Life-Cycle Assessment of road pavements containing marginal materials: comparative analysis based on a real case study

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ABSTRACT: The Life-Cycle Assessment (LCA) is a standardized procedure generally used, in Italy, in industrial engineering to evaluate the economic-environmental efficiency of production processes. LCA is aimed at optimizing the design, with special emphasis on environmental sustainability. Also in the construction sector, LCA has recently gained a fundamental role as a quantitative measurement tool able to take into account correctly the environmental and economic benefits achievable adopting different alternatives (most of them uncommon) based on the entire service life, maintenance and end-of-life procedures included. As far as pavement engineering is concerned, the use of marginal materials (such as, for example, reclaimed asphalt pavement, crumb rubber, slags, etc.) is becoming of strategic importance due to the decreasing availability of virgin natural resources and the consequent increasing public consciousness addressed to environmental protection and preservation. In this regard, the LCA applied to road pavements constructed using marginal aggregates probably represents the only effective tool able to evidence the crucial aspects on which the design choices should be based, taking also into account long-term parameters. Given this background, the present research illustrates one real case study of LCA analysis applied to asphalt pavements of a motorway. The use of industrial by-products (i.e. steel slags) instead of natural mineral aggregates is considered. Comparative evaluation of different scenarios has been carried out using specifically developed spreadsheets. The research study demonstrates that LCA is able to highlight potentialities and issues related to the different analyzed scenarios, representing a valid tool for designers and decision-makers. Moreover, the obtained results contribute to enlarge the worldwide database about the implementation of LCA for pavements.

1 INTRODUCTION

1.1 *General overview of Life Cycle Assessment methodology*

The Life Cycle Assessment (LCA) is a methodology developed to support the decision-making process in environmental terms, implemented since the Seventies. LCA is usually utilized at industrial level since it allows the evaluation of the potential product impacts, considering all life cycle stages (from design to construction, from use to final disposal). This assessment includes all the interactions between product (or service) and surrounding environment, also considering the maintenance phases.

In the international field, Life Cycle Assessment is largely widespread to improve both industrial production and services. Thanks to the policies impulses, the use of LCA is strongly encourages also in European Union in order to achieve targets such as: i) reduction of energy and resource consumption; ii) health improvement; iii) environment saving. Moreover, since LCA allows to quantify the production processes and the environmental impacts indicating the possible strategies to reduce emissions, this methodology is becoming a necessary tool for the definition of public policies and industrial competitiveness.

1.2 *The standards for LCA methodology*

Life Cycle Assessment is defined and described in ISO 14040 and ISO 14044 (ISO 2006a, b) standards. LCA framework (Fig. 1) can be divided in the following steps: 1) goal and scope definitions; 2) inventory collection and analysis; 3) environmental impact assessment; 4) obtained results interpretation.

ISO standards describe in detail principles, framework, requirements and guidelines for the LCA, including: a) the goal and scope definition of the LCA; b) the life cycle inventory analysis (LCI) phase; c) the life cycle impact assessment (LCIA) phase; d) the life cycle interpretation phase; e) reporting and critical review of the LCA; f) limitations of the LCA; g) relationship between the LCA phases; h) conditions for use of value choices and optional elements.

However, these standards do not state specific prescriptions to perform a LCA or defined methodologies for the specific LCA phase. Further, LCI phase can be performed separately from a specific LCA study, because LCI inputs/outputs introduction and quantification are not closely linked with the specific product or service evaluated with the LCA.

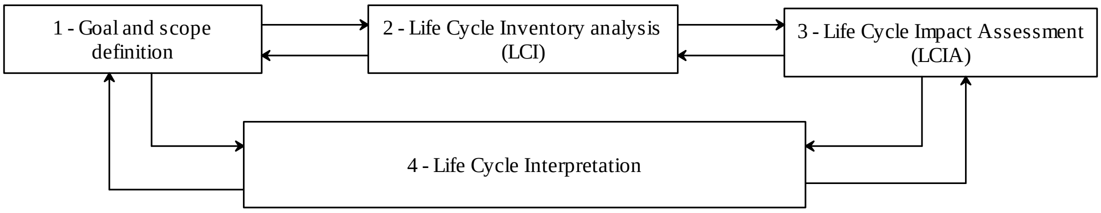

Figure 1. Life Cycle Assessment framework (from the ISO 14040 (ISO 2006b)).

1.3 *LCA in road engineering*

The attention addressed to the minimization of impacts related to the construction inclusion in the environment defines a general trend concerning the study of ecological characteristics throughout the different infrastructure project hypothesis (from design to maintenance, from use to end-of-life). LCA can be applied to several civil engineering sectors, such as the transport infrastructure one. In this sense, many researchers already ventured in LCA implementation to evaluate the environmental impacts connected to transport infrastructures, facing the most important problems related to the material type and its transport, that strongly represent onerous items in road construction and maintenance (Jullien et al. 2009, Santero et al. 2011, Azarijafari et al. 2016).

The increasing expensiveness of road design (in terms of energy request and environmental impacts) involves the need to reduce work emissions and costs during its lifetime. In this sense, even more researchers, management and construction companies develop sustainable project and utilize LCA in decision procedures which affect several environmental aspects (such as impacts of different pavement types and materials). Also the decision-makers, with an accurate life cycle cost analysis, can use LCA to evaluate the project or policy impacts (Santero et al. 2011).

Many studies evaluate the environmental issues and the effects on road construction, management/maintenance and rehabilitation. Amini et al. (2012) compared conventional and perpetual pavement (i.e. not requesting structural maintenance) and their different effects on environment and costs. Others researchers suggested to take into account the effect on the environment and infrastructure caused by road traffic (Zaabar & Chatti 2010, Santos et al. 2015a). For example, Bryce et al. (2014) evaluated through LCA the possibility to reduce the road maintenance activities considering the pavement damage and the related tire vehicles consumption (the surface type affects the vehicles pollution). Yang et al. (2015) assessed the use of Reclaimed Asphalt Pavement – RAP and Recycled Asphalt Shingle – RAS in partial substitution of virgin aggregates to check the different environmental impacts, considering also the vehicles fuel consumes as a function of the IRI index.

Others authors studied LCA applied to road infrastructure materials. DeDene & Marasteanu (2012) examined the possibility to reduce production costs and harmful emissions of asphalt pavement with 15% of RAP. Butt et al. (2014) applied LCA to bituminous mixtures assessing the energy consumption and the environmental sustainability. In this case, the analysis of significant aspects such as the asphalt concrete production temperature, the vehicles type, the material transport and the location of the work site demonstrate the need to review the road construction method.

Software implementing the LCA to evaluate the environmental, social and economic impacts of a road pavement can be found. As examples, PaLATE developed by Californian researchers in the 2004 (Horvath et al. 2007), a model elaborated at Michigan University in the 2007 (Zhang et al. 2010), OPTIPAV proposed by Portuguese researchers in the 2011 (Santos & Ferreira 2013), DuBoCalc created by the Netherlands national public works agency in the 2013 (Harvey et al. 2014), SimaPro developed by consultants agency in the Netherlands (Anthonissen et al. 2015).

1.4 *The PaLATE tool*

The present work utilizes the Excel-based tool PaLATE (Pavement Life cycle Assessment Tool for Environmental and Economic Effects), a LCA applicator useful to assess the pavement and road life cycle (considering extraction, production, construction, maintenance and end-of-life phases). PaLATE provides many results in terms of environmental effects (e.g. energy consumption, CO_2, NO_x, PM_{10} emissions, etc.) and costs (e.g. during construction and maintenance phases).

The software is divided into different parts, each one able to collect input data and information (engineering, environmental and economic-based) in order to return a wide range of output results (air quality, amount of harmful emissions, etc.). Thanks to its analytical structure and flexibility, this tool is often used for research and commercial purposes. Utilizing PaLATE, Celauro et al. (2015) checked the influence of different virgin and recycled aggregates during construction and maintenance operation of a typical Italian road pavement. Similarly, Nathman et al. (2009) analyzed road pavement construction and maintenance activities quantifying the works feasibility and the economical, environmental and social sustainability with PaLATE.

2 CASE STUDY

2.1 *LCA phases*

Based on the scheme of Figure 1, the paper herein presents a Life Cycle Assessment performed through the overall road life cycle. In this sense, five phases (Fig. 2) can be cited (Celauro et al. 2015): 1) material production, 2) construction, 3) use (in this case it is not included the emission and the delay caused by traffic), 4) maintenance and rehabilitation (discard old material, production of new material, transport and laying processes), 5) end-of-life (pavement demolition and material disposal).

Data utilized in the LCI phase were obtained from different sources, depending on the information type (materials, transport, cost, etc.). The main sources are: Italian company of motorway (called “Autostrade per l’Italia”), asphalt concrete producer companies, transport companies, typical Italian price lists and specifications as well as Italian Minister of Public Works.

2.2 *Research objective*

The presented study is based on a real road infrastructure designed in Italy. Traditional construction/maintenance techniques were compared with recycling technologies since the re-utilization of RAP and industrial by-products such as steel slags, fly ashes, municipal solid waste incinerator ashes or glass involves lower environmental impacts with respect to traditional techniques. Thus, the study is aimed at assessing the validity of LCA in order to promote the mitigation of environmental impacts, decrease costs and control energy (fuel, electrical energy, etc.) consumption when recycled materials are utilized in road construction. Moreover, in view of the importance of the maintenance policies and future investments, LCA could be a promising instrument definitely assessing costs and environmental impacts. In this sense, since pavement construction and maintenance require significant amount of materials and energy levels for treatments, the paper focuses on the comparison between alternative pavement materials with respect to traditional (high-quality and expensive) ones.

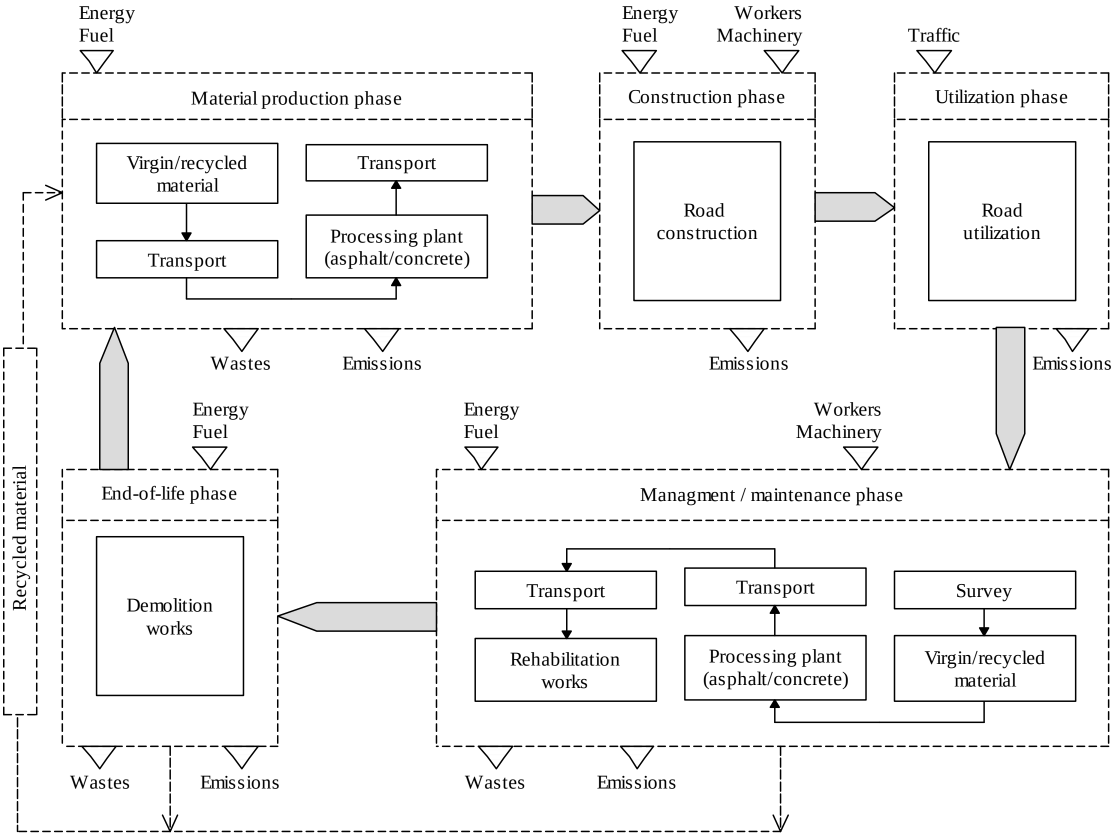

Figure 2. LCA phases and system boundary for the case study proposed.

2.3 *Functional unit description*

As mentioned above, the case study is based on a real Italian road construction project, the A3 motorway from Salerno to Reggio Calabria. LCA was applied to a motorway section of 1000 m having the geometry described in Fig. 3 (the left shoulder was considered not paved).

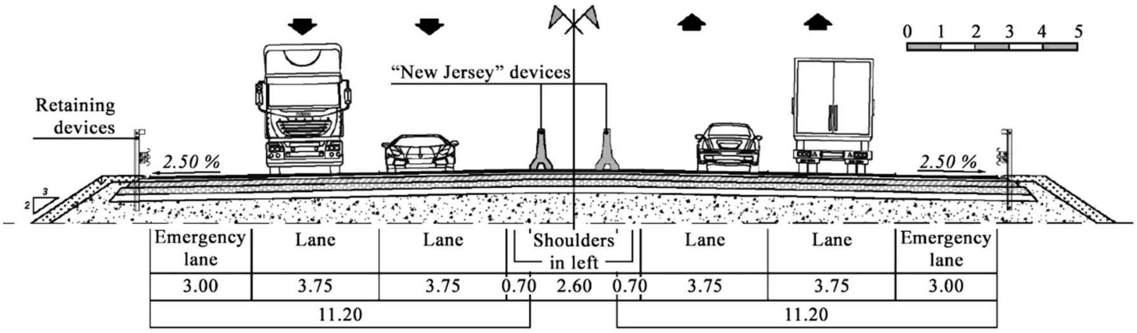

Figure 3. Scheduled maintenance activities during in-service life (20 years) for the Italian motorway A3 case study and pavement thickness description.

The semi-rigid pavement was designed using AASHTO method and it was composed by the materials and layers showed in Fig.4 (the porous asphalt was prepared with polymer-modified bitumen, whereas the asphalt concretes for binder and base courses contained traditional bitumen).

2.4 *Assumption and system boundary*

The evaluation was performed considering a motorway section length of 1000 m and comparing different scenarios: A) transport distance equal to 100 km and only virgin aggregates for construction, B) transport distance equal to 100 km and by-products reuse (steel slags and RAP) in partial substitution of virgin aggregates, C) transport distance equal to 10 km (materials available in situ) and only virgin aggregates, D) transport distance equal to 10 km (materials available in situ) and by-products reuse (steel slags and RAP) in partial substitution of virgin aggregates.

Subgrades, drainages, tack coat, road markings and other particular street furniture were not included in the evaluation.

Fig. 2 illustrated the system boundary. This system took into account different processes (both from internal and external), the inbound flows (natural resources, materials and energy) and the outbound flows (products, emissions and wastes). As example, the different machinery type, i.e. on-site construction equipment (e.g., asphalt paver) and off-site processing equipment (e.g., rock crusher), were considered from internal processes, whereas fuel and energy consumption or waste production were supposed from external processes. Differently, the feedstock energy was not examined.

The maintenance strategy is reported in Fig. 4 as found in the detailed project documents and assuming that maintenance activities will not be affected by the use of the recycled materials. The analysis period was set to 20 years after the initial construction. Every 5 years, the wearing course resurfacing (milling and laying new layer operation) was planned. Alternatively, the maintenance on the binder layer was designed after 10 years (milling and laying new asphalt operation), whereas after 20 years was scheduled a deep rehabilitation with total repaving operation (removing and reconstruction of the total pavement thickness).

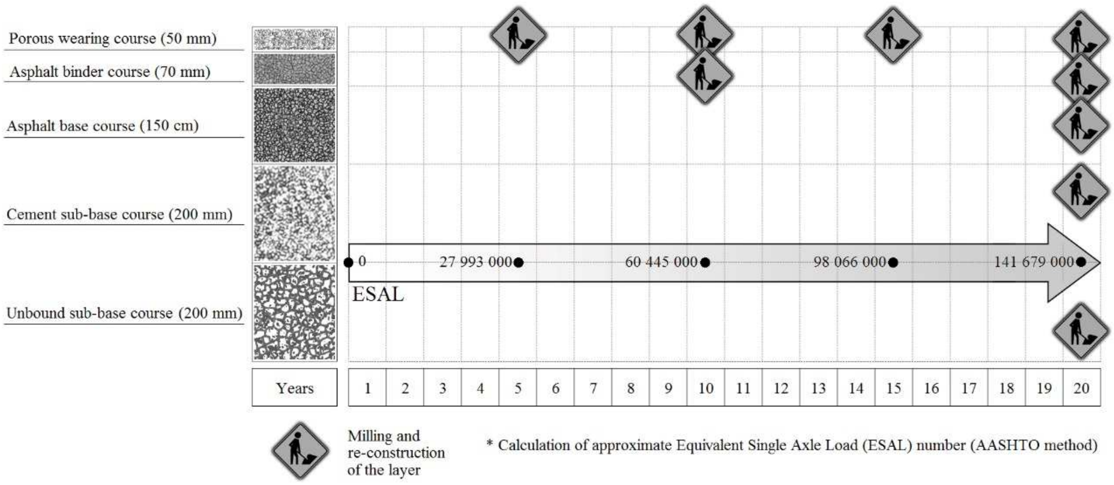

Figure 4. Scheduled maintenance activities during in-service life (20 years) for the Italian motorway A3 case study and pavement thickness description.

3 LIFE CYCLE INVENTORY

3.1 *Materials*

The materials utilized in the road construction must demonstrate adequate physical and mechanical properties, complying with prescribed range specifications. Therefore, typical Italian road materials with known characteristics were considered for the construction. The information included in the Life Cycle Inventory concerned virgin aggregates, bitumen, recycled materials (RAP) and industrial by-products (steel slags). Materials data and costs were recovered from quarry in the proximity of the construction site, asphalt concrete producers and typical Italian price list. Wearing course was composed by polymer modified porous asphalt mix, whereas traditional bituminous mixtures were taken into account for binder and base layers. Two type of mixes were used in subbase layer: the first one on the top, composed by cement bound granular mix, and the second on the bottom, composed by granular unbound mix. During binder layer maintenance phase (milling and reconstruction), 30 % of RAP coming from the milling of the same layer was used. RAP re-use was carried out with a hot in-place recycling method: RAP was sent in plant and mixed with virgin aggregates and bitumen.

3.2 *Consumption, transport and emissions*

The data of energy consumption, transport and emission are inserted in the data sheet of PaLATE tool, which contains machinery performance, fuel and energy consumptions (from manuals of construction machinery and producers), water use, truck capacities, material densities, emissions to air (from plant and machinery for transport or work), etc.

It was assumed that materials (virgin or recycled) and asphalt concrete transports, from extraction sites (quarries or stockpiles) or asphalt plants towards the construction site, were developed by road only. In this case, considering the distance from the sites and the production plants equal to 100 or 10 km (depending on the scenario), the total length (in kilometers) that had to be covered by different truck type and numbers of trips was calculated.

Emissions from paver machine was not taken into account according to other studies indicating their negligibility if compared with other impacts (Hanson et al. 2012, Giani et al. 2015).

3.3 *Cost analysis*

The prices of raw materials, related to the material production, construction and maintenance phases, were obtained from a typical Italian price list: aggregates (virgin or recycled), binders (bitumen or cement), construction and maintenance techniques (pavement laying, full depth reclamation, asphalt plant, etc.).

The discount rate to calculate the total actual cost of road infrastructure was set in two different ways: a rate equal to 1 % for the base scenario and one of 4 % for the alternative scenario (in order to consider a less favorable context). Discount rates were both referred to construction and maintenance costs.

Then, the total construction, maintenance and disposal costs for pavement (indicated in scenarios, for the two discount rates) were calculated including 23% of overall costs and company profit.

4 LIFE CYCLE IMPACT ASSESSMENT

4.1 *Environmental and costs evaluation*

The environmental impact for scenarios (A, B, C and D) is reported in Tab. 1 and Tab. 2.

The assessment was based on energy, water consumption (WC), carbon dioxide (CO_2), nitric oxide (NO_x), particulate matter (PM_{10}), carbon mono-oxide (CO), sulfur dioxide (SO_2), heavy metals (Pb and Hg), hazardous waste generated (HWG), human toxicity potential cancer (HTPC) and human toxicity potential non-cancer (HTPNC).

Fig. 5 and Fig. 6 show construction, maintenance and total costs for B, C and D scenarios, with discount rate of 1% or 4% comparing data with those of reference scenario A (Tab. 3).

4.2 *Results interpretation and discussion*

In general, it could be observed a typical decrease of different impact categories related to the substitution of virgin aggregates with recycled materials (see Tab. 1 and Tab. 2).

Otherwise, impact reductions found in this study were slightly lower with respect to other literature reporting because innovative production techniques of asphalt concrete, such as warm mix asphalt (Al-Qadi et al. 2015, Anthonissen et al. 2015, Pasetto et al. 2016), or in-place recycling practices, (Giani et al. 2015, Santos et al. 2015b) were not considered.

In this regard, in fact, many researcher authors demonstrated the strict correlation between parameter values and asphalt production technique (e.g. nitric oxide, according with Celauro et al. 2015).

Table 1. Environmental results from PaLATE tool for the four scenarios proposed.

Scenario	Energy [MJ]	WC [kg]	CO$_2$ [Mg]	NO$_x$ [kg]	PM$_{10}$ [kg]	SO$_2$ [kg]
A						
MP*	824,766,458	275,762	45,118	289,093	170,190	6,293,294
MT**	43,568,017	7,421	3,257	173,527	33,560	10,412
P***	3,904,838	367	29	6,750	710	446
Total	872,239,312	283,550	8,670	469,370	204,460	6,304,152
B						
MP*	784,998,830	261,100	42,465	277,573	155,479	6,283,626
MT**	46,761,742	7,965	3,496	186,248	35,857	11,175
P***	3,904,838	367	294	6,750	710	446
Total	835,665,409	269,432	46,255	470,570	192,046	6,295,247
C						
MP*	824,766,458	275,762	45,118	289,093	170,190	6,293,294
MT**	4,451,723	758	333	17,731	3,574	1,064
P***	3,904,838	367	294	6,750	710	446
Total	833,123,018	276,887	45,745	313,573	174,474	6,294,804
D						
MP*	781,227,517	261,100	42,564	280,836	155,510	6,544,939
MT**	4,006,379	734	322	17,152	3,400	1,029
P***	3,904,838	367	294	6,750	710	446
Total	789,138,734	262,200	43,180	304,737	159,620	6,546,414

*MP = materials production. **MT = materials transportation. ***P = processes (equipment).

Table 2. Environmental results from PaLATE tool for the four scenarios proposed.

Scenario	CO [kg]	Hg [g]	Pb [g]	HWG[kg]	HTPC	HTPNC
A						
MP*	159,794	1,065	53,168	10,596,575	174,183,222	150,792,239,042
MT**	14,461	32	1,478	314,074	1,569,208	1,954,641,048
P***	1,455	2	82	17,540	0	0
Total	175,710	1,099	54,728	10,928,190	175,752,430	152,746,880,089
B						
MP*	151,244	1,010	50,364	10,037,005	165,784,422	138,441,537,092
MT**	15,521	34	1,586	337,097	1,677,640	2,089,706,829
P***	1,455	2	82	17,540	0	0
Total	168,219	1,046	52,031	10,391,642	167,462,062	140,531,243,921
C						
MP*	159,794	1,065	53,168	10,596,575	174,183,222	150,792,239,042
MT**	1,478	3	151	32,092	241,144	300,374,143
P***	1,455	2	82	17,540	0	0
Total	162,727	1,070	53,401	10,646,207	174,424,366	152,092,613,184
D						
MP*	151,338	1,011	50,372	10,038,761	166,126,114	139,049,945,940
MT**	1,429	3	146	31,044	236,209	294,227,423
P***	1,484	2	84	18,109	0	0
Total	154,251	1,016	50,602	10,087,914	166,362,324	139,344,173,364

*MP = materials production. **MT = materials transportation. ***P = processes (equipment).

Construction and maintenance materials contribute to the greatest percentage of impacts (contribution by the materials phase varies with the type of pavement); however, the processes and equipment related to construction and maintenance phases constitute the smallest amounts (Al-Qadi et al. 2015). In general, materials production (bitumen, cement and mixtures) owns a marginal weight in life cycle of road pavement with respect to the transport processes (Anthonissen et al. 2015, Huang et al. 2009), which give a contribution about of the 20% of total impact. As far as the materials use concerns, the initial construction impact ranges from 20% to 25%, the maintenance impact varies from 75% to 70% and the end-of-life impact is around 5 %, according to literature (Anthonissen et al. 2015).

Table 3. Scenario A costs with discount rate of 1% and 4%.

Scenario	Costs [Euro]
Base (1%)	
Initial construction	21,511,453
Maintenance	19,599,351
Total	41,110,805
Alternative (4%)	
Initial construction	21,511,453
Maintenance	13,488,463
Total	34,999,917

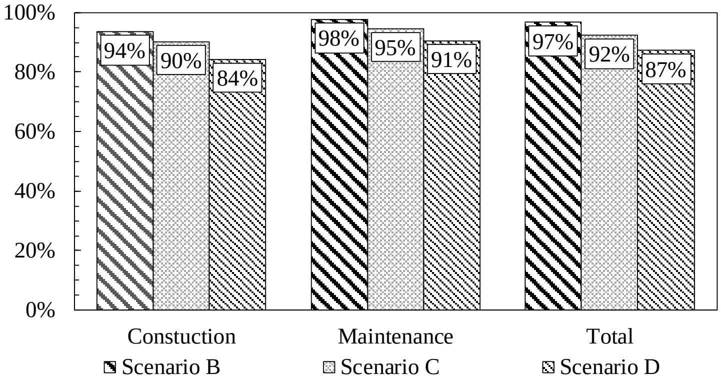

Figure 5. Costs of B, C and D scenarios compared to A scenario with discount rate of 1% (base scenario).

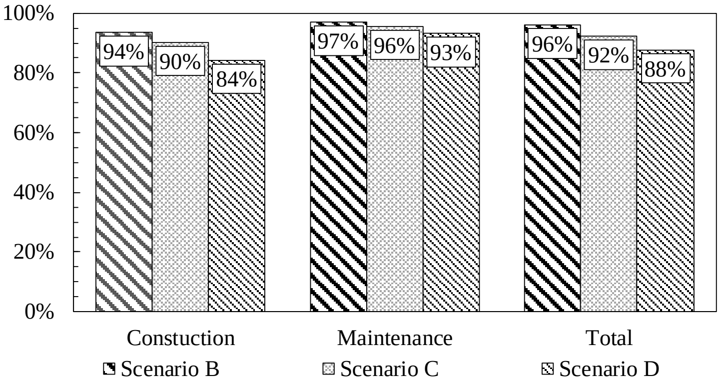

Figure 6. Costs of B, C and D scenarios compared to A scenario with discount rate of 4% (alternative scenario).

Especially during maintenance, RAP replacement (rejuvenated with the additive) reduces total energy consumption and environmental impact, requiring less virgin bitumen and allowing less landfilling material. Moreover, mechanical characteristics and durability of RAP mixtures are comparable with those of traditional ones, i.e. prepared with virgin aggregates.

Also by-products reuse (e.g. steel slags) prevents from conferring in dump, thus promoting environment protection (Mladenovic et al. 2015, Ferreira et al. 2016).

Otherwise, it has to be noticed that the higher specific gravity of steel slags burdens on the transportation costs; basing on this consideration, this project implied only the use 30% of slags by the total aggregate weight (to prevent the increasing of total impact). On the other hand, steel slags demonstrated excellent mechanical properties (which makes them suitable to be used as aggregate in asphalt pavement, for many traffic typologies), also improving skid resistance. Moreover, requested energy consumption for steel slags asphalt mixture production could be considered almost the same of that needed in the case of traditional mixes (with virgin aggregates only), even if slightly higher bitumen content, connected to steel slag surface porosity could be recommended (Pasetto & Baldo).

During construction phase, material costs are greater with respect to the equipment and worker ones. Vice versa, during maintenance phase, equipment and worker costs prevail.

Costs related to the marginal material rehabilitation operations were slightly lower with respect to those involving the virgin aggregate supply; thus B, C and D scenarios requested lightly reduced investments (in comparison with A scenario). Since A and C scenarios implicated the use of natural aggregates only, costs were higher because of the onerous activities connected to waste materials disposal towards landfills. Conversely, these items were not significant in B and D scenarios (where recycled material reutilization was planned). Figs. 5 and 6 do not clearly represent the differences between discount rates of 1% and 4 %: in this sense, it is worth noting that a light decrease in maintenance costs (thus in total investments) with the highest discount rate can be detected.

5 CONCLUSIONS

The LCA seemed to be a useful tool to check the availability of projects, and, in general, a successful way to support decision-making processes considering environmental impact assessment and costs evaluation.

The specific case study proposed in the paper evaluated four scenarios (A, B, C and D) for a motorway section 1000 m long over a maintenance period of 20 years utilizing a specific software tool (PaLATE). Initial construction, maintenance, service life and end-of-life phases, as well as material transportation distances and modes were taken into account.

Different scenarios showed that the transport distance and the substitution of virgin aggregates with recycled materials (RAP or steel slags), played a key role in costs and environment impacts. Since the consumption of natural materials (bitumen and aggregates) represented another important factor for the impact assessment, recycling practices resulted in a suitable activity to promote resources preservation due to reduced needs of waste disposal.

In conclusion, an advanced LCA analysis, performed during the designing phases of road infrastructures, is definitely able to objectively and univocally state the best design and construction alternative, evaluating different costs and determining the most (social and environmental) sustainable constructive and maintenance technologies for the correct integration of the work.

However, performed LCA represents a first-step general analysis, thus further evaluations considering supplementary variables could be promoted.

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