Comparative life cycle assessment of asphalt pavements using reclaimed asphalt, warm mix technology and cold in-place recycling

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1. Introduction

Large quantity of aggregates and asphalt are produced all over the world to fulfill the material requirements for the construc-tion of the roads: about 400 million tons of asphalt are produced annually in Europe (EAPA and NAPA, 2011) while about 5.2 million kilometers of roads are covered with asphalt.

Today, public agencies and asphalt producers responsible for roads are experiencing limited available funds together with signif-icant increases in the price of construction operations and asphalt binder. Those concerns are coupled with significant pressure to build, maintain, and rehabilitate in a sustainable way and agencies must look for alternative construction and maintenance methods as well as alternative materials.

New techniques are being developed to make production processes more efficient with less consumption of energy: these aspects can lead to both environmental and economic advantages. These practices include:

- WMA (Warm Mix Asphalt) is the name given to a variety of technologies that allow producing asphalt mixtures at lower temperatures (lower temperatures means in general lower than 140 °C) at which the material is mixed, compacted, and placed on the roadways. EAPA has stated that WMA is generally pro-duced in a temperature range from 100 to 140 °C, while HWMA (Half-Warm Mix Asphalt) is fabricated between 70 and 100 °C (EAPA, 2010). Standard HMA (Hot Mix Asphalt) is produced at about 160 °C instead. Benefits of WMA are reported in literature (Rubio et al., 2012) and include: lower plant emissions, reduced energy consumption, increased RAP content, and paving benefits among which improved workability and compaction efficiency together with quicker turnover to traffic due to shorter cooling time. Moreover, it is reported that lowering production temper-atures allows to reduce energy consumption up to 35% or more (D'Angelo et al., 2008).
- The use of RAP (Reclaimed Asphalt Pavement, generated from milling operations of existing flexible pavements) is another material-related technology that reduces asphalt binder and aggregate demand, thus saving natural resources. Several studies show that if asphalt recycling is performed properly, hot mix asphalt containing RAP has the same qualities as asphalt produced from virgin material (Miliutenko et al., 2013).
- Incorporation of recycled materials and by-products (Chiu et al., 2008; Huang et al., 2009; Jullien et al., 2006; Sayagh et al., 2010) that can contribute both to reducing wastes and preserving natural resources.

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Glossary

CED	Cumulative Energy Demand
CIR	Cold In-Place Recycling
DALY	Disability-Adjusted Life Years
EAPA	European Asphalt Pavement Association
FU	Functional Unit
GGP	Greenhouse Gas Protocol
HMA	Hot Mix Asphalt
LCA	Life Cycle Assessment
NAPA	National Asphalt Pavement Association
PAHs	Polycyclic aromatic hydrocarbons
PM	Particulate Matter
RAP	Reclaimed Asphalt Pavement
TOC	Total Organic Carbon
U.S. EPA	United States Environmental Protection Agency
VOCs	Volatile Organic Compounds
NMVOC	Non-Methane Volatile Organic Compounds
WMA	Warm Mix Asphalt

- Different maintenance strategies that can be applied to ensure pavement quality after its useful life, among these Cold-In-Place Recycling (CIR) is a technique that can lead to less environmental impacts compared with other rehabilitation techniques (Miller and Bahia, 2009; Thenoux et al., 2007). CIR consists of pulverization of the asphalt layer, addition of a stabilizer (foamed bitumen or asphalt emulsion), mixing of stabilizer and pulverized material, laydown with a recycling machine and compaction. The advantage of this technology is that recycling occurs at the roadway being rehabilitated, thus reducing the amount of material that must be hauled to the job site. Natural resources such as asphalt binder and aggregates are conserved as a result. In particular, foamed bitumen, which is considered in the present case-study, is produced by mixing a low amount of cold water with a mass of hot bitumen (160–180 °C). Once the pavement is recycled and compacted, a thin HMA layer is placed over the recycled layer.

Several researchers have studied the effects on the environment due to construction, maintenance and disposal of pavements (Stripple, 2001; Birgisdottir et al., 2007; Huang et al., 2009; Santero et al., 2011a,b; Muench, 2010) and the application of new techniques described above. These studies apply Life Cycle Assessment (LCA) that is a popular methodology in different fields of research, since it investigates environmental aspects of a product, a service, a process or an activity by identifying and quantifying the related input and output flows utilized by the system and its deliv-ered functional output in a life cycle perspective (Baumann and Tillmann, 2004). LCA studies include all the processes associ-ated with a product from its 'cradle-raw material extraction' to its 'grave-disposal'. The concept and working phases of LCA are described in the ISO 14040 series on LCA, that were released by International Organisation for Standardization (ISO) in late 1990s and 2000s. Life cycle assessment is being accepted and applied by the road industry, to measure and compare the key life-time environmental impacts of asphalt products and laying processes.

In 2001 the Swedish Environmental Research Institute published a report in which a comprehensive inventory analysis was done based on a 40-year life cycle (Stripple, 2001). Energy consumed during the construction phase is approximately 35% of the total energy consumption. Consumption for lighting and traffic con-trol is more than half of the total consumption during operation phase. In maintenance phase, energy consumption is less than 13%of the total.

Park et al. (2003) reported that the most energy intensive process occurring in a road life cycle is manufacturing of construction materials. The authors stated that construction and demolition consume more energy than maintenance/repair. This conclusion, however, is probably a result from assuming a relatively low number of maintenance cycles (Park et al., 2003).

Several LCA studies of road pavements have been focused on comparing asphalt and concrete pavements (Santero et al., 2011a,b). Results indicate that asphalt pavements imply a smaller use of energy (if the inherent energy in asphalt is not considered) – energy consumption increases to 27 TJ/km by using concrete pavement instead of asphalt (Stripple, 2001) – and lower emissions than concrete pavements. A recent study (Anastasiou et al., 2015) regarding LCA of concrete pavement construction considers the use of industrial by-products such as fly ash and steel slag as alternative aggregates, and show that a high rate of cement clinker substitution can contribute significantly to reduce environmental impacts.

Miliutenko et al. (2013) showed that hot-in-place asphalt recycling is more beneficial than hot-in-plant recycling, but do not report any combination of cold and warm techniques with CIR. Cross et al. (2011) reported that cold in-place recycling reduce energy and greenhouse gas emissions compared to other rehabilitation techniques (above all mill and fill the pavement with HMA overlay). Moreover, some studies focalize only on energy consump-tion while do not consider other impact categories: it is reported in literature that recycling with foamed bitumen can lead up to a reduction of 20–50% of the energy consumption (Thenoux et al., 2007).

A notable fact is that impacts of the traffic component are considered to be more environmentally significant than construction, operation and maintenance of the road lifetime (Stripple, 2001; Yu and Lu, 2012; Vidal et al., 2013). Several studies have shown that, including use phase (impacts from vehicles travelling on the road) in a life cycle study, impacts occurring from other phases of life cycle would be negligible, because of much higher impacts from traffic within all the life cycle. In detail, Stripple estimated that energy expended in initial construction is roughly equivalent to the energy used by traffic on the facility for 1 or 2 years depending on the specific case study.

How it can be noticed from the discussion above, it results difficult to compare the different studies regarding LCA of pavements since none of the existing LCAs include all phases of the lifecycle, different functional units are used and different assumptions are made (Santero et al., 2011a,b; Muench, 2010). Moreover, the environmental performance of asphalt pavements is very sensitive to transportation distances, hence the comparisons that can be done are very site specific (Miliutenko et al., 2013).

In the present case study use of RAP, WMA technology and CIR is combined in order to assess what can be the advantages in terms of impacts on the environment. According to the annual report Asphalt in figures (EAPA, 2014) the total production of HMA and WMA in Italy in 2013 reaches 22.3 million tons while the available reclaimed asphalt consist of 10 million tons, 20% of which is used in hot and warm recycling. Comparing asphalt pavements consider-ing different percentages of RAP, different production temperatures and the use of CIR is a relatively new study among the pavement LCA literature. The present study is site-specific; therefore, it can be compared with LCAs studies that consider the use of WMA, RAP and CIR technology separately.

2. Methodology (LCA framework)

The life cycle assessment methodology observes and analyzes a product or service over its entire life cycle in order to determine its environmental impacts (ISO, 2006a,b). The LCA studies are carried out in the following steps:

- Definition of the scope of the study according to the aspired goals. This phase includes the description of road pavements to be analyzed (functional unit and physical dimensions), the identification of processes occurring in life cycle phases analyzed and the definition of the analysis period.
- Quantification of inputs and outputs (energy, materials, emissions, etc.) for all analyzed processes (Life Cycle Inventory, LCI).
- Assessment of determined inputs and outputs according to the selected environmental indicators chosen (Life Cycle Impact Assessment, LCIA).
- Discussion and interpretation of results.

In detail the stage of impact assessment translates inventory data in potential environmental impacts. To this end, the impact categories under study must be defined, the inventory data must be sorted according to the type of environmental impact they contribute to (classification) and the relative contributions to each type of environmental impact are calculated according to the predefined assessment methods (characterization). Impact assessment may also include other additional steps (normalization, grouping and weighting) to facilitate the interpretation phase; however, these steps are not mandatory according to ISO standards and may also introduce additional uncertainties in the study.

In this case the software used to conduct the analysis is SimaPro 7.3 (PRé Consultants, 2010) and in the LCIA phase two different approaches are considered:

(a). Partition according to the European Standard EN 15804 (EPD: Environmental Product Declaration): *Product stage* (includes raw materials extraction and processing, transports to the plant and asphalt production), *Construction process* (includes transports from the plant to the yard and road construction), *Use and maintenance* (includes production and all activities necessary to repave the wearing courses during the maintenance cycle) and *End of life* (includes pavement milling and transport of RAP to be recycled to the plant)

(b). Partition that does not consider the temporality of the different phases: *Raw materials extraction and processing*, *Consumptions of the plant*, *Yard operations* and *Transports*. This partition can lead to a more comprehensible origin of the impacts.

Whatever the distribution of impacts, indirect upstream processes (such as electricity generation and fuel production) are included in all the phases of this LCA study.

2.1. Goal and scope

This work is a site-specific and process based LCA carried out in collaboration with Impresa Bacchi S.r.l., a mid-size Italian asphalt-producing company, and it is finalized in quantifying the environmental savings producing asphalt pavements with a major percentage of RAP and using WMA. Furthermore, this study is aimed to find out how much the rehabilitation of the base layer through CIR technology can reduce energy consumption and emissions generation and conserve natural resources (aggregate and asphalt binder). The analyzed innovative options are compared to the virgin asphalt layers (referred as 'conventional proposal') of the same size and function: this is a comparative LCA study. LCA is made according to ISO 14040 series (ISO, 2006a,b). In order to reach these goals, all processes needed to construct and maintain a typi-cal asphalt road pavement in Italy are analyzed in this study. These processes are shown in Fig. 1: material production, pavement construction, pavement maintenance, deconstruction and recycling are considered.

2.2. Functional unit and system boundaries

The functional unit (FU) is a measure of the performance of the analyzed product system and it is a reference to which all inputs and outputs are related. For road pavements, physical dimension and pavement performance describe the functional unit: in the present case study it is defined as 1 km of suburban road (4 lanes) composed of two independent roadways each with 2 lanes in each direction separated by a traffic island. The width of the pavement is 15 m and the total depth is 25 cm. Average lifetime of road pavements (which includes all processes showed before) is difficult to determine due to the fact that road infrastructure is maintained frequently to ensure an adequate level of service. In a first analysis, lifetime was set to 15 years (which is an average lifetime according to the company experience). At a later time, it was extended to 30 years in order to figure out the effect of Cold In-Place Recycling of the base layer, needed to maintain the pavement after its first life.

Maintenance strategies were chosen based on expert opinions. Every 5 years maintenance of the surface course is expected: it consists of milling and reconstruction of the upper layer of the pavement. The replacement of the base layer is expected after 15 years and it can be done ex-situ or in-situ. These options are analyzed only for RP3, which is the most environmentally sustainable option analyzed, as the results presented below will show. A flowchart of the unit processes in the asphalt pavement construction is illustrated in Fig. 2 in which system boundaries are detailed.

As presented in Fig. 2, production of bituminous emulsion is not included in this study, due to unavailable data: in any case, impacts from this process were estimated to be the same for all the pavements analyzed, therefore this process is not considered to avoid adding uncertainties to the inventory. Also the waste management process is not considered due to the fact that quantity of waste produced during the pavement lifecycle is very scarce (about 880 kg/year of bag filters and 2 kg/year of containers for lubricating oils).

2.3. Data source, quality and allocation

Data needed for this LCA study are obtained primarily from materials suppliers and contractors: all data regarding the core process (production of asphalt in plant) are primary data coming especially from Impresa Bacchi S.r.l. Missing data, regarding the upstream processes, are taken from Ecoinvent database and literature; in detail, for electricity used at the plant the Italian mix is selected, while European processes are considered for transports and production of fuels.

A problem that arises in the LCI phase is related to the fact that the company plant produces asphalt and other materials, such as concrete mixes for the sub base of pavements that are not taken into account in this study; therefore, the fluxes entering the systems have to be allocated between the various products. This problem is called 'problem of allocation' and it is defined as the partition of inputs and outputs of a process or a system between the ana-lyzed system and one or more external systems. ISO standards (ISO, 2006b) indicate that allocation should be avoided by dividing the unit process in sub-processes or by the system's expansion that means including also the additional functions related to the co-products. System expansion means that the industrial system is credited with the environmental load from the production that is avoided. If allocation cannot be avoided, the impacts should be allocated between the various co-products following a physical relation

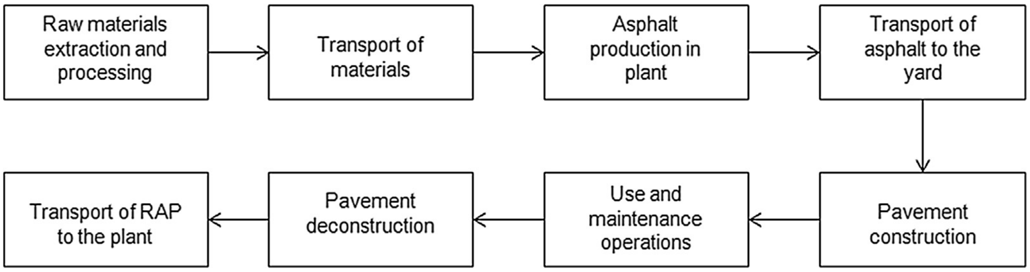

Fig. 1. Processes included in the study.

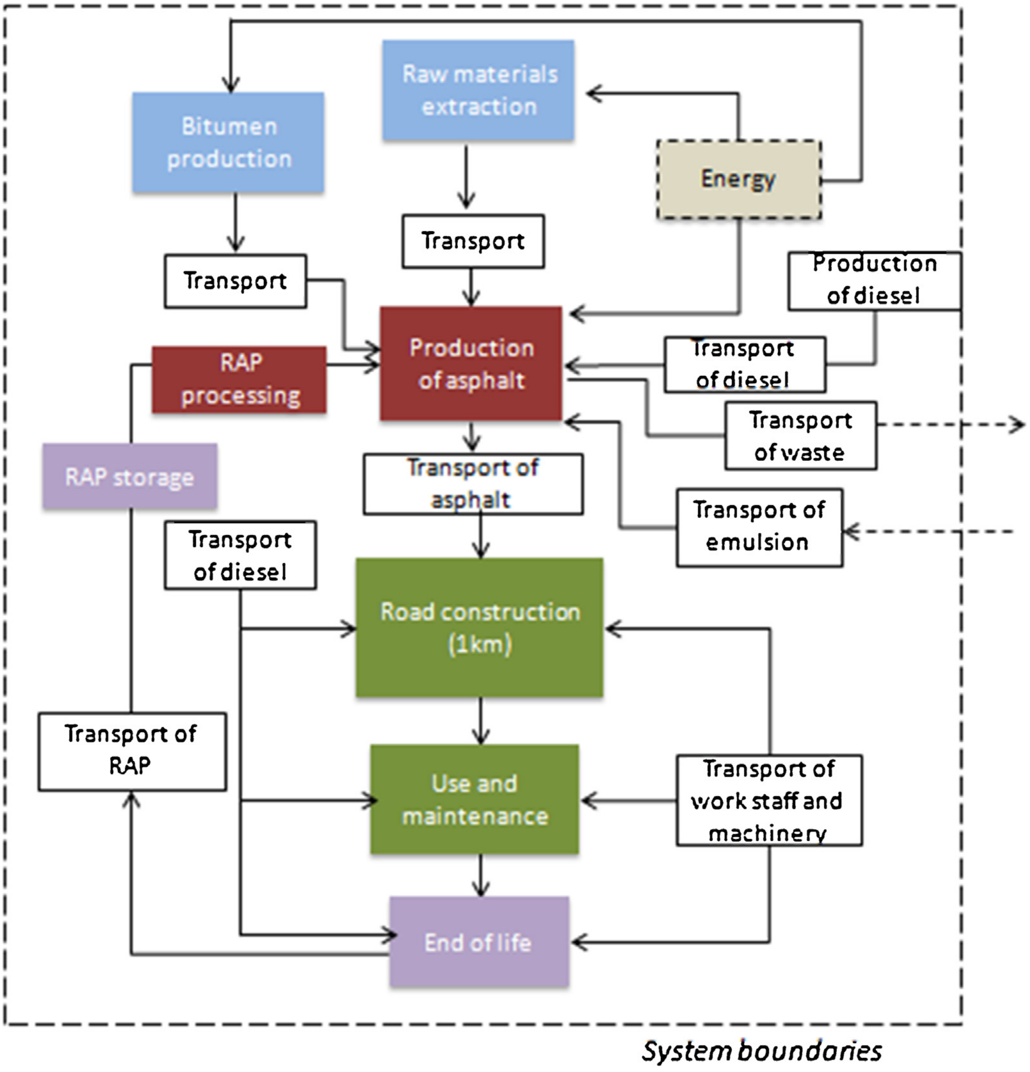

Fig. 2. System boundaries.

or an economic relation. In this case allocation between co-products is necessary for electricity, natural gas and water used in the plant; it is made by economic value according to the standards (ISO 14044: 2006, EN 15804: 2012).

2.4. *End of life*

To model the end-of-life of the pavement, it is assumed that all the materials of the pavement can be recycled and all the recycling processes and transport processes to the plant are attributed to Impresa Bacchi S.r.l. Because all the RAP is transported back to the plant and it will be used for other purposes (concrete granulates or asphalt granulates). As presented in literature (Huang et al., 2013), LCA studies of road pavement tend to take the ‘cutoff’ method: each product is assigned only the burdens directly associated with it. In other words, all benefits of recycling are given downstream to using the recycled material, with no indication of the actual rate of, or potential for, recycling. This approach is also known as the ‘recycled content’ method (Hammond and Jones, 2010), prescribed by PAS 2050 as in Eq. (1)

$$\text{Emission/unit} = (1 - R_1) \times E_V + (R_1 \times E_R) + (1 - R_2) \times E_D \qquad (1)$$

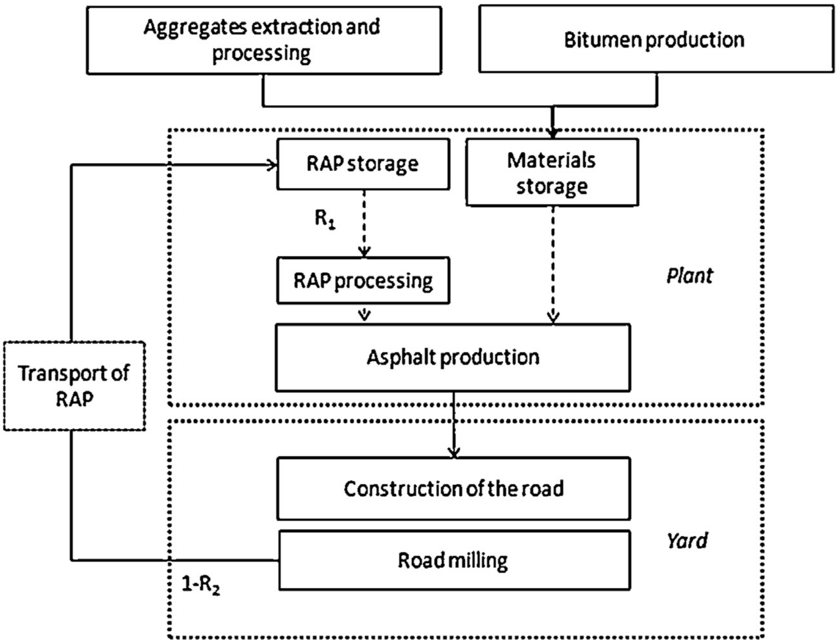

Fig. 3. End-of-life modeling of the pavement.

where (Fig. 3),

- R_1 = proportion of recycled material input, depending on the selected asphalt recipe (10%, 20% or 30%);
- R_2 = proportion of material that is recycled at end of life. In this case $R_2 = 0$;
- E_V = emissions arising from virgin material input, per unit of material;
- E_R = emissions arising from recycled material input, per unit of material;
- E_D = emissions arising from disposal of waste material, per unit of material.

2.5. Impact assessment methods

The lifecycle of a pavement involves environmental impacts both in terms of local and regional (soil consumption, toxicity, acidification, and eutrophication) and in global terms (resources consumption, emissions of GHG, and ozone depletion), for this reason environmental impacts are assessed using 4 different meth-ods (Greenhouse Gas Protocol, ReCiPe 2008, Cumulative Energy Demand and Selected LCI results, and Additional: water consump-tion).

The GGP method is chosen to perform a Carbon Footprint of the different alternatives analyzed. This method leads to measure the amount of greenhouse gases (in kg CO_{2eq}) emitted in the atmosphere and contributing to global climate change and includes emissions from fossil and biogenic carbon sources, emissions caused by land use change and carbon uptake by plants over a 100-year time horizon. To calculate carbon dioxide equivalents (CO_{2eq}) of all non-CO_2 gases (CH_4, N_2O, SF_6, HFCs and CFCs) the 100-year IPCC global warming potentials (GWP) are used in (IPCC, 2007). The 100-year GWP is a metric used to describe the time-integrated radiative characteristics of well mixed greenhouse gases over a 100-year time horizon.

Carbon Footprint by itself cannot justify environmental sustainability; therefore, it is necessary to investigate a larger number of impact categories by assessing the impact with ReCiPe 2008 method (Goedkoop et al., 2009). This method allows both midpoint and endpoint assessments. Eighteen impact categories can be assessed at the midpoint level; these are then converted and aggre-gated into three endpoint categories: damage to human health, damage to ecosystem diversity and damage to resource availability. Three weighing sets can be used to evaluate cultural perspective: 'hierarchist', 'egalitarian' and 'individualist'. In this work we use the hierarchic weighting set both for midpoint and endpoint impacts, this set is considered the most balanced among the three. ReCiPe also allows normalization, grouping and weighting of the impacts. All midpoint impacts are normalized in this study according to the normalization factor for Europe in year 2000: these factors express the annual impact score of an average European citizen for every midpoint impact category, so the impacts calculated represent the magnitude of each midpoint impact relative to the annual impacts of an average European citizen. Aggregated environmental impacts are measured in 'points' (Pt), which are dimensionless figures.

The Cumulative Energy Demand (CED) (Frischknecht et al., 2007) is assessed in order to ease energy comparisons and it is chosen since energy consumption is the most popular metric evaluated in existing pavement LCAs (Santero et al., 2011a,b). This method represents a measure (expressed in megajoules) of direct and indirect energy use over the entire life cycle of a product; it accounts for energy produced from non-renewable sources (fossil, nuclear, and non-renewable biomass) and renewable sources (wind, solar, geothermic, hydro, and renewable biomass).

Finally, water use (expressed in m^3) is evaluated through the method Selected LCI results, additional (Frischknecht et al., 2007). The selected life cycle inventory indicators are, in most cases, the summation of selected substances emitted to all different sub-compartments; in this study we are interested in water use during the lifecycle, then we have considered only the category 'water consumption').

3. Case study—life cycle inventory

The asphalt pavement design considered is defined by experts of Impresa Bacchi S.r.l. and refers to suburban roads (4 lanes). In detail a suburban road is composed of two independent roadways each

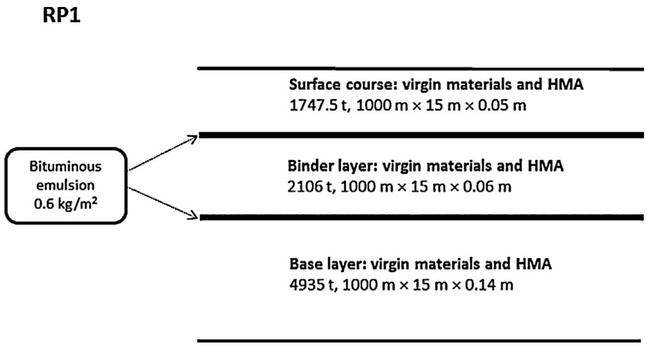

Fig. 4. Road Pavement 1.

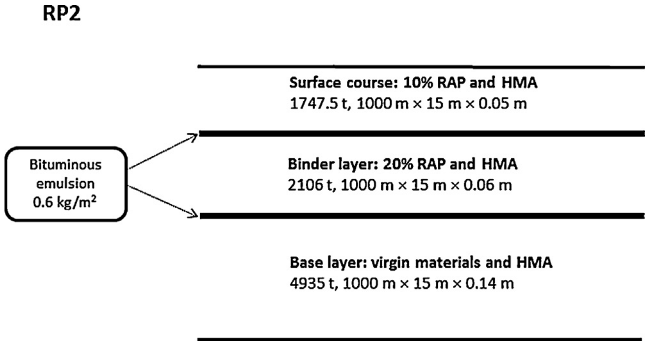

Fig. 5. Road Pavement 2.

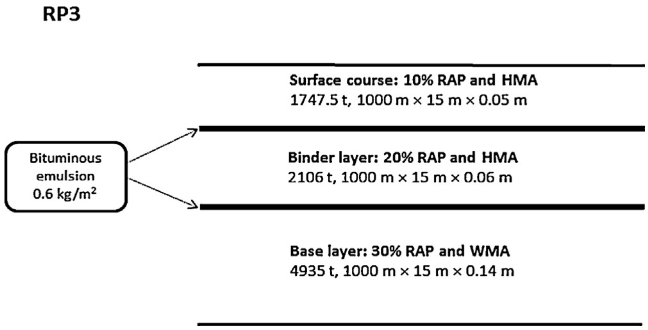

Fig. 6. Road Pavement 3.

with 2 lanes in each direction separated by a traffic island. The width of the pavement is 15 m and the total depth is 25 cm. The three different sections of the pavement (surface course, binder course and base) are studied so that they have the same Structural Number (SN) that is a synthetic value of the useful lifetime of the pavement for the same boundary conditions, with particular reference to the loads to which it is subjected. The amount of material for each layer is determined considering a 1 km long stretch of road, composed of only the parts normally transited (two lanes in each direction). The docks and the area of the lateral divider are not considered for simplicity of calculation and since they are less subjected to the action of loads.

Also subgrades, embankments, drainages and road marking are not included in the analysis: these aspects are also excluded in previous pavement LCA studies reported in literature (Santero et al., 2011a,b).

Table 2
Additional materials for CIR (unit: ton).

Material	RP3—CIR
Bitumen 70/100	197.4
Water	4.9

3.1. *Raw materials and RAP*

The materials for the road construction are aggregates and bitumen: no additive's usage is reported in this case study, only bituminous emulsion that consists of about 45% of water and 55% of bitumen (with very small quantity of soaps). RAP is used instead of virgin aggregates and bitumen when asphalt is recycled; the percentage of RAP varies between 10% and 30% because excessively high percentages of RAP would diminish the quality of the pavement. In literature it is reported that RAP generally do not exceed 50% (EAPA and NAPA, 2011). In collaboration with Impresa Bacchi S.r.l. three variants of road packages are considered. Pavement dimension, asphalt recipe and materials tonnage for the three analyzed options (called RP1, RP2, and RP3 where RP stand for Road Pavement) are showed in Figs. 4–6.

RP1 is set as the baseline and, as mentioned before, every variant has the same structural characteristics so the options analyzed have the same performance. The layers investigated and the materials used in each layer are reported in Table 1.

The coarse fraction of RAP is used for binder layer and base layer, while it is not used for the surface course because this layer requires finer aggregates than the lowest layers. In the case of CIR applica-tion, additional bitumen and water are necessary: 3–4% of bitumen referred to the weight of base layer and 1.5–3.5% of water referred to the weight of bitumen (Table 2).

In the present case study feedstock energy of bitumen is included in terms of energy embedded in crude oil (45.8 MJ/kg): this data is taken from the Ecoinvent 2.2 process "Bitumen at refinery RER/U" and is greater than the specific energy content of bitumen of 40.2 MJ/kg as reported in literature (Garg et al., 2006; Butt et al., 2014). Only few pavements' LCA account for the feedstock energy (Santero et al., 2011a,b) although ISO 14044 standard defines that chemical energy needs to be included in any energy assessment. Feedstock energy of bitumen is approximately 7 times the process energy of the refinery, therefore it is significant enough to alter the results of the assessment. The range of bitumen production energy is between 0.4 and 6 MJ/kg in the pavement life cycle analysis lit-erature (Santero et al., 2010; Zapata and Gambatese, 2005), while in the present case study it results approximately 2.7 MJ/kg.

Table 1
Materials used for each layer (unit: ton).

Material	Surface virgin materials HMA	Surface 10% RAP HMA	Binder virgin materials HMA	Binder 20% RAP HMA	Base virgin materials HMA	Base virgin materials WMA	Base 30% RAP WMA
Sand	295.3	284.8	511.8	417.0	1993.7	1993.7	1919.7
Limestone	99.6	83.9	40.0	40.0	187.5	187.5	0.0
Gravel	1263.4	1123.6	1457.4	1173.0	2546.5	2546.5	1431.2
Bitumen 70/100	89.1	83.9	96.9	80.0	207.3	207.3	153.0
RAP 0/15	–	171.3	–	–	–	–	–
RAP 0/25	–	–	–	395.9	–	–	1431.2

Table 3
Consumption of electricity (kWh/t), natural gas (Nm^3/t) and water (m^3/t) of the plant during the production of asphalt, divided by material and process.

Consumption per 1 ton of asphalt	Virgin HMA	HMA with RAP	Virgin WMA	WMA with RAP
Electricity (kWh/t)	8.70	8.39	8.12	8.39
Natural gas (Nm^3/t)	8.01	8.01	3.49	3.49
Water (m^3/t)	0.0067	0.0067	0.0085	0.0085

Table 4
Consumption of electricity (kWh/km), natural gas (Nm^3/km) and water (m^3/km) for asphalt production during the lifecycle.

Consumption per 1 km of pavement	Layer	Virgin HMA	HMA with RAP	Virgin WMA	WMA with RAP
Electricity (kWh/km)	Surface course	16,162.6	15,620.9	–	–
	Binder course	19,478.4	18,825.5	–	–
	Base	45,643.8	–	42,781.5	42,781.5
Natural gas (Nm^3/km)	Surface course	14,086.6	14,086.6	6187.9	6187.9
	Binder course	16,976.5	16,976.5	7457.3	7457.3
	Base	39,781.0	39,781.0	17,474.8	17,474.8
Water (m^3/km)	Surface course	104.3	104.3	107.5	107.5
	Binder course	125.7	129.5	125.7	129.5
	Base	294.6	294.6	303.5	303.5

3.2. Energy consumption and water use

Machinery performance, diesel consumption, natural gas consumption, and electricity consumption are obtained from manuals of construction machinery and jobsite data. The following consumptions are calculated:

3.2.1. Consumption of the asphalt plant

During asphalt production electricity (kWh) is needed to run the whole plant while natural gas is necessary to heat the aggregates in the drum dryer, data are presented in Tables 3 and 4. As shown in Table 3, WMA production can lead to more than 50% less of natural gas consumption. Consumption of the wheel loader and the vibrating screen (used for RAP) must be taken into account and they are shown in Table 5.

3.2.2. Consumption of the construction machinery

Diesel consumption of machinery used to place and compact asphalt layers are calculated: this is done also for the demolition process and the recycled base construction. Fuel consumption of construction vehicles is reported in Table 6: according to the capacity and performance of different equipment used for placing and compacting a cubic meter of granular material, fuel consumption is calculated.

3.3. Transports

Consumption associated with haulage in each process is a function of the transported volume, truck capacities and distance to the construction site. The methodology used is as follows:

- Calculate the weight of materials (aggregates, machinery, etc.) to be transported to the plant or to the yard.

Table 5
Consumption of the wheel loader and the vibrating screen.

Machinery	Unit	Surface virgin materials HMA	Surface 10% RAP HMA	Binder virgin materials HMA	Binder 20% RAP HMA	Base virgin materials HMA	Base virgin materials WMA	Base 30% RAP WMA
Vibrating screen	kWh/km	–	372.7	–	465.8		–	1683.6
Wheel loader	l/km[a]	138.5	140.4	175.0	176.5	403.5	403.5	424.9

[a] The fuel used is diesel.

Table 6
Machinery parameters (paving, demolition and in-situ recycling).

Equipment used	Model machine	Layer	Effective capacity (m^2/h)	Performance (l/h)	Paving time (efficiency) (h)	Fuel consumption (l/km)
Finisher (paver)[a]	VOGELE 1900-2	Surface course	1144.5	23.2	13.1	304.1
		Binder course	1028.8	23.2	14.6	338.3
		Base	540.4	23.2	27.8	644.0
Emulsion applier[b]			80E+03	8.3	0.19	1.6
Roller[a]	Bomag BW 154 AP-4	Surface course	1144.5	16.3	13.1	213.6
	Bomag BW 161 AC-4	Binder course	1028.8	18.8	14.6	233.0
	Bomag BW 190 AD-4	Base	540.4	21.2	27.8	500.2
Milling machine	WIRTGEN W210 671 HP S/N	Surface course	1545.1	99.8	9.7	968.9
		Binder course	1282.1	99.8	11.7	1167.7
		Base	410.3	99.8	36.6	3648.2
Recycler	WIRTGEN WR 200		545.2	54	27.5	1485.7
Roller[a]	HAMM 3520 ht		545.2	25	27.5	27.5
	Bomag BW 161 AC-4		545.2	18.8		
Grader	O&K F 156		545.2	24	27.5	660.3

[a] Number of passes for the compactors are 6, while for the paver there is a unique pass.

[b] The emulsion applier is the van that spreads the emulsion between different layers.

Table 7
Transport parameters.

	Freight	Mileage[a] (distance) (km)	Vehicle type (ton)
Input to the plant	Sand	90	Truck 16–32[b]
	Limestone	75	Truck 16–32
	Gravel	45	Truck 16–32
	Bitumen	120	Truck 16–32
	Bituminous emulsion	150	Truck 16–32
	Lubricating oil	65	Van < 3.5[b]
To the yard	Asphalt[c]	25	Truck 16–32
	Operation vehicles	25	Truck 16–32
	Work staff	25	Van < 3.5

[a] Distance will double as loaded trucks will roll to the required site and unloaded when coming back.

[b] Fuel consumption for Truck 16–32 t is 0.5 l/km while for Van <3.5 t is 0.1 l/km.

[c] 25 km is a mean between the different distances covered by truck.

Table 8
Direct emissions to air in kg per ton of asphalt produced[a].

	Emission (kg/t)	Percentage of reduction from HMA to WMA[b]
CO_2	9.58	−35%
N_2	278.87	–
O_2	52.42	–
Dust	1.08E-3	−40%
NO_x	7.26E-3	−65%
TOC	4.4E-3	−50%
PAHs	0.0024E-3	–

[a] These emissions are measured at the chimney of the asphalt plant.

[b] The percentages of reduction are mean between minimum and maximum values indicated in literature (D'Angelo et al., 2008).

- Determine the number of trips needed, dividing the volume to be transported by the truck capacity.
- Calculate total length of kilometers to be covered. The distance traveled is determined multiplying the number of trips by distance; the resulting value is multiplied by 2 to consider the trucks round trip.

The transport vehicles and distances covered are seen in Table 7.

3.4. Emissions

Regarding emissions to air, in the present case study only direct emissions of the plant are calculated: these are measured at the chimney of the plant and are presented in Table 8. In addi-tion to direct emissions there are also fugitive emissions from the plant and emissions from paving operations on the yard. The fugitive ones (VOCs, PAHs) result from load-out of the materials and silo-filling operations, they are calculated with valuation pre-sented in literature (U.S. EPA, 2004; Hanson et al., 2012), but are not taken into account due to the fact that they result negligible regarding the impacts compared to the direct ones (contribution lower than 1% on the whole lifecycle). Emissions from paving operations on the yard are not considered in this case-study due to the lack of measurements on the construction site and uncertainties regarding damage on yard workers. Despite these concerns a qualitatively evaluation of the emissions from paving operations is made on the basis of Jullien et al. (2006), but they result negligible regarding the impacts compared to the direct ones (about 8 orders of magnitude lower). Emissions from traffic are not taken into consideration due to the reasons defined earlier in the introduction section.

4. Results (Impact assessment) and discussion

Life cycle impact assessment associates life cycle inventory data with specific environmental impact categories and category indicators. Results relating to the different methods taken into account in this study are presented below.

4.1. GGP

The global warming impact is expressed in tons of CO_2 equivalent. Results for GGP are presented in Table 9. More than 99% of CO_{2eq} emitted comes from fossil sources; indeed, during the entire lifecycle fossil fuels are used mostly. The percentage of reduction (tCO_{2eq}/km) is −6.8% (from RP1 to RP2), −5.5% (from RP2 to RP3) and −11.9% (RP1–RP3). In the last step of this LCA study, the "best pavement" (RP3) is analyzed over the period of 30 years. This period, as mentioned before, takes into account all material production, material haulage, pavement construction, layer deconstruction and layer reconstrucion processes occurring due to the selected maintenance strategy (recycling in plant or in situ through CIR technology).

The CO_2 uptake has a low contribute (about 0.5% on the total CO_2 emissions) and it vanishes with the biogenic CO_2 emissions. The uptake comes from processes that considers the use of biomass that stores an amount of CO_2: these processes are production of energy from biogas starting from sewage sludge (about 15% of the uptake) and production of energy from hardwood and softwood (about 80% of the uptake).

In the present case study the total emission of CO_{2eq} results about 52–60.2 kg CO_{2eq}/ton (calculated considering the amount – ton – of each layer needed during the lifecycle) and it is comparable to data found in literature: 57 kg CO_{2eq}/ton (Miliutenko et al., 2013), 45 kg CO_{2eq}/ton (Hammond and Jones, 2010).

The results partitioned between different phases of the lifecycle are presented in Fig. 7.

Material extraction and processing (that includes production of bitumen and extraction of aggregates in the caves) is the stage with higher impacts (40% of the total) on the lifecycle; this percentage is slightly lower for RP3 because of the quantity of RAP used that implies less production of virgin materials. On the other hand RP3 has major impacts in the plant stage, compared to RP2, due to a higher quantity of RAP, so more electricity is needed for the vibrating screen. Also transports have a great importance on CO_2 equivalent emissions, mainly due to the fact that they occur by truck with high tonnage and a high consumption of diesel (about 0.5 l/km at full load). Contributes of yard operations are the same

Table 9
CO_{2eq} (t CO_{2eq}) emissions during the lifecycle, including the rehabilitation phase only for RP3.

	RP1	RP2	RP3	RP3 recycled in plant	RP3 recycled in situ
Fossil $CO_{2\ eq}$	737.8	687.8	649.9	1298	1183
Biogenic CO_{2eq}	3.81	3.59	3.31	6.52	5.92
CO_{2eq} from land transformation	0.01	0.01	0.01	0.02	0.02
CO_2 uptake	−3.63	−3.43	−3.18	−6.27	−5.69
Total	738	688	650	1298	1183

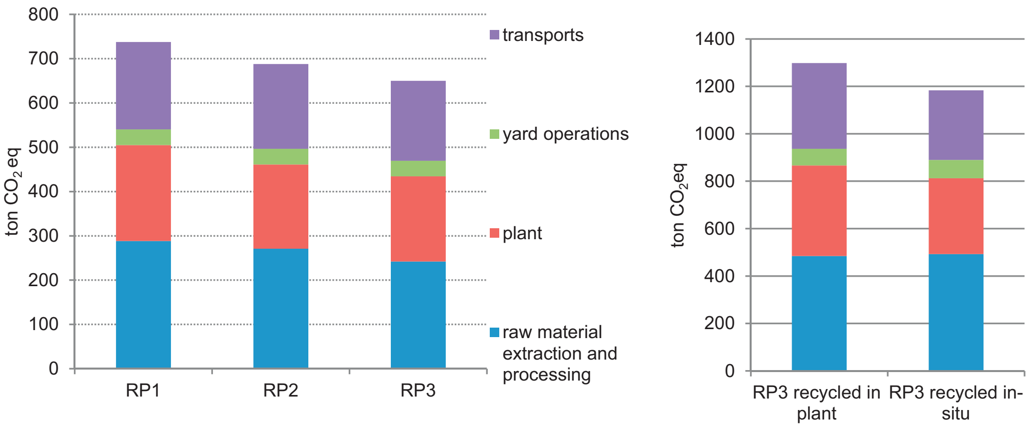

Fig. 7. GGP results.

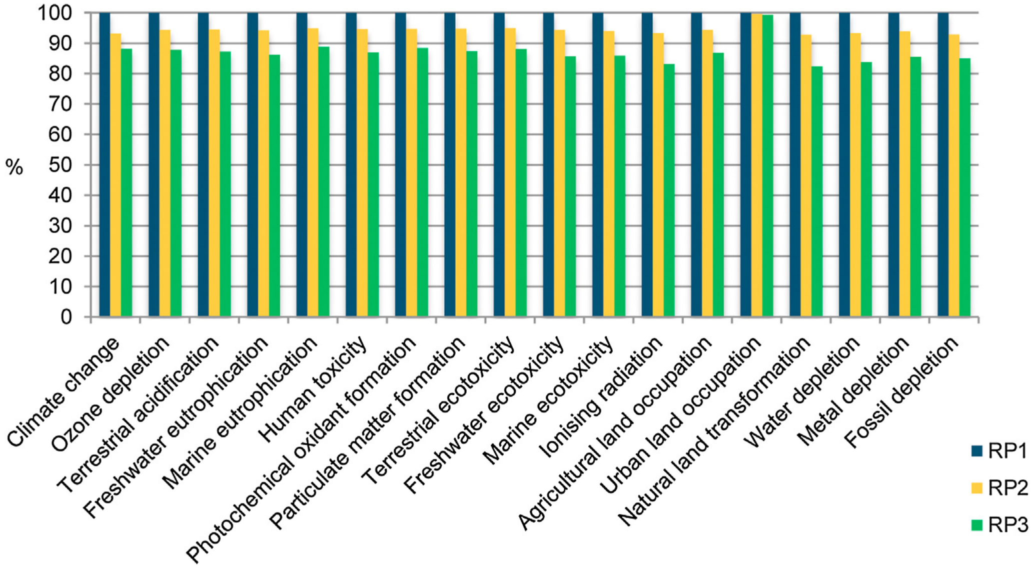

Fig. 8. ReCiPe Midpoint H, characterization results, comparison between RP1, RP2 and RP3.

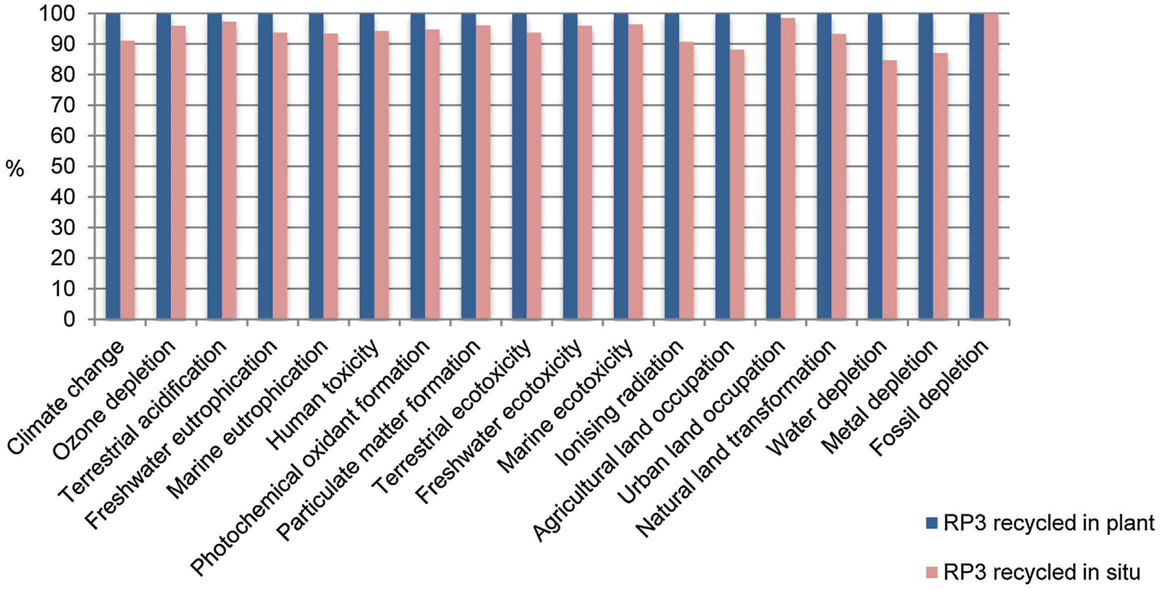

Fig. 9. ReCiPe Midpoint H, characterization results, comparison between the different rehabilitation techniques.

Table 10
ReCiPe Midpoint H, normalization results in kPt, including the rehabilitation phase only for RP3.

Impact category	RP1	RP2	RP3	RP3 recycled in plant	RP3 recycled in situ
Climate change	65.8	61.3	58.0	115.8	105.5
Ozone depletion	18.2	17.2	16.0	32.0	30.7
Terrestrial acidification	130.5	123.3	113.8	227.1	221.1
Freshwater eutrophication	12.6	11.9	10.9	21.7	20.3
Marine eutrophication	12.2	11.6	10.9	21.6	20.1
Human toxicity	87.8	83.0	76.1	152.1	145.9
Photochemical oxidant formation	82.1	77.8	72.5	144.3	136.8
Particulate matter formation	104.3	98.9	91.1	181.4	174.4
Terrestrial ecotoxicity	24.1	22.7	20.8	41.5	41.2
Freshwater ecotoxicity	138.1	130.5	118.5	236.9	231.1
Marine ecotoxicity	221.6	208.5	190.5	380.9	369.9
Ionizing radiation	18.7	17.5	15.6	31.1	28.3
Agricultural land occupation	0.7	0.7	0.6	1.2	1.1
Urban land occupation	596.5	594.6	592.5	1185	1168
Natural land transformation	14.76E 03	13.7E + 03	12.16E + 03	24.31E + 03	22.7E + 03
Water depletion	0.0	0.0	0.0	0.0	0.0
Metal depletion	51.8	48.7	44.3	88.7	77.2
Fossil depletion	558.6	518.9	475.0	949.5	951.4

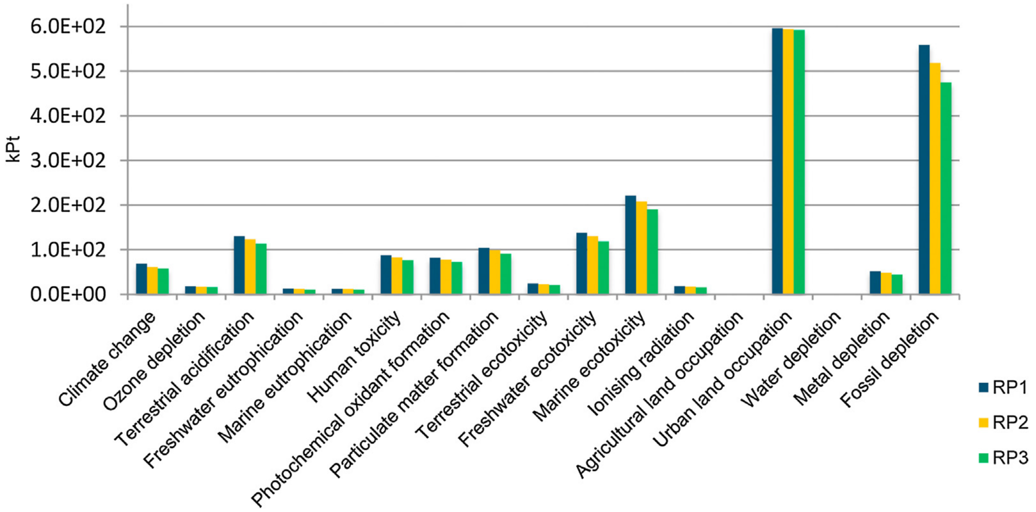

Fig. 10. ReCiPe Midpoint H, normalization results, comparison between RP1, RP2, and RP3.

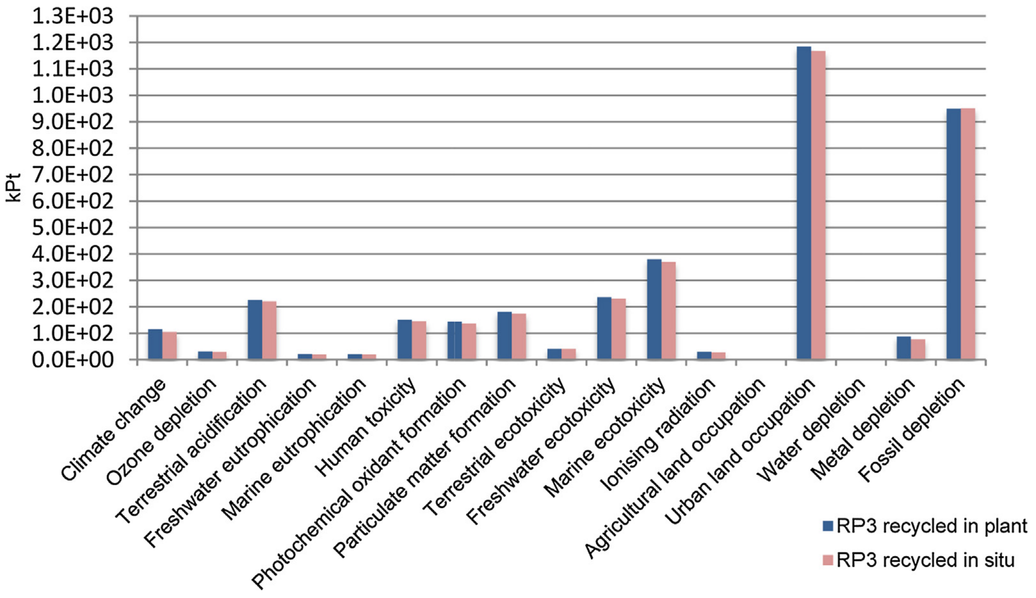

Fig. 11. ReCiPe Midpoint H, normalization results, comparison between the different rehabilitation techniques.

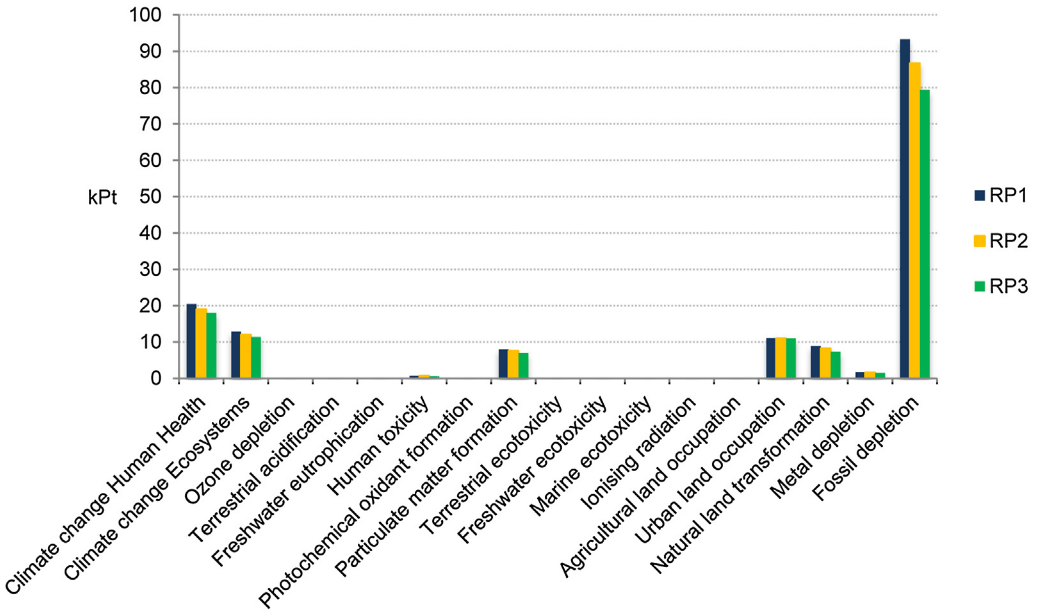

Fig. 12. ReCiPe Endpoint H, after normalization.

Table 11
Results for the damage macro-categories, including the rehabilitation phase only for P3.

Impact category	Unit	RP1	RP2	RP3	RP3 recycled in plant	RP3 recycled in situ
Human health	DALY	1.476	1.383	1.297	2.588	2.398
Ecosystem quality	Species·yr	0.015	0.014	0.014	0.027	0.026
Resources	$	14.36E + 04	13.34E + 04	12.21E + 04	24.87E + 04	24.86E + 04

for the three options and are clearly lower than other phases. Considering CIR technology, Fig. 7 shows as RP3 recycled in-situ has slightly higher impacts from yard operations and raw material extraction because of major consumption of diesel of the recycling machinery and the slightly higher quantity of bitumen used for the pavement recycled in-situ. During the analysis of the only techology in itself used for rehabilitating the base layer, it is found that CIR technology can lead to a reduction of impact of 54% compared with recycling in plant. The reason is that using CIR at the 15 year there is the absence of the plant stage and the reduction of transports, while there is an increase in the impact associated with raw material extraction and processing, due to the major amount of bitumen required to foam the base layer in situ. Considering all the lifecycle (30 years) the advantages of the application of CIR are less relevant and the whole advantage decreases to 9% of reduction of impacts because of the major time considered: the improvement due to CIR technology is diluted over time (in the whole lifecycle).

In literature (Santos et al., 2015) it is reported that, comparing the in-place recycling activity against a traditional reconstruction activity, a reduction of 75% is expected to be achieved exclusively due to the materials phase if the CIR is undertaken.

The analysis of all the processes divided as defined by UNI EN15804 demonstrates that (for all the pavements and the rehabilitation options analyzed) material production processes have the greatest influence on the environmental results both for product stage and maintenance. While considering 15 years product stage causes more impacts, followed by use/maintenance stage, considering also the rehabilitation phase involves that the stage with major impacts is use/maintenance (about 60% of the impacts) because of the materials required during the many maintenance stages needed in the 30 years.

4.2. ReCiPe

For the ReCiPe method, firstly it is used as the midpoint approach with hierarchical set of weights, secondly also the approach with endpoint categories is evaluated. The results of the characterization phase are shown in Figs. 8 and 9.

A major percentage of RAP in the recipes and the WMA production allow an improvement of all the parameters analyzed (Fig. 8). The contribution of *Fossil depletion* is the largest (reaching up to 4 order of magnitude greater than the other categories), this can be explained by the fact that the processes associated with bitumen's use can cause the most important impacts because bitumen derives from oil processing. Through the application of CIR technology reductions can be achieved for all the categories analyzed (Fig. 9) except a small increase in *Fossil depletion*, this is explained by the fact that CIR option requires more bitumen.

To get a better feeling of the relative importance of the several effect scores, the so-called normalization step can be introduced: each score is compared with the total known effect of the examined category in a certain region and a certain year (in this study Europe in the year 2000 has been chosen as the reference). The result is a fraction and represents the contribution of the category to the total environmental loading for the functional unit under consideration. The results of the normalization are shown in Table 10.

The value of the category *Natural land transformation* is the largest above all, in fact during the lifecycle of the pavement, natural land transformation happens due to the extraction of aggregates and oil: these processes impact very much at midpoint level. A graphical representation of this data is shown in Figs. 10 and 11 where 'Natural land transformation' is not reported in order not to hide the results for the other categories.

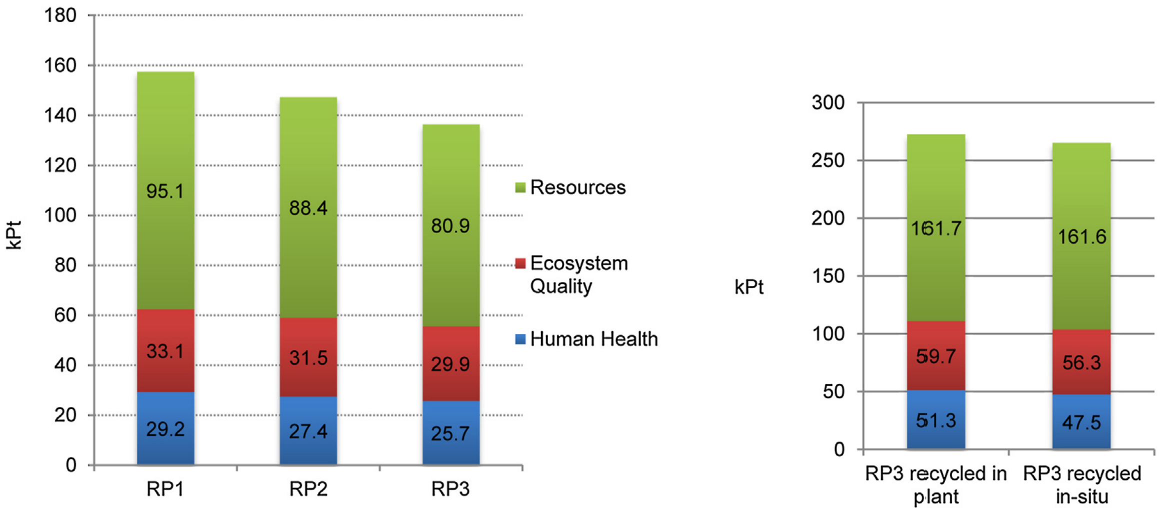

Fig. 13. Single score for the three macro-categories of damage.

Table 12
Energy consumption evaluated with CED method, including the rehabilitation phase only for RP3.

	Unit	RP1	RP2	RP3	RP3 recycled in plant	RP3 recycled in situ
Non renewable, fossil	TJ	39.03	36.26	33.22	65.57	65.65
Non-renewable, nuclear	TJ	1.18E + 00	1.10E + 00	9.81E-01	1.95	1.77
Non-renewable, biomass	TJ	5.85E-05	5.49E-05	4.99E-05	9.89E-05	9.51E-05
Renewable, biomass	TJ	3.33E-02	3.14E-02	2.87E-02	5.71E-02	5.23E-02
Renewable, wind, solar, geothermic	TJ	1.69E-01	1.62E-01	1.60E-01	3.19E-01	2.58E-01
Renewable, water	TJ	2.68E-01	2.52E-01	2.30E-01	4.60E-01	3.98E-01
Total	TJ	40.68	37.80	34.62	68.36	68.13

Table 13
Water use and energy consumption during the lifecycle, including the rehabilitation phase only for RP3.

	RP1		RP2		RP3		RP3 recycled in plant		RP3 recycled in situ	
	Water [m^3]	CED [TJ]	Water [m^3]	CED [TJ]	Water [m^3]	CED [TJ]	Water [m^3]	CED [TJ]	Water [m^3]	CED [TJ]
Product stage	19.83E + 03	26.5	18.62E + 03	24.2	16.2E + 03	21.2	17.05E + 03	21.2	16.73E + 03	21.2
Construction process	356	0.7	356	0.7	356	0.7	352.5	0.7	352.9	0.7
Use stage	8510	12.6	7920	12.0	7640	12	30.83E + 03	45.6	25.03E + 03	45.4
End of life	466	0.9	466	0.9	466	0.9	464.6	0.9	485.6	0.9
Total	2.86E + 04	40.7	2.68E + 04	37.8	2.44E + 04	34.6	4.87E + 04	68.4	4.26E + 04	68.1

Figs. 10 and 11 show all the reductions achieved passing from RP1 to RP3 and also from RP3 recycled in plant to RP3 recycled in situ.

At the endpoint level the most important categories are *Fossil depletion* and *Climate change* (Fig. 12), this means that these categories contribute mainly in terms of damage.

In this case study, where bitumen originates a large percentage of the impacts, fossil resources consumption has a great influence because bitumen comes from oil distillation process. An interesting aspect is that the use of RAP can low down the score related to *Fossil depletion* (−15% turning from RP1 to RP3). Final results for the macro-categories of damage are presented in Table 11.

The final single score, after normalization and weighting, can permit to compare the results for the three macro-categories of impact, as shown in Fig. 13.

The category that has a major weight in the impacts is *Resources*, and this reflects what presented before: fossil resources consumption has the greater influence on the impact assessment. Reducing the use of virgin materials can allow to reduce the score of the category *Resources*, while the other macro-categories are not particularly affected by the use of more environmental sustainable technologies for asphalt production. Moving from RP1 to RP3 there is a reduction of the total score of about 13%, while switching to recycling in-situ can permit to reduce the total score of about 3%. In literature (Vidal et al., 2013) reported a reduction of all endpoint impacts of 13–14% by adding RAP.

4.3. CED

Another useful indicator analyzed in this case study is Cumulative Energy Demand that represents the direct and indirect energy consumed during the entire lifecycle of the product or service under investigation. Table 12 presents SimaPro-generated energy consume for the options evaluated.

The clearly predominant contribution is that of fossil energy and this reflect the results of GGP, while nuclear energy derives from the production of electric energy (Ecoinvent data about European mix for fuels supply). Savings achieved in terms of CO_{2eq} is con-firmed also in terms of CED: going from option RP1 to RP3, there is a saving of about 6 TJ (15% of savings), comparable to literature data regarding the use of WMA technologies (D'Angelo et al., 2008 reported a range of 11–35% of savings when WMA is used instead of HMA). Also Vidal et al. (2013) reported a decrease of 14% of CED by adding 15% of RAP. The consideration above is not true regarding

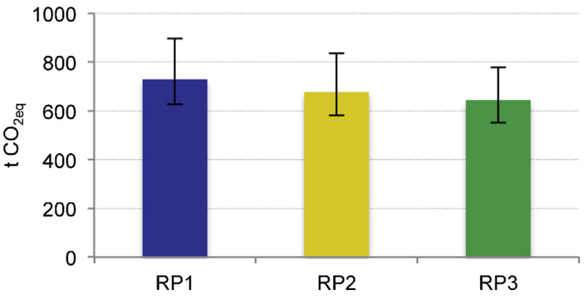

Fig. 14. Fossil CO$_{2eq}$ uncertainty assessment for RP1, RP2 and RP3.

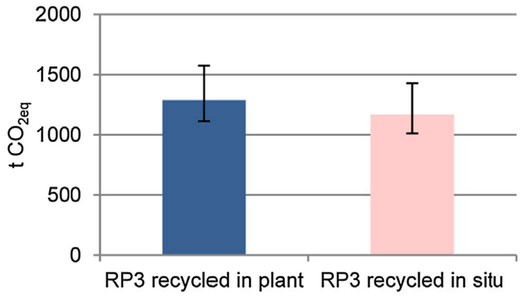

Fig. 15. Fossil CO$_{2eq}$ uncertainty assessment for the different rehabilitation technique.

CIR: this technology lead to a −0.5% of reduction in the impacts. This is due to the high weight assumed by the production of bitumen along the lifecycle (76% of the impact) meanwhile the processes of transport has a minor contribution (6%); by using GGP method instead production of bitumen represents about 40% of the total impact while the processes of transports assume greater impor-tance (20% of the total impact). Instead literature data report high reduction for energy spent in pavements using CIR: 11–35% less energy than overlay projects (Thenoux et al., 2007).

Results partitioned between the different phases of UNI EN 15804 are shown in Table 13. The contribution of production and use/maintenance phases is predominant: the reason is that in these phases the production of materials is included for the asphalt recipes, that is the most energy-consuming stage of the lifecycle and it is included in the phases just mentioned.

4.4. *Water use*

Regarding water use, although a major consumption of water in plant due to the WMA production, there is a saving of water during the whole lifecycle. The reason is that about 35% of water use derives from the use of bitumen, so the process that uses more RAP in the asphalt recipe, can lead to water use reduction of about 15%.

4.5. *Uncertainty assessment*

An uncertainty assessment was also conducted in order to deter-mine the variability of the LCA results due to uncertainties in LCI data. Monte Carlo simulations were then performed to estimate the variability with a 95% confidence interval for the environmental impacts for each of the asphalt pavements assessed. Each simu-lation consisted of 1000 samples. Regarding the most important categories in the lifecycle (that present the major impacts) CV are admissible: about 9% for Fossil CO$_{2eq}$ (GGP) and Climate change (ReCiPe), 3.6–4% for Fossil depletion, 0.9–1.3% for Urban land occu-pation and 3.8–4% for non-renewable fossil energy. Moreover the single score of ReCiPe Endpoint resulted with a CV of 4.7–5.3%. On the other hand uncertainty is very high (CV major than 60%) for the categories that have low or negligible impacts in the life-cycle such as ionising radiation, freshwater eutrophication and non-renewable biomass.

Moreover, to infer more certainty to the results comparisons were made again through Monte Carlo simulations to compare the results for the different pavements. In Figs. 14 and 15 are reported the results for Fossil CO$_{2eq}$, they show an admissible variability.

Moreover, in Fig. 16 it is reported the comparison between the results of the Monte Carlo analysis for different rehabilitation techniques in the ReCiPe method. The probability that the impacts related to recycling in plant are higher than the impacts of recycling in situ are near 100% for the categories evaluated.

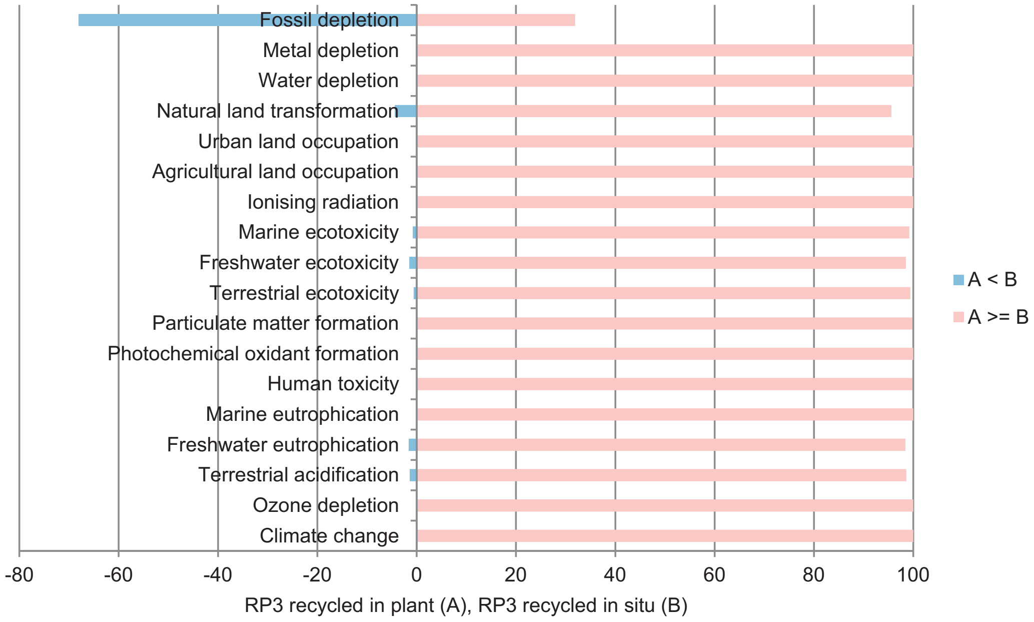

Fig. 16. ReCiPe Midpoint H, uncertainty assessment for the different rehabilitation technique.

The pavement recycled in situ show high impact compared to RP3 recycled in plant. However regarding Fossil depletion, in the 70% of the cases simulated recycling in situ results less environmental sustainable, this is due to the high weight of the bitumen, as highlighted before.

5. Conclusions

The present study aims to understand and quantify the environmental benefits resulting from the use of reclaimed asphalt pavement, technologies to lower temperature of production in plant and to reconstruct the pavement after its useful life. All the stages of the lifecycle have been considered, from extraction of virgin materials to the end of life. The results show that extraction and production of virgin materials have the higher impacts in the lifecycle (up to 40% of CO_{2eq}), mainly due to the presence of bitumen, a petroleum derivate which has high impacts during its production. For this reason material production processes for asphalt pavements offer larger reduction potentials (with regard to all indicators). Asphalt production using RAP (which saves virgin materials), coupled with higher savings from production of WMA, is the key to a sustainable design of road pavements, dealing with environmental improvement. In fact the achieved reductions are in the order of 12% for CO_{2eq}, 15% for energy consumptions and 15% for water used during the lifecycle. Considering ReCiPe method the use of RAP can low down the score related to Fossil depletion (−15% turning to RP1–RP3) and the total score of about 13%.

Regarding the rehabilitation phase for the base, when the CIR option is compared with recycling in-plant, the data reveal that:

- CIR option requires more bitumen.
- Reduction of impacts with CIR, compared to RP3 recycled in-plant.

Application of cold in-place recycling means decreasing the use of aggregate, transport and the consumption of the plant, all these things have benefits in terms of CO_{2eq} emitted (reduction of 9% on the whole lifecycle and 54% considering only the phase of recycling). On the other hand the savings obtained in terms of GHG emissions are not confirmed in terms of CED: recycling in-situ only lead to a -0.5% of reduction in the impacts.

It is important to notice that impacts from depletion of fossil fuels are slightly higher for the pavement recycled in-place, due to higher consumption of bitumen: recycling of asphalt pavement may of course significantly reduce natural aggregate use and all the processes associated with, but still requires further examination either during the stage of production of the materials used for the pavement, and at the time of the pavement operating stage. The uncertainty assessment through Monte Carlo simulations confirmed that the impacts could be effectively reduced by adding RAP and WMA to the asphalt mixes and also through the application of CIR technology.

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