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Sustainable Management Framework for Transportation Assets: Application to Urban Pavement Networks

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Abstract

Transportation assets play a crucial role in the development of society, being the backbone of socio-economic development but also a key contributor to climate change. Transportation asset management systems include a set of tools to support agencies in the decision on which infrastructure of a network should be preserved, maintained and/or rehabilitated. However, the evaluation of these networks has traditionally focused on economic and technical aspects of interurban networks. Considering the direct impacts on the evolution of social and natural environments, management of these assets needs to be sustainable. This article proposes a methodology for the sustainable management of transportation assets, by integrating technical, economic, environmental, social and political aspects in the Life Cycle-Assessment of a network. The methodology proposes a framework that integrates these aspects in the various components and processes considered in a management system. It incorporates a Geographic Information System as the main platform to pursue the socio-political analysis based on geographical referencing of formalized variables. The proposed framework is applied to a case study for the management of an urban pavement network. Outcomes demonstrate that it is possible to integrate sustainable aspects, despite their diverse nature, in a management system supported by a Geographic Information System.

Keywords: *sustainable transportation asset management, pavement performance, pavement management, urban pavement networks, Geographic Information System (GIS)*

1. Introduction

Transportation assets play a crucial role in the evolution of social and natural environments, being the backbone of socio-economic development but also a key contributor to climate change. Several studies have evaluated positive impacts in the development of societies caused by infrastructure investments when suitable public policies have been applied (Chamorro, 2012; Fan *et al.*, 1999). Poverty alleviation in developing countries, for example, depends on the synergy and simultaneous improvement of infrastructure, productive sectors, social and economic services. All of these can be provided by an appropriate macroeconomic framework and good governance policies (Lebo and Schelling, 2001). The effects of a growing transportation system, however, are being critical to the natural environment. By 2050, the global investment needs for ground transportation infrastructure are estimated to reach an average of USD 3 trillion per year (Dulac, 2013). Studies have demonstrated that the transport sector is the second largest source of Global Greenhouse Emissions (GHG) and contributes 23% of carbon dioxide (CO_2) emissions from fossil-fuel combustion. In the absence of new policies, these CO_2 emissions are estimated to double between 2010 and 2050 (Ang and Marchal, 2013). Under this scenario, a sustainable approach for the management of transportation infrastructure is crucial, where socio-economic, technical and environmental aspects have to be strategically integrated into public policies.

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In order to assist in the decision-making process, transportation asset management systems include a set of tools that support agencies in the decision on which assets of a network should be preserved, maintained and/or rehabilitated (P&M&R). Traditionally, the evaluation of maintenance alternatives has been focused in economic and technical terms (Hong *et al*., 2013; Santos *et al.,* 2015). However, considering sustainability as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987); it seems that the sole consideration of technical and economic criteria are insufficient for the sustainable management of infrastructure. Indeed, the Southern African Development Community (2003) proposes seven dimensions for the provision of sustainable road infrastructure, considering that decisions need to be: technically appropriate, socially acceptable, environmentally sustainable, financially sound, economically viable, institutionally possible and politically supported. Under this approach, sustainable pavement management should at least integrate technical, economic/financial, environmental, social and political/institutional aspects throughout the infrastructure life-cycle (SADC, 2003; Chamorro and Tighe, 2009).

Several attempts have been made to adapt existing transportation asset management systems to consider sustainable aspects for network assessment. Two examples of management systems considering sustainable aspects are the Highway Economic Requirement System – State Version (HERS-ST) (FHWA 2002) – and the Highway Design and Management Model (HDM-4) (Kerali *et al.*, 2006). Furthermore, recent applications have developed tools for the minimisation of maintenance costs, GHG emissions and energy (Gosse *et al*., 2013; Zhang *et al.*, 2013). However, all these tools remain limited in terms of the sustainable aspects related to socio-politic and environmental assessment that are considered in the evaluation. An attempt to integrate sustainable aspects was a four-year study at the University of Waterloo resulting in a sustainable management system for rural road networks (Ang and Marchal, 2013; Gosse *et al.*, 2013; Chamorro and Tighe, 2015). The study successfully integrated socio-political, technical and economic aspects in the Life-Cycle Assessment (LCA) of rural networks; however, environmental aspects were not accounted by the system. From this experience, the opportunity of developing a sustainable management system applicable to transportation assets arose, where technical, economic/financial, environmental, social and political/institutional aspects may be adequately integrated throughout the life cycle of evaluated infrastructure.

Another limitation observed in current management systems is that they fail to use the entire potential of the Geographic Information Systems (GIS) in decision-making. As Ferreira and Duarte (2006) state in their research, the use of GIS becomes increasingly important with the development of integrated infrastructure management systems. However, except for a few examples (Sadek *et al*., 2005; Pantha *et al.,* 2010; Ward *et al.*, 2014), existing management systems do not consider the GIS tool for data integration and spatial analysis. In fact, the GIS tool is primarily used to generate and display information maps (Tsai and Gratton, 2002; Scott *et al.*, 2011).

The objective of this study is to propose a methodology for the sustainable management of transportation assets that comprise a road network. For this, a management framework is developed, which integrates technical, economic, environmental, social and political aspects during the LCA of the network under study. Thus, the various components and processes required in a management system are consistently defined under a sustainable perspective. A case study developed in Chile is presented to illustrate the application of the proposed framework at the network level. The methodology incorporates a Geographic Information System as the main platform to pursue the analysis based on geographical referencing socio-political variables and combining them accordingly with technical, economic and environmental aspects. The scope of the application is to enhance the management of urban pavement networks by proposing an integrated sustainable approach for the future development of a pavement management system that will assist institutions responsible for decision-making.

The study is part of a four-year project developed in Chile by the Pontificia Universidad Católica de Chile (PUC) named Fondef D09I1018 "Research and Development of Solutions for Urban Pavement Management in Chile". The main goal of the project was the development of a Sustainable Management System for Urban Pavement Networks with an integrated GIS platform (Osorio *et al.,* 2014; Torres-Machi *et al.,* 2016; Videla *et al.*, 2015). The development and validation of the management system, however, will be addressed in future publications.

To achieve the primary goal of the study, the following five-step methodology was defined:

- Identification of requirements needed by a sustainable management system
- Development of indicators considering sustainable aspects: social, technical, economic, environmental and political
- Integration of the sustainable indicators in a management framework
- Application of the proposed framework in an urban pavement network
- Improvements of the framework based on feedback

2. Requirements of a Sustainable Transportation Asset Management System and Proposal of Sustainable Indicators

As stated in the introduction, sustainable transportation asset management should at least consider technical, economic, environmental, social and political aspects, in an integrated manner, during the infrastructure life-cycle. Several methods have been defined and applied for infrastructure systems, in particular multi-criteria methods that consider some of these dimensions have been identified from the current-state-of-the-art and -the-practice (Niksa *et al*., 2010; Santos *et al*., 2017; Kabit *et al.*, 2014; Wang, 2014). These methods, however, have mainly centred their efforts on integrating economic, environmental and technical aspects in decision making, but lack of the socio-political dimension. In addition, these have mostly been developed as decision indicators without incorporating the geographical and territorial dimension of decision making. In light of the analysis, this section proposes how to evaluate socio-political, technical, economic and environmental aspects in order to include and combine them accordingly in a sustainable management process.

2.1 Technical Evaluation

Infrastructure performance assesses the degree to which an asset serves its users and fulfils the purpose to which it was built or acquired. In technical terms, transportation asset performance includes both functional and structural evaluation; ensuring that an infrastructure serves users' needs in a comfortable and safe manner.

Among the available evaluation methods, performance indicators that represent the overall infrastructure condition have demonstrated to be effective and reliable for managing networks (Chamorro *et al.,* 2009; Chamorro and Tighe, 2009; Osorio *et al*., 2014). Technical performance indicators have been developed for different transportation assets, such as pavements (Chamorro and Tighe, 2009; Osorio *et al.*, 2014; Chamorro *et al*., 2010), bridges (Neves and Frangopol 2005), railroads (El-Sibaie and Zhang 2004), among others. These indicators differ in the type of distresses and criteria considered to quantify severity and density of distresses. The key for the development of a technical indicator is to recognise the subjective nature of the problem and the associated techniques that are able to quantify qualitative and quantitative information (Osorio, 2015). Therefore, the technical indicator used in a sustainable management system must be tailored to the special features and environment of the transportation asset that is going to be managed.

Once a representative indicator is defined, its evolution over time should be analysed through condition performance models. Deterioration of transportation assets is a complex process to be modelled, as it is determined by the combination of several factors, namely: load, environment, maintenance, construction quality and structure (TAC, 2013). Most of these factors present a stochastic nature, being affected by the variability of its sources, their correlation and local conditions making them difficult to quantify (TAC, 2013). This is the reason why performance models are not easily transferable between agencies, and they must be adapted, calibrated or specifically developed. Condition performance models have been specifically developed by transportation agencies for the management of infrastructures, in particular, several pavement performance models are available in the literature for interurban networks (Butt *et al*., 1987; Giummarra *et al.*, 2007; Kobayashi *et al.*, 2010).

2.2 Economic Evaluation

Economic evaluation enables the optimised the allocation of scarce resources and for agencies to better account for their decisions (FHWA, 2003). Different economic indicators are available for the evaluation of P&M&R alternatives, such as net present value, equivalent annual cost, etc. (Torres-Machi *et al.,* 2014). Transportation assets often present special features that make difficult to undertake a monetary evaluation of costs and benefits. Due to this complexity, this study proposes an economic evaluation based on cost-effectiveness (CE). CE is the ratio of effectiveness divided by the current worth of costs summarised over the infrastructure life (Fig. 1). The effectiveness of a maintenance alternative is calculated as the area under the performance curve and a condition threshold (Fig. 1). CE is one of the most extensively used methods used in pavement management for integrating technical and economic aspects in decision-making (Haas *et al*., 2006; Khurshid *et al*., 2009; Torres-Machi *et al.*, 2014, 2015) The aim is to maximize CE, as a well-maintained infrastructure (with a larger effectiveness) provides greater benefits than a poorly maintained infrastructure (Khurshid *et al*., 2009). Moreover, the effectiveness can be used as a surrogate for overall user benefits that can be difficult to quantify in monetary terms (Khurshid *et al*., 2009).

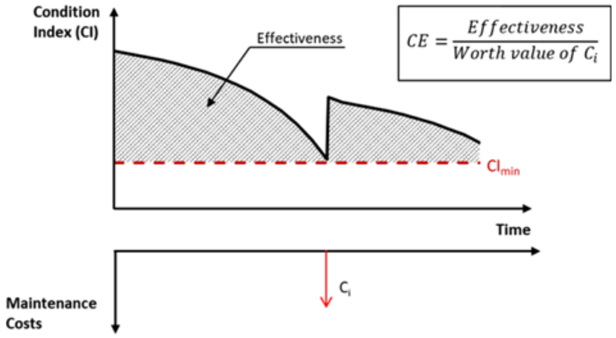


Fig. 1. Calculation of Cost-effectiveness

In addition to CE calculation, the system also verifies that the total maintenance cost does not exceed the available maintenance budget. Scarcity in maintenance funds is a common trend all around the globe, as stated in different reports developed in the United States (ASCE, 2017), Spain (AEC, 2016), and Canada (CCA *et al.*, 2016), among others. Given this situation, the proposed methodology aims to optimize the allocation of available maintenance funds.

2.3 Environmental Evaluation

With respect to the environmental impact, the proposed framework considers an evaluation based on a Life-Cycle Assessment (LCA). The LCA, supported by the ISO 14040 series guidelines, quantifies the environmental performance of products across a suite of environmental metrics that include all important interactions with both human and natural systems (ISO, 2006). The environmental evaluation in the proposed framework is intended to recognise those maintenance alternatives using recycled materials and technologies respectful to the environment. As the development of a specific LCA tool exceeds the scope of the project, the proposed system would first rely on existing environmental evaluations to quantify the environmental impact of maintenance alternatives. This environmental evaluation is proposed to be included in the economic analysis based on CE by reducing the effectiveness of those practices that are less environmentally friendly. This study considers an environmental coefficient proposed by Torres-Machi *et al.* (2017) aimed to enhance the application of treatments that are more respectful toward the environment. This environmental coefficient ($\beta_{env,sn}$) is assessed for each maintenance alternative (s_n) and has a value between 0 to 1, being 0 the corresponding value of the least environmentally-friendly alternative (Eq. (1)). By using this environmental coefficient, maintenance alternatives producing lower greenhouse gas (GHG) emissions will receive lower penalizations and thus better evaluations than those alternatives producing higher GHG emissions. This evaluation considers:

$$\beta_{env,sn} = (1-w_{env})\cdot\frac{GHG_{sn}+GHG_{min}}{GHG_{max}-GHG_{min}}+\frac{GHG_{max}-GHG_{sn}}{GHG_{max}-GHG_{min}}; \qquad (1)$$

$$\text{with } w_{env}\in[0,1]$$

where, GHG_{sn} is the GHG emissions produced by the treatment under evaluation; GHG_{min} and GHG_{max} are the minimum and maximum GHG emissions of the maintenance alternatives that could be applied to the section n under evaluation; and w_{env} is an environmental parameter, ranging from 0 to 1, that accounts for the importance of the environmental evaluation.

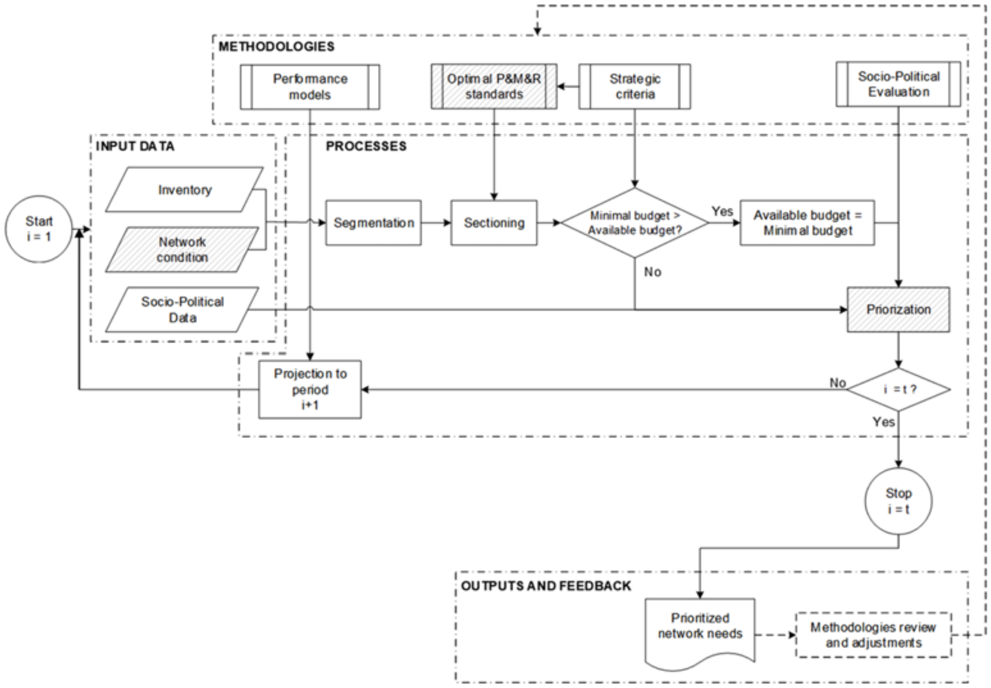
2.4 Social and Political Evaluation

As stated in the introduction, most of the infrastructure management systems rely on technical and economic aspects. However, criteria related to socio-political aspects are also considered in the decision-making process. The problem is that the information that decision-makers possess in relation to evaluate socio-political aspects is difficult to analyse. In fact, the criteria used are part of the know-how and the expertise of each decision maker. These aspects are thus usually neither documented nor standardised. Hence, the criteria used are partly subjective and not always consistent with the actual needs.

This study considers a socio-political indicator that captures the specific needs of an agency in charge of a network. As the proposed framework is defined for the management of transportation assets, criteria such as connectivity, accessibility, mobility and benefited population may be included in the evaluation. However, the final definition of the aspects to be included may reflect the special features of the network. One of the novelties of the proposed framework is that these socio-political aspects are quantified by a GIS, using spatial analyses based on data layers and mathematical operations. As a result of this evaluation, each section in the network is assigned a Socio-political Factor (SPF), which assesses the relevance of the section of the network in socio-political terms. This assessment is an effort to include indirect benefits and costs that are not considered by the CE analysis.

3. Proposal of A Sustainable Management Framework

The framework described in this section aims to combine the proposed sustainable indicators in the decision-making process for the management of infrastructure networks. The framework includes four types of components: input data, evaluation methodologies, processes and outputs (Fig. 2). In broad terms, the framework consists of an iterative analysis, developed for each year of the analysis period. As depicted in Fig. 2, the system



NOTE: Shaded components are applied in a case study in the following section.

Fig. 2. Proposed Sustainable Management Framework

starts analysing the first year of the analysis period (i = 1). A series of processes that will be described below are performed for this analysis year. Once the last process considered in the system (Prioritization) is finished, the system verifies if all the years of the analysis period have been analysed. If that is the case, the system will stop the process. If not, the system will predict the condition of the network in the next year of the analysis period (i + 1) and will repeat the whole process for this year. In each of these iterations, input data and methodologies feed processes that, in turn, activate other processes and/or deliver outputs. The interaction between these components (Fig. 2) is presented in this section. For illustrative purposes, one application of the components marked with shading in Fig. 2 (network condition, optimal P&M&R standards and prioritization) is described in the case study.

The first process to be executed is the network segmentation. It consists of a dynamic process in which the network is divided into segments with similar conditions and inventory characteristics. Therefore, the segmentation is performed based on two types of input data: inventory and network condition. The inventory includes data related to the physical features, including structural components, physical dimensions, material properties and construction details. Meanwhile, the network condition is assessed in terms of a technical performance indictor.

Then, the network is analysed using a sectioning process. Sectioning groups segments that may be treated with similar P&M&R standards. These standards, which are pre-loaded into the system, consist of a set of available treatments, their possible combination, their estimated unit cost, their application thresholds and their effect on infrastructure condition (in terms of the technical performance indicator). These P&M&R standards are optimised based on a cost-effective methodology in which different options of treatments, performance models and strategic criteria are analysed. This sectioning process results in a list of candidate projects to be treated in the analysis year as well as their effectiveness and economic and environmental costs.

Based on the economic cost of candidate projects, the proposed framework evaluates the base cost needed to accomplish the strategic criteria. Strategic criteria include the policies and the overall goals and objectives in the short, medium and long term. These criteria are defined by the institutions responsible for the network and may include a target level of all sustainable aspects considered in the system. A few of these targets are presented below:

- Technical: Acceptable threshold for the overall network and particular sections.
- Economic: Economic parameters should be defined, such as the period of analysis, discount rate, etc.
- Environmental: Environmental policies, such as the environmental impact of each P&M&R treatment will be included.
- Socio-Political: The set of criteria related to the social and political aspects and their assessment criteria should also be defined.
- Available Budget: Available funds for the network maintenance over the analysis period should also be set at the strategic decision level.

The comparison of available and required budget constitutes the first decision box of the framework. Two scenarios may be derived from this comparison:

- "Yes": In this scenario, the budget needed to accomplish the strategic criteria ("minimal budget" in Figure 2) is higher than available funds. This scenario reflects a contradiction between strategic criteria and, specifically, between available funds and the acceptable threshold for the network condition. In order to ensure that the iterative process developed in the proposed framework could be calculated for all the years of the analysis period, the system considers that the strategic objectives prevail over the budgetary restriction. This consideration assumes that available funds equal the minimal budget and enables to continue the iterative process. This assumption is only considered for simulation purposes. When all the years of the analysis period have been analyzed, the system highlights the contradiction between strategic needs and alerts the need to adjust them.
- "No": In this case, the available budget is equal to or higher than the minimal budget needed to accomplish the strategic criteria. Therefore, adjustments in the available budget are not needed and the prioritization process can be directly performed.

The prioritization process defines a ranked list of sections to treat. These alternatives are ranked in terms of their sustainable evaluation. This sustainable evaluation collects the technical, economic and environmental evaluations assessed in the sectioning process in terms of CE and the socio-political evaluation.

The socio-political evaluation is assessed in terms of the SPF of each section in the network. Because the SPF is based on aspects such as connectivity and benefited population, its evaluation requires a set of social-political data.

Once the SPF has been assessed for all sections in the network, it is integrated with the CE evaluation, which results in a sustainable indicator. This sustainable indicator is used to rank the sections of the network and their P&M&R standards. The sections to treat in the analysis year are selected based on this ranking until the available budget is depleted. Once selected, the system checks whether all of the years of the analysis period have been analysed. This decision box results in two possible scenarios:

- "No": If all of the years of the analysis period have not been analyzed, the iterative process should be repeated considering the following year of the period. In this new year of analysis, the network condition will be assessed based on performance models or in field evaluations. The development of the performance models constitutes a specific methodology of the system that will reflect the infrastructure deterioration over time.
- "Yes": In this case, the selection of projects has been per-

formed for all of the years of the analysis period, and the iterative process is finished.

Because of this iterative process, the system defines the prioritised network needs. This output specifies the sections that should be treated in each year of the analysis period, the P&M&R standard to be applied, the network condition and the technical, economic, environmental and socio-political aspects derived from the proposed maintenance program.

Finally, a feedback loop is considered to review and adjust existing methodologies based on the results obtained in the process.

4. Sustainable Indicators and Application of the Proposed Framework to an Urban Pavement Network

This section presents an illustrative case study in which an urban pavement network is analysed. The network selected in the study considers pavements of three municipalities within Santiago, Chile, with a total extension of 810 km (MINVU, 2008a). Sustainable indicators are specifically defined to the urban pavement network and an illustrative application of the framework is presented.

4.1 Sustainable Indicators in the Case Study

4.1.1 Technical Evaluation

The proposed technical indicator consists of a condition index known as the Urban Pavement Condition Indicator (UPCI). The UPCI represents the overall condition of urban pavements, including objective measures obtained by manual or automated evaluation. Currently, three UPCI equations, Eqs. (2), (3) and (4) have been calibrated and validated for asphalt and concrete pavements (Osorio *et al.*, 2014).

$$UPCI_{Manual}^{Asphalt} = 10 - 0.038FC - 0.049TRC - 0.046DP - 0.059R - 0.237P \quad (2)$$

$$UPCI_{Auto}^{Asphalt} = 10 - 0.031FC - 0.040TRC - 0.028DP - 0.082R - 0.143IRI \quad (3)$$

$$UPCI_{Manual}^{Concrete} = 10 - 0.042LC - 0.025TC - 0.063DP - 0.263F - 0.038COB - 0.018JD \quad (4)$$

Where, FC is fatigue cracking; TRC is sum of transversal and reflection cracking; DP is deteriorated patch; R is rutting, calculated as the average rutting of segments in the sample unit; P is potholes; IRI is the International Roughness Index in m/km; LC is longitudinal cracking; TC is transversal cracking; F is faulting in mm; COB is the sum of corner and oblique breaks; and JD is the percentage of damaged joints.

Pavement performance models allow the prediction of future UPCIs of the network condition for different pavement types (asphalt and concrete), climates (dry, humid and Mediterranean) and hierarchies. As historical deterioration data were not available, four periods of field data collection were planned to be analysed during the project. Considering these data, Markov models will then be used to develop the performance curves based on the quantity of data and the project timeframe (Osorio, 2015).

The list of P&M&R treatments considered in the system were defined based on current practices in Chile as well as state-of-the-art practices that include more sustainable and effective solutions. Using this information, P&M&R standards could be developed for each type of pavement based on UPCI, performance models and thresholds defined in the strategic level for different hierarchies.

4.1.2 Economic Evaluation

As stated above, the proposed economic evaluation is based on CE. Compared to other economic indicators, CE has the advantage of incorporating nonmonetary benefits in the evaluation, such as the benefits to non-users derived from better pavement condition. This is the reason why CE has been widely used in the pavement management field (Haas *et al.*, 2006; Khurshid *et al.*, 2009; Torres-Machi *et al.,* 2014, 2015).

4.1.3 Environmental Evaluation

A LCA was conducted to account for the environmental impacts of the P&M&R treatments. The carbon emissions derived from the application of the P&M&R treatments were considered to develop the environmental assessment. This indicator was chosen because carbon emissions are the main driving force of climate change (IPCC, 2007). However, the methodology presented in the proposed framework could similarly consider other emissions or environmental impacts.

It is important to note that the proposed environmental evaluation could be enhanced by including the effect of pavement condition on carbon emissions. However, most of the existing models relating carbon emissions and pavement condition are based on fuel consumption, which is mainly driven by pavement roughness and vehicle speed (Santos *et al.*, 2015). These models could be considered in those applications where IRI is a suitable indicator of pavement condition. However, previous studies developed by La Torre *et al.* (2002) and Shafizadeh and Mannering (2003) have concluded that IRI is not a suitable for urban areas.

The emissions considered in the case study were estimated with the PaLATE Excel worksheet proposed by Nathman *et al.* (2009) and international studies related to environmental impact of P&M&R treatments (Chan and Tighe, 2010; Chehovits and Galehouse, 2010; Robinette and Epps, 2010). It is worth mentioning that the direct application of these estimations may not reflect the peculiarities of Chilean practices. These estimations should thus be considered a point of departure that aims to enhance the sustainable management of urban pavements in Chile. Indeed, the development of a specific LCA tool exceeds the scope of the project. This is the reason why the proposed system would first rely on existing environmental evaluations that quantify the environmental impact derived from the application of maintenance alternatives. This approach, already considered in previous studies (Giustozzi *et al*., 2012; Gosse *et al*., 2013), is intended to recognise those maintenance alternatives using recycled materials and technologies respectful to the environment. Future developments of the proposed system could address the calibration of environmental impacts to the Chilean conditions and the incorporation of other environmental impacts such as the ones derived from new traffic flows.

4.1.4 Social and Political Evaluation

The socio-political criteria considered in this case study were obtained from interviewing experts of municipalities, including big cities and small rural communities. These criteria were then analysed by an expert group, who defined the standardised set of socio-political criteria:

- Proximity to major infrastructure: Roads near health, education or emergency facilities have a larger social impact in the area under analysis.
- Benefited population: This criterion prioritizes roads that support public transportation or covers areas with a greater number of people living, working or doing tourism in the nearby areas.
- Connectivity: This criterion considers the presence of alternative routes.
- Complaints made by users: This criterion considers the complaints made by users related to poor pavement conditions. Even though this criterion is partially related to the UPCI, it also includes a political consideration of a social perception, which is not necessarily consistent with the technical assessment.

These socio-political criteria are quantified by a GIS through several spatial analyses. For example, in the case of the proximity to major infrastructure, the GIS calculates the number of infrastructure within a certain network distance from the analysed street segment divided by its length. This is done for all the segments considered in the prioritization. The results are normalized to produce results in a 0-to-1 scale, which represents the relevance of each of the segments regarding this criterion. Similar analyses are done for each of the other. Socio-political criteria are then integrated into the SPF using a polynomial expression that considers weights that represent the preferences of Chilean decision makers. In a different scenario, these weights must be calibrated to represent the preferences of the actual decision makers.

Additionally, the interviews showed that many decisions are based on political criteria such diverse as the support to other policies, commitments with interest groups, pressure from political parties, focus on particular issues, etc. However, these criteria were very case specific and difficult to quantify so we included them as a single criterion called "Strategic selection based on public policy." This is a binary criterion that gives maximum priority to certain parts of the network. Godoy et al. (2015) explains this criterion in detail.

The above criteria are not necessarily a proposal from this research but a formalization of informal considerations made by Chilean decision makers. It is important to consider that, as in any socio-political consideration, the resulting decisions can be seen as unjust to areas with low population or without major infrastructure nearby. One approach to this problem is the use of strategic selections based on public policy that, with some reservations, can be used to favour systematically neglected areas. On the other hand, the above criteria can be used as a starting point to test the "social justice" of the management system and propose future improvements.

4.2 Application of the Proposed Framework to the Case Study

In this section, an example of the application of one input data (network condition), one methodology (optimal P&M&R standards) and one process (prioritization) is presented for the analysis of one year in the analysis period.

4.2.1 Input Data: Network Condition

This case study considers a network composed of ten sections and presents a Mediterranean climate. The sections consist of asphalt pavements belonging to six functional classes: express, trunk, collector, service, local and passages. The first four categories comprise the primary network while the last two categories are under the secondary network. Traffic volumes can range from 14,400 to more than 96,000 AADT (Annual Average Daily

Table 1. Inventory Data and Technical Evaluation of Asphalt Pavement Sections

ID	Municipality	Functional class	Length [m]	FC [%]	TRC [%]	P [%]	DP [%]	R [mm]	UPCI
1	Santiago	Trunk	800	17.45	10.72	0.04	0.94	3.40	8.56
2	Santiago	Collector	750	107.88	0.00	0.09	0.00	3.67	5.66
3	Santiago	Trunk	1400	88.51	0.00	0.00	0.00	5.40	6.32
4	Santiago	Trunk	750	11.20	0.00	1.26	116.44	5.20	3.61
5	Santiago	Trunk	700	0.00	0.00	0.00	0.00	0.00	10.00
6	Santiago	Local	850	180.52	0.00	0.00	9.69	4.00	2.46
7	Santiago	Collector	1300	137.20	0.00	1.03	55.73	1.60	1.89
8	Santiago	Trunk	1900	3.80	14.22	0.00	0.00	1.00	9.10
9	Ñuñoa	Collector	850	109.09	19.03	2.25	18.72	2.00	3.41
10	Macul	Local	110	0.00	66.46	0.40	0.00	1.00	6.59

Traffic) for primary streets and less than 14,400 AADT for secondary streets (MINVU, 2008b). The structures were designed based on traffic volumes, equivalent axles and types of soils based on the structural design recommended by the Ministry (MINVU, 2008b). The technical manual evaluation data and the obtained UPCI based on Eqs. (1) and (3) are presented in Table 1.

Where, FC is Fatigue cracking; TRC is Sum of transversal and reflection cracking; DP is Deteriorated patch; R is Rutting, calculated as the average rutting of segments in the sample unit and P is Potholes.

4.2.2 Methodology: Optimal P&M&R Standards

The set of P&M&R treatments considered in this study are presented in Table 2. The service life of treatments considered in this case study for each P&M&R treatment has been acquired from American and Canadian studies (Hicks *et al.*, 2000; TAC, 2013).

The threshold values of condition where a specific treatment may be applied are defined by the treatment classification (preservation, maintenance or rehabilitation) and the functional class of the street (Table 3). The condition thresholds in which each treatment can be applied were determined following three septs:

(1) Determination of the intensity of distresses that triggers each treatment; based on information from decision trees and matrixes from the international state-of-the-art and current practices in Chile, the extension and intensity of distresses that trigger the application of certain treatment was determined. For example, in this phase, the research team identified the % of cracking that will trigger the application of crack sealing.

(2) Estimation of the UPCI values corresponding to the intensity of distress defined in step (1). Considering the intensity of distresses obtained in the previous step, these values were transform into UPCI values. In order to do so, the different sections in the network were analyzed looking for the UPCI values of the sections having the distress intensity defined in step (1).

(3) The values obtained in step (2) were summarized in order to define global threshold values for each treatment classification (preservation, maintenance and rehabilitation) within the primary and secondary network. The different values on the primary and secondary networks reflect the minimum and maximum UPCI values obtained in sept (2).”

Because urban pavement deterioration models are not available for the LCA, the methodology for the optimization of the P&M&R standards cannot be based on cost-effectiveness (CE). Therefore, the optimal P&M&R standards will be defined based on currently available tools, such as the initial cost and the total present worth of costs in the pavement life cycle. The former corresponds to a reactive practice while the latter corresponds to a sustainable approach that considers the effect of treatment alternatives in the long term. Due to the lack of performance models, this case study considers an analysis period of 25 years, in which each of the treatments are applied repetitively every time the service life of the treatment has been exceeded. For example, a treatment with a service life of 5 years is considered to be applied 5 times over the 25 years of the analysis period. Thus, the life-cycle cost of this treatment is assessed by the present worth cost of the 5 applications in the analysis period of 25 years.

Unit costs for the P&M&R treatments considered in this case study were primarily obtained from Chilean maintenance contracts in the Municipality of Santiago and from meetings with professionals from the Ministry of Public Works of Chile. Treatments not currently applied in Chile were extracted from international literature and included in the analysis to broaden the scope and future applications for other countries (Chan and Tighe, 2010; Hicks *et al.*, 2000). A discount rate of 6% is considered, as proposed for the social evaluation of projects in Chile (Ministerio de Desarrollo Social, 2014). Based on these considerations, the initial and life-cycle costs of treatment

Table 3. Threshold Value of Condition for the Application of Treatments

Treatment classification	Pavement condition (UPCI)	
	Primary network	Secondary network
Preservation	$\mathrm{UPCI} \geq 9$	$\mathrm{UPCI} \geq 8$
Maintenance	$5 \leq \mathrm{UPCI} < 9$	$3 \leq \mathrm{UPCI} < 8$
Rehabilitation	$\mathrm{UPCI} < 5$	$\mathrm{UPCI} < 3$

Table 2. Treatment Alternatives Considered for Asphalt Pavements

Treatment		Classification	Service life [years]	Initial cost [US\$/m^2]	Total present worth of costs in 25 years [US\$/m^2]
P1	Crack sealing	Preservation	2	0.99	7.02
P2	Fog seal	Preservation	3	1.02	5.04
M1	Slurry seal	Maintenance	4	2.82	10.91
M2	Micropavement	Maintenance	5	23.24	43.46
M3	Milling and functional resurfacing	Maintenance	10	3.07	9.32
R1	Milling and structural resurfacing	Rehabilitation	12	25.44	44.37
R2	Hot in place recycling	Rehabilitation	10	35.39	66.19
R3	Reconstruction	Rehabilitation	25	66.74	66.74

NOTE: Total present worth of costs considered a discount rate of 6% (Ministerio de Desarrollo Social, 2014).

Table 4. Initial and Total Present Worth of Costs of Optimal Treatment Strategies

ID	Minimum initial cost			Minimum life-cycle cost		
	Optimal treatment	Initial cost [US$]	Total present worth of costs in 25 years [US$]	Optimal treatment	Initial cost (US$)	Total present worth of costs in 25 years [US$]
1	M1	7,896	30,549	M3	8,596	26,086
2	M1	7,403	28,640	M3	8,059	24,456
3	M1	13,818	53,461	M3	15,043	45,651
4	R1	66,780	116,461	R1	66,780	116,461
5	P1	2,426	17,203	P2	2,499	12,351
6	R1	75,684	131,989	R1	75,684	131,989
7	R1	115,752	201,865	R1	115,752	201,865
8	P1	6,584	46,693	P2	6,783	33,523
9	R1	75,684	131,989	R1	75,684	131,989
10	M1	1,086	4,200	M3	1,182	3,587
	Total	373,111	763,049	Total	376,062	727,958

alternatives considered in this case study are shown in Table 2.

Table 4 provides the results of the application of P&M&R standards for the sections in the network. The total budget needed to treat the network differs depending on the criterion for selecting optimal treatments at the section level. In fact, the life-cycle approach implies an initial overrun of 0.8% compared to that of the minimal initial cost approach. However, this trend is reversed if the total costs are compared in the 25-year analysis period. The selection of treatments with lower total costs over the analysis period represents savings of 4.6% of total costs against the alternative of lower initial costs. Therefore, slight increases in initial costs lead to significant savings in the long term. These results highlight the need for LCA for the sustainable management of pavement networks.

From Table 4, it is evident that environmentally friendly treatments (such as R2 and hot in place recycling) are not considered in the optimal set of alternatives. This may be because recycling is a costly activity whose environmental benefits have not been considered in this analysis. This result highlights the need for an environmental evaluation of alternatives in the optimization process of P&M&R standards.

4.2.3 Process: Prioritization

Once the optimal treatment strategies are defined at the section level, the sections to treat are selected based on a sustainable prioritization and available budget. The UPMS proposes to prioritise sections based on Cost-effectiveness (CE) and weighted by the socio-political factor (SPF). In this case study, the socio-political aspects considered are major infrastructures near the road (MI) and Benefited Population (BP). Both the MI and BP criteria are dichotomous variables with two possible values (yes or no for MI and high or low for BP). The MI is a positive value if there is a major infrastructure located within 300 m of the road section under analysis. Meanwhile, the BP criterion is high if the road section serves an area of high-density city blocks. The Socio-political Factor (SPF) is assessed by a weighted sum of socio-political criteria in a 0-1 base, where 1 indicates a high socio-political impact. The weights considered for the MI and BP were 0.66 and 0.33, respectively (Table 5). This simplification of the socio-political criteria, both in criteria number and assessment ranges, aims at facilitating the presentation of the case study. It is important to emphasize the relevance of the CE-SPF weighting criteria for its influence in maintenance, which can be seen as unfair to areas that are not favoured by the higher preference criteria. It is not the purpose of this document to address the weighting mechanisms but there is a need to calibrate them to local needs, culture and the reliability of available information.

Table 5. Social and Political Evaluation of the Sections in the Network

ID	Major Infrastructure (MI)	Benefited Population (BP)	Socio-Political Factor (SPF)
1	Yes	Low	66%
2	No	High	33%
3	Yes	Low	66%
4	Yes	High	100%
5	Yes	Low	66%
6	No	High	33%
7	No	Low	0%
8	No	Low	0%
9	No	High	33%
10	No	High	33%

The socio-political factor (SPF) is considered in the prioritization process to weight the alternatives' cost-effectiveness by hypothetically reducing the costs of the alternatives. This approach will allow those alternatives with major SPFs to be less "expensive" and more competitive in the prioritization process. However, as deterioration curves are not yet available for the assessment of treatment effectiveness, this case study compares alternatives based on their life-cycle cost. This comparison is equivalent to comparing cost-effectiveness, assuming that all of the alternatives have similar effectiveness. This assumption will not be necessary once validated deterioration curves for urban pavements are available. Thus, this case study compares three scenarios considering different prioritization criteria: condition,

Table 6. Prioritization Process Considering Three Criteria: Condition, Cost-effectiveness and Cost-effectiveness Weighted by Social and Political Factors

Priority	Priority based on condition			Priority based on CE			Priority based on CE and SPF		
	ID	ICPU	Initial cost [US$]	ID	ICPU	Initial cost [US$]	ID	ICPU	Initial cost [US$]
1	7	1.9	115,752	10	6.6	1,182	10	6.6	1,182
2	6	2.5	75,684	5	10.0	2,499	5	10.0	2,499
3	9	3.4	75,684	2	5.7	8,059	1	8.6	8,596
4	4	3.6	66,780	1	8.6	8,596	2	5.7	8,059
5	2	5.7	8,059	8	9.1	6,783	3	6.3	15,043
6	3	6.3	15,043	3	6.3	15,043	8	9.1	6,783
7	10	6.6	1,182	4	3.6	66,780	4	3.6	66,780
8	1	8.6	8,596	6	2.5	75,684	6	2.5	75,684
9	8	9.1	6,783	9	3.4	75,684	9	3.4	75,684
10	5	10.0	2,499	7	1.9	115,752	7	1.9	115,752

cost-effectiveness (assuming similar effectiveness among treatment alternatives) and cost-effectiveness weighted by the social and political factors (Table 6).

Based on Table 6, it is observed that priority based on conditions requires a high budget to treat the first ranked sections. For example, if the available budget were 50% of the total budget needed to treat the network (50% of 376,062 = 188,031 US$), priority based on condition will only consider treating section 7. Meanwhile, priority based on cost-effectiveness provides an advantage to sections with fair, good and very good conditions and, consequently, preservation and maintenance treatments versus rehabilitation treatments. This result highlights the fact that proactive practices, based on preservation and maintenance, result in more efficient policies in the long-term than reactive policies based on rehabilitation. Additionally, considering social and Political Factors (SPF) in the prioritization process leads to small changes when prioritising sections to treat. Although social and political factors are currently considered in the pavement management decision process, the proposed framework allows these factors to be included in a structured and objective manner using a GIS, capable to quantify them and esuring better understanding of the scenario.

5. Conclusions

This study presents a methodology for the sustainable management of transportation assets by defining a generic framework applicable to various infrastructures and proposing processes and components required by a management system. For a better understanding of this methodology an illustrative case study applied to urban pavement networks is presented. From this application, the following conclusions may be derived:

1. The proposed indicators for the evaluation of technical, economic, environmental and socio-political aspects allows a sustainable approach to be incorporated in the management of urban pavement networks.
2. The framework allows the integration of sustainable aspects in an easy-to-use tool that will assist institutions responsible for decision-making.
3. The formalization and standardization of socio-political criteria allow the integration of social and political variables in the decision-making process. The consideration of these criteria affects the prioritization of sections to treat at the network level.

The case study analysed in this document is based on existing tools for the management of urban pavement networks. Outcomes of the case study demonstrate that it is possible to integrate sustainable aspects, despite their diverse nature, in a management system supported by a Geographic Information System. This application has revealed the need of future research in the following areas:

4. The sustainable evaluation of maintenance alternatives requires the calibration of performance curves specifically developed for the transportation asset under study. These curves will enable a LCA of maintenance alternatives based on cost-effectiveness analysis.
5. A sustainable management system needs to incorporate a methodology for the environmental evaluation of maintenance alternatives. Because environmentally friendly practices (i.e., using recycled materials) may imply higher economic direct costs, they thus become uncompetitive when the evaluation is only performed in economic terms.

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