construction materials

Article

An Index for Assessing the Environmental Impact of Pavement Maintenance Operations on the Motorway Network: The Environmental Asphalt Rating

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Abstract: In recent years, attention on pavement management is increasing and the research is focused on the development of innovative protocols and comparative evaluation of maintenance alternatives. Among these, the concept of sustainability related to the management of pavements is gaining ground and, more generally, infrastructure and the quantification of environmental impact as a combination of emissions and energy consumption. To properly estimate the environmental impact of different pavement interventions, a calculation methodology is presented in this paper that can summarize all the different aspects of environmental impact for both the production and paving phases of asphalt mixtures. The innovative approach takes into account also the need to evaluate new methodologies and new production processes in order to compare these new technologies with already used materials and processes. The result of this paper is a dimensionless index based on Environmental Product Declaration (EPD) certification which has been named Environmental Asphalt Rating (EAR) with weighting factors and performance coefficients fine-tuned on the European scenario. The EAR computation wants to be a certified procedure ensuring the repeatability and the quality of the environmental evaluation but also able to include in the evaluation noise and mechanical characteristics of the pavement. Several applications are expected such as the design stage of maintenance operations, and awarding criteria in tenders of monitoring phases of the pavement maintenance interventions.

Keywords: road pavement; road pavement maintenance; environmental impact; Asphalt; LCA; EPD

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1. Introduction

Construction, rehabilitation, and maintenance of highway pavements require obtaining, processing, transporting, manufacturing, and placement of large amounts of construction materials. Pavements, in fact, represent one of the most important infrastructural assets and require massive investments. The need to design and provide a sustainable maintenance service is becoming a priority and this comes mutually with the intention to reduce impacts caused by maintenance treatments to the environment.

Several tools are available to quantify and compare materials and techniques in terms of environmental sustainability. Unfortunately, articles and manuals describing such tools base the evaluation of the environmental impact on a different set of data. This makes it difficult to adopt a single, universally-recognized method to have a direct comparison of pavement preservation and maintenance treatment options in terms of environmental sustainability [1].

With the recent inclusion of environmental consideration into public procurement, also known as Green Public Procurement (GPP), a comprehensive and official approach to the sustainability analysis of flexible pavements is needed. Starting from that, a third-parties verified declaration known as Environmental Product Declaration (EPD) certification was introduced.

In 2013, the EU founded the EDGAR project, aiming at supporting the National Road Administrations in the sustainability assessment of novel green bituminous mixtures and bridging the gap between innovation and adoption [2]. The methodology developed within the project considered both the environmental aspects which rule the EPD declaration, but also socio-economic factors and a long-term vision of sustainable aspects. In 2013, starting from the Norwegian EFFEKT model [3], the LICCER model was presented with the objective to provide planners with quantitative information to assess life cycle cumulative energy consumption and greenhouse gas emissions of road corridor alternatives [4]. Additional efforts were also made in the characterization of maintenance operations with the HERMES project that developed a methodology enabling the selection of the best available technology and strategy with the lowest cost for the environment and society. The overall objective of this research project was to establish a long-term dynamic inventory of carbon emissions deriving from the analysis of a variety of urban roads, based on best practices in Europe and China [5]. All of the projects mentioned emphasize the complexity of the assessments resulting from the large number of factors to be considered. In some cases, the models developed are based on simplifications that consider a limited set of parameters included in EPD certifications. In each project, however, the need to have a single indicator that is overall representative of the environmental impact is noted. Lastly, it can be pointed out that, none of the mentioned projects took into account parameters related to performance and, in particular, the durability of the materials considered.

Starting from these considerations, the present work proposes to develop an innovative index named Environmental Asphalt Rating (EAR) which, still starting from the parameters derivable from EPD certifications, aims to:

- Unambiguously quantify the potential environmental impact due to different maintenance strategies;
- Provide to Autostrade per l'Italia (ASPI), in its capacity as contracting authority, a reference parameter for the evaluation of technical offers and the assignment of scores in the tender phase in terms of environmental impact;
- Monitor and fully estimate the impacts on the basis of the bids submitted by the awarded contractors.

The EAR index proposed here has been designed as a dimensionless value that can collect and summarize all the information that can be extracted from EPD certifications. To do this, it was necessary to define values to normalize the different parameters in order to make them comparable in numerical terms and congruent from a physical and mathematical point of view. Moreover, since the different environmental parameters do not have the same impact in relation to the specific application context under study, it was decided to assign different weights to the different parameters. The definition of these weights has been described in Section 5.1.

The index obtained through the normalization and weighting processes of the different parameters then provides a dimensionless number summarising the different environmental impacts of a given pavement maintenance process. However, the opinion of the authors is that an environmental impact index defined only from the parameters derived from EPD certifications cannot be considered exhaustive if it does not also take into account the mechanical performance and the service life of the mixtures evaluated through the index itself. Since the index must be able to quantify any proposals for improvement over the entire life cycle, the assessment must necessarily also take into account the service life of the asphalt mixtures considered in order to compare them to reference mixtures (i.e., the current state-of-the-art). For this reason, alongside the environmental parameters, it was decided to create performance parameters to be applied to the overall definition of the EAR index. These parameters are used as multiplier coefficients for the EAR index obtained from environmental data only, as will be explained in the next Section Section 5.2.

Finally, the EAR index was set in order to have variability between zero and one, hypothetical values representing the minimum and maximum environmental impact, respectively. On the contrary, the value of the index does not have a maximum threshold value but increases as the environmental impact increases. The decision not to have a maximum threshold value was also supported by the fact that it is not possible to identify absolute reference values against which to relate the value of the index.

2. Regulatory Framework

The issue of environmental aspects in public administration spending appeared for the first time in the Green Paper "Public Procurement in the European Union", a communication adopted by the European Commission on 27 November 1996 (COM (1996) 583) [6], which introduced the possibility of integrating environmental aspects into the definition of procedures for the purchase of goods and services and the execution of works. The Green Paper takes note of the role of the Public Administration as a consumer, which can condition the supplier market towards products and production processes that pursue sustainability.

European Union legislators have implemented the Green Paper through a series of communications and directives. Communications COM (2001) 264 [7], and COM (2001) 274 [8], emphasized that EU member states should use public procurement to promote environmentally friendly products and services and that EU law offers the possibility of integrating environmental considerations into public procurement procedures. Communication COM (2003) 302 [9] explicitly requires member states to adopt National Action Plans for Green Public Procurement (GPP). The GPP is defined in the Communication COM (2008) 400 [10] as "a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured". GPP is a voluntary instrument so each Member State and public authorities can determine the extent to which they implement it. In Italy, the legislation has been implemented in the National Action Plan on Green Public Procurement (PAN GPP) [11], updated by the Ministerial Decree of 10 April 2013. From this plan comes the Minimum Environmental Criteria (CAM) that, as far as flooring is concerned, is currently being defined. Subsequently, the inclusion of the CAM within the tender documentation was introduced by Legislative Decree 50/2016 [12].

In general, the regulatory framework discussed shows how public bodies and infrastructure managers are called upon to set environmental objectives and to do so by preparing criteria that are scientifically supported, easily verifiable, and that tend to encourage innovation in products and processes to reduce their impact on the environment. It is from these considerations that the present study and the formulation of the EAR environmental index proposed here originated.

3. Environmental Product Declaration EPD

The development of the index for the quantification of the environmental impact of the asphalt concrete production and paving cycle developed in this article stems from the information and the adopted procedures for the production of the Environmental Product Declaration (EPD) certification. EPD certification has been presented and described in the standards ISO 14025 and EN 15804 [13,14]. It is based on the adoption of common criteria and calculation rules derived from the Life Cycle Assessment (LCA) methodology applicable to a very wide range of products and processes. As discussed in the introduction, several scientific works, including the not previously mentioned work [15], have demonstrated their effectiveness in assessing the production process and use of asphalt concrete.

Furthermore, in the present work, it was decided to adopt this certification because it allows the use of common and internationally recognized criteria and calculation rules for a large number of product categories, reporting information in a common and uniform format. To ensure this uniformity and harmonization of EPD certification formats, documents called Product Category Rules (PCRs) have been defined. These PCRs define the principles and requirements for the drafting of EPDs for each specific category of product or service. Specifically, the PCRs for asphalt concrete have been developed by the National Pavement Association [16].

For the entire life cycle of materials, the assessment of environmental impact is carried out through the determination of several environmental factors described below by means of summary tables: parameters related to emissions (Table 1), consumption of resources intended as raw materials and as energy (Table 2), generation of waste and the management of different output flows (Table 3).

All the pollutant components shown in the respective tables are quantified throughout production, installation (construction), use, and end-of-life phases, also assessing the potential for reuse, recovery, or recycling. All the different phases are reported and briefly described in the Table 4. Table 4 also indicates the relative codifications described in the EN standards used and reported in the EPD certifications. The phases considered in this study are highlighted in grey.

Table 1. Environmental impact parameters related to emissions.

Parameter	Abbreviation	Unit of Meas.
Global warming potential (over 100 years)	GWP	kg of CO_2 eq.
Depletion potential of the stratospheric ozone layer	ODP	kg of CFC_{11} eq.
Acidification potential of soil and water	AP	kg of SO_2 eq.
Formation potential of tropospheric ozone	POCP	kg of C_2H_4 eq.
Eutrophication potential	EP	kg of $(PO_4)^{3-}$ eq.
Abiotic Depletion Potential-Elements	ADPE	kg of Sb eq.
Abiotic Depletion Potential-Fossil fuels	ADPF	MJ

Table 2. Environmental impact parameters related to use of resources.

Parameter	Abbreviation	Unit of Meas.
Use of renewable primary energy excluding renewable primary energy resources used as raw materials	PERE	MJ
Use of renewable primary energy resources used as raw materials	PERM	MJ
Total use of renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PERT	MJ
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw materials	PENRE	MJ
Use of non-renewable primary energy resources used as raw materials	PENRM	MJ
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PENRT	MJ
Use of secondary material	SM	kg
Use of renewable secondary fuels	RSF	MJ
Use of non-renewable secondary fuels	NRSF	MJ
Use of net fresh water	FW	MJ

Table 3. Environmental impact parameters related to output flows and waste categories.

Parameter	Abbreviation	Unit of Meas.
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Total Radioactive waste disposed	RWD	kg
Components for reuse	CRU	kg
Materials for recycling	MFR	kg
Materials for energy recovery	MER	kg
Exported electrical energy	EEE	MJ
Exported thermal energy	EET	MJ

For the establishment of EPD certifications, it is possible to identify three different approaches that consider different system boundaries by considering only some of the phases described in Table 4. These approaches are referred to as:

- *From cradle to gate*. This is the most widely used approach to quantify the impact of the production cycle of materials, including the production and procurement of raw materials. In relation to the production phases, it can be said to correspond to phases A1 + A2 + A3.

- *From cradle to grave*. This approach evaluates the entire production, construction, use, and end-of-life cycle, i.e., from stage A1 to stage D.
- *From cradle to gate with options*. This last one is a hybrid approach that includes the minimum requirements present in the cradle-to-gate option with a few additional information modules from the cradle-to-grave EPD variation.

Table 4. System boundaries according to EN 15804 and EN 15978.

Life Cycle Stage	Description	Module
Product stage	Raw material extraction and processing Transport to the manufacturer Manufacturing	A1 A2 A3
Construction process stage	Transport to the construction site Construction	A4 A5
Use stage	Use of the product Maintenance Repair Replacement Refurbishment Operational energy use Operational water use	B1 B2 B3 B4 B5 B6 B7
End-of-life stage	Deconstruction/Demolition Demolition waste transport Waste processing Waste disposal	C1 C2 C3 C4
Benefits and loads beyond the system boundary	Reuse, Recovery, Recycling, Potential	D

In the case of asphalt concretes, and in the context of maintenance works, the approach most commonly followed is the "from cradle to gate" one, since performance in terms of construction, use and end-of-life depends on variables that are difficult to control and measure [15]. However, in the case under consideration, it was deemed appropriate to also quantify the phases of transport to the site and paving, i.e., phases A4 and A5, as they are strongly correlated with the effective organizational skills and efficiency of the machines employed by the contractor. In fact, in the context of maintenance works, a maximum distance of the production site from the paving site is set and the average distance of the production sites, with respect to the highway axis, represents a rewarding requirement. The hybrid approach has also been used to assess the impact of the transport phase in the yard and the paving phase with respect to the entire production cycle. Referring to Table 4, the parts in grey represent the phases considered in this study.

4. Data Collection

EPD certification can be issued by specific certifying bodies and all published certifications can be consulted at the "EPD Italia" database [17]. Therefore, the work of defining the EAR index continued with a collection of data derived from EPD certifications related to asphalt concrete published internationally [18–24]. These certifications have been used to define the environmental impact due to phases A1, A2, and A3, as described in the next subsection. For what concern phases A4 and A5, referred to the impact due to the execution phase, the EPDs certifications very often provide no information. For this reason, it has been chosen to identify reference values (which have been used in the normalization process) no longer based on EPD certifications, but based on some characteristics of maintenance worksites commonly performed on Italian highway networks, better described in the following Section 4.2.

4.1. EPD Certified Asphalt Mixtures

Publicly available EPD certifications were used to collect data on asphalt mixtures produced in European facilities. The names of the plants, the state in which they are located, and the reference to the EPD certification are listed below:

- Riksten, Sweden [18];
- Tarmac, Sweden [19];
- Kärra, Sweden [20];
- Porsen, Sweden [21];
- Svevia, Sweden [22];
- Arlanda, Spain [23];
- Collosa, Spain [24].

In addition to the EPD certifications of the plants mentioned above, the data reported in the following summary reports relating to the national contexts:

- Environmental Product Declaration from Cradle to Gate. Production of hot mix asphalt concrete representative of the French market [25] referred to in the following as "French market".
- Two summary reports provided by The Norwegian EPD Foundation representative of the asphalt mixtures of the Norwegian market, one for the wearing course [26] and one for the base course [27]. In the following, they will be referred to as "Norge wearing" and "Norge base".

4.2. Impact Estimation of Construction Process Stage

The evaluations related to phases A4 and A5 (i.e., transport and laying of the asphalt concrete at the site) were carried out considering a typical work shift of 8 h during which there is an overlap of the phases of production of the asphalt concrete with the phases of the installation of the site, milling and transport to the landfill of the milled material. Specifically, the following assumptions were made for the various transport and installation phases:

- Site signage installation operations have been neglected in the analysis.
- For the analysis of emissions and consumption relating to the arrival of operating machinery at the construction site, the maximum distance between the production plant and the construction site allowed by the specifications, equal to 80 km, has been considered (i.e., the worst case).
- During the production cycle, a quantity of produced material equal to 400 tons was considered as well as the use of 10 trucks to transport the asphalt granulate to the storage site and the hot mix from the production plant to the construction site. For the tractor-trailers, 4 trips of 80 km each were considered. The machines are transported by means of an articulated lorry equipped with a semi-trailer. It has been assumed that this operation involves 10 trips of 80 km.
- The consumption of operating machinery was estimated in terms of hours of use for each 8-h shift. The adopted operating machines and the parameters for the evaluation of emissions related to phases A4 and A5 are reported in Table 5.

The data extracted by the mentioned summary reports and construction process stage impact estimation are reported in Table 6.

Table 5. Considered operating machines for phases A4 and A5 (cycle of transport and laying of asphalt on site) and estimate of the average duration of use and kilometers traveled.

Operating Machine	Quantity	Usage Hours per op. Machine	Kilometers Traveled per op. Machine	Total Usage Hours	Total Kilometers Traveled
Trolley	1	4	800	5	800
Milling machine	1	4	0	4	0
Road sweeper	1	5	0	5	0
Water tanker	1	1.5	0	1.5	0
Emulsion tanker	1	1.5	0	1.5	0
Skid-steer loader	1	2	0	2	0
Paver	1	3	0	3	0
Roller compactor	1	3	0	3	0
Tractor-trailer	10	6	320	60	3200
			Total	**84 h**	**4000 km**

Table 6. Data retrieved by the European EPD certifications. All values are referred to 1 ton of asphalt mixture produced.

Parameter	French Market	Collosa	Norge Wearing	Norge Base	Porsen Mean *	Porsen Max **	Karra Mean *	Karra Max **	Svevia	Arlanda	Tarmac	Riksten
Emissions												
GWP	$4.57 \cdot 10^{1}$	$7.83 \cdot 10^{1}$	$5.12 \cdot 10^{1}$	$4.88 \cdot 10^{1}$	$2.40 \cdot 10^{1}$	$3.90 \cdot 10^{1}$	$2.20 \cdot 10^{1}$	$4.53 \cdot 10^{1}$	$4.87 \cdot 10^{1}$	$3.10 \cdot 10^{1}$	$7.00 \cdot 10^{1}$	$2.95 \cdot 10^{1}$
ODP	$6.63 \cdot 10^{-6}$	$3.34 \cdot 10^{-5}$	$6.70 \cdot 10^{-6}$	$6.55 \cdot 10^{-6}$	$5.80 \cdot 10^{-8}$	$7.40 \cdot 10^{-8}$	$5.90 \cdot 10^{-9}$	$5.90 \cdot 10^{-9}$	$1.00 \cdot 10^{-5}$	$5.12 \cdot 10^{-1}$	$3.23 \cdot 10^{-5}$	$8.40 \cdot 10^{-8}$
AP	$2.24 \cdot 10^{-1}$	$3.40 \cdot 10^{-1}$	$3.00 \cdot 10^{-1}$	$2.71 \cdot 10^{-1}$	$1.30 \cdot 10^{-1}$	$2.30 \cdot 10^{-1}$	$1.60 \cdot 10^{-1}$	$2.70 \cdot 10^{-1}$	$3.22 \cdot 10^{-1}$	$1.32 \cdot 10^{-1}$	$4.09 \cdot 10^{-1}$	$0.00 \cdot 10^{0}$
POCP	$1.50 \cdot 10^{-2}$	$2.08 \cdot 10^{-2}$	$1.64 \cdot 10^{-2}$	$1.51 \cdot 10^{-2}$	$2.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-2}$	$2.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-2}$	$1.03 \cdot 10^{-2}$	$2.12 \cdot 10^{-2}$	$7.35 \cdot 10^{-2}$	$0.00 \cdot 10^{0}$
EP	$2.98 \cdot 10^{-2}$	$5.90 \cdot 10^{-2}$	$4.76 \cdot 10^{-2}$	$4.43 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$5.00 \cdot 10^{-2}$	$9.00 \cdot 10^{-2}$	$9.00 \cdot 10^{-2}$	$1.00 \cdot 10^{-1}$	$1.72 \cdot 10^{-2}$	$1.02 \cdot 10^{-1}$	$6.40 \cdot 10^{-4}$
ADPE	$5.46 \cdot 10^{-5}$	$4.92 \cdot 10^{-5}$	$3.10 \cdot 10^{-5}$	$3.08 \cdot 10^{-2}$	$4.90 \cdot 10^{-6}$	$8.40 \cdot 10^{-6}$	$3.30 \cdot 10^{-6}$	$4.10 \cdot 10^{-6}$	$3.15 \cdot 10^{-2}$	$7.39 \cdot 10^{-6}$	$2.36 \cdot 10^{-4}$	$3.20 \cdot 10^{-2}$
ADPF	$2.71 \cdot 10^{3}$	$2.75 \cdot 10^{3}$	$3.19 \cdot 10^{3}$	$2.65 \cdot 10^{3}$	$2.64 \cdot 10^{3}$	$3.14 \cdot 10^{3}$	$2.95 \cdot 10^{3}$	$3.39 \cdot 10^{3}$	$2.74 \cdot 10^{3}$	$1.85 \cdot 10^{3}$	$2.74 \cdot 10^{3}$	$2.77 \cdot 10^{3}$
Use of resources												
PERE	$1.10 \cdot 10^{1}$	$2.22 \cdot 10^{2}$	$5.60 \cdot 10^{1}$	$5.69 \cdot 10^{1}$	$4.64 \cdot 10^{2}$	$4.64 \cdot 10^{2}$	$5.21 \cdot 10^{2}$	$5.39 \cdot 10^{2}$	$7.17 \cdot 10^{1}$	$1.27 \cdot 10^{2}$	$1.00 \cdot 10^{2}$	$3.45 \cdot 10^{2}$
PERM	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$1.76 \cdot 10^{0}$	$1.86 \cdot 10^{0}$	$4.30 \cdot 10^{0}$	$4.30 \cdot 10^{0}$	$6.40 \cdot 10^{1}$	$6.40 \cdot 10^{1}$	$1.63 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$6.40 \cdot 10^{1}$
PERT	$1.10 \cdot 10^{1}$	$0.00 \cdot 10^{0}$	$5.78 \cdot 10^{1}$	$5.87 \cdot 10^{1}$	$4.68 \cdot 10^{2}$	$4.72 \cdot 10^{2}$	$5.85 \cdot 10^{2}$	$6.03 \cdot 10^{2}$	$7.33 \cdot 10^{1}$	$1.27 \cdot 10^{2}$	$1.00 \cdot 10^{2}$	$4.09 \cdot 10^{2}$
PENRE	$8.96 \cdot 10^{2}$	$2.81 \cdot 10^{3}$	$6.50 \cdot 10^{2}$	$6.44 \cdot 10^{2}$	$2.65 \cdot 10^{3}$	$3.15 \cdot 10^{3}$	$2.23 \cdot 10^{2}$	$6.34 \cdot 10^{2}$	$2.91 \cdot 10^{3}$	$4.08 \cdot 10^{2}$	$2.79 \cdot 10^{3}$	$3.40 \cdot 10^{2}$
PENRM	$1.93 \cdot 10^{3}$	$1.83 \cdot 10^{3}$	$2.56 \cdot 10^{3}$	$2.03 \cdot 10^{3}$	$2.20 \cdot 10^{3}$	$2.47 \cdot 10^{3}$	$2.73 \cdot 10^{3}$	$2.78 \cdot 10^{3}$	$1.54 \cdot 10^{1}$	$1.45 \cdot 10^{3}$	$0.00 \cdot 10^{0}$	$2.43 \cdot 10^{3}$
PENRT	$2.83 \cdot 10^{3}$	$0.00 \cdot 10^{0}$	$3.20 \cdot 10^{3}$	$2.67 \cdot 10^{3}$	$4.84 \cdot 10^{3}$	$5.63 \cdot 10^{3}$	$2.95 \cdot 10^{3}$	$3.41 \cdot 10^{3}$	$2.92 \cdot 10^{3}$	$1.86 \cdot 10^{3}$	$2.79 \cdot 10^{3}$	$2.77 \cdot 10^{3}$
SM	$9.51 \cdot 10^{1}$	$9.50 \cdot 10^{0}$	$1.57 \cdot 10^{-1}$	$1.25 \cdot 10^{-2}$	$2.07 \cdot 10^{2}$	$4.05 \cdot 10^{2}$	$1.49 \cdot 10^{2}$	$4.34 \cdot 10^{2}$	$1.50 \cdot 10^{2}$	$2.99 \cdot 10^{2}$	$1.63 \cdot 10^{2}$	$3.50 \cdot 10^{2}$
RSF	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$7.76 \cdot 10^{-4}$	$7.62 \cdot 10^{-4}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$1.91 \cdot 10^{0}$	$1.06 \cdot 10^{-2}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$
NRSF	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$1.15 \cdot 10^{-2}$	$1.13 \cdot 10^{-2}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$1.61 \cdot 10^{-1}$	$1.13 \cdot 10^{2}$	$0.00 \cdot 10^{0}$
FW	$1.34 \cdot 10^{-1}$	$1.55 \cdot 10^{0}$	$2.16 \cdot 10^{0}$	$2.45 \cdot 10^{0}$	$9.00 \cdot 10^{-2}$	$5.60 \cdot 10^{-1}$	$1.90 \cdot 10^{-1}$	$6.60 \cdot 10^{-1}$	$0.00 \cdot 10^{0}$	$1.38 \cdot 10^{-1}$	$4.55 \cdot 10^{-1}$	$2.80 \cdot 10^{-1}$
Output flows and waste												
HWD	$6.43 \cdot 10^{-1}$	$7.56 \cdot 10^{-4}$	$3.32 \cdot 10^{-3}$	$2.85 \cdot 10^{-3}$	$6.00 \cdot 10^{-3}$	$1.00 \cdot 10^{-2}$	$1.30 \cdot 10^{-1}$	$1.30 \cdot 10^{-1}$	$1.23 \cdot 10^{-4}$	$3.87 \cdot 10^{-6}$	$1.26 \cdot 10^{-3}$	$4.40 \cdot 10^{-3}$
NHWD	$9.29 \cdot 10^{0}$	$1.98 \cdot 10^{9}$	$9.21 \cdot 10^{0}$	$1.03 \cdot 10^{1}$	$1.20 \cdot 10^{0}$	$1.20 \cdot 10^{0}$	$9.20 \cdot 10^{-1}$	$9.60 \cdot 10^{-1}$	$3.82 \cdot 10^{0}$	$3.18 \cdot 10^{-1}$	$4.31 \cdot 10^{0}$	$1.50 \cdot 10^{0}$
RWD	$3.92 \cdot 10^{-3}$	$1.91 \cdot 10^{-2}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$2.60 \cdot 10^{-5}$	$1.20 \cdot 10^{-4}$	$1.00 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$	$9.61 \cdot 10^{-4}$	$2.79 \cdot 10^{-3}$	$4.39 \cdot 10^{-4}$	$1.00 \cdot 10^{-3}$
CRU	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$
MFR	$2.02 \cdot 10^{-1}$	$0.00 \cdot 10^{0}$	$4.64 \cdot 10^{-2}$	$5.37 \cdot 10^{-2}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$6.70 \cdot 10^{-1}$
MER	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$3.40 \cdot 10^{-1}$
EEE	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$3.40 \cdot 10^{0}$
EET	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$	$0.00 \cdot 10^{0}$

* Mean values registered at the plant; ** Maximum values registered at the plant.

5. Data Processing and Definition of the EAR Index

As mentioned in the introduction, the process of calculating the EAR index for a generic asphalt mixture involves two main steps:

- Normalization and weighting of the EPD parameters (EAR calculation). The first stage involves the normalization of the values of each individual EPD parameter. Moreover, since the different environmental parameters do not have the same impact in relation to the specific application context under study, it was decided to assign different weights to each parameter. Subsequently, the EAR index value is obtained through a linear combination of the different impact categories (emissions, use of resources, and output flows and waste categories).
- Correction according to the expected performance of the asphalt mixture (EAR_c calculation).

Details of the calculation process of both indicators, EAR and EAR_c, have been given in Sections 5.1 and 5.2.

5.1. Definition of the Normalization and Weight Values

The identification of factors for normalizing the environmental parameters started from the following considerations:

- The parameters PERE and PENRE, related to resource consumption, are defined as a linear combination of other parameters namely:

$$PERE = PERM - PERT \quad (1)$$

$$PENRE = PENRT - PENRM \quad (2)$$

  Therefore, it was decided not to directly consider PERE and PENRE for the calculation of the EAR index in order to avoid redundancies.
- At the current state of technology, the measurement of fresh water consumption and energy consumption material production data is highly error-prone. Therefore, in the current definition of the index, these parameters have been associated with a weight of zero. Nevertheless, the index has been defined so that these parameters can be included in the future as a result of advances in measurement technologies.
- For normalization purposes, it was necessary to distinguish factors into *positive* versus *negative* ones. Positive factors mean those parameters whose environmental impact is lesser the greater the value presented by them. Conversely, negative factors are those parameters for which an increasing value implies a greater environmental impact. For example, the SM factor is considered a positive factor since it represents the number of materials used in the mixture and obtained from recycling processes (such as, for example, milled material or synthetic aggregates obtained from blast furnace slag). On the contrary, GWP represents the global warming potential in terms of kg of CO_2 equivalent for which a higher value implies a higher negative impact on the environment. The factors labeled as positive are: PERM, PERT, SM, and RSF, CRU, MFR, MER, EEE, EET.
- For all indicators, the normalization factor has been assumed to be equal to the maximum value obtained from the investigated sample consisting of EPD-certified mixtures.

The values of the weights have been identified through a preliminary assessment of the most significant impacts of the entire asphalt production process. In general, it is important to note that the impacts falling into category [A]—Emissions and impacts falling into category and [B]—Use of resources, are mutually influenced, especially since the production of CO_2 is directly related to fuel consumption. The sum of the weights associated with each category has been set equal to 10. The highest weight was associated with GWP, while all factors associated with category [B] were given the same weight (with the exception of the PERE, PENRE and FW parameters as discussed above).

The normalization factors (indicated as V_n in the following), have been established as the maximum values reported in the EPD considered in the present study with the addiction of the impacts due to the phases A4 and A5. Both normalization and weight factors (indicated as w_f in the following) are reported in Table 7.

Table 7. Selected values for weighting and normalization factors.

Parameter	Weighting Factor w_f	Normalization Factor V_n	Normalization Factor m.u.
	Emissions—Category [A]		
GWP	3.00	$8.86 \cdot 10^{1}$	(kg of CO_2 eq.)$^{-1}$
ODP	1.00	$5.12 \cdot 10^{-1}$	(kg of CFC_{11} eq.)$^{-1}$
AP	1.00	$4.35 \cdot 10^{-1}$	(kg of SO_2 eq.)$^{-1}$
POCP	1.00	$7.39 \cdot 10^{-2}$	(kg of C_2H_4 eq.)$^{-1}$
EP	1.00	$1.07 \cdot 10^{-1}$	(kg of $(PO_4)^{3-}$ eq.)$^{-1}$
ADPE	1.00	$2.36 \cdot 10^{-4}$	(kg of Sb eq.)$^{-1}$
ADPF	2.00	$3.39 \cdot 10^{3}$	(MJ)$^{-1}$
	Use of resources—Category [B]		
PERE	0.00	-	-
PERM	1.43	$6.40 \cdot 10^{1}$	(MJ)$^{-1}$
PERT	1.43	$6.03 \cdot 10^{2}$	(MJ)$^{-1}$
PENRE	0.00	-	-
PENRM	1.43	$2.78 \cdot 10^{3}$	(MJ)$^{-1}$
PENRT	1.43	$5.75 \cdot 10^{3}$	(MJ)$^{-1}$
SM	1.43	$4.34 \cdot 10^{2}$	(kg)$^{-1}$
RSF	1.43	$1.91 \cdot 10^{0}$	(MJ)$^{-1}$
NRSF	1.43	$1.13 \cdot 10^{2}$	(MJ)$^{-1}$
FW	0.00	-	-
	Output flows and waste—Category [C]		
HWD	1.00	$6.43 \cdot 10^{-1}$	(kg)$^{-1}$
NHWD	1.00	$1.98 \cdot 10^{9}$	(kg)$^{-1}$
RWD	1.00	$1.91 \cdot 10^{-2}$	(kg)$^{-1}$
CRU	0.00	-	-
MFR	2.50	$6.70 \cdot 10^{-1}$	(kg)$^{-1}$
MER	2.50	$3.40 \cdot 10^{-1}$	(kg)$^{-1}$
EEE	2.00	$3.40 \cdot 10^{0}$	(MJ)$^{-1}$
EET	0.00	-	-

For the calculation of the EAR index, the absolute value of each environmental parameter v_m is normalized through the normalization factor V_n obtaining a value that expresses the relative impact I_f of each environmental parameter:

$$I_f = \frac{v_m}{V_n} \quad (3)$$

The weighted value v_w for each parameter is obtained as a combination of the relative impact and the weighting factor according to the following relationships:

$$v_w = I_f \cdot w_f \quad \text{for all positive impacts} \quad (4)$$

$$v_w = (1 - I_f) \cdot w_f \quad \text{for all negative impacts} \quad (5)$$

the overall value for each category is derived as the sum of the respective contributions. For convenience, the results of the three different sums are indicated with the same symbol associated with the environmental impact category (i.e., *A*, *B* e *C*).

Finally, the value of the EAR index is evaluated as the weighted sum of the three contributions A, B and C according to the following equation:

$$EAR = w_A \cdot A + w_B \cdot B + w_C \cdot C \quad (6)$$

The application of the three different weights w_A, w_B and w_C for each environmental impact category, respectively, equal to 0.65, 0.25, and 0.10, was decided on the basis of the following considerations:

- Emissions are quantified through established methodologies and therefore it was decided to emphasize the impact by assigning a higher coefficient;
- Energy consumption and emissions are mutually affected;
- Since the from cradle to the gate approach has been adopted, a lower coefficient was chosen to be applied to the "output flows and waste category.

Table 8 shows an example of EAR index calculation for the wearing course of the Norwegian market (Norge wearing). The source data are the ones reported in Table 6.

Table 8. Example of evaluated EAR index for the different impact categories related to the wearing mixture from the Norwegian market (Norge wearing, ref. third column of Table 6). The relative impact is reported as a percentage value.

Parameter	Absloute Value (v_m)	Weighting Factor (w_f)	Normalization Value (V_n)	Relative Impact (I_f%)	Weighted Value (v_w)
Emissions—Category [A]					
GWP	$6.15 \cdot 10^1$	3.00	$8.86 \cdot 10^1$	69%	2.08
ODP	$6.70 \cdot 10^{-6}$	1.00	$5.12 \cdot 10^{-1}$	0%	0.00
AP	$3.25 \cdot 10^{-1}$	1.00	$4.35 \cdot 10^{-1}$	75%	0.75
POCP	$1.68 \cdot 10^{-2}$	1.00	$7.39 \cdot 10^{-2}$	23%	0.23
EP	$5.24 \cdot 10^{-2}$	1.00	$1.07 \cdot 10^{-1}$	49%	0.49
ADPE	$3.10 \cdot 10^{-5}$	1.00	$2.36 \cdot 10^{-4}$	13%	0.13
ADPF	$3.19 \cdot 10^3$	2.00	$3.39 \cdot 10^3$	94%	1.88
				Total for emissions-A =	**55.59**
Use of resources—Category [B]					
PERE	$5.60 \cdot 10^1$	0.00	$5.39 \cdot 10^2$	-	-
PERM	$1.76 \cdot 10^0$	1.43	$6.40 \cdot 10^1$	3%	1.39
PERT	$5.78 \cdot 10^1$	1.43	$6.03 \cdot 10^2$	10%	1.29
PENRE	$7.80 \cdot 10^2$	0.00	$3.28 \cdot 10^3$	-	-
PENRM	$2.56 \cdot 10^3$	1.43	$2.78 \cdot 10^3$	92%	1.32
PENRT	$3.33 \cdot 10^3$	1.43	$5.75 \cdot 10^3$	58%	0.83
SM	$1.57 \cdot 10^{-1}$	1.43	$4.34 \cdot 10^2$	0%	1.43
RSF	$7.76 \cdot 10^{-4}$	1.43	$1.91 \cdot 10^0$	0%	1.43
NRSF	$1.15 \cdot 10^{-2}$	1.43	$1.13 \cdot 10^2$	0%	0.00
FW	$2.16 \cdot 10^0$	0.00	$2.45 \cdot 10^0$	-	-
				Total use of resources-B =	**76.80**
Output flows and waste—Category [C]					
HWD	$3.32 \cdot 10^{-3}$	1.00	$6.43 \cdot 10^{-1}$	1%	0.01
NHWD	$9.21 \cdot 10^0$	1.00	$1.98 \cdot 10^9$	0%	0.00
RWD	$0.00 \cdot 10^0$	1.00	$1.91 \cdot 10^{-2}$	0%	0.00
CRU	$0.00 \cdot 10^0$	0.00	0.00	-	-
MFR	$4.64 \cdot 10^{-2}$	2.50	$6.70 \cdot 10^{-1}$	7%	2.33
MER	$0.00 \cdot 10^0$	2.50	$3.40 \cdot 10^{-1}$	0%	2.50
EEE	$0.00 \cdot 10^0$	2.00	$3.40 \cdot 10^0$	0%	2.00
EET	$0.00 \cdot 10^0$	0.00	$0.00 \cdot 10^0$	-	-
				Total output flows and waste-C =	**68.32**
				EAR =	**62.17**

5.2. Definition of the Performance Coefficients

As already briefly discussed at the beginning of this section, in order to correctly assess the environmental impact of a generic bituminous mixture, it is necessary to also consider its performance. In fact, even if a benefit in terms of emissions and consumption can be obtained for the whole production process, it is still necessary to verify that the service life and the mechanical characteristics of the mixture are equal or higher than the traditional mixtures already adopted.

To do this, a series of parameters have been identified that allow the definition of corrective performance coefficients to be applied to the EAR index defining a *corrected* EAR index indicated as EAR_c. The main effort in the definition of these performance coefficients was represented by the identification of models that allow quantifying the most significant performance aspects for each type of mixture starting from the *pre-qualification* data of the materials. Pre-qualification is a procedure for the verification and acceptance of bituminous mixtures carried out in the Fiano Romano laboratory which is currently performed for all the mixtures used in Autostrade per l'Italia's maintenance process.

Regarding mechanical performance, two different coefficients were evaluated for open and dense-graded mixtures, respectively. For open-graded surface mixtures, a coefficient related to the behavior with respect to the top-down cracking phenomenon was considered. For dense graded mixtures instead, it was decided to consider a coefficient related to fatigue behavior. Finally, a coefficient has been considered to take into account the noise to be applied to all surface mixtures, both open and dense-graded. The models illustrated in the following sections have been chosen on the basis of the data required as input from each model. In fact, it was chosen to take advantage of all the information on the mixtures obtained in the pre-qualification phase in order to both not vary the procedures for pre-qualification and analysis of materials and easily extend the assessment to the asphalt mixtures already used in the past.

5.2.1. TDC Coefficient

At a structural level, the occurrence of top-down cracking (TDC) is an increasingly common problem on highway networks characterized by draining mixtures and in correspondence with particularly strong superstructures. This phenomenon was fully investigated in Phase 1 of the HiPER project: a project launched by the Autostrade per l'Italia group in 2020 aimed at optimizing the management of motorway pavement maintenance processes [28] during which a model and a methodology for calculating and quantifying the TDC based on traffic volume, age of the asphalt and the indirect tensile strength of the material were identified. The parameters used in the model are actually available following pre-qualification, making this methodology particularly well suited for the purpose.

The evaluation of the TDC coefficient (simply indicated as TDC) follows the procedure developed by Canestrari et al. [29], which starts from the evaluation of the *traffic factor n* according to (7), that expresses the passages of N_{sa} standard axles of 120 kN (i.e., $ESAL_{120}$) scaled by a factor equal to 10^8.

$$n = N_{sa}/10^8 \tag{7}$$

The second and third steps consider the evaluation of the *aging factor a* of the pavement according to (8) and the parameter β linked to the indirect tensile strength value (ITS) of the wearing course of draining mixtures according to (9). τ_y is the age of the pavement expressed in years.

$$a = 1.008 - 0.071 \cdot \tau_y \tag{8}$$

$$\beta = 0.716 - 0.220 \cdot ITS \tag{9}$$

Finally, the TDC, expressed in millimeters, can be evaluated for different passages N_{sa} as:

$$TDC(N_{sa}) = TDC_{max} \cdot e^{-\left(\frac{a}{n}\right)\beta} \tag{10}$$

In the evaluation of the EAR_c index, the corresponding multiplication factor I_1 is evaluated by setting the age of the asphalt mixture equal to 10 years and a traffic volume equal to 80 $MESAL_{120}$ as:

$$I_1 = \frac{1}{\frac{TDC_{ref}}{TDC(N_{sa})}} \tag{11}$$

The value of $TDC_{\mathrm{ref}} = 85$ mm is used to normalize the I_1 index. It was obtained by applying the model described in (11) by setting a value τ_y equal to 10 years (which is a typical value for pavement resurfacing) and annual traffic equal to 80 MESAL_{120}. The value of 85 mm is the average value obtained by varying ITS between 0.4 and 0.9 (which are the limit values imposed by the specifications [30–34]) and is therefore taken as the reference value.

Hence, the coefficient I_1 owns a value higher than 1 if the characteristics of the asphalt mixture lead to a top-down cracking type lesion deeper than 85 mm after 10 years. It is worth recalling that this coefficient applies to the open-graded mixtures but it is set equal to one for all other kinds of mixtures.

5.2.2. Fatigue Coefficient

One of the most widely used parameters in the literature for the mechanical characterization of bituminous materials is represented by the complex stiffness modulus E^*. This parameter depends on temperature, loading speed, age, and other characteristics of the mixture. As suggested by the American standard NCHRP Project 1-37A Report [35] at level 3 of the analysis, it is possible to evaluate E^* by means of the sigmoidal function at the reference temperature of 70 °F (i.e., about 21.1 °C):

$$\begin{aligned}\log E^* = 3.750063 + 0.02932\rho_{200} - 0.001767\rho_{200}^2 - 0.002841\rho_4 - 0.0058097V_A + \\ - 0.802208\frac{V_{b,eff}}{V_{b,eff+V_A}} + \frac{3.871977 - 0.0021\rho_4 + 0.003958\rho_{38} - 0.000017\rho_{38}^2 + 0.005470\rho_{34}}{1 + e^{(-0.603313 - 0.313351\log f - 0.393532\log\eta)}}\end{aligned} \quad (12)$$

where η is the viscosity of bitumen (equal to 10^6 Poise), f is the frequency of the load expressed in hertz, V_A is the percentage of void content in the asphalt mixture, $V_{b,eff}$ is the percentage effective content of bitumen, ρ_{34}, ρ_{38}, ρ_4 are the percentage retained on the $^3/_4$, $^3/_8$ and 4 sieve, respectively, ρ_{200} is the percentage passing on the 200 sieve.

All these parameters are requested during the pre-qualification stage except the viscosity. However, this parameter can be derived, according to (13) on the base of the penetration grade of bitumen which is information available downstream the pre-qualification stage.

$$\log\eta = 10.5012 - 2.2601\log P_{\mathrm{en}} + 0.00389\log P_{\mathrm{en}}^2 \quad (13)$$

P_{en} is the value of the penetration test of the asphalt binder. Once the complex stiffness modulus is derived, it is possible to use its absolute value E to evaluate the residual number of standard fatigue axles $N_{\mathrm{res,sa}}$ for each mixture through the following relationship:

$$N_{\mathrm{res,sa}} = k_1\epsilon^{-k_2}E^{-k_3} \quad (14)$$

where ϵ is the maximum horizontal strain at the base of the asphalt mixture. Three different reference values of ϵ have been assumed in order to take into account the different typologies of pavement:

- $\epsilon = 3.61 \cdot 10^{-5}$ for dense graded asphalt concrete;
- $\epsilon = 3.49 \cdot 10^{-5}$ for binder asphalt concrete;
- $\epsilon = 3.29 \cdot 10^{-5}$ for base asphalt concrete.

k_1, k_2 and k_3 have been assumed as follows:

- $k_1 = 0.0796$;
- $k_2 = 3.291$;
- $k_1 = 0.854$.

It may be noted that, using (14), a value of $N_{\text{res,sa}}$ referring to a standard 80 kN axles is obtained. This value has been reported to a value referred to standard axles of 120 kN (i.e., the reference load in the Italian context) through (15) [31–34]:

$$N_{\text{sa,120kN}} = N_{\text{sa,80kN}} \left(\frac{80}{120} \right)^2 \quad (15)$$

Finally, the coefficient to be applied at the EAR index can be evaluated, for each mixture, according to the equation:

$$I_2 = \frac{N_{\text{res,sa}}}{N_{\text{ref,sa}}} \quad (16)$$

in which the number of cycles to fatigue failure, expressed in terms of 120 kN standard axle, is normalized by a factor $N_{\text{ref,sa}}$ assumed equal to:

- Eighty-four MESAL_{120} for dense graded asphalt concrete;
- Ninety-one MESAL_{120} for binder asphalt concrete;
- One-hundred-and-five MESAL_{120} for base asphalt concrete.

Furthermore, in this case, it is recalled that the coefficient I_2 applies to the closed graded mixtures but it is set equal to one for all other kinds of mixtures.

5.2.3. Noise Coefficient

The last parameter related to the characteristics of the mixtures that have been considered is related to the acoustic emissions. It is known from the literature that acoustic performances are strictly related to surface texture, temperature, size, and shape of the aggregates. Moreover, noise represents an environmental parameter that, in the opinion of the authors, is worth taking into account as it has a relevant impact on people's health and quality of life. In order to evaluate the performance of surface mixtures from this point of view as well, it has been decided to adopt the model proposed by Losa et al. in 2013 [36] that links acoustic emissions, represented by the close proximity rolling noise index $CPLX$ to the sieve diameter associated with the 95th percentile of the passerby D_{95}, the fractal dimension D_{f}, and characteristics in terms of percentage of voids in the asphalt mixture V_{A} and percentage of voids in the mineral aggregates VMA:

$$CPXL = a_1 + a_2 \log \frac{S}{S_0} + \left[a_3 + a_4 \log \frac{S}{S_0} \right] \frac{D_{95}}{D_{\text{f}}} + \left[a_5 + a_6 \log \frac{S}{S_0} \right] \frac{V_{\text{A}}}{VMA} \quad (17)$$

S is the reference speed assumed equal to 130 km/h and S_0 is the reference speed equal to 40 km/h. More specifically, the term associated with the ratio ${}^{D_{95}}/{}_{D_{\text{f}}}$ represents the granulometric properties of the mixture while the one associated with the ratio ${}^{V_{\text{A}}}/{}_{VMA}$ represents the properties of the compacted asphalt mixtures and in particular, the contribution of the voids to the reduction of noise.

Finally, the index related to noise emissions associated with the EAR index is evaluated as:

$$I_3 = \frac{CPXL}{CPXL_{\text{ref}}} \quad (18)$$

where $CPXL_{\text{ref}}$ is the reference limit value assumed equal to 103.5 dBA. The I_3 index is applied to all surface mixtures while it is set equal to 1 for all base, binder, and base-binder mixtures.

5.3. Final Calculation of the EAR Index

For the definition of the EAR index, the last required step consists of applying the different performance indexes I_1, I_2 and I_3 defined in the previous paragraphs, as multiplicative coefficients of the EAR_p index according to the formula:

$$EAR_c = EAR \cdot I_1 \cdot I_2 \cdot I_3 \tag{19}$$

The methodology and the different steps followed to obtain the EAR and EAR_c indices have been summarized in the flowchart in Figure 1.

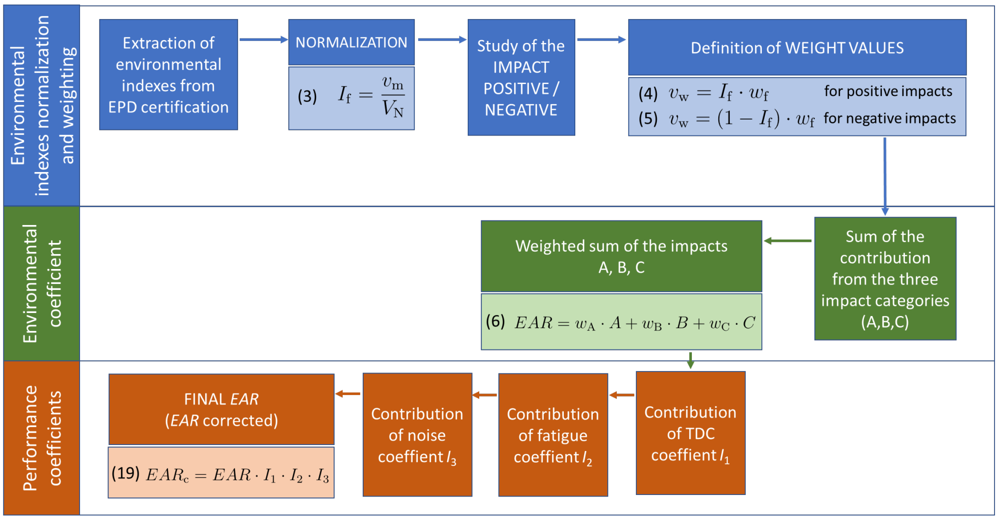

Figure 1. EAR and EAR_c calculation flow chart.

6. Results and Discussion

Based on the illustrated procedure, EAR index values were calculated for all EPD-certified mixtures analyzed in this study, resulting in the values shown in the following Figure 2. The EAR values obtained vary in a range from 29.58 to 63.23, demonstrating good variability in the results.

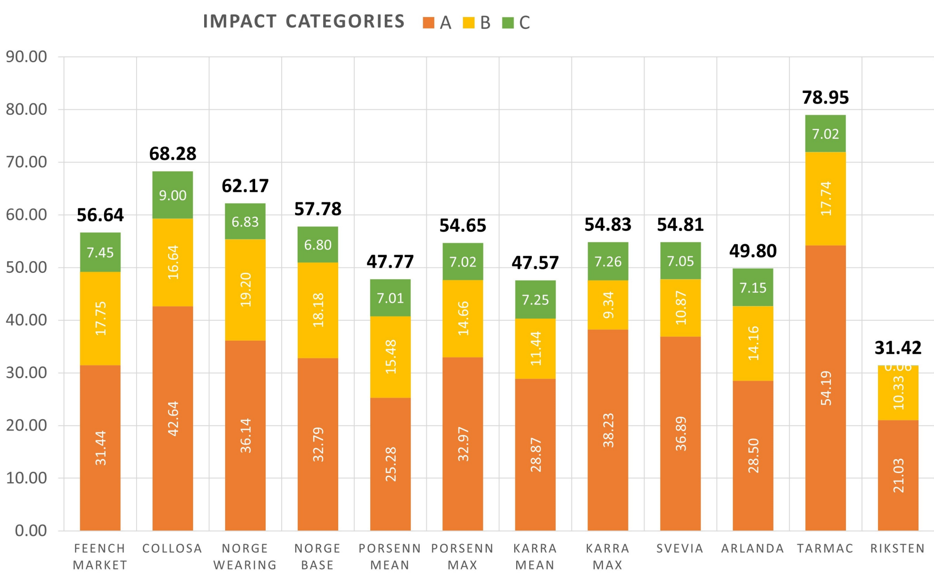

Figure 2. EAR values calculated per certified mixtures. Share related to the each impact category reported with different colors.

As can be seen from data summarized in Table 9, the greatest impact on the composition of the EAR index is due to the raw material production stage, which impacts about 60%, followed by the in-plant production stage, which impacts for 20%. The impact of the transportation (A2 and A4) and material paving phases is the least incisive.

Table 9. Impact due to the different phases of the production process.

Mixture	EAR/t	A_1	A_2	A_3	$A_4 + A_5$
French market	56.64	60%	10%	23%	6%
Collosa	68.28	64%	6%	25%	5%
Norge wearing	62.17	69%	9%	16%	6%
Norge base	57.68	63%	12%	19%	6%
	Average	**63**%	**11**%	**20**%	**6**%

Based on the available data on the analyzed mixtures, a direct calculation of the EAR_c is not possible since no such data are available for the considered EPD-certified mixtures. However, to provide a comprehensive example of the application of the proposed methodology, it was decided to derive the corrective parameters from the pre-qualification data available for mixtures similar to Norge Wearing (labeled as MIX1 and MIX2) and Norge Base (labeled as MIX3 and MIX4). The pre-qualification values of the equivalent mixtures are summarized in Table 10 while the derived coefficients I_1, I_2 a and I_3 and the corresponding corrected value of the EAR index are reported in Table 11.

Table 10. Pre-qualification values of asphalt mixtures.

Code	Type	GG (g/cm^3)	GM (g/cm^3)	PB orig. %	VA	VMA %	VBEFF	ρ_{34}	ρ_{38}	ρ_4	ρ_{200}	PEN	ITS (MPa)	CTI (MPa)
MIX1	Wearing course	2.698	2.495	5.20	3.3	15.0	9.033	0	12.8	40.6	7.1	50	1.37	118.01
MIX2	Wearing course	2.652	2.458	5.20	3.6	15.1	8.535	0	17.6	41.4	6.8	50	1.3	128.71
MIX3	Base course	2.673	2.499	4.50	3.5	13.8	7.217	8.7	47.4	57.5	5.1	50	1.31	137.11
MIX4	Base course	2.681	2.505	4.50	3.6	13.7	7.169	12.6	57.2	64.5	4	50	1.31	108.91

Table 11. Application of the coefficients to the EAR values.

Code	EAR	I_1	I_2	I_3	EAR_c
MIX1	44.53	1.0302	1.0000	1.0751	59.22
MIX2	50.24	0.9845	1.0000	1.0781	56.75
MIX3	39.47	1.0219	1.0000	1.0000	50.89
MIX4	39.66	1.0102	1.0000	1.0000	50.31

As visible in Table 11, the value of I_2 is equal to 1 for all mixtures as the TDC coefficient only applies to open-graded mixtures. Even for the I_3 coefficient applied to base mixtures (MIX3 and MIX4), the value is the same and equal to 1 since this kind of mixture is not involved in the rolling noise generation process.

Finally, the obtained values of EAR and EAR_c are reported in Figure 3.

The application of performance coefficients ensures effective differentiation between mixtures. It can be seen that the difference between EAR and EAR_c is more pronounced for wearing courses than for base courses. This is mainly due to the application of the corrective parameter I_3 related to the impact of noise emissions.

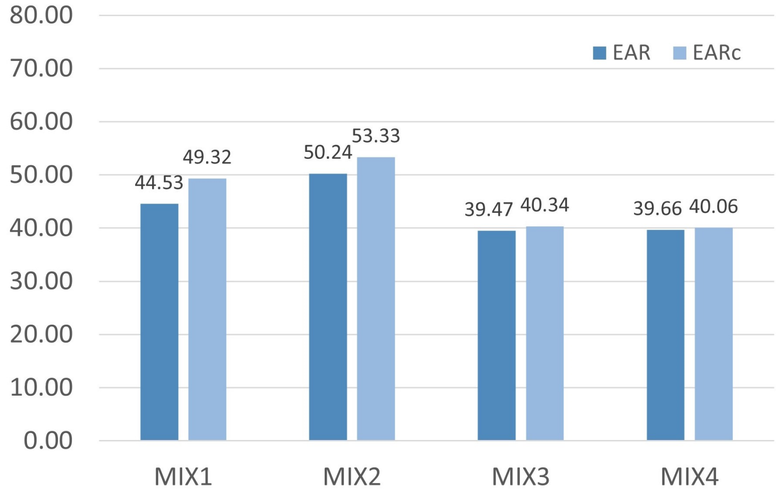

Figure 3. Comparison of EAR and EAR_c values evaluated for the four reference mixtures.

7. Conclusions

The present study has been carried out with the aim of developing a tool for monitoring the environmental impact resulting from pavement maintenance works. The study was based on a certified methodology for measuring environmental impact that ensures the repeatability and quality of the results. As shown in the work, EPD certifications make it possible to take into account all the variables involved, including future benefits obtained from new production technologies, eco-friendly materials, and other future aspects that may affect the environmental impact of pavement maintenance.

In general, the EPD certification contains a detailed list of information related to the environmental impact of the production processes used to manufacture a given product. On the other hand, the calculation process illustrated in the work starts from this list of values and leads to the definition of a synthetic index that can be more easily implemented within Pavement management tools. It should be borne in mind that while EPD certification is standardized for any type of product, the process of calculating the EAR index is specific to asphalt mixes and that, therefore, the standardization values, as well as the choice of weights, have been determined on the basis of the specific production process. The developed methodology also allows for the evaluation of environmental performance as a function of mechanical performance: the application of performance multipliers, defined in Section 5.2 is intended to ensure a "performance parity" evaluation and thus to assess the impact associated with the effective useful life of the material.

The EAR index can be applied at different stages of maintenance:

- Design stage of maintenance operations: the impact is calculated from the quantities and types of asphalt concrete planned in the project. At this stage, the EAR_c index considered is the maximum derived from the analysis of the mixture authorized and therefore takes the name “Potential Impact".
- The EAR_c index can be used as a reward criterion for awarding scores to the bids of competitors in tenders. The calculation of the index may be made on the basis of EPD certifications submitted by the contractor for each proposed mixture and on the basis of the location of the facilities on the territory, i.e., the average distance of the construction site from the facility. The score for each individual bid may be awarded according to the decrease in the EAR index compared to the potential impact described in the previous point.
- In the monitoring phase: the index may be recalculated based on data obtained from the execution of works and material control.

The results derived from the considered EPD certifications show values of the EAR index ranging from a minimum of 31.42 to a maximum of 78.95. For each EAR value, the impact in terms of emissions (Category A), resource consumption (Category B), and reuse potential (Category C) has been quantified. As discussed in Section 5.1, the most decisive contribution is given by Category A. This is also because of the combination of weights adopted among the three categories discussed in Section 5.1.

Further considerations concern the impacts due to the different phases of the asphalt production and paving cycle: in all cases examined, the greatest impact is due to the raw material production phase (phase A1) followed, respectively, by the impact of in-plant production (phase A3) and transportation for raw material procurement (phase A2). The lowest impact is due to the transport and paving phase at the site (phases A4 and A5).

Finally, the application of performance coefficients ensured the effective differentiation between mixtures. This is of paramount importance in order to be able to guarantee that the quantification of the environmental impact is effectively related to the performance of the mixtures.

Subsequent steps related to the procedure that is the subject of this article will involve the calculation of the EAR and EAR_c indexes for a number of mixtures to date used in maintenance cycles related to pavement management, with a view to regularly adopting the EAR_c indicator as part of a Pavement Management System.

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