

Article

Integrating Circularity in the Sustainability Assessment of Asphalt Mixtures

Konstantinos Mantalovas * and Gaetano Di Mino

Dipartimento di Ingegneria, Università degli Studi di Palermo, Palermo 90128, Italy; gaetano.dimino@unipa.it

* Correspondence: konstantinos.mantalovas@unipa.it; Tel.: +44-746-0705-153 or +39-391-7494-647

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Abstract: Rising concerns about the impacts that the road engineering industry is imposing to the environment have redirected national road authorities to firmly re-consider the sustainability implications of their operations. Lately, though, sustainability has established a forceful correlation with the Circular Economy and its principles. The road engineering industry, therefore, is moving towards more circular approaches. However, this is occurring without the assessment of the potential impacts of such a transition. For this reason, in this study, a composite indicator, namely, Environmental Sustainability and Circularity indicator (ESC_i), for investigating the potential effects that increased circularity could have at the environmental sustainability of asphalt mixtures is developed. It can be utilized as a decision-making support tool from stakeholders involved in both asphalt mixture production and road pavement management. In addition, in this study, four asphalt mixtures with different percentages of Reclaimed Asphalt (RA) were assessed in terms of their “cradle-to-gate” environmental impacts and circularity, by means of Life Cycle Assessment, and Material Circularity Index, respectively. Their fatigue and permanent deformation performances play a key role in the assessment and distinctive results obtained for the asphalt mixtures with increasing RA% and thus, significant environmental benefits and increased circularity are observed after specific RA% thresholds.

Keywords: circular economy; material circularity index; sustainability; asphalt mixture; reclaimed asphalt; asphalt recycling; sustainability assessment; circularity assessment

1. Introduction

A concept that persistently keeps on being in the centre of attention by numerous governments, institutions, businesses and researchers, is Circular Economy (CE). It is a concept that is currently being promoted by the European Union and by various governments individually, including Japan, the United Kingdom, China, France, Canada, Sweden, The Netherlands, and Finland [1,2]. The reason behind this, is that numerous advantages could be exploited by the implementation of a holistic circular economic approach. According to recent publications, the European Commission estimated that the EU manufacturing sector alone could potentially have a benefit of 600 billion euros annual economic growth, if a transition to CE was to be achieved [3–5]. Finland’s annual economy is estimated to experience growth of 2.5 billion euros, while when it comes to the global annual economy, the magnitude of the numbers significantly increases and estimates reach values of 1000 billion US dollars per year [6–8]. Furthermore, China is recognised as the first country worldwide to actually have implemented legislations related to circular economy [5]. In other words, lately, the consensus seems to be that CE could be utilized as a means of economic growth that complies with the definition of sustainable development [4,5,9–12]. The linear economic patterns of “make-use-dispose”, which currently dominate, seem to be agreeably unsustainable [13,14]. On the contrary, CE is able to provide alternative energy and materials flow-models, within the economic system; flow-models that are circular and

opt to minimise waste production and maximise the service life of each and every material, service or product within a system [4,15,16]. The increasing demands for raw materials, the dependence on other countries, the increasing population and energy demand, and the impact on the planet, comprise the most crucial factors leading to the belief that shifting towards such an economic approach can have great advantages. They are not just limited to environmental gains, but instead, the adoption of CE seems able to deliver economic benefits as well, according to L. Frodermann [17]. According to Su et al. [13] and Geng et al. [18], the adoption of CE can lead to improved competitiveness of enterprises, more efficient use of materials and energy, increased competitive advantage, revenues from “waste” sales, and reduced environmental penalties. Park et al. [19] and Preston et al. [20] state that the implementation of CE can lead to more direct relationships with the consumers through collaborative consumption, while reducing the costs through the usage of recycled materials, the utilization of centralized waste management plans and the resale of used products, projecting a more positive corporate image. Sinkin et al. identified the benefits of CE as reduced costs through fewer waste inefficiencies, and increased firm value. Kienbaum Management Consulting [21] published a report identifying the contribution of CE implementation as reduced costs through less waste pollution, reduced material and energy costs and competitive advantage. Additional income streams from the selling of refurbished products, reduced labour costs, enhanced customer value and differentiation, are the most important benefits of the CE according to Accenture [22]. Finally, through multiple publications of the Ellen MacArthur foundation (EMF), namely, “Towards the Circular Economy” [4], “Towards a Circular Economy: Business Rationale for an Accelerated Transition” [9] and “Towards the Circular Economy Vol.3: Accelerating the scale-up across global supply chains” [23], the potential benefits of a transition to a CE in Europe are described as annual net material cost savings in the European economy; reduced labour and energy costs, and costs for carbon emissions, along with improved customer interaction and dependency on resource prices. Finally, reduced product complexity and simpler lifecycles with reduced warranty risks and improved product design could be achieved. It thus, becomes apparent that the transition to CE is essential and stakeholders along with governmental bodies should aim towards the support and acceleration of this transition.

Having reported the potential benefits of the implementation of the CE in an economic and environmental perspective, it becomes essential to also highlight some of the most important limitations that could be encountered towards the way of its implementation. Global economic systems are mostly linear. Around 75% of global energy production is based on non-renewable energy resources [1]. Non-renewable resources are extracted from nature, processed, used, exploited and then are dumped again back into nature in a harmful form [1]. Along these lines, although sustainable development is a worldwide objective, CE-type initiatives that have been executed and/or will be realized in the not so distant future, will consistently be local or regional at most. Moreover, there is not a global administrative instrument. Be that as it may, gradually—and obviously—step by step, the future could be shaped towards a change, projecting a global improvement aligned with the principles of CE and sustainability [1,24]. Strongly rooted in environmental sustainability, the CE framework lacks an elaborated description of the social dimension of sustainability (e.g., the fulfilment of human needs, territorial implications). Its principles are primarily based upon a business perspective and strive equally for environmental and economic benefits. Social benefits are often omitted. Stahel has shown that additional manufacturing processes in a Circular Economy—e.g., refurbishing or recycling, demand more human labour, as these processes cannot often be standardized [8,25]. Even if this can create employment opportunities, it is not guaranteed that the jobs are created locally. Moreover, people’s basic needs at a global level may still be further undermined by abuses of power, unhealthy or unfair labour and living conditions or a disrespect of human rights. As such, the circular economy framework does not necessarily fulfil all the dimensions of sustainability [1]. To achieve a compatible fit, CE initiatives have to be analysed via means of global sustainability net gains in the long-term, before being implemented. When market patterns and their revolving clusters, networks, stakeholders, and the financial investments are directed towards CE, the resulting innovations will have many

difficulties to break through in the market. This would happen even if they were economically, ecologically, and socially superior to the prevailing technologies. In other words, the recycling market, just like any other market, has operational patterns, cultures and structures that have already been well-established. CE-based, high-value product reuse, remanufacturing and refurbishment, will have to compete with the aforementioned aspects, plus the managerial aspect of these actions. The economics and business logic of path dependency may prevent many of the emerging CE innovations from penetrating alternative markets [1]. The material and energy flows extracted from nature travel via many different non-interconnected parts within the economic production-distribution-consumption system before ending up as wastes and emissions within ecosystems. These flows do not necessarily respect pre-defined administrative, geographic, sectoral or organizational borders and/or system boundaries. Innovative business models including designing for multiple life cycles, functional economy and product-service systems have been proposed for the implementation of the CE. However, these have as a prerequisite interorganizational sustainability management. Cooperation is required between the supplier firm and the customer firm and between the producer and consumer [1,6,23,26]. Circular material flows and renewable energy cascades exhibit a noteworthy opportunity towards more sustainable energy and material exploitation. And this is the case also in the context of entropy. The second law of thermodynamics suggests that all the CE-type initiatives should be thoroughly examined for their net environmental sustainability contribution on a global scale. A cyclic flow does not secure a sustainable outcome [1]. For instance, in the utilization of forest residues as a source for renewable energy and for replacing fossil fuel combustion, nutrient-rich vegetation parts are extracted from an ecosystem where they could support ecosystem health, biodiversity and forest growth. This process demands energy. The machine manufacturing process also requires energy and materials and produces wastes and by-products. Hence, the sustainability contribution of this circular process can be conflicting. Due to this, and the fact that sustainability can be characterized context-sensitive, it is imperative that CE-related initiatives and processes are carefully examined case-by-case [1,10,27,28].

Such initiatives in the sector of road engineering, which can be widely observed, are the recycling of reclaimed asphalt (RA), the extension of the service life of asphalt pavements through preventive maintenance, the utilization of wastes in the production of asphalt mixtures, the attempt of increasing the allowed percentage of recycled materials inside the asphalt mixtures [29] and partially the prioritization of regenerative energy sources. Sometimes however, these practices are already being implemented by the national road authorities or the involved stakeholders not because they serve the principles of circular economy and are beneficial in terms of sustainability, but just because they are economically profitable; and by the rule of thumb are considered as best practices. Again, nothing has been published in terms of asphalt mixtures when it comes to legislative guidelines towards more circular asphalt mixtures. This however, has not stopped some individual stakeholders to move towards this direction. The company KRATON, for example, has moved forward by producing SYLVAROADTM RP1000; an additive derived from Crude Tall Oil (CTO), a renewable raw material, characterized as a by-product of the paper industry. It is able to increase the levels of RA incorporated into the asphalt mixtures while avoiding significant environmental burdens [10,30]. Another noteworthy attempt towards more circular products has been made by Tarpaper Recycling, along with Super Asphalt. They have proposed the production of REC100. It is a mobile asphalt plant that ensures 100% utilization of the resources in roofing felt and asphalt waste, in order to produce asphalt mixtures incorporating 100% recycled resources. Finally, the world's first fully recycled road, has recently been developed and constructed by Eurovia, the VINCI subsidiary, that is specializing in the urban development and transportation infrastructure spheres. This was achieved via the utilization of a mobile continuous asphalt plant, TRX100%, which is capable of recycling up to 100% of asphalt aggregates.

2. Scope and Objectives

However, the effort of the pavement engineering industry towards more circular products has not yet been assessed in terms of its environmental impacts. In other words, as aforementioned, CE-related initiatives should be carefully examined case-by-case; and in the context of asphalt mixtures, a composite approach that can identify and evaluate the impacts of the asphalt mixtures' increased circularity in the environment, needs to be adopted. An approach towards the integration of circularity within the framework of Life Cycle Sustainability Assessment has to be followed and supported. Hence, an integrated framework of environmental sustainability and circularity assessment of asphalt mixtures is developed in this study. A methodology of quantifying the combined environmental sustainability and circularity of asphalt mixtures, towards an increased uptake of the latter, is presented. Moreover, a case study, implementing the aforementioned framework has been orchestrated and undertaken. A brief representation of the concept developed and presented in this study can be seen in Figure 1. Schematic presentation of the components constituting the assessment methodology and composite indicator developed.

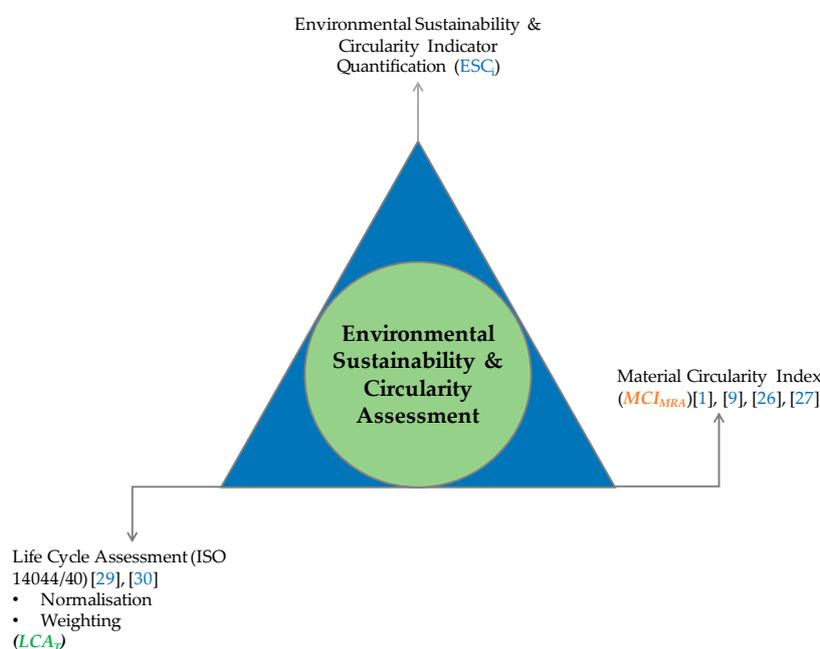


Figure 1. Schematic presentation of the components constituting the assessment methodology and composite indicator developed.

The purpose of this work is to provide a methodological approach able to quantify and evaluate the combined environmental sustainability and circularity of asphalt mixtures that incorporate reclaimed asphalt (RA), through the development of an analytical approach. It is worth highlighting at this point that the scope of this work, is limited in the assessment of the circularity and the environmental pillar of sustainability of the life cycles of asphalt mixtures. No previous attempts of the integration of circularity assessment within the sustainability assessment of asphalt mixtures have been recorded. Thus, naturally, the first step towards this integration is the combined assessment of the environmental impacts of the life cycle of asphalt mixtures along with their levels of circularity. However, the CE economy, or better, CE-related initiatives in the context of asphalt mixtures, seem to be significantly more influential on the environmental pillar of sustainability than the social or economic pillars [1]. This is why, the first attempt for the aforementioned integration, was decided to be the development of a parameter that is able to address the change in environmental impacts of asphalt mixtures while their levels of circularity are fluctuating; addressing in this way the environmental pillar of sustainability. In detail, perceivably, the results of the Life Cycle Assessment (LCA) study of the

production of an asphalt mixture can project the environmental relevance of the production process of the mixture itself, while on the other hand the Material Circularity Index (MCI) is able to provide an end-product label that characterizes the final product itself. Thus, when combined, LCA and MCI are able to provide a holistic assessment on both the final product and the process through which it was produced. To do so, a case study has been developed and undertaken in order to shed light on the underlying processes of developing this indicator. Firstly, the environmental impacts of four different asphalt mixtures that contain 0%, 30%, 60%, and 90% RA, respectively, were quantified, via the utilization of the LCA framework. Secondly, the product MCI of the very same asphalt mixtures was quantified, by using the methodology developed by the EMF [28] and specifically tailored for the context of asphalt mixtures by Mantalovas and Di Mino [10]. Finally, the composite indicator of environmental sustainability and circularity that has been developed, was implemented in order to rank the four different alternatives. The usefulness of this assessment is inextricably correlated with the understanding of the underlying importance of the sustainability and circularity assessment coupling. As mentioned above, in some cases and under specific circumstances, a CE-related initiative could be unsustainable. The implementation of this methodology to asphalt mixtures could lead to increased awareness of national road authorities and stakeholders belonging to the sphere of road engineering and the management sector, about the level of their businesses' circularity and environmental sustainability and could eventually constitute a tool for the involved decision-makers for evaluating how environmentally sustainable their circular practices and choices are. Finally, this methodology, along with the indicator developed is not geographically restricted and is widely applicable even on an extended geographical scale.

3. Methods

3.1. Life Cycle Assessment of Asphalt Mixtures with Reclaimed Asphalt

Firstly, in order to quantify the environmental impacts of the production of the asphalt mixtures with reclaimed asphalt under study, defined in Section 4, the framework of LCA was utilized. LCA is a potent tool, able to provide an insight into the environmental impacts of a product, service or process during its whole life. It is widely utilized as a decision-making support tool amongst national road authorities and it is able to provide a comparative ranking between different designs or material alternatives. It is a framework that has been standardized [31,32] and there are also Environmental Product Declarations (EPDs) and Product Category Rules (PCRs) when it comes to asphalt mixtures [33,34]. In this study, the approach adopted for the LCA exercise was "cradle-to-gate", since the analysis is focusing on asphalt mixtures as end-products. Moreover, a declared unit was defined instead of a functional unit since asphalt mixtures agreeably do not exhibit a function during their "cradle-to-gate" life cycle stage, according to EN 15804 and the PCRs for asphalt pavements and mixtures of the European Asphalt Pavement Association (EAPA) and the National Asphalt Pavement Association (NAPA), respectively [34–36].

3.2. Product Level Material Circularity Index of Asphalt Mixtures with Reclaimed Asphalt (MCI_{MRA})

Secondly, the quantification of the product level Material Circularity Index of the examined asphalt mixtures with RA became possible with the utilization of the methodology developed by the EMF and adjusted for asphalt mixtures with RA by Mantalovas and Di Mino [10,28]. The basis of the methodology can be seen in Figure 2. The definitions of the parameters/inputs required for the quantification of the Material Circularity Index that can be seen in Figure 2 can be found in Table 5.

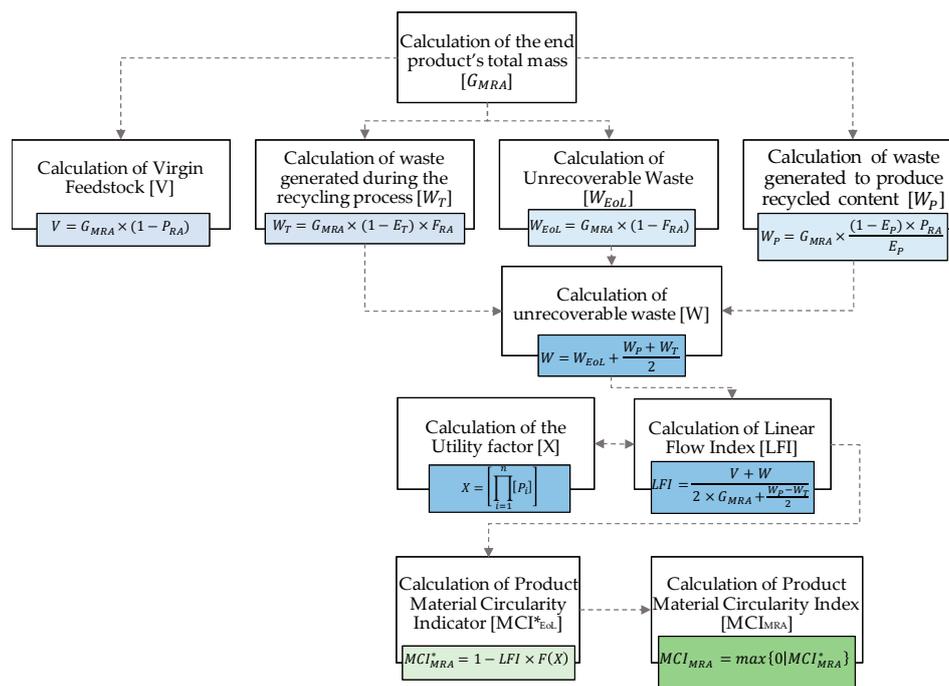


Figure 2. Workflow followed for the quantification of the product level Material Circularity Index (after Mantalovas and Di Mino, 2019 [10]).

Compared to the original methodology based on the EMF framework, the quantification of the utility factor $[X]$ now incorporates two types of mechanical performances of the end-products, namely, the asphalt mixtures. These are the resistance to fatigue and the resistance to permanent deformation. By considering both of the aforementioned performances, widely accepted as key drivers for the design of asphalt mixtures, the utility factor is capable of comprehensively describing the behavior of the asphalt mixtures during their service life [37]. Thus, the product level Material Circularity Index of asphalt mixtures with RA (MCI_{MRA}) is also taking under consideration technical aspects of the mixtures. In order to do so, laboratory tests were conducted to assess the behavior of the investigated asphalt mixtures in terms of fatigue and permanent deformation resistance; the test themselves and their results are described in Section 4.3.1.

3.3. Development of the Environmental Sustainability and Circularity Assessment Indicator (ESC_i)

Finally, having quantified the environmental impacts of the “cradle-to-gate” life cycle stage of the examined products, i.e., the asphalt mixtures with RA, and their Material Circularity Index, the final step is the definition of the indicator able to assess their combined circularity and environmental sustainability, under a closed-loop product system perspective. This was deemed essential since the framework of LCA is not taking under consideration the circularity of the end-product, and the framework of the MCI_{MRA} quantification is not considering the environmental impacts of the corresponding production process. Thus, it appears necessary, for a decision-making friendly indicator that can rank different alternatives in terms of their intertwined environmental sustainability and circularity, to be developed. As mentioned before, attempts to improve the circularity of asphalt mixtures, might end up exhibiting adverse effects for the environment; and oppositely, attempts to reduce the environmental impacts of the production of asphalt mixtures could potentially lead to decreased circularity [1,38]. For this very reason, the indicator developed has as its base value the aggregated, normalized and weighted LCA results (LCA_T) to the power of the value $(1 - MCI_{MRA})$.

It actually thus, proposes the weighting of the aggregated environmental impacts of an asphalt mixture's production, by its circularity level. The formula describing the indicator can be seen below:

$$ESCi = \frac{1}{LCA_T^{(1-MCI_{MRA})}} \times 100 \quad (1)$$

In order to calculate the Environmental Sustainability and Circularity Indicator, as described in the previous chapters, the environmental impacts of the examined product and its' Material Circularity Index have to be quantified. In order to do so, the environmental impacts quantified via the conduction of an LCA exercise, have to be converted to a single unitless number through a reductive process. The suggested process is constituted by two sub-processes; the utilization of normalization and weighting; two optional elements of the Life Cycle Impact Assessment phase of an LCA, as described in the International Standard ISO 14044 [39]. Normalization is the calculation of the magnitude of the category indicators results relative to reference information. Thus, it is able to assist with the communication of the information on the relative significance of the indicator results [32,39]. Weighting is the process of converting the impact category indicators' results by utilizing numerical factors and it allows for further aggregation of the converted indicators [32,39]. Consequently, the combined normalization and weighting can ultimately provide a single unitless number (LCA_T) that describes the magnitude of the environmental impacts of a product and enables the comparison between different alternatives. In other words, this methodology can be used as a tool to rank different alternatives of asphalt mixtures with RA, in terms of their environmental sustainability and circularity. The higher the value of the indicator for an alternative, the more preferable it is compared to the lower-ranked ones. An essential aspect of this methodology is that both types of assessment, environmental sustainability and circularity, are following identical system boundaries. Thus, the product system under study for the quantification of the environmental impacts of the asphalt mixtures is identical with the corresponding product system used to quantify the Material Circularity Index. This is an important consideration, that enables the incorporation of both assessments' outcomes into one single indicator.

4. Case Study and Results

4.1. Definition of the Case Study

In order to demonstrate the usefulness and functionality of the developed indicator and provide an insight into how it ought to be utilized in a comparative approach, a case study has been defined and undertaken. In this study, four different asphalt mixtures for wearing courses are analyzed in terms of their environmental impacts (LCA_T), Material Circularity Index (MCI_{MRA}) and ultimately environmental sustainability and circularity indicator ($ESCi$). As the baseline of the comparison, a conventional asphalt concrete mixture with nominal grain size of 20 mm with 0%RA (AC20) was selected and the rest of the alternatives were defined as three asphalt concrete mixtures with 20 mm nominal grain size, containing 30%, 60% and 90% RA, respectively [29,40–44]. The asphalt mixtures were designed according to the ANAS (Italian National Road Authority) specification, which is followed for the asphalt mix designs in Italy [45] and were produced in Catania, Italy. The description of the asphalt mixtures under study can be seen in Table 1.

Table 1. Specifications and recipes of the investigated asphalt mixtures.

Mixture	0% RA	30% RA	60% RA	90% RA
Definition	Asphalt mixture for wearing courses, Type A grading band, following the ANAS specifications			
Coarse aggregates [Kg]	505.5	399.69	238.4	88.5
Fine aggregates [Kg]	368.1	223.4	95.8	-
Filler [Kg]	65.4	36.4	38.5	-
Virgin Bitumen [Kg]	61	40.51	27.3	11.5
RA [Kg]	0	300	600	900

The values refer to a total of 1tonne of asphalt mixture produced.

Moreover, the transport distances of the raw materials from the quarry to asphalt mixing plant were 23 km for the coarse and fine aggregates, and the filler; 35 km for the bitumen, while for the RA, the transport distance has been considered 0 km. This assumption encompasses two considerations. Firstly, the transport distance and the impacts of the transportation itself, between the site where the asphalt layer was milled and the asphalt mixing plant, was already considered at the end of life stage of the previous life cycle of the asphalt pavements. Secondly, the RA after being produced through milling was transported and stored inside the very same mixing plant, where the production of the asphalt mixtures took place, setting thus the transport distance 0 km. Finally, in Table 2, the energy and fuel requirements for the production of 1 tonne of each mixture can be seen. Finally, considering the utilization of RA, according to the EAPA's guidance document for preparing PCR and EPD for asphalt mixtures [34], the energy requirements for the screening and processing of 1 tonne of RA was assumed as 47 MJ/t.

Table 2. Energy and fuel requirements for the production of the asphalt mixtures [46–49].

Mixture	0% RA	30% RA	60% RA	90% RA
Electricity [MJ/t]	23	17.02	11.3	8.9
Diesel [Kg/t]	7.8	7.1	6.6	6.2
Heating Oil [Kg/t]	7.3	5.4	4.38	3.86
Natural Gas [Kg/t]	0.95	0.81	0.67	0.54

4.2. Quantifying the Environmental Impacts of the Asphalt Mixtures through Life Cycle Assessment

4.2.1. Goal and Scope

After the definition of the asphalt mixtures used in the case study, the LCA exercise was undertaken. As mentioned in Section 3, the LCA was conducted following the ISO 14040 and 14044. The software and databases utilized were Gabi ts, by Thinkstep—a Sphera company—and Gabi Professional and Ecoinvent 3, respectively. The data for the completion of the LCA was secondary data, acquired by EPDs, PCRs and reputable literature sources [46–49]. The goal of the study is to quantify the environmental impacts of the predefined asphalt mixtures following a “cradle-to-gate” approach, to normalize and weight them, for use in the quantification of the ESC_i . The impact assessment methodology utilized was the ReCiPe 2008 (H), along with its EndPoint Normalization [Europe, including biogenic carbon (person equivalents)], and EndPoint Weighting [(H/H) including biogenic carbon (person equivalents)] methodologies [50].

4.2.2. System Boundaries and Declared Unit

The system boundaries of the product systems under study were defined as the production of the asphalt mixtures, namely Product Stage A1–A3. This stage includes the extraction of raw materials, their transport to the asphalt mixing plant and the production of the final asphalt mixtures. The system boundaries' definition was conducted according to the EAPA and NAPA guidelines, and the EN 15804 specifications [34,35,51]. A more detailed representation of the system boundaries can be seen in Figure 3.

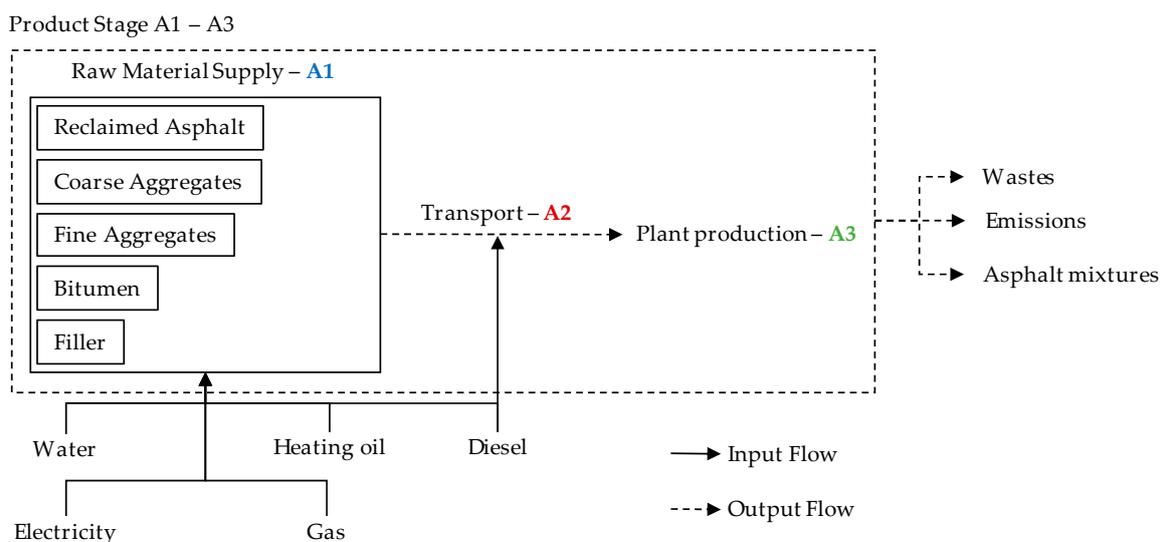


Figure 3. System boundaries of the investigated product systems.

Finally, since the adopted approach is “cradle-to-gate”, the declared unit defined for the LCA exercise, according to EAPA and NAPA guidelines and the EN 15804 specifications [34,35,51], is 1tonne of produced asphalt mixture.

4.2.3. Normalized and Weighted Results of the LCA

Having defined the case study and acquired all the required data, the LCA exercise was conducted, along with the normalization and weighting of the final outcomes of the impact category indicators. The results are summarized in Table 3. As mentioned before, the methodologies utilized for the normalization and weighting were:

- ReCiPe2008 (H): EndPoint Normalization [Europe, including biogenic carbon (person equivalents)];
- ReCiPe2008 (H): EndPoint Weighting [(H/H) including biogenic carbon (person equivalents)].

Table 3. Normalized and weighted results of the LCA exercise.

Mixture	LCA _T
0% RA	18.10
30% RA	12.90
60% RA	9.32
90% RA	5.71

It is worth mentioning, for transparency reasons, that the normalization and weighting factors can be found in the official document describing the ReCiPe 2008 life cycle impact assessment methodology [50].

4.3. Quantifying the Product Level Material Circularity Index of the Asphalt Mixtures

Moving on to quantify the product level Material Circularity Index of the predefined asphalt mixtures with RA, the methodology proposed by Mantalovas and Di Mino was utilized [10]. It is a methodology based on the EMF, with the exception that it also incorporates within the Utility factor [X] of the end-products, the asphalt mixtures in this case, their fatigue and permanent deformation resistance. In other words, the utility factor, is now calculated through a two-step process. Firstly, the performance of the asphalt mixtures in terms of fatigue and permanent deformation is defined and secondly, the utility factor is calculated. At this point, it is worth mentioning that for higher utility of the asphalt mixtures, it is preferable that for the same value of microstrain, a higher amount of loading

cycles is achieved regarding the fatigue resistance of the mixtures, while for the permanent deformation resistance, lower rutting depth is preferred for the same amount of loading cycles. The formulae, that are used for the calculation of the utility factors' performances parameters can be found below:

$$P_F = \frac{F}{F_{av}}, \quad (2)$$

$$P_{PD} = \frac{1}{\frac{PD}{PD_{av}}}, \quad (3)$$

where F , is the average number of loading cycles before fatigue failure, and F_{av} is the actual average lifetime of an industry average asphalt mixture; namely, the asphalt concrete mixture with 0%RA in this case. Accordingly, PD is the average number of loading cycles before achieving a specific rutting depth value and PD_{av} is the equivalent number of loading cycles of an industry-average asphalt mixture before reaching the very same value of rutting depth. The utility factor in this way can be calculated as the product of all the quantified performances; In this study, the fatigue and permanent deformation performances were utilized, as they are two independent characteristics of the end-products that correspond to different mechanical stresses. The formula quantifying the utility factor can be seen below:

$$X = \prod_{i=1}^n [P_i], \quad (4)$$

It hence, becomes apparent that for the evaluation of the final Material Circularity Index of the investigated asphalt mixtures, data about their fatigue and permanent deformation resistance is necessary.

4.3.1. Results Obtained by the Laboratory Testing and Calculation of the Utility Factors

In order to proceed, two experimental campaigns were launched and undertaken. The first one included the implementation of a permanent deformation resistance test by utilizing a wheel tracking machine (WTM) [52], while the second one was the identification of the fatigue resistance of the asphalt mixtures by means of Four-point bending test on prismatic asphalt specimens [53]. Table 4 presents the results obtained by the completion of the aforementioned tests in terms of the number of loading cycles when $0.5 \mu\epsilon$ of deformation was reached for fatigue, and depth of rutting (mm) after 20.000 loading cycles for permanent deformation. Moreover, the final values of the utility factors $[X]$ can be seen in Table 4, as well.

Table 4. Results obtained for the fatigue and permanent deformation resistance for the asphalt mixtures under study.

Mixture	0% RA	30% RA	60% RA	90% RA
Number of loading cycles at $0.5 \mu\epsilon$ [N_f]	4461	3641	5527	1198
Rutting depth at 20.000 loading cycles [mm]	5.2	6.7	3.1	2.7
Utility Factor $[X]$	1	0.63	2.08	0.52

4.3.2. Final Calculation of the Material Circularity Index of the Asphalt Mixtures (MCI_{MRA})

Having obtained the corresponding utility factors for every asphalt mixture, the next step is to calculate the Material Circularity Indices of the asphalt mixtures. To do so, the described methodology has been utilized. The required data for the quantification has been acquired and summarized in Table 5, where the inputs and outputs of the final Material Circularity Index can be found.

Table 5. Inputs and outputs of the Material Circularity Index quantification.

MCI_{MRA} of the Investigated Asphalt Mixtures with RA		0%RA	30%RA	60%RA	90%RA
<i>DEFINITION</i>	<i>SYMBOL</i>	<i>VALUE</i>			
Mass of Virgin Feedstock used	V (Kg)	1000.00	700.00	400.00	100.00
Fraction of feedstock derived from recycled sources	P _{RA}	0.00	0.30	0.60	0.90
Mass of the finished product	G _{MRA} (Kg)	1000.00	1000.00	1000.00	1000.00
Fraction of the mass of the product collected for recycling at the End-of-Life	F _{RA} = ΔU	0.00			
Amount of waste going to landfill or energy recovery	W _{EoL} (Kg)	1000.00	700.00	400.00	100.00
Quantity of waste generated in the recycling process	W _T (Kg)	0.00	0.00	0.00	0.00
Quantity of waste generated to produce any recycled content used as feedstock	W _P (Kg)	0.00	6.12	12.24	18.37
Efficiency of recycling process as treatment	E _T	98%			
Efficiency of the recycling process as production	E _P	100%			
Overall amount of unrecoverable waste	W (Kg)	1000.00	703.06	406.12	109.18
Linear flow index (LFI)	LFI	1.00	0.70	0.40	0.10
Utility factor	X	1.00	0.63	2.08	0.52
Utility factor built as a function of the utility factor X of the asphalt mixtures	F[X]	0.90	1.43	0.43	1.73
Product Level Material Circularity Index	MCI _{MRA}	0.1	0.1	0.83	0.82

4.4. Assessing the Environmental Sustainability and Circularity Indicator (ESC_i)

The final step of the methodology is the quantification of the Environmental Sustainability and Circularity Indicator. As described in Section 4.3, the required inputs for this quantification are the normalized and weighted results of the LCA exercise (LCA_T) per mixture, and the MCI_{MRA} with the integrated fatigue and permanent deformation performances, also per mixture. The latter has been calculated and presented in Section 4.2.3 and the former in Section 4.3.2. The calculation has been performed according to the formula (1), as defined in Section 3.3. The final values of the ESC_i can be seen in Table 6 below.

Table 6. Final results of the ESC_i quantification.

Mixture	ESC_i
0% RA	7.38
30% RA	10.01
60% RA	68.42
90% RA	73.08

It can be clearly seen that the higher the percentage of reclaimed asphalt into the asphalt mixtures, the higher the value of the ESC_i. However, a higher rate of increase in the value of the described indicator can be observed between the alternatives with 30% RA and 60% RA than between the cases of 0% RA and 30% RA and 60% RA and 90% RA, respectively. This is something strongly correlated with the fatigue and permanent deformation performances of the asphalt mixtures, and with the increasing reclaimed asphalt percentages utilized in the mixtures. The higher the RA% incorporated into an asphalt mixture, the higher the energy demands for its screening and processing since an increased amount of RA is now in need to undergo these processes.

Discussion of the Obtained Results

In addition, Figure 4 depicts the summarized results for the LCA_T, MCI_{MRA}, and ESC_i, versus the RA% incorporated into the asphalt mixtures. For the specific case study, the higher the percentage of the incorporated RA in the asphalt mixtures, the higher their combined environmental sustainability and circularity, as end-products. This is something to be expected. Significantly fewer virgin materials are introduced into the product system, less energy is required for the heating and mixing of the

aggregates and the bitumen for the production of the asphalt mixtures, and fewer materials have to be transported to the asphalt mixing plant from distant location. All these parameters are assisting towards reducing the damage to humans, ecosystems and resource availability in this way. Moreover, decreasing the utilization of virgin raw materials seems to have direct effects on the environmental performance of the asphalt mixtures. In other words, increasing the RA% within the asphalt mixtures, their aggregated environmental impacts to human health, ecosystems and resource availability are consistently decreasing. It is also noteworthy that the developed indicator is capable of emphasizing the most environmentally-friendly alternative since it can provide an enhanced discriminating criterion. This criterion is the ratio between the maximum and minimum values per alternative and indicator quantified. In other words, for the LCA_T , the aforementioned ratio accounts for $18.10/5.71 = 3.17$, for the MCI_{MRA} is $0.83/0.1 = 8.3$, and finally, for the ESC_i the value is $73.08/7.38 = 9.9$, indicating an even more rigorous discriminative aspect between the most environmentally-friendly and circular alternative, than only considering the environmental impacts and the Material Circularity Index of the asphalt mixtures separately.

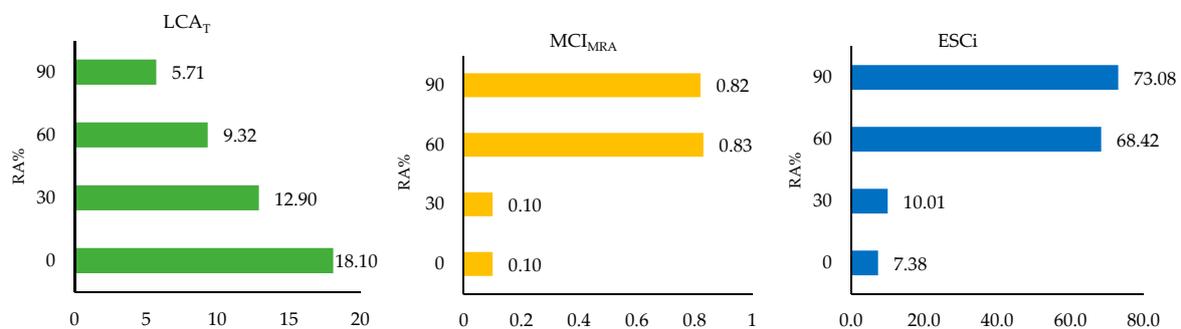


Figure 4. Summarized results for the LCA_T , MCI_{MRA} , and ESC_i values per mixture (0%, 30%, 60%, and 90%).

However, the same trend is not exhibited for the MCI_{MRA} of the asphalt mixtures, if investigated individually. From Figure 4, it can be seen that the MCI_{MRA} of the mixture with 0%RA is the same with the MCI_{MRA} of the 30%RA mixture. In addition, it is noteworthy that the Material Circularity Index of the 60%RA mixture is higher than the corresponding MCI_{MRA} of the asphalt mixture with 90%RA. A key parameter that led to these results is the technical performance of the mixtures. The environmental benefits acquired by the inclusion of RA within the 30%RA and 90%RA mixtures, are partially jeopardized by their poorer performance in terms of fatigue and permanent deformation. In detail, for the same achieved deformation ($0.5 \mu\epsilon$), the mixture with 60%RA had to undergo 5527 loading cycles, while for the mixture with 90%RA, 1198 loading cycles were required, indicating the superiority in terms of fatigue resistance of the former. This also indicates the key role that the technical performance of an asphalt mixture plays for its circularity. Regarding the investigated RA values, the percentage of 30% is considered, in current technical practices, as a threshold not to be exceeded, especially if the final bituminous mixture is designed for the wearing course of an asphalt pavement. However, several studies confirm the adequacy of the mechanical performance of mixtures with higher percentages RA [29,54–57]. It is therefore essential, for the RA content threshold, to be revised and updated upwards, so that the impacts of the asphalt mixture production on ecosystems, humans and resources, can actually be reduced. Hence, although the actual recycling practice of re-incorporating RA into asphalt mixtures is environmentally sustainable, it cannot be characterized circular in every case and under any circumstances. This proves that, as aforementioned, it is important that the sustainability implications of a CE-related action must be thoroughly investigated case by case.

5. Summary and Conclusions

Paving the path towards more sustainable and circular operational patterns within the road engineering industry and its satellite clusters, frameworks such as the Life Cycle Sustainability Assessment, Life Cycle Assessment, Life Cycle Cost Analysis, and Multi-Criteria Decision Analysis, seem to be gaining strength and establishing their influence on decision-making processes in a steadily increasing rate. However, so far, during the implementation of these frameworks, individually or in parallel, a significant element for these assessments seems to be missing; the Circularity Assessment [58–60]. This study, thus, attempts to provide a stepping stone towards the merging of two assessments; Sustainability and Circularity. To do so, a composite indicator expressed as a relationship between the aggregated, by means of normalization and weighting, environmental impacts of the “cradle-to-gate” life cycle stage of asphalt mixtures and their product level Material Circularity Index, was developed. It can be characterized as a weighting method, capable of weighting the aggregated environmental impacts of an asphalt mixture with RA, using as a weighting factor its own circularity. In this way, when different alternatives are considered, the utilization of the indicator, can provide national road authorities and involved stakeholders a ranking of their alternatives in terms of combined environmental sustainability and circularity. In this way, the road engineering industry can progress towards more accurate environmental assessment of their circular practices and their operational patterns in general.

A case study has been defined and undertaken in order for the functionality and usefulness of the indicator to be presented. Four asphalt mixtures with 0%, 30%, 60%, and 90% Reclaimed Asphalt, respectively, have been assessed in terms of their Environmental Sustainability and Circularity Indicator. It became apparent that the mixture with 90%RA exhibits the highest ESC_i , along with the lower environmental impacts and the second highest Material Circularity Index. While the RA% that is incorporated into the asphalt mixtures is increasing, the values of the ESC_i indicator are increasing as well, proving that the most circular and environmentally sustainable alternative, for the context of this study is the one with 90%RA. Having developed the ESC_i indicator and utilized it into the described, pragmatic case study the following conclusions can be drawn from it:

- For the specific case study, the asphalt mixture with 90%RA presents the highest value of ESC_i and thus, represents the most environmentally sustainable and circular alternative among all the investigated ones.
- Higher RA% in some cases are able to alter the mechanical performances of the asphalt mixtures but they tend to reduce the cradle-to-gate environmental impacts of the asphalt mixtures.
- The circularity of the asphalt mixtures with RA is highly dependent upon the fatigue and permanent deformation resistances of the asphalt mixtures and thus, directly related to the RA% incorporated in them.
- The utilization of the ESC_i indicator is able to weight the cradle-to-gate environmental impacts of an asphalt mixture through its circularity and thus, provide a more appropriate ranking factor than considering the mixture’s environmental impacts or level of circularity individually.

Road authorities, public or private, along with the involved stakeholders and actors could utilize the developed indicator in the stages of design, construction and maintenance to better discriminate and promote asphalt mixture alternatives that can be environmentally beneficial while exhibiting high levels of circularity and adequate mechanical performance [29,54–57]. The results that can be obtained through its utilization can help them identify the most environmentally sustainable option that simultaneously exhibits the most desirable levels of circularity. A more sustainable and circular decision-making approach, which is also data and evidence-based can be adopted in this way; and the riddance of the currently dominating linear operating patterns can be achieved in a controlled way, promoting the desirable preservation or even enhancement of ecosystems, societies and human health. Responsible governmental bodies along with their corresponding national road authorities and pavement engineers should move towards the implementation of sustainability and circularity

assessment methodologies and support the update of technical standards and specification, in order to promote the utilization of increased percentages of recycled and innovative materials that are affiliated with lower environmental impacts, higher circularity indices and equivalently accepted mechanical performances.

This process, which is aligned with the global attempts of safeguarding natural resources, the environment and the human health, seems to be strictly dependent upon the will of national road authorities to implement policies aimed at revising and updating technical standards and specifications. This could be achieved through the inclusion of innovative and/or circular materials, after having evaluated both the technical and economic compliance, as well as the environmental profitability of their production and utilization processes, which is something that the developed indicator is taking under consideration and can ultimately project. In this direction, the research revolving around innovative tools, methodologies and decision-making support criteria, such as the ESC_i , is set with the aim to establish the choices made by the national road authorities and the relevant actors as scientifically valid and publicly transparent. This can support a controlled and transparent transition from the currently linear approaches, to scientifically-sound, circular and environmentally sustainable ones.

The extensive application of the decision-making tool to other products and materials belonging to the civil construction market, or in any case to other product markets, appears absolutely adequate when the type of circular approach is of a closed loop type; namely, when the original product, materials or components are integrated back into the manufacturing process or processes in which they were generated, and manufactured into new, similar, or equal value and performance products.

However, even circular processes of products that go through different sectors and/or markets, the developed decision-making tool can still be utilized via sensitivity analyses of the ESC_i indicator, since the LCA_T and MCI_{MRA} parameters vary respectively, by giving prominence to the one considered strategically most relevant in a case-by-case perspective.

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