SUSTAINABLE PAVEMENT MANAGEMENT: HOW TO INTEGRATE ECONOMIC, TECHNICAL AND ENVIRONMENTAL ASPECTS IN DECISION-MAKING

Cristina Torres-Machi, Ph.D. Candidate (corresponding author)
School of Civil Engineering
Universitat Politècnica de València – Spain
Camino de Vera, s/n, 46022, Valencia, Spain
Phone: +34963879562
Escuela de Ingeniería, Departamento de Ingeniería y Gestión de la Construcción
Pontificia Universidad Católica de Chile – Chile
Av. Vicuña Mackenna 4860. Edif. San Agustín Piso 3, Santiago, Chile
critorma@upv.es

Alondra Chamorro, Ph.D., Assistant Professor
Research Associate, National Research Center for Integrated Natural Disaster Management, CONICYT/FONDAP/15110017
Escuela de Ingeniería, Departamento de Ingeniería y Gestión de la Construcción
Pontificia Universidad Católica de Chile – Chile
Av. Vicuña Mackenna 4860. Edif. San Agustín Piso 3, Santiago, Chile
Phone: +56223544244
achamorro@ing.puc.cl

Eugenio Pellicer, Ph.D., Associate Professor
School of Civil Engineering
Universitat Politècnica de València – Spain
Camino de Vera, s/n, 46022, Valencia, Spain
Phone: +34963879562
pellicer@upv.es

Víctor Yepes, Ph.D., Associate Professor
ICITECH, Department of Construction Engineering
Universitat Politècnica de València – Spain
Camino de Vera, s/n, 46022, Valencia, Spain
Phone: +34963879563
vyepesp@upv.es

Carlos Videla, Ph.D., Professor
Escuela de Ingeniería, Departamento de Ingeniería y Gestión de la Construcción
Pontificia Universidad Católica de Chile – Chile
Av. Vicuña Mackenna 4860. Edif. San Agustín Piso 3, Santiago, Chile
Phone: +563544244
cvidela@ing.puc.cl

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ABSTRACT

Sustainability, which is founded in the reconciliation of economic, environmental and social aspects, has become a major issue for infrastructure managers. The economic and environmental impacts of pavement maintenance are not negligible. More than 400 billion USD are invested globally each year in pavement construction and maintenance. These tasks increase the environmental impacts of vehicle operation by 10%. Because maintenance should be technically appropriate, it is important to integrate technical, economic and environmental aspects in the evaluation of maintenance alternatives over the life cycle of pavement. However, these aspects are normally assessed in different units that are difficult to combine in the decision-making process.

This research examines and compares different methods for the integrated consideration of technical, economic and environmental aspects. This study aims to assist highway agencies, researchers and practitioners with the integration of these aspects for the sustainable management of pavement. For this purpose, a set of maintenance alternatives for asphalt pavements are evaluated. Different methods for the integration of these aspects are explored, leading to recommendations for the most suitable methods for different scenarios. Because of this analysis, the Analytic Hierarchy Process (AHP) is recommended when the number of alternatives is reduced. In these situations, the AHP leads to results that are similar to those of the Weighting Sum and Multi-Attribute approaches that are frequently used for intuitive selection. However, when the number of alternatives is large, pair comparison becomes difficult when using the AHP and the Weighting Sum method becomes more appropriate.

INTRODUCTION

Sustainability is defined in the Brundtland Report as "*the development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" *(1)* and is founded on the integration of social, economic and environmental demands. Transportation infrastructures, such as pavement, are important contributors to sustainability. In economic terms, more than 400 billion USD are invested each year in construction and maintenance activities *(2)*. These tasks are estimated to increase the environmental impact caused by vehicle operation by 10% *(3)*. In this scenario, there is a need for incorporating a sustainable approach in pavement maintenance management to ensure technically appropriate solutions that are economically viable and environmentally sustainable *(4–6)*. However, these aspects are normally assessed in different units that are difficult to combine in the decision-making process.

Numerous studies have attempted to develop methods for integrating sustainable aspects. One of the most extensively used methods for integrating technical and economic aspects is the cost-effectiveness (CE) method *(7–9)*. The CE method uses the ratio of effectiveness (assessed as the area bounded by the pavement performance curve and a threshold value of condition weighted by traffic and length) divided by the present worth of costs. However, the traditional CE method fails to consider environmental aspects. One way to overcome this limitation is to include the environmental costs in the calculation of the CE. Delucchi *(10)* developed one of the first models for the economic evaluation of environmental impacts that assessed the social costs generated by vehicles. The main limitations of this model are that it does not consider the environmental impacts of maintenance operations and that the economic estimations were developed in 1990 (excluding the advances that have occurred in the last decades). This second limitation can be easily overcome by using estimations that are more recent. Indeed, the Environmental Protection Agency (EPA) recently updated the proposed value of the Social Carbon Cost (SCC) *(11)*. The SCC was proposed in 2009 and was intended to monetize damages that are associated with incremental increases in carbon emissions.

Another possible approach for the integration of sustainable aspects is the use of multicriteria or multiobjective methods. These methods involve (*a*) a given set of alternatives that are provided by the decision-maker; (*b*) a set of criteria for comparing the alternatives; (*c*) assigning weights for the criteria; and (*d*) a method for ranking the alternatives based on how well they satisfy the criteria. A detailed revision of these methods was recently presented by Wu et al. *(12)*. Previous studies have considered specific methods for the integration of multiple criteria in pavement management. For example, Wu and Flintsch *(13)* defined optimal preservation treatments by considering a weighting sum method (WS). Cafiso et al. *(14)* applied the Analytic Hierarchy Process (AHP) for the evaluation of maintenance strategies. Furthermore, Giustozzi et al. *(15)* developed a Multi-Attribute approach (MA) for the evaluation of maintenance treatments using technical, economic and environmental criteria. These studies provide important insights regarding the integration of different criteria in the decision-making process. However, to our knowledge, a comparative analysis of these methods has not been conducted yet. This is going to be the contribution of this study.

Objectives and Scope of the Study

The objective of this paper is to analyze and compare the different methods for the integration of technical, economic and environmental aspects for the sustainable management of pavement. Based on this comparative analysis, the scope of this study is to recommend an overall indicator that will enhance the sustainable management of pavement by assisting public agencies in their decision-making.

For this purpose, a case study developed in Chile is presented to illustrate the evaluation of different preservation, maintenance and rehabilitation (P+M+R) treatments in urban pavements. This study is part of a three year project developed in Chile by the Pontificia Universidad Católica de Chile (PUC) and named Fondef D09I1018 "Research and Development of Solutions for Urban Pavement Management in Chile". The project is being partnered and advised by the Centre for Pavement and Transportation Technology (CPATT) at the University of Waterloo, Canada. The overall project aims to address the current and future needs of urban pavement and provide effective management tools for assisting the agencies that manage the urban networks. The study presented in this article will be used as a basis for developing a methodology for the sustainable evaluation of maintenance alternatives that will be included in the management system that results from this project.

Research Methodology

To achieve the proposed objectives, this study considered a four-step research methodology. The first two steps correspond to previous activities necessary for the main purpose of the study, which deals with the comparison of different methods for the integration of technical, economic and environmental aspects for the sustainable management of pavement.

- Evaluate the suitability of different preservation, maintenance and rehabilitation treatments regarding their technical, economic and environmental impacts.
- Explore and assess a set of overall indicators that measure the sustainability of each treatment by integrating technical, economic and environmental aspects over the life cycle of pavements.
- Perform a comparative analysis of these sustainable indicators by identifying the advantages and limitations of their applications in various scenarios.
- Recommend the most suitable sustainable indicators for future implementation in Pavement Management Systems.

EVALUATION OF ALTERNATIVES IN TECHNICAL, ECONOMIC AND ENVIRONMENTAL TERMS

As previously stated, this study analyzes the suitability of different preservation, maintenance and rehabilitation (P+M+R) treatments on asphalt pavements. The P+M+R treatments differ regarding their intensities and their effects on pavement serviceability and structural capacity. For example, preservation treatments restore the pavement's condition and extend its service life but do not increase its capacity or strength *(16)*. Thus, preservation will address pavements while they are in good condition and before serious damage occurs. Meanwhile, maintenance treatments can retard future deterioration and improve the functional condition of pavements without significantly increasing their structural capacity *(16)*. Therefore, maintenance is applied to pavements that are in good or fair condition with significant remaining service lives. Finally, rehabilitation activities consist of structural enhancements that extend the service life of an existing pavement and/or improve its structural capacity *(16)*.

Table 1 shows the set of P+M+R treatments that are considered in this study, including two preservation, six maintenance and five rehabilitation alternatives. Most of these treatments reflect current practices in Chile based on meetings with professionals that are in charge of urban network maintenance. The treatments that are not currently applied in Chile were extracted from international literature and included in the analysis to broaden the scope and future application of this study in other countries. Each alternative consists of applying a specific treatment each time the pavement has reached a trigger condition. These alternatives are compared by analyzing their technical, economic and environmental impacts for a constant analysis period of 25 years. These impacts are assessed in terms of their increased service life, costs and CO_2 emissions that result from the application of the treatments. A description of these evaluations is provided in the following sections.

Table 1. Treatment alternatives

ID	Treatment	Classification	Service life increase (ΔSL) [years]	Unit cost [US$/m^2]	Unit emissions [kg CO_2/m^2]
P1	Crack sealing	Preservation	2	1.06	0.11
P2	Fog seal	Preservation	3	1.02	0.04
M1	Slurry seal	Maintenance	4	3.39	0.76
M2	Microsurfacing	Maintenance	7	7.75	1.51
M3	Single chip seal	Maintenance	5	4.90	0.4
M4	Double chip seal	Maintenance	6	5.15	0.5
M5	Milling and functional resurfacing	Maintenance	10	23.37	6.91
R1	Milling and structural resurfacing	Rehabilitation	12	63.79	13.11
R2	Hot in place recycling	Rehabilitation	10	53.54	6.70
R3	Cold in place recycling	Rehabilitation	13	54.65	5.49

ID	Treatment	Classification	Service life increase (*ΔSL*) [years]	Unit cost [US$/$m^2$]	Unit emissions [kg CO_2/m^2]
R4	Full depth reclamation	Rehabilitation	13	41.93	8.93
R5	Reconstruction	Rehabilitation	25	143.59	27.36

Data sources: *(17–23)* and meetings with professionals from the Ministry of Public Works of Chile

Technical Evaluation

The technical evaluation is assessed in terms of a performance index and its evolution over the analysis period. This study considers a performance indicator that was developed by Osorio et al. *(24)* within the context of the Fondef project. This indicator, called the Urban Pavement Condition Index (UPCI), assess the urban pavement condition based on objective measures of surface distresses and on the evaluations of an expert panel. The UPCI is an overall condition index for urban pavements that represents the more relevant distresses for use in network analysis. The UPCI has been developed and validated for both asphalt and concrete pavements and rates pavement condition on a scale of 1 to 10, with 1 representing the worst condition and 10 representing the best condition.

Because the performance models for urban pavements were being developed at the time of this study, this application adopts a model developed by Smith *(25)*, which relates the Pavement Condition Index (PCI) to the pavement age (Eq. 1). In this study, the PCI model was adapted to a scale of 1-10 to be consistent with the UPCI evaluation. Based on two field evaluations that were conducted in Chile within the Fondef project, the parameters of the PCI model were adjusted as follows: $\alpha = 37.5$, $\beta = 0.5$ and $\rho = 38.8$. The age of the pavement at the beginning of the analysis period was nine years. These performance models may not reflect the true deterioration of urban pavement. However, this consideration would similarly affect the technical evaluations of all alternatives and would not affect the comparative analysis among them. Indeed, other performance models may be considered and future urban performance models will be incorporated into the management system that will result from the Fondef project.

$$PCI\ (age) = \left(100 - \frac{\rho}{\left(\ln(\alpha) - \ln\,(age)\right)^{1/\beta}}\right) \qquad (1)$$

The application of each P+M+R treatment leads to an increase in the pavement service life (*ΔSL*). Thus, an immediate increase in the pavement condition (*ΔUPCI*) occurs at the moment of application. The treatment service lives (*ΔSL*) that were considered in this study are presented in Table 1. The adopted values were obtained from Canadian *(19)* and US *(17)* studies because the *ΔSL* are currently being calibrated for the Chilean case.

Finally, the technical suitability of the P+M+R treatments was assessed in terms of the effectiveness of the treatments. The effectiveness was evaluated as the area bounded by the performance curve and a threshold condition value (Figure 1). This value is normally weighted by traffic and length. Because only one pavement section is analyzed in this study, all of the P+M+R alternatives were compared based on 1 km, one lane and under the same traffic conditions. In addition, to consider the pavement condition, a technical evaluation based on effectiveness allowed us to indirectly consider the benefits of users because well-maintained pavement (having therefore a larger effectiveness) provides a greater benefit than poorly maintained infrastructure *(7)*. This study considered a UPCI threshold value of 3. This value corresponds to the threshold condition below which pavements were qualified as very poor by a group of Chilean experts. This qualitative scale is currently being validated within the Fondef project. Under these considerations, the technical evaluation of the P+M+R alternatives regarding their effectiveness is provided in Table 2.

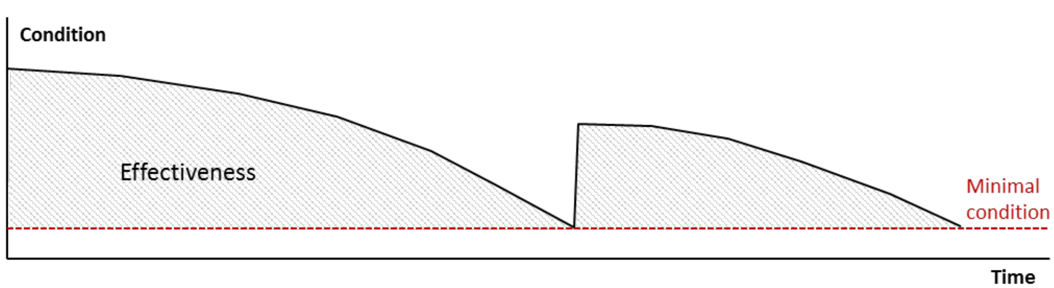

Figure 1. Effectiveness of a treatment alternative

Economic Evaluation

The Life-Cycle Cost and Benefit Analysis (LCCBA) represents an established procedure for evaluating projects in asset management systems *(7, 15)*. The LCCBA discounts current and future costs and benefits to present worth by applying a discount rate. This paper proposes a LCCBA method that considers the agency costs that are derived from the application of the P+M+R treatments over the analysis period. The unit costs of the P+M+R alternatives (Table 1) were mainly obtained from Chilean maintenance contracts in the Municipality of Santiago and from meetings with professionals from the Ministry of Public Works of Chile. Economic information of treatments not currently applied in urban pavements in Chile was extracted from international literature *(17, 20)*.

In addition, this study considers a salvage value that accounts for the remaining value of the pavement at the end of the analysis period. Although there is no consensus regarding how to estimate this salvage value, this study estimated the salvage value by calculating the relative value of the remaining serviceability with respect to the cost of reconstruction. This salvage value is included as a negative cost in the agency costs.

A discount factor of 5% was considered in this study. This value is consistent with the values of 3 and 5% that are historically reported in the USA *(26)* and close to the 6% rate recommended by the Chilean government *(27)*. Under these considerations, Table 2 shows the present worth cost of the P+M+R alternatives.

Environmental Evaluation

A life-cycle assessment was conducted to account for the environmental impacts of the P+M+R treatments. The objective of this evaluation was to identify more environmentally friendly practices. Life-cycle assessment examines the net environmental performance of products and services across a suite of environmental metrics, including all important interactions with human and natural systems *(28)*. The carbon emissions derived from the application of the P+M+R treatments were considered to develop the environmental assessment. These emissions (provided in Table 2) were estimated based on the PaLATE Excel worksheet that was proposed by Nathman et al. *(21)* and based on the data available in the literature for some specific treatments *(20, 22, 23)*.

Results of the Technical, Economic and Environmental Evaluation

Several preliminary conclusions were derived from the evaluation of the technical, economic and environmental aspects for each P+M+R treatment (Table 2).

Table 2. Long-term evaluation of treatment alternatives in technical, economic and environmental terms

ID	Treatment	Effectiveness [UPCI*years]	Total cost [US$]	Total emissions [kg CO_2]	Total environmental cost [US$]
P1	Crack sealing	132	51,590	9,153	392
P2	Fog seal	135	34,426	2,268	97
M1	Slurry seal	68	50,803	23,966	1,107
M2	Microsurfacing	83	73,223	28,539	1,294
M3	Single chip seal	77	60,143	10,080	462
M4	Double chip seal	78	50,526	9,450	421
M5	Milling and functional resurfacing	95	160,829	87,106	3,804
R1	Milling and structural resurfacing	92	403,304	165,186	7,505
R2	Hot in place recycling	85	350,910	84,420	3,761
R3	Cold in place recycling	94	339,633	69,174	3,173
R4	Full depth reclamation	94	260,598	112,572	5,164
R5	Reconstruction	107	583,124	172,368	6,995

With respect to preservation treatments, fog seal (P2) is the best alternative under the three sustainable criteria because its effectiveness is higher than that of crack sealing (P1), it has a lower cost and it results in lower CO_2 emissions. Therefore, it is not necessary to combine these evaluations to conclude that fog seal (P2) is the most sustainable preservation treatment. Thus, the calculation of the overall indicator was omitted for the preservation treatments in the following sections.

The evaluation of maintenance alternatives indicates more variability than preservation treatments, not existing a clearly advantageous alternative under all of the criteria. From the data in Figure 2, it is apparent that some maintenance alternatives, such as double chip seal (M4) and functional resurfacing (M5), have different evaluations under the criteria. Indeed, double chip seal (M4) is the most advantageous alternative under economic and environmental criteria but is not competitive regarding technical terms. Similarly, functional resurfacing (M5) is the most effective alternatives but it is not competitive in economic and environmental terms. Finally, chip seals (M3 and M4) show a similar trend in the evaluation of the different criteria, being the double chip seal (M4) the most advantageous alternative in environmental terms. The remaining maintenance alternatives (M1, M2 and M3) do not show a clear competitive advantage for any criteria.

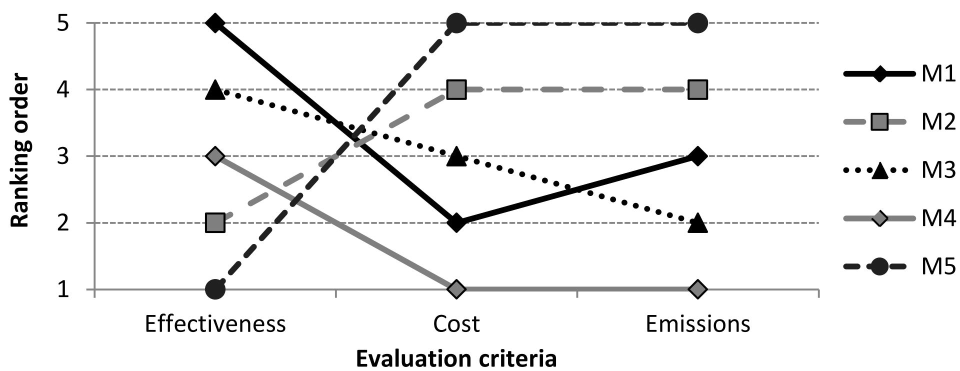

Figure 2. Ranking of maintenance alternatives under technical, economic and environmental criteria

Finally, the rehabilitation alternatives present diverse evaluations under the criteria considered. Similarly to maintenance treatments, some rehabilitation alternatives have different evaluations under the criteria (Figure 3). This is the case of reconstruction (R5), which is the most effective alternative but it is not competitive regarding economic and environmental terms. Apart from R5, any of the alternatives show a clear competitive advantage. However, structural resurfacing (R1) presents a consistent evaluation because it is the second best alternative under technical, economic and environmental criteria.

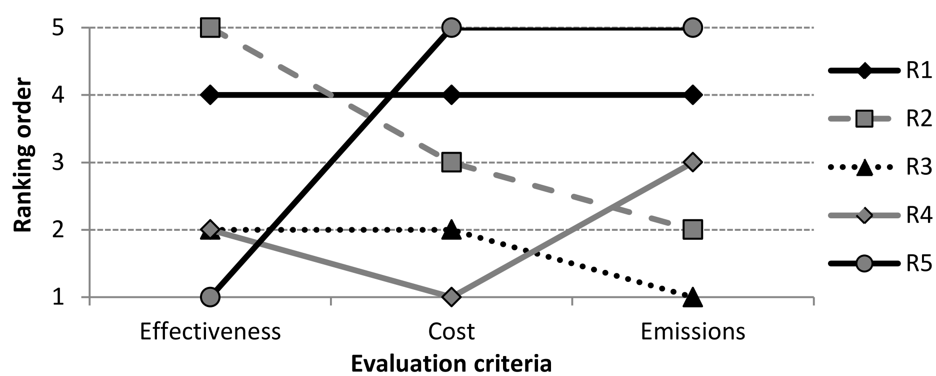

Figure 3. Ranking of rehabilitation alternatives under technical, economic and environmental criteria

INTEGRATED SUSTAINABLE EVALUATION

This section explores different methods for integrating the sustainable aspects to obtain an overall sustainable indicator.

Cost-effectiveness with an Economic Evaluation of Emissions

This approach is a variation of traditional CE in which the present costs include an economic evaluation of carbon emissions. In this study, the economic evaluation of CO_2 emissions is assessed in terms of the SCC proposed by the Environmental Protection Agency (EPA) for evaluating emissions between 2010 and 2015 *(11)*. In this study, the SCC proposed by the EPA was updated to 2013 values by considering the National Highway Construction Cost Index (NHCCI) that was published by the FHWA *(29)*.

An economic evaluation of CO_2 emissions for each P+M+R treatment was undertaken under these considerations (Table 2). These evaluations were included in the economic evaluation of alternatives that result in a sustainable CE indicator (Table 3). For illustrative purposes, Table 3 also shows the traditional CE of alternatives in which only economic and technical aspects are considered.

Table 3. Overall sustainable indicators of the M+R treatments according to the cost-effectiveness, weighting sum, multi-attribute and analytic hierarchy methods

Treatment	Cost-effectiveness [UPCI*years/US$] x 10^3		Weighting sum method		Multi-attribute approach		Analytic hierarchy process
	Traditional CE	Sustainable CE	WS1	WS2	MA1	MA2	AHP
M1	1.34	1.31	0.69	0.78	0.28	0.36	0.22
M2	1.13	1.11	0.63	0.65	0.20	0.21	0.18
M3	1.22	1.21	0.84	0.85	0.61	0.59	0.24
M4	1.54	1.52	0.93	0.95	0.82	0.85	0.26
M5	0.59	0.58	0.47	0.43	0.03	0.03	0.11
R1	0.23	0.22	0.64	0.64	0.23	0.22	0.18
R2	0.24	0.24	0.78	0.78	0.49	0.45	0.21
R3	0.28	0.27	0.87	0.85	0.67	0.59	0.22
R4	0.36	0.35	0.82	0.87	0.54	0.61	0.25
R5	0.18	0.18	0.61	0.57	0.18	0.13	0.14
w_{tech}	-	-	0.33	0.25	1.00	1.59	-
w_{eco}	-	-	0.33	0.50	1.00	0.79	-
w_{env}	-	-	0.33	0.25	1.00	0.79	-

Weighting Sum Method

This approach combines the evaluation criteria into a single indicator by assigning positive weights to each of the criteria (Eq. 2). This approach presents the advantage of being easy-to-understand and simple to implement *(12)*.

$$WS = \sum_{i=1}^{k} w_i \cdot F_i; \qquad \text{with} \quad \sum_{i=1}^{k} w_i = 1 \text{ and } \quad w_i > 0 \quad \forall i \qquad (2)$$

Where, w_i is the weight assigned to criteria i and F_i is the normalized value of the alternative under the criteria i.

To handle variables that have different unit measures (effectiveness, US$ and kg of CO_2 emissions), it is necessary to normalize these values using a scale of 0-1, where 1 is the most advantageous alternative under a certain criteria. This rescaling allowed us to compare the scores that were obtained under different criteria and to combine them into an overall indicator. Because a sustainable approach will look for alternatives that have minimal costs and minimal emissions, these two variables were normalized by assigning a value of 1 to the alternatives with the lowest costs and emissions. With respect to the technical evaluation, a value of 1 was assigned to the alternative that showed the highest effectiveness. The values obtained in this rescaling are provided in Table 4.

Two scenarios were evaluated using the weighting sum method while accounting for these normalized values. The first scenario (WS1) involves assigning the same weights to technical, economic and environmental criteria (w_{tech} = w_{eco} = w_{env} = 0.33). The second scenario (WS2) assigns a higher weight to economic criteria and a lower but equal weight to the technical and environmental criteria (w_{eco} = 0.5; w_{tech} = w_{env} = 0.25). The results of these evaluations are provided in Table 3.

Table 4. Normalized values of the sustainable indicators that were obtained for the M+R treatments

ID	Treatment	Effectiveness	Cost	CO_2 emissions
M1	Slurry seal	0.72	0.99	0.39
M2	Microsurfacing	0.87	0.69	0.33
M3	Single chip seal	0.77	0.84	0.94
M4	Double chip seal	0.82	1.00	1.00
M5	Milling and functional resurfacing	1.00	0.31	0.11
R1	Milling and structural resurfacing	0.86	0.65	0.42
R2	Hot in place recycling	0.80	0.74	0.82
R3	Cold in place recycling	0.88	0.77	1.00
R4	Full depth reclamation	0.88	1.00	0.61
R5	Reconstruction	1.00	0.45	0.40

Multi-Attribute Approach

Multi-Attribute Approach is an axiomatized mathematical framework for analyzing and quantifying choices that involve multiple competing outcomes *(12)*. In this study, the procedure proposed by Giustozzi et al. *(15)* is considered. This approach consists of displaying the normalized values of the sustainable criteria (effectiveness, cost and CO_2 emissions) in a three-dimensional representation. The suitability of each alternative will be assessed in terms of the volume enclosed in the three-dimensional representation. This study proposes using Eq. 3 for calculating this volume, which enables the consideration of different weights of the criteria. Under these considerations, the optimal solution according to the three criteria will be displayed in the point (1,1,1) and will have a volume of 1.

$$MA = \prod_{i=1}^{k} (F_i)^{w_i}; \qquad \text{with} \quad \prod_{i=1}^{k} w_i = 1 \text{ and } \quad w_i > 0 \quad \forall i \qquad (3)$$

Where w_i is the weight assigned to criteria i and F_i is the normalized value of the alternative under criteria i.

When accounting for the normalized values of the alternatives shown in Table 3, two scenarios were evaluated by using the multi-attribute approach. Similarly to the scenarios considered in the weighting sum method, the first scenario (MA1) involves assigning the same weights to the technical, economic and environmental criteria (w_{tech} = w_{eco} = w_{env} = 1). The second scenario (MA2) assigns a higher weight to the economic criteria and a lower but equal weight to the technical and environmental criteria (w_{eco} = 1.59; w_{tech} = w_{env} = 0.79). Both scenarios verify a product of weights equal to 1, as required in Eq. 3. The results of these evaluations are provided in Table 3.

Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a mathematical technique that aims to simulate how people think and make decisions. This method is based on a pair comparison of criteria that uses a scale ranging from 1 to 9 and expresses 1 as equal importance and 9 as extreme importance *(30)*. When the number of alternatives is limited (a threshold of seven or eight is recommended), this method presents the advantage of incorporating subjective judgments in an easy to understand procedure *(12, 14)*.

The scenario analyzed in this study considered that cost has a moderate importance over effectiveness and a strong importance over emissions. Meanwhile, effectiveness presents a moderate importance over emissions. The consistency in these preferences was checked in terms of the consistency ratio (CR), which resulted in an acceptable value of 4.8% because the method recommends values that are less than 10%. Based on these considerations, the AHP method resulted in the evaluation of the M+R treatments are shown in Table 3.

Analysis of the Overall Sustainable Indicators

This section analyzes the consistency of the results that were obtained by using the different sustainable indicators. For this purpose, Table 3 shows the values of the different overall sustainable indicators while Figures 3 and 4 represent the rankings of the maintenance and rehabilitation treatments that were obtained using these indicators.

With respect to maintenance alternatives, Figure 4 shows that ranking obtained under the different overall indicators are generally consistent. For example, functional resurfacing (M5) is the least sustainable alternative for all of the overall indicators, followed by microsurfacing (M2). Although M5 was the best solution in terms of effectiveness (Figure 2), this competitive advantage is not significant when the criteria are combined in a sustainable indicator. The low competitiveness of M5 in terms of cost and emissions becomes a determinant factor in the overall evaluation. On the other hand, double chip seal (M4) is the most sustainable alternative. These treatments are coherent with the preliminary results that were obtained in the evaluation of the sustainable aspects, where M5 and M2 received the worst evaluations for the economic and environmental criteria, while M4 received the best evaluations (Figure 2). Meanwhile, the rankings for slurry seal (M1) and single chip seal (M3) slightly differ between the different overall indicators, being the second and third best alternatives.

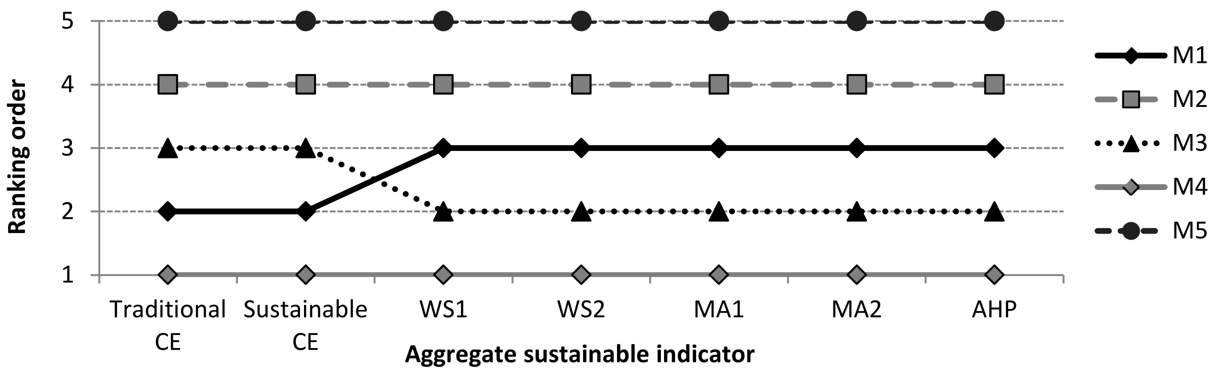

Figure 4. Ranking of maintenance alternatives under the different overall sustainable indicators

The data in Figure 4 show that the traditional and sustainable CEs result in the same rankings of the maintenance treatments. Therefore, the ranking is not altered when the environmental costs are included in the evaluation of CE. This result potentially occurred because the order of the magnitude of the environmental costs is significantly lower than the economic treatment costs.

Another interesting observation from Figure 4 is that the overall sustainable indicators WS1, WS2, MA1, MA2 and AHP have the same treatment rankings. These indicators differed on the importance of the economic evaluation relative to the technical and environmental evaluations, which were given the same importance. On average, the most valued maintenance treatment are chip seal treatments (M4 and M3), followed by the slurry seal (M3) and microsufacing (M2) treatments. Milling and functional resurfacing (M5) had the worst evaluations.

With respect to rehabilitation treatments, Figure 5 indicates that the ranking resulted from different overall indicators were slightly less consistent than the one obtained for maintenance treatments. The following conclusion was derived and was similar to the conclusion that was obtained in the analysis of the maintenance treatments: the consideration of environmental costs in the CE evaluation does not affect the obtained ranking. Therefore, the direct addition of environmental costs to the economic evaluation does not allow for the consideration of benefits that are gained by using more environmental friendly practices (such as recycling).

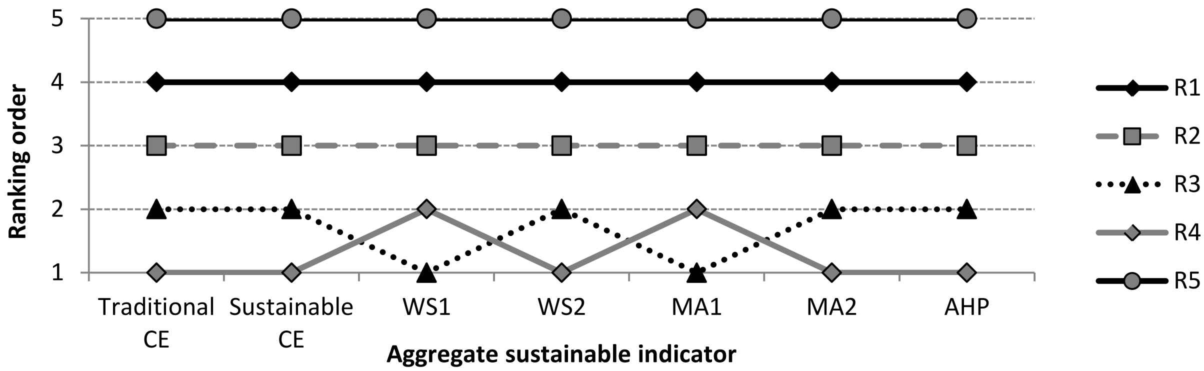

Figure 5. Rankings of rehabilitation alternatives under the different overall sustainable indicators

In addition, Figure 5 shows that the overall indicators of WS2, MA2 and AHP result in the same rehabilitation treatment rankings; while WS1 and MA1 are also consistent. All these indicators gave a higher importance to economic evaluation relative to the technical and environmental evaluations, which were given the same importance. From Figure 5, it can be observed that the recycling alternatives (hot in place recycling (R2) and cold in place recycling (R3)) received the best scores in the WS1 and MA1 evaluation. Although MA1 considers the same weights for the technical, economic and environmental criteria, this method provides more advantages for eco-friendly practices. In average terms, the most advantageous rehabilitation treatment is the full depth reclamation (R4), followed by the cold in place (R3) and hot in place recycling (R2) treatments. Structural resurfacing (R1) and reconstruction (R5) treatments were the least sustainable alternatives.

CONCLUSIONS AND RECOMMENDATIONS

This paper examines and compares different methods for the integrated consideration of technical, economic and environmental aspects in the decision-making process of pavement management. Six overall sustainable indicators based on the cost-effectiveness, weighting sum method, multi-attribute approach and analytic hierarchy process were analyzed and applied in a case study in Chile. The following conclusions and recommendations were made based on the results of this study:

- Considering the environmental cost in the cost-effectiveness evaluation did not change the rankings of the maintenance and rehabilitation treatments. This result potentially occurred because the order of magnitude of the environmental costs was significantly lower than the economic costs of treatments. Thus, a revision of the environmental costs could be conducted to account for the overall benefits that are gained by the eco-friendly alternatives.
- Analytic Hierarchy Process (AHP) generally results in rankings that are consistent with those obtained from weighting sum method and multi-attribute approach. AHP is advantageous for establishing priorities based on paired comparisons among the criteria. This selection may be more intuitive than assigning weights to criteria because it simulates how people think and make decisions. In addition, this method allows for the consideration of both qualitative and quantitative criteria in the evaluation. Nevertheless, this pair comparison and the calculation of AHP matrices become difficult when the number of criteria and alternatives under evaluation is large. Therefore, AHP may be recommended when the number of alternatives or criteria is lower than seven.
- Weighting sum method and multi-attribute approach result in similar treatment rankings when a similar importance of criteria is considered. The importance of criteria should be based on the goals and objectives of the agency. Because the weighting sum method is an easy-to-understand approach, it may be recommended when the number of alternatives or criteria is greater than seven.

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