The design hypotheses have been traced considering the average noise level of the area and the presence of single hotspots with high acoustic impacts. As reported in paragraph 5.1, noise levels generally exceed noise limits by 1 to 4 dB(A), with the only exception of some residential buildings facing the road infrastructure where the noise levels exceed the legal limits by more than 11 dB(A). Therefore, the reduction of noise levels can be achieved with a holistic approach, in which different types of measure coexist and integrate to globally restore the area. In this study, 2 possible scenarios, named A and B, were evaluated.

5.2.1 Scenario A

In this scenario, two solutions have been identified:

- A low-noise pavement, to reduce the noise levels exceeding the legal limits by 1 to 3 dB(A).
- Noise barriers for critical hotspots alongside the A90’s carriageways and the traffic divider.

Considering that the A90 motorway has a drainage type pavement, whose acoustic characteristics are not known, it is reasonable to assume that it might be capable of producing a sound attenuation of 2 dB. Therefore, a low-noise pavement able to reduce the noise impact by at least 5 dB is necessary to fulfil the project objectives.

It should be noted that a low noise pavement allows for mitigating even the most backward receivers, acting uniformly in the whole area, contributing also to contain the impact of the noise barriers necessary to reduce the noise levels at the most critical receivers. Table 2 shows the type and size of the designed measures.

Table 2. Type and size of the designed measures (Scenario A)

Type	L (m)	H (m)	Overhang		Surface (m²)
			Extension (m)	Tilt (°)	
Noise barriers internal carriageway	470	5	3	45	3.760
Noise barriers external carriageway	340	5	3	45	2.720
Noise barriers on traffic divider	525	4	-	-	2.100
Low noise pavement	1.300		-	-	36.400

Scenario B

As in scenario A, scenario B includes a low-noise pavement and the installation of noise barriers, but only to the outer sides of the A90's carriageways. Where the use of noise barriers would require significant investments to guarantee the fulfilment of the noise objectives, the solution opts for implementing direct measures on some of the receivers (silent windows). Table 3 shows the type and size of the designed measures.

Table 3. Type and size of the designed measures (Scenario B)

Type	L (m)	H (m)	Overhang		Surface (m²)
			Extension (m)	Tilt (°)	
Noise barriers internal carriageway	470	5	3	45	3.760
Noise barriers external carriageway	340	5	3	45	2.720
Low noise pavement	1.300		-	-	36.400

5.3 Sustainability analysis of the designed noise mitigation measures

Considering the infrastructural context of the designed solutions, it was decided to apply the ENVISION protocol to assess their sustainability.

The ENVISION protocol involves the evaluation of 64 criteria, not all of which are applicable to the specific context. Consequently, considering the object of the planned interventions, only those criteria strictly related to it or for which it is possible to find the information necessary for their quantification, also in relation to the level of detail achieved in the planning phase, should be selected. ENVISION defines five criteria categories, within which further sub-categories are identified:

1. Quality of life: Wellbeing, Mobility, Community
2. Leadership: Collaboration, Planning; Economy
3. Resource Allocation: Materials, Energy, Water
4. Natural World: Siting, Conservation, Ecology
5. Climate and Resilience: Emissions, Resilience.

In relation to the proposed case study, a series of criteria have been selected (see Table 4) which can be objectively evaluated based on the level of design detail achieved.

Table 4. Selected criteria for evaluating the sustainability of suburban design scenarios.

Category	Subcategory	Criteria
Quality of Life	Wellbeing	QL1.1 Improve Community Quality of Life
		QL1.2 Enhance Public Health & Safety
		QL1.4 Minimize Noise & Vibration
	Community	QL3.1 Advance Equity & Social Justice
		QL3.3 Enhance Views & Local Character
Leadership	Collaboration	LD1.2 Foster Collaboration and Teamwork
	Planning	LD2.1 Establish a Sustainability Management Plan
		LD2.3 Plan for Long-Term Monitoring and Maintenance
		LD2.4 Plan for End-of-Life
	Economy	LD3.3 Conduct a Life-Cycle Economic Evaluation
Resource Allocation	Materials	RA1.2 Use Recycled Materials
	Energy	RA2.3 Use Renewable Energy
		RA2.4 Commission and Monitor Energy Systems
Natural World	Siting	NW1.4 Preserve Undeveloped Land
	Ecology	NW3.1 Enhance Functional Habitats
Climate and Resilience	Emissions	CR1.1 Reduce Net Embodied Carbon
		CR1.3 Reduce Air Pollutant Emissions

Currently, the proposed design documents correspond to a definitive project, in which some aspects are not yet known which will be outlined during the executive design or in the tender phase, as regards the construction methods. The application of the ENVISION protocol entails an incremental approach, which progressively extends to all the criteria identified, as new details are acquired. In other words, the ENVISION protocol provides the tools to evaluate the degree of sustainability of a project during the various development phases and to address the decision-making process towards solutions optimizing the overall performance.

5.4 Results

In Table 5 the results achieved are reported. The results show that scenario B is more sustainable than scenario A, even if some peculiar aspects of the designed solutions are not quantified in any way, such as the lower acceptance by the exposed population of mitigation measures directly implemented at receivers.

Table 5. Results achieved by applying the ENVISION protocol to the case study.

Criteria	Scenario A	Scenario B
QL1.1 Improve Community Quality of Life	5	5
QL1.2 Enhance Public Health & Safety	16	16
QL1.4 Minimize Noise & Vibration	12	10
QL3.1 Advance Equity & Social Justice	13	13
QL3.3 Enhance Views & Local Character	14	14
LD1.2 Foster Collaboration and Teamwork	15	15
LD2.1 Establish a Sustainability Management Plan	1	1
LD2.3 Plan for Long-Term Monitoring and Maintenance	2	2
LD2.4 Plan for End-of-Life	13	13
LD3.3 Conduct a Life-Cycle Economic Evaluation	14	14
RA1.2 Use Recycled Materials	2	2
RA2.3 Use Renewable Energy	0	0
RA2.4 Commission and Monitor Energy Systems	0	0
NW1.4 Preserve Undeveloped Land	18	18
CR1.1 Reduce Net Embodied Carbon	5	10
CR1.3 Reduce Air Pollutant Emissions	4	4
Total score	134	137

The latter, poses a problem of social justice and appreciation by the resident population, which should be given due consideration. Furthermore, although economic analyses such as LCCA and cost/benefit analysis are mentioned in criterion LD3.3, quantitative evidence affecting the evaluation doesn't emerge, unlike what is found for other criteria, such as those related to the use of recycled materials (RA1.2) or CO_2 emissions (CR.1.1). The application of the ENVISION protocol has highlighted a series of shortcomings that are essentially due to the general nature of the proposed evaluation method. These highlight the need to customize some of the proposed criteria in relation to the object of evaluation.

6. CONCLUSIONS

The application of the ENVISION protocol to the case study has highlighted some shortcomings. These shortcomings are essentially due to the general nature of the proposed method and highlight the need to customize some of the proposed criteria in relation to the object of evaluation. To overcome these shortcomings, additional parameters should be included to make a quantitative estimate of the effects considered sensitive or specify the scores to be taken as a function of the results of the evaluations called for by the protocol itself. Although the ENVISION protocol proposes itself as an easier alternative for sustainability assessment, it still presents some critical issues that can be solved by considering the peculiarities of the proposed solutions.
However, this does not detract from the merit of the ENVISION protocol in having proposed a structured approach that is easy to understand and implement, as opposed to models that are less easy to manage and interpret, such as LCSA, which is still subject to scientific debate.

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