LCCA for silent surfaces

F.G. Praticò
University Mediterranea of Reggio Calabria, Reggio Calabria, Italy

ABSTRACT: Traffic noise (and in more detail rolling noise) affects the health of thousands of citizens. Consequently a number of silent technologies (quiet surfaces) are available, with different weaknesses, noise performance, and expected life. This notwithstanding, addressing noise impacts from a Life cycle cost analysis (LCCA) perspective is still an issue. Indeed, characterization factors, inventory data, underlying methodology are neither clear nor well established. Complexity increases when not only environmental costs but also agency and/or user costs are considered as a whole. This implies that the assessment of the "overall" appropriateness of a "silent technology" may emerge as uncertain. In the light of the above, the study described in this paper focuses on setting up a methodology for the synergistic consideration of agency, user and environmental/noise-related costs. The methodology set up was applied to a given case study. Results can benefit both researchers and practitioners.

1 INTRODUCTION

1.1 *Overview*

According to the standard ISO 15686-5, "Life Cycle Costing (LCC) is a valuable technique which is used for predicting and assessing the cost performance of constructed assets".
LCC can be defined as "the cost of an asset or its part throughout its life cycle, while fulfilling the performance requirements". LCC includes construction, operation, maintenance, end of life, environment (including energy and utilities) costs (ISO 15686-5). The following definitions apply: i) External Costs: costs associated with an asset which are not necessarily reflected in the transaction costs between provider and consumer (e.g. business staffing and productivity, user costs, etc). Collectively these elements are referred to as externalities. ii) Environmental cost impacts: …costs (or savings via rebates) to LCC depending on the effects .. on the environment. Examples could include cost premiums for the use of non-renewable resources or for green house gas emissions. Where these costs are external to the constructed asset they will form part of a Whole Life Cost (WLC) analysis. iii) WLC elements: typically the difference to LCC is that the elements of WLC include a wider range of externalities or non-construction costs, such as finance costs, business costs and income streams.

LCC (or LCCA, life cycle cost analysis) entails the assessment of the estimated service life (see BS ISO 15686-1). To this end, the standard ISO 15686-1 focuses on service and design life, especially for buildings. For environmental impacts and their inclusion in LCCA, the standard BS ISO 15686-6 clarifies main environment-related components. LCC algorithms build on present values of costs (PV). PV is the current worth of a future sum of money given a specified rate of return and inflaction. Future cash flows are discounted, and the higher the discount rate, the lower the present value of the future cash flows.

Note that unlike the nominal rate, the real interest rate takes the inflation rate into account.

Key issues in LCCA include the following: i) the same end-of-life concept implies the introduction of a salvage (or residual, remaining service life) value. This notwithstanding, there are different methods to derive these values (ACPA, 2011; West et al, 2012). Furthermore, from an epistemic and mathematic standpoint, several issues emerge (Weeds, 2001; Praticò and Casciano, 2015); ii) The discount rate (interest and inflation rates) can be assesses, in the U.S., through the OMB circular A-94, Appendix C. Anyhow, it is extremely variable and results may depend on the selected options; iii) the estimate of user costs (UC, delay costs, crash costs, vehicle operating costs) is debated, uncertain, and difficult (even if software is available, see Caltrans, 2011). Furthermore, there are doubts about merging agency and user costs in LCCA analyses (current FHWA policy does not recommend this practice) and UC value is usually higher or comparable with respect to agency costs (AC, see Delwar and Papagiannakis, 2001); iii) functional, structural, premium properties of pavements have to be considered in terms of agency costs, including their variability of time for the given pavement type (macrotexture modeling,,,,, a study on the relationship…..; iv) the assessment of the environmental impacts is included in LCCA, but the synergistic consideration of environmental and "traditional" (i.e., UC, AC) impacts poses theoretical and practical issues (Praticò et al, 2010; Praticò et al., 2012). This consideration pertains also to the simultaneous assessment of different environmental impacts (e.g., noise and carbon footprint of a pavement); v) several authors and road agencies (Mallela and Sadasivam, 2011) observe that the monetized impacts of user costs include travel delay costs, vehicle operating costs, crash costs, emissions costs, impacts of nearby projects. At the same time, they classify under other, non-monetary impacts the following items: noise, business impacts, inconvenience to local community. This method implies that environmental impacts are split into two different classes: monetized and non-monetary. Although necessary from a practical standpoint, from a logical standpoint, this division is quite unsatisfactory because: i) the same emission costs were once non-monetary and are now monetized through a given methodology; ii) this brings to variable results, based on CO2e unitary cost.

For noise-related impacts, Cucurachi and Heijungs, 2014 provided characterization factors to allow for the quantification of noise impacts on human health in the LCA framework. Garrain et al, 2009 proposed a specific indicator as the best unit to measure the negative impacts of noise upon human health. Doka, G. (2009) provided practical figures to estimate road, rail and airplane noise damages for Life Cycle. Buckland and Muirhead, 2014 analyzed the expected reduction in property value for an increase of 1dB(A). They found reductions in the range 0.2-2.2%. In terms of monetary evaluation of road traffic noise, values which range from zero (when the 24-hour A-weighted equivalent outdoor sound level is about 50 dB) to about 1040 €/year/exposed person (for 72dB) were proposed (see Vanchieri, 2014).

Overall, despite the simplicity of the logical bases for the derivation of noise costs (the higher the distance from a given threshold, around 50-55dB, the higher the cost), the following specific criticalities may be highlighted: i) order of magnitude of the unitary costs (per dB, per person, per year); ii) linear versus non-linear dependency on dB; iii) variability over time of pavement noise performance (Licitra, 2014).

1.2 *Objectives*

Based on the above, the study described in this paper aims at:

i) Setting up a series of algorithms to carry out comprehensive LCCAs on transportation infrastructures;

ii) In more detail, considering the effect of noise-related performance of pavements.

2 METHODOLOGY

2.1 *The template file*

The methodology set up and implemented builds on the estimate of the present value of each agency, user, and environmental cost.

The analysis of costs over time is carried out in terms of present values (PV). Based on Fisher equation (Fisher, 1930), the following expression is used in PV estimates:

$$R = \left(\frac{1 + INF}{1 + INT} \right) \quad (1)$$

Where INF is the inflation rate (e.g., 0.04) and INT is the nominal interest rate (e.g., 0.08). Note that based on 1-st order Taylor expansion, it is possible to demonstrate the relationship between the real interest rate (r) and R:

$$\frac{1}{1 + r} \approx R = \left(\frac{1 + INF}{1 + INT} \right) \quad (2)$$

Importantly, for the above quantities, the Fisher equation is as follows:

$$INT \approx r + INF \quad (3)$$

For user costs (UC), the following primary contributions can be taken into account: i) delays (D) due to rehabilitations (REH); ii) delays due to resurfacing (RES); vehicle operating costs (VOC). In the following two equations E is the expected life of rehabilitation and O is the expected life of successive resurfacing, Cs refer to costs.

$$PV_{UC\_D\_REH} = \left(1 + \frac{R^E}{1 - R^E} \right) \cdot C_{UC\_D\_REH} \quad (4)$$

$$PV_{UC\_D\_RES} = \left(\frac{\sum_{i=1}^{i=INT\left(\frac{E}{O}-1\right)} R^{i \cdot O}}{1 - R^E} \right) \cdot C_{UC\_D\_RES} \quad (5)$$

Note that i represents the index of summation, 1 is the lower bound of summation, and the upper bound of summation is given by the integer derived based on E and O. The index, i, is incremented by 1 for each successive term, stopping when i=N, where

$$N = INT\left(\frac{E}{O} - 1 \right) \quad (6)$$

Vehicle operating costs (VOC) are given by:

$$PV_{UC\_VOC} = \left(\frac{R}{1 - R} \right) \cdot C_{VOC} \quad (7)$$

It results:

$$PV_{UC} = PV_{UC\_D\_REH} + PV_{UC\_D\_RES} + PV_{UC\_VOC} \quad (8)$$

For agency costs (AC), the following primary parts are considered:

$$PV_{AC\_REH} = \left(1 + \frac{R^E}{1 - R^E} \right) \cdot C_{REH} \quad (9)$$

$$PV_{AC\_RES} = \left(\frac{\sum_{i=1}^{i=INT\left(\frac{E}{O}-1\right)} R^{i \cdot O}}{1 - R^E} \right) \cdot C_{RES} \quad (10)$$

From above, it derives:

$$PV_{AC} = PV_{AC\_REH} + PV_{AC\_RES} \quad (11)$$

For environmental costs (EX), the following main quantities are considered: i) CO2e-related impact in rehabilitation and resurfacing (which include production/quarrying-related, recycling-related, and landfill-related impacts); pollution-related impacts; iv) noise-related impact; v) positive impact from trees planting:

$$PV_{EX\_CO2e\_REH} = \left(1 + \frac{R^E}{1 - R^E}\right) \cdot C_{EX\_CO2e\_REH} \tag{12}$$

$$PV_{EX\_CO2e\_RES} = \left(\frac{\sum_{i=1}^{i=NINT\left(\frac{E}{O}-1\right)} R^{i \cdot O}}{1 - R^E}\right) \cdot C_{EX\_CO2e\_RES} \tag{13}$$

$$PV_{EX\_POLL} = \left(\frac{R}{1 - R}\right) \cdot C_{EX\_POLL} \tag{14}$$

$$PV_{EX\_TREES} = \left(\frac{R}{1 - R}\right) \cdot C_{EX\_TREES} \tag{15}$$

$$PV_{EX\_Noise} = \left(\frac{R}{1 - R}\right) \cdot C_{EX\_Noise} \tag{16}$$

$$C_{EX\_Noise} = \left(\frac{\alpha}{(\mathrm{USL} - \mathrm{L}_{\mathrm{dn}})^{\beta}} - \frac{\alpha}{\mathrm{USL}^{\beta}}\right) \cdot \mathrm{L}_{\mathrm{dn}} \cdot (V \cdot L) \tag{17}$$

Where α and β are coefficients to calibrate, L_{dn} is a sound pressure level, USL is the corresponding upper specification limit, V is the number of vehicles per year, L is the length of the road stretch.

It follows:

$$PV_{EX} = PV_{EX\_CO2e\_REH} + PV_{EX\_CO2e\_RES} + PV_{EX\_Noise} + PV_{EX\_POLL} + PV_{EX\_Trees} \tag{18}$$

For the environmental costs, note that the quantification of the CO2e emissions is a well-established practice (European Union emissions trading system, see Sijm et al, 2006). On the other hand, the fluctuation of the carbon price is a matter of fact and the price of carbon dioxide (€ per tonne) is highly variable. This may increase the variability and unreliability of the results in terms of EX. To this end, the following procedure is herein proposed (for each i-th project or solution among the k ones). The first step is to derive the indicator which refers to the critical relationship between "traditional" and environmental costs:

$$\nu = \min_{i=1,\,2,\,k} \frac{PV_{ACi} + PV_{UCi}}{PV_{EXi}} \tag{19}$$

The second step is to operate in this vector space of the "internalized" factors to get a linear magnification:

$$PV_{EXi}^{*} = \nu \cdot PV_{EXi} \tag{20}$$

In pursuit of the estimation of the overall gain for each solution, note that agency costs (AC), user costs (UC) and environmental costs (EX) contribute to the overall present value, PV given as:

$$PV = PV_{AC} + PV_{UC} + PV^{*}_{EX} \quad (21)$$

Based on the above the comparison between two competing projects/alternatives 1 and 2 can be carried out based on the lowest present value, i.e., based on gains, G:

$$G = PV_1 - PV_2 = \left(PV_{AC1} - PV_{AC2}\right) + \left(PV_{UC1} - PV_{UC2}\right) + \left(PV^{*}_{EX1} - PV^{*}_{EX2}\right) \quad (22)$$

Note that equations 1-4, 8, 9, 11, 12, 14-16, 18-22 build on (Fisher, 1930; Pratico' et al, 2011; Pratico', 2017). In contrast, equations (5-7) and 10, 13, 17 are new. Note that in the above algorithms other parts may be added, based on specific issues.

3 DESIGN OF EXPERIMENTS AND RESULTS

Tables 1 and 2 and Figures 1-5 illustrate main inputs and outputs. Table 1 focuses on the options considered. Three different friction courses were considered: dense-graded (DGFC, 30mm), open-graded (PA, 50mm), and recycled open graded (RPA, 50mm, 55% of reclaimed porous asphalt). The underlying pavement structure was the same: binder course (BIC, 40mm), base course (unbound, BA, 200mm), and subgrade (MR=310MPa). A total surface area of 10000 m2 was considered. Note that the structure of the equations above basically presents two terms: a terms which allows deriving the impact of costs over time (the one containing R) and a coefficient (e.g., $c_{UC\_D\_REH}$). Table 2 illustrates the coefficients derived (see equations above, Euro), which are the main inputs used in the case-study.

Table 1. Factorial plan of experiments.

	DGFC		PA		RPA	
Pavement structure	DGFC	30	PA	50	RPA	50
	BIC	40	BIC	40	BIC	40
	BA	200	BA	200	BA	200

Table 2. Main inputs and outputs.

Coefficients (rounded)	DGFC	PA	RPA
UC_D_REH	59000	59000	59000
UC_D_RES	29000	29000	29000
UC_VOC	70000	70000	70000
AC_REH	124000	175000	128000
AC_RES	55000	106000	78000
EX_CO2e_REH	1147000	1855000	1476000
EX_CO2e_RES	491000	708000	329000
EX_Noise	557000	392000	392000
EX-POLL	61000	61000	61000
Main outputs		PVAC	
		PVUC	
		PVEX	

Figures below illustrate the main results. Figure 1 illustrates how the present value of agency costs (y-axis, M€) varies over pavement life (x-axis, years), for the three selected options (see table 1). Note that Porous asphalts (PA) have costs which are higher than the ones of DGFCs and a durability which is lower. It turns out that present values for PAs are higher than the ones for DGFCs. In contrast, due to the lower initial costs, recycled porous asphalts yield a present value which is slightly lower that the one exhibited by PAs (see Figure 2).

By referring to Figure 2, note that the carbon footprint of PAs is higher than the one of DGFCs, due to the different durability. In contrast, when an appreciable percentage of recycling is considered (about 50%, RPA) there is a gain in terms of CO2e (a lower quantity of bitumen and aggregates is required). This gain balances the lower durability of PAs/RPAs with respect to DGFCs. It turns out that the RPA achieve the best result in terms of CO2e (see also Figure 2).

For the noise, note that under the hypothesis of having a similar sound pressure level for PAs and RPAs, the financial impact of noise is higher when DGFCs are used instead of porous asphalts (PAs or RPAs).

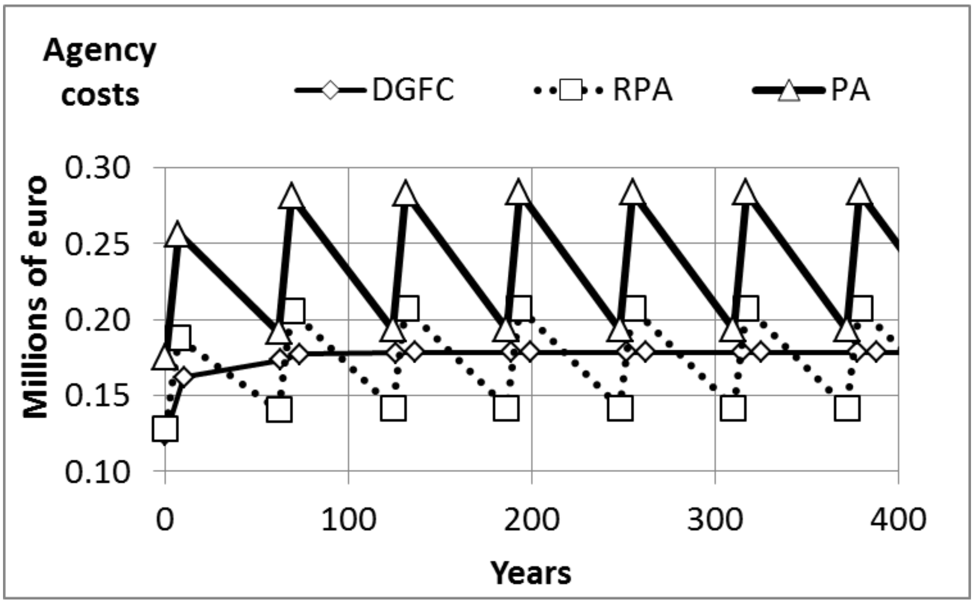


Figure 1. Present value of agency costs (y-axis, M€) over pavement life (x-axis, years).

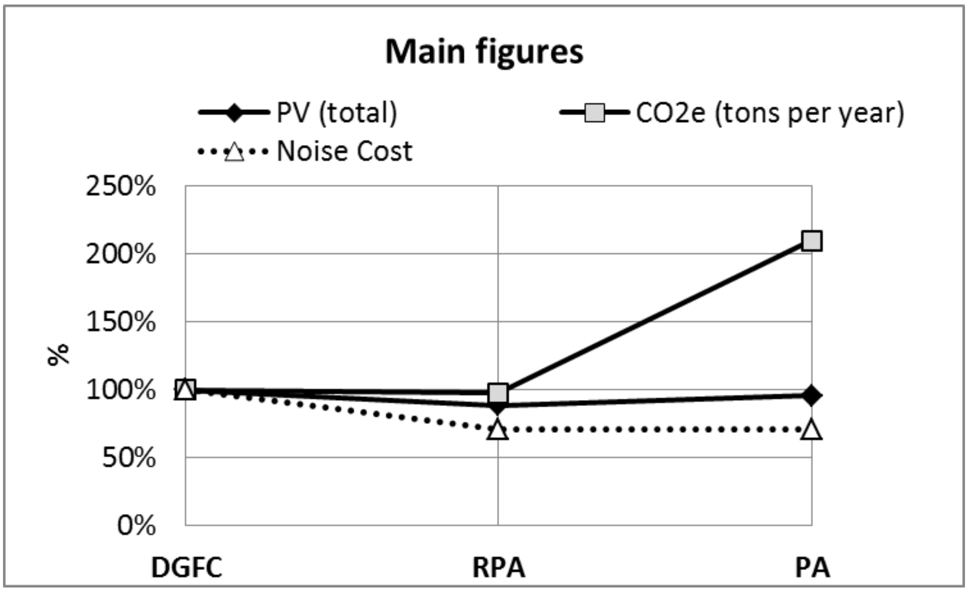
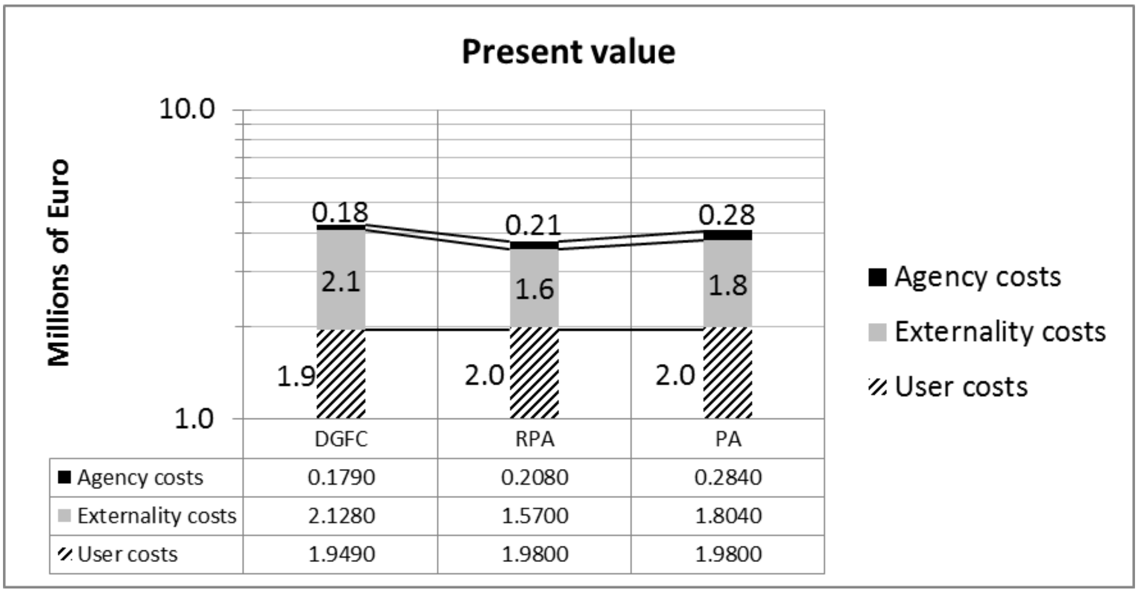


Figure 2. Total present value, noise impact, carbon footprint ad a percentage of the reference option, for the three options (DGFC, RPA, PA)



	DGFC	RPA	PA
Agency costs	0.1790	0.2080	0.2840
Externality costs	2.1280	1.5700	1.8040
User costs	1.9490	1.9800	1.9800

Figure 3. Present value of agency, user, environmental costs (millions of euro) for the three options (DGFC, RPA, PA)

Figure 3 summarizes the three classes of costs (AC, UC, EX) under the three abovementioned hypotheses (DGFC, RPA, PA). Note that the present value of environmental costs includes operation- and rehabilitation-related impacts. It takes into account pollution, noise, and carbon footprint. It results higher when DGFCs are used (Figure 3). Positive outcomes derive from recycling (e.g., RPAs) and planting trees (herein not considered). Note that user costs have a magnitude which is about ten times the one of agency costs. This is quite consistent with literature (Delwar and Papagiannakis, 2001). Finally, note that PA agency costs are higher the ones of RPA (due to material cost and durability). In turn, RPA agency costs are higher than DGFC agency costs, due to their lower durability.

Noise relative impact (with respect to the overall environmental impact of DGFCs) is depicted in Figure 4. Note that noise-related impact ranges from 56% to 79%, while pollution-related impact accounts for 18-29%.

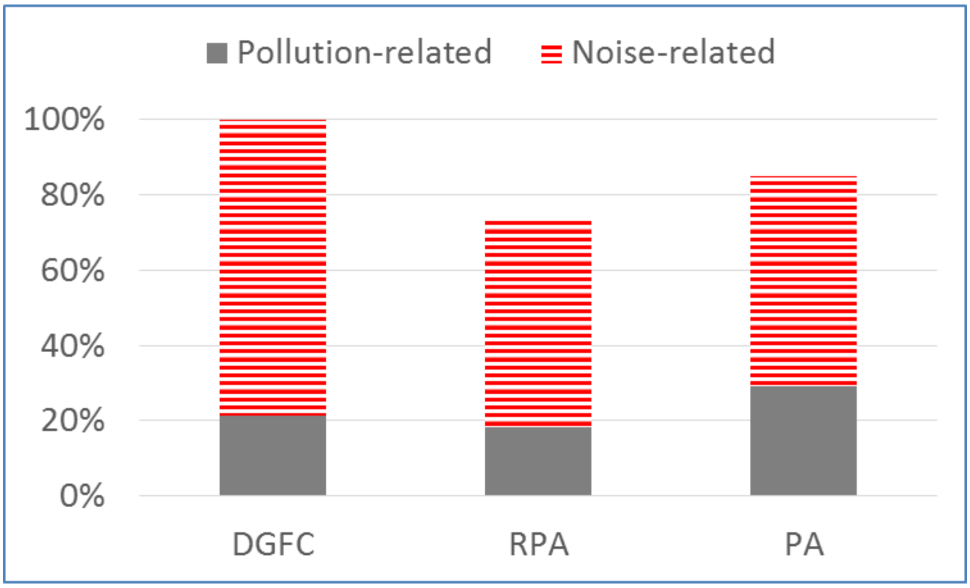


Figure 4. Noise-related versus pollution-related impacts (percentages by the total environmental costs for DGFC)

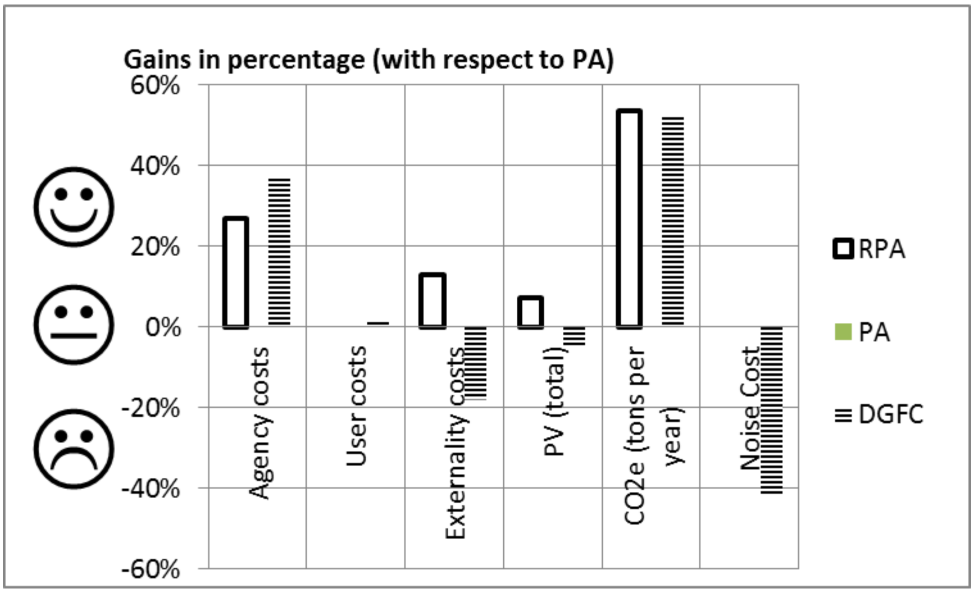


Figure 5. Gains in percentage (y-axis), with respect to porous asphalt (PA), for the for the three options (DGFC, RPA, PA), in terms of costs (AC, UC, EX, total), carbon footprint, and noise

Figure 5 focuses not only on present values but also on carbon footprint and noise cost, which are sensitive environmental targets. Gains are used, i.e., differences of PVs, with respect to PA (equation 22). It may be observed that RPA and DGFC perform better than PA when agency costs or carbon foot print are considered. In contrast, by referring to the overall environmental impact (EX) and to the overall PV, RPA perform better than the remaining ones, while DGFC perform worse than the remaining ones.

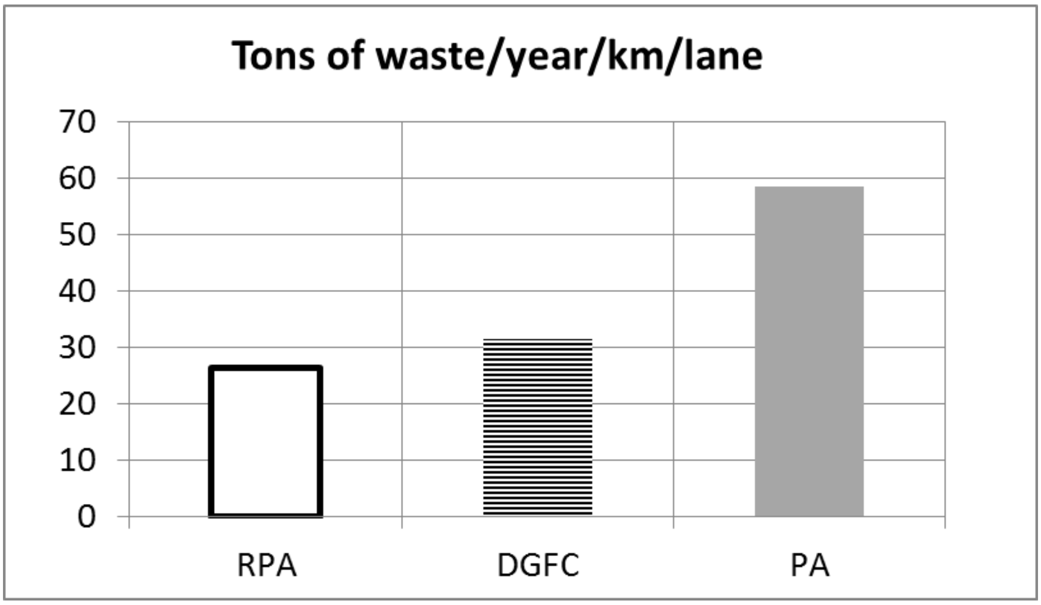


Figure 6. Tons of waste produced (y-axis ton/year/lane) for the for the three options (DGFC, RPA, PA).

By referring to waste balance (Figure 6), note that this is affected by hot mix asphalt durability (the higher the durability is the lower waste production is) and by recycling percentage (the lower the recycled percentage is the higher waste production is). It is noted that porous asphalt recycling implies an appreciable reduction of waste (reclaimed asphalt pavement, RAP) production (per year and per lane). In more detail, RPA exhibits a RAP production that is lower than the ones of DGFCs or PA, despite the differences in expected life.

4 CONCLUSIONS AND SUMMARY

Life cycle costing is a complex procedure which handles simple items such as costs of construction and delay. Issues arise in terms of holistic approaches, which, in turn, are needed to get sound conclusions. A set of algorithms was set up to deal synergistically with a large number of impacts and an analysis period theoretically unlimited. A case study was considered. Based on the results above the following conclusions may be drawn: i) The impact of recycling is outstanding and can make the difference; ii) Durability is a key-factor which plays an important role in favour of traditional solutions (DGFCs). The unsatisfactory durability of porous asphalt has to be balanced through supplementary characteristics. High recycling percentages and low carbon footprint can be the right answer; iii) Densely-populated areas experience high levels of noise pollution, as do areas in which the land is not used in a smart and sustainable way. This impact has to be assessed singularly and objective thresholds must be in place. This concept is herein addressed by considering a non-linear cost curve with a vertical asymptote. On the other hand, noise and carbon footprint are different and concomitant aspects of the environmental problem. This concept is addressed by summing the concerned PVs. In turn, from a holistic standpoint, environmental and traditional PVs are features of the same problem. This concept is addressed by a standardization procedure. Under the above conditions, with respect to the overall environmental impact of a traditional, dense-graded solution, noise impact ranges from 56% to 79%, while pollution-related impact accounts for 18-29%.

Future research will address the application of the above algorithms to high-durable, high-cost solutions. Result of this study are supposed to benefit both researchers and practitioners.

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